Marine Institute

Sustainable Energy Ireland

Accessible Wave Energy Resource Atlas : Ireland : 2005

4D404A-R2

ESBI Engineering & Facility Management Ltd
Stephen Court, 18/21 St Stephen’s Green, Dublin 2, Ireland
Telephone+353-1-703 8000 Fax+353-1-661 6600
www.esbi.ie

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Change History of Report

Date	New Rev	Author	Summary of Change

Abstract

This report, to accompany the Irish Wave Power Atlas 2005, describes an initial comparison between several years of hourly wave forecasts (using WAM) on a grid of points located off the Irish coast with corresponding records from a number of buoys installed in recent years.

Based on the level of agreement found the wave forecasts were then modified slightly and used to estimate and map the mean annual power and energy resources at the theoretical, technical, practicable and accessible levels.

The work builds on previous studies to advance understanding of the factors that influence the scale and distribution of these resources. It also places them in context with other users of these waters to facilitate decision making and minimise possible hindrance to future resource utilisation.

The average annual accessible electrical energy available from the 'box' considered almost equates with the annual output of ESB at present with an annual market value of approximately €2.7 billion. Indications are that the projected levelised cost may lie in the range 10.5 – 18 cents/kWh using currently available technology in favourable areas reasonably close to shore with installations in the range of 20-160kW. The range is extended to include indicative resource cost curves for projected developments of differing scale utilising the Mayo and Kerry wave fields and showing the impact of the differing transmission voltages.

The report contains 31 figures, 43 tables and 127 graphs and is based on the analysis of approximately 51 million individual forecast and recorded values of significant wave height and wave period.

Accessible Wave Energy Resource
Ireland : 2005

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Marine Institute,
Galway Technology Park,
Parkmore,
Galway.

ESBI Environmental Services,
Stephen Court,
18-21 St. Stephen’s Green,
Dublin 2.

Sustainable Energy Ireland,
Glasnevin,
Dublin 9.

Contents

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A. Fitzgerald, E. Sweeney, G. Westbrook, Marine Institute; Ms. K. Polaski, Sustainable Energy Ireland; M. White, A. Jarocki, Nowcasting International, T. Burke, A. Kineen Dept. of Communications Marine and Natural Resources; K. Packer, G. Griffiths, Dept. of Agriculture and Rural Development (N.I.), Capt. K. O'Higgins, Capt. R. McCabe, Commissioners of Irish Lights; Lt. Cdr. A. McGinn, Naval Service, Capt. C. Mowlds, Ms. B. Moncrieff, Irish Maritime Development Office; O. Tully, D. Rihan, M. Keatinge, Ms. G. O'Brien, Bord Iaschaigh Mara; Dr. A. Lewis, B. Holmes, Dr. J. Murphy, Hydraulic & Maritime Research Centre, Cork; D. McGinnes, A. Scott, D. Pizer, Ocean Power Delivery; E. Friis-Madsen, H.C. Soerensen, L. Christensen, Wave Dragon; W. Dick, Dr. P. Brewster, Wavebob; B. Mahon, Duchas, Ms. W. VanHoeve, Met. Eireann; J. Woge Neilsen, Danish Meteorological Institute; Kingfisher Information Services, G. Ewing, Dr. A. Buckley, Ms. E. Cleary, Ms. M. Gibbons, Mr. D. Finn, Ms B. Byrne, A. Higgins, ESBI.

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P.J. McCullen, Project Manager

Glossary of Terminology

More specialised terms are defined in the appendices where they occur.

Clapotis:	A standing non breaking wave caused by a combination of incoming and reflected waves off vertical structures or cliffs.
Bathymetry:	Characterisation of seabed elevation by charting depths from sea surface at different locations around coast.
Bivariate Distribution:	A rectangular table linking Hs and Tz (located along the vertical and horizontal edges respectively to define a unique box in the table for each value of Hs and Tz). The boxes may contain the number of occurrences of these joint values within a given time or the power developed by a particular wave converter for each such occurrence. Combining two such tables gives an estimate of electrical conversion from a given sea state over a period of time e.g.

	5	0	0	0	0	0	0
	4	0	0	0	0	1	0
Hs	3	0	1	**8**	7	2	0
	2	2	7	15	12	4	0
	1	4	16	20	12	3	0
		3	4	5	6	7	8

Tz

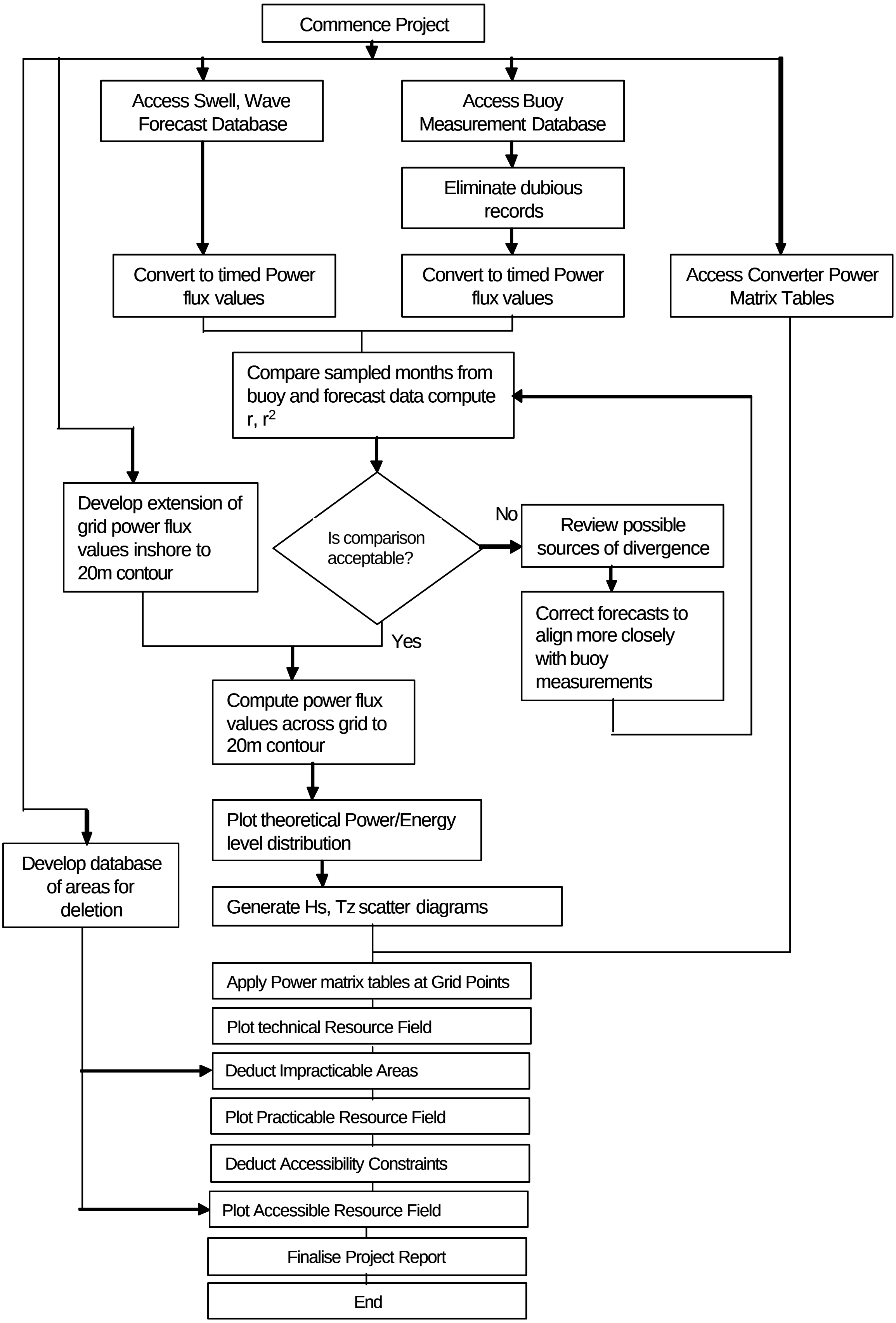
A simplified bivariate distribution table for a period showing that there were 8 simultaneous occurrences of Tz = 5 secs, and Hs = 3m. A similar table could be produced for a particular converter showing the power that it would generate for each Tz, Hs pair. Combining the tables allows estimation of energy output for the period in question.

Diffraction:	Where waves pass around a sharp obstruction, an abrupt change in wave height along the crest produces diffracted waves that transfer energy from the area of higher waves to that where they are lower. This is most marked at the ends of breakwaters but can occur in the sound between an island or reef and the mainland.
DMI:	Danish Meteorological Institute

Energy Units:	The basic unit of energy is the Joule. The basic rate of energy production (Power) = 1 Joule/sec = 1 watt • Units of Power: 1000 Watts = 1 kilowatt (kW) 1000 kilowatts = 1 Megawatt (MW) 1000 Megawatts = 1 Gigawatt (GW) 1000 Giga Watts = 1 Tera Watt (TW) • Units of Energy generated over time: 1000 Watts for 1 hour = 1 kilowatthour (kWh) 1000 Kilowatt hours = 1 Megawatt hour (MWh) 1000 Megawatt hours = 1 Gigawatt hour (GWh) 1000 Gigawatt hours = 1 Terawatthour (TWh) (Where electrical as opposed to physical or dynamic hydropower and energy is referred to, the above abbreviations have (e) added).
GIS:	Geographical Information System
HMRC:	Hydraulic and Maritime Research Centre (University College Cork)
Hs:	Significant Wave Height, originally being the mean height of the highest 33.3% of waves or more commonly 4 $(Mo)^{0.5}$ where now Mo is the variance of the sea surface elevation about its mean value.
Hydrodynamic Power Flux:	0.55 H^2_s Tz kW/metre length of wave crest.
Mn	The nth moment of a given wave spectrum.
Overfalls:	Irregular localised turbulent wave areas caused by a combination of wind wave and tide flowing over an irregular sea bed.
Pelamis:	A floating wavepower converter developed by Ocean Power Delivery Ltd. in Scotland.
r	Statitistical coefficient of correlation between two data sets.
r^2	Statistical coefficient of determination between two data sets.
RCPWPM:	Regional Coastal Processes Wave Propagation Model
RMS:	Root Mean Square Value of Measurements
Shoaling	As waves enter shallow water they are increasingly subject to frictional drag from the sea bed. The higher waves tend to break first leading to a gradual reduction in residual wave height and energy content. The effect is quantified by a shoaling coefficient Ks.

SPECTRUM:	A model developed by HMRC for estimation of the inshore wave regime along the Atlantic coast of Ireland.
SWAN:	A set of computer models for studying nearshore wave action (Simulating Waves Nearshore).
Talus:	A submerged slope of fallen rock debris found at the base of sea cliffs.
Tz:	Zero crossing period which is the average of the series of time intervals between two successive crossings of the mean sea elevation in an upward direction by waves in a given time record. Tz = (M2/Mo) where M2 is the second moment and Mo is the zeroth moment of the spectrum derived from the particular wave record.
WAM:	A widely used wave prediction model that links meteorological parameters to production of ocean wave regimes. (Wave Model).
WCB:	Whole Circle Bearing: The measurement of angles with reference to the whole clockwise circle between 0^o and 360^o rather than to a segment of that circle.
Wave Bob:	A floating wave power converter under development in Ireland.
Wave Dragon:	A floating wave power converter under development in Denmark.
Wave Spectrum:	The random elevation of the sea surface in deep water may be approximated as the sum of sinusoidal waves of different frequencies. Reversing the process the time record of the surface level may be analysed to identify its frequency content and the result plotted in the form of a curve to identify energy level versus predominant frequencies. This curve is the wave spectrum. Mo, M2, Mn are moments of the area within this curve. (This is not to be confused with the SPECTRUM model mentioned above).

Wave Energy Resource Atlas Flowchart 2004



Executive Summary

- **Introduction**

The Irish Wave Power Atlas was commissioned from ESBI by the Marine Institute in late 2004 with a view to documenting the differing levels of resource that exist around the coast as an aid to policy planning and development and in line with its objective of marine resource development and wealth creation. The project was cofunded by Sustainable Energy Ireland.

The Atlas permits a preliminary assessment to be made of the level of correlation available between the widely used WAM wave forecast model and measurements now being made at six recording buoys located around the Irish coast for meteorological purposes. A reasonably good degree of correlation was found but the work highlighted a number of potential areas for improvement into the future. Even at this relatively early stage (the buoys have only been installed over the past few years primarily in the interest of marine safety) the amount of data to be handled is very large and will increase into the future.

From an energy perspective it is particularly important to capture reference data throughout the Autumn, Winter and Spring periods of high production and electrical demand. The hourly WAM wave and swell forecast data was available for a grid of 724 points surrounding the country. Because of the shape of the coastline this still left a significant gap in places between the grid and the 20m depth line which was to be the inner boundary of the Atlas. Bridging of this gap was necessary to permit contouring of the resource outward and methods were evolved for this which formed a major preliminary part of the project.

There is no single unique level of the Irish wave power or energy resource. They vary non linearly with times and distance from the coast. The approach adopted has been to plot offshore power flux and energy contours and to tabulate the magnitude of the mean annual resource crossing the contours over their respective lengths within the study area. Thus the maps and tables are intrinsic parts of the Atlas and for this reason it is presented as a single document.

The initial mean ***Theoretical Resource*** distribution was then computed and mapped using a Geographical Information System. This represents hydrodynamic rather than electrical energy and is shown on Fig. 6.

The annual resource is, on average, significantly seasonal in character as shown in the accompanying diagram. In this it reflects electricity demand being high in winter and low in Summer, with Spring and Autumn at intermediate levels. The low level of Summer production facilitates the projected pattern of plant outages for access and maintenance purposes.

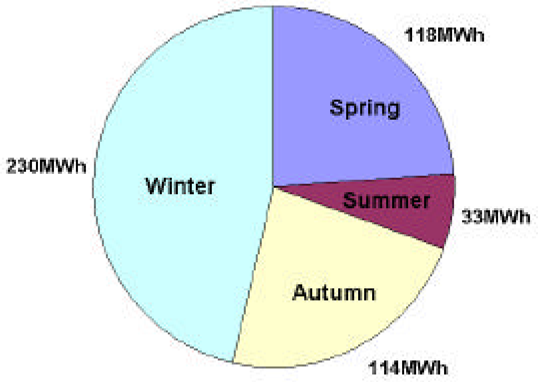


Fig. ESI

Seasonality of Theoretical Energy Resource

(MWh/m width of Wave front)

The next step was to convert this to electrical power utilising the conversion characteristics of one of the currently available converter types such as the Pelamis, Wave Dragon or the projected Wave Bob. This allowed mapping of the mean annual ***Technical Resource*** as shown on Fig. 16 using the Pelamis as reference converter.

This resource reflects the level of conversion efficiency available with current technology. The next stage is to identify the ***Practicable Resource*** following removal of shallows and rocky platforms or excessively deep areas where it would be currently physically impracticable to locate floating converters. Figs. 25,26

The final set of deletions are then made to yield the ***Accessible Resource*** Figs. 27, 28. These include all institutional/regulatory deletions based on environmental, safety, planning or other user criteria that would make wave farm development inappropriate. In general only part of the Accessible Resource may be commercially viable at a particular point in time depending on market conditions etc. Table ESI summarises the respective totals estimated for each of the above resource levels.

The distributions of the respective resources are important as significant development presupposes the availability of matching market and infrastructure onshore. Analysis of the foregoing maps and supporting data shows that, using the Pelamis as reference converter, the average annual electrical power flows and energy arising in the area of interest would range (depending on distance from the coast) as per Table ES1:

Table ESI

Summarised Electrical Resource Levels within Study Area

	Power Flow GWe (Mean)	Energy TWhe/yr (Mean)
Technical Range	0.29 – 4.1 (2.0)	2.4 – 28 (15.46)
Practicable Range	0.18 – 2.77 (1.6)	1.2 – 24.0 (13.93)
Accessible Range	0.14 – 2.4 (1.36)	1.06 – 20.76 (11.72)

It will of course be borne in mind that where results derived from forecasts or wave measurements are presented in terms of annual or seasonal averages these averages reflect the influence of intermittent storm events interspersed with longer more quiescent periods and should be used with care.

The accessible resource approximates to about 75% of the annual output on the ESB system with a current market value of €2 billion. Key issues relating to reduction of capital cost, improvement of capacity factors and management of medium and short term intermittency must be resolved if the resource is to contribute usefully to the Irish energy portfolio.

Production of comprehensive resource-cost curves was outside the scope of the project but curves to 2020 in the form of step functions prepared for the prime Mayo and Kerry wave power fields indicate the importance of economy of scale and the limits imposed by typical transmission distances and network voltage levels.

These suggest that installed capacities of 360-460 MW in the Mayo field could bring projected cost down to 8-8.5 cents/kWh while corresponding figures for Kerry suggest that capacities in the range 170-230 MW would yield a cost range of 9.6 – 10.6 cents/kWh.

In both cases the transmission voltage would need to be 110kV as use of 38kV would result in a doubling of cost/kWh.

While much of the report is concerned with the derivation and mapping of the offshore wave power resource, a key part of the project is the presentation of this along the coastal margin together with the onshore electrical network infrastructure. This is achieved via a series of sixteen lettered plates (A-P) which closely match the arrangement used previously for mapping the national wind power resource, with some modifications to permit inclusion of maximum sea area although for reasons of scale it cannot extend as far off shore as the areas shown in figures 1-28.

The Atlas of necessity provides a broad brush guide to the resource distribution and should not be taken as excluding the likelihood that well chosen hot spots may yield higher localised output and capacity factors.

Figure ES-2 Projected Resource-Cost Curves to 2020 Utilising 110kV Lines (Mayo, Kerry Wave Fields)

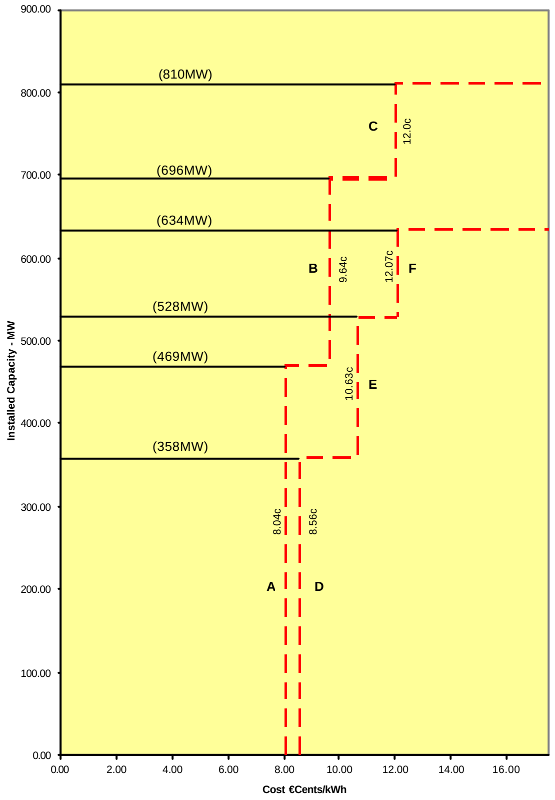
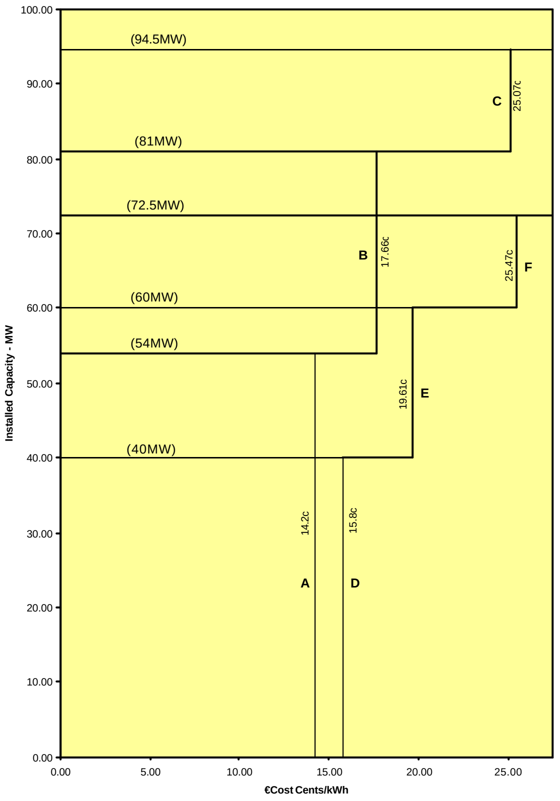


Figure ES-3 Projected Resource-Cost Curves to 2020 Utilising 38kV Lines (Mayo, Kerry Wave Fields)



1 Introduction

The Marine Institute has, in line with its mandate, been actively promoting the development of ocean energy resources with a view to enabling the development of commercially viable technical and industrial capacity in Ireland.

As part of the process of assessing the national ocean energy resource a strategic study of Ireland’s coastal resource was commissioned in 1999. In the light of the evolution of wave energy technology from fixed shoreline structures to floating converters and of recent new sources of wave data it was decided to update that study. Terms of reference issued by the Institute in July 2004 called for a limited study to assess the total, feasible and practical offshore wave energy resource addressing

- Wave energy levels impacting on the offshore environment in areas suitable for deployment of floating wave energy converters using computer models of wave climate validated with actual recorded data where possible.
- Conversion of estimated annual average wave energy levels to electrical output using relevant availability data and expected efficiency of suitable wave energy converters.
- Assessment of this data in terms of total, feasible and practical energy generation taking account of infrastructural, legal, planning and other constraints as appropriate.
- Production of a graphical/textual presentation of data acquired as well as an accessible GIS tool for presentation of data.

Based on its earlier detailed mapping and GIS database of the Irish wind energy resource on the onshore, offshore and related work (Ref. 1) for Sustainable Energy Ireland (SEI), and Dept. of Enterprise Trade and Industry (NI), ESBI has implemented a similar approach for this assignment that took account of the common hierarchy of resource availability now in use for assessing different types of renewable resource (Ref. 2).

It is intended that this report together with associated maps and CD should fulfil the final obligation above.

2 Scope of Report

The extent of the area for which data is provided in this study lies within the rectangle or ‘box’ bounded by the lines

East	(-4.25°W)	West	(-12.5°W)
North	(57.5°N)	South	(50°N)

Areas within UK waters are excluded with the exception of those areas around Northern Ireland which are included for information purposes on the basis that there is now a whole island energy market. The area to the west does not include the full extent of the continental shelf to which Ireland has rights, on the basis that the area is too far offshore for economic ocean energy development in the foreseeable future. A proportionately large wave power resource also exists there.

To familiarise readers with the terminology employed the report opens with a glossary and an explanatory section. The next stage is an evaluation of the unconstrained mean annual hydrodynamic wave power level across a grid of points in the seas surrounding the island (Fig. 1). These values are calculated from forecast hourly values of significant wave height, (Hs) (m), and wave zero crossing periods, Tz (sec.) at each point on the grid. The forecasts were originally produced by the Danish Meteorological Institute (DMI) using the WAM model (Ref. 10) for the Atlantic wind/wave regime and had been archived by Nowcasting International.

These records are calibrated via reports issued at regular intervals by DMI. The hourly records span the period 2001 – 2004 at 724 grid points. The grid point spacing is 0.25^{o} Latitude and Longitude which translates into a spacing between grid points of 27.5km North-South and 16.5km East-West respectively.

At this stage a comparison is made between the unconstrained hydrodynamic wave power data for key grid points and that derived from adjacent Marine Institute and other buoys on a monthly basis. Where the forecast values are found to be significantly different an adjustment is made.

In order to plot contours of theoretical resource throughout the grid it is necessary to define a string of values along an inshore boundary between the grid points and the coast. This represents the inshore coastal strip across which the offshore energy is dissipated through turbulence, refraction over shallows, reflection from cliffs and beach run up. It had been intended to use the results of the HMRC Spectrum model (produced for the Marine Institute) for this purpose but this proved to be unavailable for use as intended and a different approach became necessary.

The first constrained resource is reached when the technical resource is produced from the above theoretical figures. This involves consideration of the efficiency of the currently available technology to extract renewable energy in electrical form from the theoretical resource.

As the Pelamis converter is currently undergoing full scale tests and is scheduled for installation in Portugal in 2006 it was decided to utilise it as the basis for estimation of the technical power resource. Based on a power bivariate table of H_s, Tz values provided by Ocean Power Delivery, appropriate converter spacing and availability estimate, the above theoretical hydrodynamic power distribution was converted into electrical power output thus providing mean annual technical power and energy resource distribution.

The technical resource is constrained by deletion of areas of practical physical constraint such as shoals, lack of depth, infrastructure etc. to yield the practicable wave energy resource. This is then constrained further by the deletion of manmade, institutional or regulatory constraints that limit power extraction e.g. environmental, health and safety, energy policy, planning zonation etc. to identify the mean annual accessible power resource.

The extent of the accessible resource that is commercially viable will vary over time depending on cost and other pressures, constraints and opportunities.

This is displayed via contoured mean annual accessible power resource distribution around the coastline with the layout of the onshore electrical network shown via Geographic Information System.

It should be borne in mind that where results derived from wave measurements are presented in terms of annual or seasonal average figures, even though developed from hourly values, they will be distorted by intermittent events such as storms and must be carefully used in an informed way.

3 Earlier Work

3.1 Irelands Wave Power Resource (1982)

This report was commissioned by the then National Board for Science and Technology and Electricity Supply Board from Dr. D. Mollison of Heriot-Watt University in 1982 (Ref. 15). The report focussed on sea waves in deep water (> 90m) and was based on the use of three years of data (1978-81) from the UK Met. Office model spaced on a 50km grid.

Five reference sites were selected around the Irish coast (Malin, Belmullet, Porcupine, Valentia, Rosslare) and the power output calculated based on the directionality and mean power available between these points.

Monthly, seasonal and annual power flux levels utilising 30^o sectors, and corresponding exceedence curves were provided together with scatter diagrams of Hrms versus Te.

Three unequal seasons were utilised – Winter: (Oct. – March) inclusive

Summer: (May – August inclusive) and Equinoxial: (April, September).

The Salter or Edinburgh duck was used as the reference electrical power converter in estimating power output. The importance of the contributions arising in the 30^o sectors centred on true bearings of 235^o, 265^o, 295^o was emphasised, thus explaining the relatively poor power levels obtained on the south coast and particularly in the Irish sea. The projected mean power levels available and as output (utilising 1981 Salter duck design) were:

Table 3.1

Available Output kW/m

Location	Available Power kW/m	Output Power kWe/m
Malin	57	18.4
Belmullet	70	20.8
Porcupine	77	21.6
Valentia	62	19.0
Rosslare	24	9

The figure of 77kW/m for the Porcupine Basin was measured in circa 500m depth of water at an appropriate location of 52^o-42'N, 12^o–40'N. Intermittent measurements by others at depths of 360-830m over a period of one particular year around 52^o–23'N, 12^o-36'W suggested a weighted average of only 34kW/m.)

In considering whether the 1978-81 period was typical of long term records, Mollison noted that estimates of wave power levels off Belmullet were more closely correlated with wind speeds for Benbecula than for the much closer Belmullet meteorological station. He concluded that, given the number of variables involved, it was best to use the 1978-81 data without long term correction.

In this connection it may be noted that the North Atlantic Oscillation (NAO), which is a north-south oscillation of the track of storms across the North Atlantic and is measured by an index giving the difference between mean winter sea level pressures at Gibralter and Iceland, is closely related to winter storminess in the seas around UK and Ireland. The index showed an upward trend between 1965 and 1995 as did the observed storminess. The Mollison study used data from the middle of this period whereas the present work uses data from the period 2001 – 2004. Between 1995 and 2000 annual storminess was reducing although individual climatic events (terrestrial floods, freeze ups, heat waves, storms) were locally significant. In general long term records show high year on year variability in winter storminess with consequential impact on wave statistics.

In general Mollison's work formed an extremely useful early study.

3.2 Wave Climate Atlas of the British Isles (1991)

The results of several hundred instrument years of wave data from about 80 stations together with data from about 20 further stations, where measurements were conducted by other organisations, were utilised by L. Draper of IOS (Ref. 8) in the production of the first wave climate atlas of the waters around Britain and Ireland. Based on extensive consideration of wave height throughout the year in all relevant waters, the year was divided into four equal length seasons

Winter – January, February, March

Spring – April, May, June

Summer – July, August, September

Autumn – October, November, December

This was a compromise necessitated by the observation that the roughest months could be quite different in different UK waters e.g. North Sea and Western Approaches. Instrumental measurements being made at 3 hour intervals precluded the availability of monthly distributions due to the amount of sampling scatter involved.

With regard to persistence, it was noted that the number of occurrences of any particular combination of wave height and duration was so small that attempts to derive data amenable to consistent presentation in the Atlas without being misleading were not successful.

The data presented in the Atlas were arranged to provide scatter plots, contour maps, Hs exceeded for 10, 25, 50, 75% of year, and Hs exceeded for 10, 25, 50, 100% of each season together with an annual mapping of the most common value of Tz in these seas. Mean annual values as such were not provided.

The scatter diagrams (occurrences in parts per thousand to nearest integer, 0 < .5 ppt) were provided for wave measurements made at six light vessels (in UK waters only).

Where the nearest measurement location to a coast indicated moderately high waves the locations of the lower height contours were considered to be uncertain and a cut off was applied leaving the maps blank between the lowest defined wave contour and the coast. In coastal locations where measured wave heights were low it was possible to indicate the 0.5m Hs contour and avoid any cut off between it and the coast. Even in Summer this did not permit significant wave heights less than 2.0m to be shown along much of the Irish west coast apart from parts of Donegal and North Mayo. This Atlas gave a good overview of the distribution of Hs particularly east of a line from Derry to Cork and in the Irish sea. It did not specifically address issues of wave power or energy other than in a very broad sense as the amount of wave zero crossing period information is limited. Site specific measurements would be required for any projected wave power installation.

3.3 European Wave Energy Atlas (1996)

The European Wave Energy Atlas (WERATLAS) (14) was the first attempt to assess the offshore European wave energy resource using a common methodology and homogeneous data sets whose accuracy had been carefully evaluated.

Of the two wind wave models that had been routinely producing good quality hind casts for European waters since the mid 1980’s (UK Meteorological Office Model and the WAM model) the latter model was selected for the development of WERATLAS after comparison with four buoy stations in the Atlantic and two in the Mediterranean over a one year period. The global WAM model was run on a 3^o x 3^o latitude/longitude grid. As noted earlier the grid used in the current study is now at 0.25^o spacing.

Monthly, seasonal and annual wave power histograms and exceedance curves with scatter diagrams were presented. From an Irish perspective wave power roses are provided for a number of points in deep water off the Irish coast. The five calibration points used here were part of the UK Met Office Marine Automatic Weather Station (MAWS) network of open ocean buoys. In essence the European Wave Energy Atlas is an earlier and more general work than the present atlas which, although also based on WAM output, utilises more recently installed buoys for reference and is applicable to waters closer to the Irish coast.

3.4 Atlas of UK Marine Renewable Energy Resources (2004)

This recent document (Ref. 9) provides resource information on a regional scale over the extent of the UK Continental Shelf. It is intended primarily for use in strategic level considerations with later site specific measurements being required where a particular site is nominated for development. At the boundaries of the UK – Irish areas of Continental Shelf the UK Atlas and this present atlas show good agreement.

3.5 Eurowaves

This was (16) a prototype tool, developed with EU support (under MAST3) by Oceanor and its associates, capable of quickly and reliably assessing the wave climate at a coastal or shallow water location in Europe. It was envisaged as leading to the development of commercial packages and/or atlases initially for the European market. It involves integration of several modules including offshore wave statistics, detailed bathymetry of the relevant areas, wave models to transfer the wave conditions to the desired nearshore location and statistical evaluation of the nearshore wave statistics. The Eurowaves software links all the elements under Matlab on PC or Workstation to provide statistical wave data at a given European location in the coastal zone out to approximately 100km from the coast.

3.6 Seasonality

The seasonality adopted in this present report is

Winter	December, January, February
Spring	March, April, May
Summer	June, July, August
Autumn	September, October, November

This coincides with that adopted in Refs. (9, 22). The validity of this approach appears to be borne out by the close correlation of the Spring and Autumn resource regimes and the marked differences between those of Summer and Winter.

3.7 General Swell Directionality

The available buoys are non directional but the WAM data provided an hourly record of forecast directionality at the mapped grid points. This is discussed in Appendix 1 for eight stretches of coast where the frequency of approach direction is evaluated against each of twelve 30^o sectors. It is found that the bulk of the annual incident wave energy arriving on the Irish coast approaches from sectors 240^o to 300^o, with the 270^o sector predominating. There is relatively little seasonal variation in dominance of these directions although there is a small increase in the influence of the northerly 300^o sector in the north west (Donegal) and of the 240^o sector in the south west (Kerry) during winter. These results are tabulated in Appendix 1, (Table A1-1).

3.8 Buoy Locations

Table 3.2

Buoy Locations

Buoy M1	Latitude	53^o – 7.6’N	Longitude	11^o - 12’W
Buoy M2	“	53^o - 28.8’N	“	5^o – 25.5W
Buoy M3	“	51^o – 13’N	“	10^o – 33’W
Buoy M4	“	54^o – 40’N	“	9^o – 04’W
Buoy FSI	“	51^o – 22.25’W	“	7^o – 56.7’W

4 Unconstrained Theoretical Energy Resource

4.1 Calibration against Wave Buoy Records

This is discussed in detail in Appendix 2.

Initially the hourly wave buoy records were screened and cleared of anamolous values of Hs and Tz. From the resulting records, the mean monthly, seasonal and annual gross hydrodynamic power flux (kW/m) and energy levels are calculated and tabulated as % exceedance curves.

Corresponding data were prepared from the WAM records at grid locations close to the positions of the buoys and the output from both sets of data was compared. When sufficiently good agreement was obtained the WAM records are used to compute the theoretical resource distribution across all the available grid points in the sea area outside the 20m bathymetric contour line.

A series of 134 points on the 20m sounding line around the coast were evaluated using the methods of Appendix (4) to provide an inner set of boundary values for the contouring process. The offshore grid and buoy locations are shown on Fig. 1.

4.2 Wave Regime between Grid Points and Coast

4.2.1 Introduction

In order to provide acceptably representative contours of power flux between the innermost DMI grid points and the coastal margin, i.e. the 20m contour, it is necessary to calculate the significant wave height along that contour. The other variable factor in the power flux equation is the period Tz and this is taken to be essentially constant through the transition between deep and shallow water as the coast is approached.

The significant wave height at the 20m contour is in the general case a function of

- Initial deepwater significant wave height
- Subsequent shoaling effect
- Refraction effect (wave front turning to align with bed contours)
- Diffraction effect (around shoals or islands)
- Wave set up where deep water waves increase in height as they are forced upwards by the shallowing bed
- Reflection effect from cliffs and near vertical structures
- Tidal range (influence of varying depth) and current direction (e.g. against wind)

These variables are functions of the bathymetry of the bed in a particular location and the directionality of the incoming waves. As the bathymetry varies around the coast these are location specific elements and will give different results depending on the particular circumstances prevailing. For particular combinations of these elements nearshore energy ‘hot spots’ may be identified where by virtue of wave focussing the local power flux levels will be even higher than for a considerable distance offshore. The potentially short cable length requirement and influence on the true representation of conditions between the 20m and 50m depth contours suggest that this is an important resource factor even for floating converters.

The accurate analysis of the energy field in this inshore zone is a significant task which it was understood had been completed for the Atlantic Coast (at 1km spacing) via the HMRC SPECTRUM model and it had been proposed therefore to utilise this model in the present work.

4.2.2 SPECTRUM

An inshore wave model, SPECTRUM had been developed by the Hydraulic and Maritime Research Centre (UCC) for the Marine Institute to provide an estimate of the mean power level along the 20m bathymetric depth level which represents the inshore limit of the scope of this project. Unfortunately HMRC cautioned against application of Spectrum as envisaged on this project and it became necessary to utilise alternative methods for dealing with the loss in power flux that occurs in the shallowing water between the offshore grid points and the 20m contour. The unavailability of this model (utilising the updated offshore wave regime input) for this purpose was therefore a significant early setback.

Numerous methods exist whose cost of implementation would place them well outside the available budget of the present project, particularly when applied to the intricacies of the Irish west coast with its numerous bays, islands and shoals where refraction, diffraction, shoaling and reflection occur.

Several methods were reviewed in depth to resolve this issue and to distinguish between swell and local sea regime (Refs. (4-17, 18).

The method for estimating coefficients of refraction for shoaling and hence significant wave height at points on the 20m depth contour utilising linear (Airey) wave theory given in the Coast Protection Manual (Ref. 20) was selected. Its application is discussed in detail in Appendix 4.

4.2.3 Review of Selection Process

As noted elsewhere the gap between the offshore WAM grid points and the 20m contour was unacceptably large in a number of areas such as North Mayo and the South Coast due to the coastal orientation. It was therefore an intrinsic part of the study that this gap which had arisen in the absence of the SPECTRUM model should be filled. Recognising that the amount of WAM and buoy data available is less than the desirable ten year duration and that the level of bathymetric information available could also be usefully amplified it is reasonable that at this stage an approximate method would suffice as part of an overall learning process.

In a future site specific exercise the use of a grid or mesh based method such as SWAN or similar could provide a more precise assessment of the wave regime between the offshore grid points and the interaction of tidal streams with wave and swell regime where these may be locally significant. An important pre-requisite for such work would be high quality bathymetry. Fortunately this could be available by then for the important Atlantic coast where the changeable conditions that characterise some of the east coast sand banks are absent.

4.2.4 Rock Cliffs

These occur along many parts of the coast e.g. Donegal, Mayo, Clare, Kerry, Cork and Waterford on the Atlantic coast. Here wave reflection may be equal to the incoming wave giving the standing clapotis non breaking wave of high energy level where deep water occurs adjacent to the near vertical cliff face. Most cliffs will have some unknown level of talus or fallen rock piled against their bases leading to shallowing of water and increased wave breaking at the foot of the cliff. Reflection is reduced where wave breaking occurs. Again (Ref. 12) provides information on the non breaking (clapotis) case but the energy levels arising from the breaking case are not defined.

4.2.5 Nearshore Directionality

The underlying directionality associated with the swell component of the waves was evaluated for the sample months for which buoy data has been compared with the forecast combination of wave and swell and is discussed in Appendix 1 where Table A9.2 shows the percentage occurrence spread over twelve 30^{o} sectors at eight representative locations around the coast.

This gives an indication of the predominant direction from which the waves passing the innermost line of grid points will approach the 20m contour closer to the shoreline. The bulk of the annual incident wave energy arriving on the Irish coast approaches the Atlantic coast from the sectors 240° – 300° with 270° predominating. At the northern end of the coast 300° tends to emerge as dominant direction. Although it was outside the scope of this project to carry out a fully detailed distribution of wave regime including shoaling refraction and reflection etc. between the grid points and the coastline it was necessary to bridge the gap between grid points and 20m bathymetric contour and the methodology used in detailed in Appendices 4 and 5.

As the wave trains may approach the 20m contours at oblique angles the effective slope of the bed will differ from that applicable to an orthogonal approach and is estimated as detailed in Appendix 4. Using the forecast hourly wave data for the offshore grid points in combination with the sea bed slope between these points and the 20m contour permits the significant wave height and hence the theoretical power resource at the 20m contour to be estimated on an hourly basis.

The distribution of the mean annual theoretical power flux is shown on Fig. 5 and from this is derived the mean annual theoretical energy distribution as shown on Fig. 6. These are based on the records analysed during this study and it will be appreciated that with a longer record duration more extreme years, where the resource is higher or lower than average, are to be anticipated. The corresponding mean seasonal distributions are shown in Figs. 7-14. These are again solely based on the records available.

It can be seen that, as would be expected, the resource increases with increasing distance from the coast.

When compared with projections from other sources (Refs. 8, 9, 15) reasonably good agreement is obtained.

The directional impact leading to relative sheltering from prevailing swell direction is well brought out and accounts for the downward gradient in resource level as the Irish sea is approached from either north west or south west. The low values obtained in the Donegal Bay area facing west and north west into the Atlantic are at first sight surprising but are borne out by measurements at buoy M4.

The results are quantified by summing along the power contours and tabulating the output, Table 4.1.

This does not of course represent the gross theoretical resource above the Irish portion of the Continental Shelf. Full evaluation of that resource over the Continental Shelf is outside the scope of the current report which relates to the area covered by the grid shown on Fig. 1.

4.3 The Theoretical Annual Energy Resource

4.3.1 Introduction

Recognised renewable resource classification criteria were developed in Ref. (2) and are discussed in Appendix 3. They may be summarised as per Fig. 2. As stated above, this is estimated as the averaged gross hourly hydrodynamic power flux (kW/m) over the gross sea area outside the 20m sounding line. This is summed to obtain monthly, seasonal and annual hydrodynamic energy levels.

The use of the 20m sounding automatically deletes numerous islands, shoals and shallows. The figures in this report form an integral part of the interpretive process for all levels of resource.

4.3.2 Theoretical Resource Appraisal

Figure No. 3 shows that the mean annual significant wave height distribution exceeds 3m to within 50-100km of the west and northwest coasts. The south and east coasts and Donegal Bay are sufficiently sheltered from the prevailing wave direction for Hs to remain below 1.5m within 40-50km of the coast. Only in the southern part of the Irish Sea does mean Hs reach 1.5-1.75m at all. (It is probable that the locally high range of 1.5 – 1.75m in Galway Bay is an overstatement due to absence of data points there).

Figure No. 4 shows that the variation of mean annual distribution of Tz is very broadly similar to that of Hs. It is is however less variable. Mean annual Tz exceeds 8 seconds west of a north/south line lying about 10.5^o west (i.e. approximately 50-100km off the west coast). East of this there is a band along the west coast showing an average value of 7.5-8 sec. (In fact there is relatively little variation in Tz between the offshore values and those within this band but that small amount, derived from the available hindcast data is sufficient to project the existence of this band along the coast. Further data may lead to revision of the position in the future). Along much of the south coast Tz lies between 5.5 – 7.5 secs falling to 5.5 secs at the extremes to the Irish sea and 4-5 secs north of 53^oN.

The mean annual theoretical wave power flux is derived from the information summarised in Figs. 3,4 and is shown in Fig. No. 5. Power levels tend to reflect the importance of Hs where this is large and Tz where Hs is small. Based on the input as utlised, mean theoretical hydrodynamic power flux lies between 50-60kW/m within 25km of the Mayo and Kerry coasts. It falls rather sharply as one moves eastwards along the south and north coasts toward the Irish Sea, where the mean annual theoretical power flux is as low as 10kW/m. While Donegal Bay has poor levels between 10-20kW/m, the projecting coasts of West Galway, Mayo, Kerry reach annual values of 40-50kW/m at or within short distances of the coast. These are about 15% below the figures quoted in Ref. (15) for similar locations off Donegal, Mayo, Kerry and Wexford. Based on the available data, West Donegal appears to be somewhat sheltered from the contribution that waves from a south westerly direction would otherwise provide. This picture may improve as further data becomes available. The best sites near the coastline lie off the Mullet and Dingle Peninsulas.

Figure No. 6 shows the effects of summing the hourly power flux values to give the mean annual theoretical energy resource in MWh/m of crest width. As would be expected the more exposed parts of the coast show highest returns of energy (N.W. Donegal, W. Mayo, W. Galway and S.W. Kerry). The highest value obtained within 50km of the coast is 550MWh/m off N.W. Mayo. Near the coastline, values of 250-375MWh/m are more common on the Atlantic seaboard. East of a line joining Derry to the Fastnet Rock these fall to around 125MWh/m or below.

Examination of the mean seasonal theoretical wave power flux distribution Figs. 7-10 shows the marked impact of seasonality. As noted elsewhere the months have been grouped as follows:

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

The mean theoretical wave power flux varies significantly between seasons although close to the coast (within 50km) the Spring and Autumn flux distributions are very similar reaching 30-50kW/m on the western coast. On the southern, eastern and northern coasts the corresponding figures are only 10-20kW/m. During the Summer the whole coastline experiences a mean flux in the range 0-10kW/m with only the north west Mayo and Blasket Island areas (Kerry) penetrating into the 10-20kW/m regime that lies about 25km out in the Atlantic to the west.

The mean theoretical power flux during the Winter is strikingly different except in the Irish Sea and its adjoining areas on the north east and south coasts.

Much of the western coast lies in an area subject to 50-70kW/m. Within 25km of the most favoured parts of the coast 80-100kW/m is attainable while 100-120kW/m is shown to be available within 50-100km of the coast.

Figures No. 11-14 show the corresponding mean seasonal energy distributions in terms of MWh/m. Once again Spring and Autumn are largely similar in Irish waters, with the Spring levels being slightly higher than Autumn, thus bringing the 100-125MWh/m region to within 50-100km of the west coast. Summer is in general a very quiet season on average with levels of 0-25MWh/m on virtually the whole coast apart from the western promontories. Winter energy levels reach 225 MWh/m within 50km of the Kerry and Mayo coasts.

In general therefore the average available theoretical hydrodynamic power flux and energy levels peak during the Winter, fall significantly during Spring and Autumn and are particularly low during Summer. This is of course the expected pattern which superficially matches electricity demand and plant serviceability requirements.

The actual size of the resource in power and energy terms may be estimated by measuring the length of a particular contour for which the local level is known. For the purposes of this report it is conservatively assumed that as the bulk of the waves under consideration are swells originating at great distance they will cross each contour only once and that if the power is given up there, these swells will not gain further power en route to the coast. Thus the length of contour within the reference area is the key factor of interest.

Considering Figs. No. 5, 6 it may be deduced (Fig. 5) that given the lengths of the contours within the area under consideration, in power terms these yield averages annual as shown in Table 4.1.

Table 4.1

Theoretical Annual Average Hydrodynamic Power Flux

Contour Level kW/m (Fig. 5)	Contour Length km (Fig. 5)	Total Power Flux Crossing Contour GW
10	425	4.25
20	475	9.5
30	625	18.75
40	815	32.6
50	850	42.5
60	833	50.0
70	710	50.0
80	281	22.5

In annual energy terms Fig. 6 and the derived Table 4.2 show that the theoretical average annual hydrodynamic energy level varies with distance off the coast as shown by the contours of Fig. 6 within the “box” considered in this report, it varies between 49TWh and 525TWh, the lower figure being at the 125GWh/km line. (It will of course be appreciated that the gross energy occurring over the more distant parts of the Irish section of the Continental shelf will be a multiple of the above figures. Consideration of this additional resource lies outside the scope of the present report).

Comparison with Ref. (8) shows that the data is presented in somewhat different form from that adopted here. This makes direct comparison difficult. Nevertheless comparison of Fig. No. 3 herein showing Average Annual Hs Distribution with Plate No. 3 of Ref. (8) showing Hs exceeded for 50% of year, indicates good agreement. In addition Fig. No. 4 shows that the mean annual Tz distribution compares reasonably well with Plate 21 of Ref. (8), which shows the most common value of Tz. The seasons defined in Ref. (8) differ from those used in the present report which precludes seasonal comparisons.

During the preparation of this report the power and energy distributions were also evaluated for each individual year. In essence it was found that the proximity to the coast of given power flux and energy contours varied year on year, being closer in stormy years than in more quiescent years. This effect is compounded somewhat by swell directionality which is discussed in Appendix 1, where it is shown that the bulk of the annual wave energy arriving on the Irish coast does so from the sectors 240^o – 300^o with 270^o predominating. At the northern end of the coast 300^o is the dominant direction. The theoretical resource described above forms the driving force for the technical resource discussed in the next section.

Table 4.2

Theoretical Average Hydrodynamic Energy Resource

Contour Level MWh/m (Fig. 6)	Contour Length km (Fig. 6)	Annual Hydrodynamic Energy (TWh)
50	225	11.25
75	388	29.06
100	460	46.0
125	395	49.4
150	400	60
175	450	78.75
200	545	109
225	608	136.7
250	610	152.5
275	640	176
300	720	216
325	770	250.25
350	833	291.4
375	825	309.4
400	805	322
425	853	362.3
450	858	385.9
475	853	404.9
500	845	422.5
525	838	439.7
550	838	460.6
575	838	481.6
600	875	525
625	550	343.8
650	363	235.6
675	328	221.1
700	275	192.5
725	105	76.1

Table 4.3

Seasonal Theoretical Hydrodynamic Power Resource (GW)

Season	Contour Level kW/m	Contour Length kM	Total Power Flux Crossing Contour GW
Spring	10	450	4.5
(Fig. 7)	20	588	11.75
	30	713	21.38
	40	863	34.5
	50	850	42.5
	60	875	52.5
Summer	10	800	8.0
(Fig. 8)	20	325	6.5
Autumn	10	450	4.5
(Fig. 9)	20	563	11.25
	30	750	22.5
	40	823	33.3
	50	875	43.75
	60	875	52.5
	70	255	11.9
Winter	10	200	2.0
(Fig 10)	20	435	8.7
	30	375	11.25
	40	495	19.8
	50	613	30.6
	60	700	42
	70	800	56
	80	833	66.6
	90	855	76.95
	100	850	85
	110	825	90.75
	120	863	103.5
	130	395	51.35
	140	325	45.5
	150	185	27.75

Table 4.4

Seasonal Theoretical Hydrodynamic EnergyResource (TWh)

Season	Contour Level kWh/m	Contour Length kM	Total Energy Crossing Coutour TWh
Spring	25	463	11.56
(Fig. 11)	50	688	34.38
	75	800	60.0
	100	835	83.5
	125	875	109.38
Summer **(Fig. 12)**	25	825	20.6
Autumn	25	450	11.25
(Fig. 13)	50	615	30.75
	75	825	61.87
	100	863	86.25
	125	863	107.81
	150	313	46.88
Winter	25	250	6.25
(Fig 14)	50	525	26.25
	75	450	33.75
	100	575	57.5
	125	690	86.25
	150	790	118.5
	175	813	142.2
	200	850	170.0
	225	838	188.44
	250	838	209.38
	275	538	147.81
	300	325	97.5
	325	113	36.6

5 The Annual Technical Energy Resource

5.1 Introduction

It is necessary to consider some real converter when evaluating the technical resource. The ‘Pelamis’ is taken as the reference wave energy converter. The annual technical energy resource is estimated by averaging the annual electrical power that would arise at each node point when the sequence of hourly Hs, Tz pairs are inserted in the converter power table, working within the spacing, depth ranges and cabling limits specified for the particular converters. The power levels are summed to obtain the annual average electrical energy resource level.

Thus in the cases of both the theoretical and technical resource the averages have been obtained by the summation of the real individual hourly values rather than via the creation of an arbitrary resource level from a notional annual “average” Hs and an “average” Tz.

Evaluation of the technical resource requires that the theoretical resource be converted to its equivalent technical value via use of converter-specific scatter diagrams or bivariate distributions linking electrical output to the occurrence of particular significant wave heights (Hs) and zero crossing periods (Tz) from the statistical records that are available at each grid point and reference point on the 20m contour. Thus the occurrence of electrical power levels at these grid and reference points can be determined, leading to corresponding contours of power level across the area of interest. Figs. 15, 16. This highlights the fact that different power converter types will have different outputs depending on their particular response to the input data (Hs and Tz). The output values are calculated hour by hour and summed over time to get the mean levels.

At this point it is assumed that there is no restriction on laying out converter cordons in the sea so that the technical resource can be evaluated. Clearly the scatter tables provided by the developers must be considered to be indicative only and based on the limited duration of information available at this stage. (No warranty is expressed or implied that they will be found to represent specific ongoing conditions at the respective points or elsewhere).

5.2 Converter Spacing

Relatively little work has been published on the interaction between groups of wave converters and the extent to which energy continues to be available in the lee of a cordon of converters. For the purposes of this report it is assumed that a single linear cordon of converters two machines deep in staggered (echelon) formation, spaced at distances recommended by the respective developers can be used to estimate the electrical power and energy resource. (One developer whose converter spacing is quite generous (1km) suggests that a second cordon might be located 30-35km leeward of the outer cordon with a reasonable prospect of collecting additional power. This option has not been considered further in the current study but suggests an area for active research and quite possibly an enhanced resource).

The spacings suggested by the reference converter developer are

Pelamis: 40 @ 750kW machines to give 30MW capacity on an area of 2.1km length x 0.6km width implies 19 x 750kW = 14.25MW/km machines/km x 0.6km cordon width (machines 2 deep in echelon pattern).

This configuration of machines leads to the ranges of energy recovery and mean power levels shown in the figures. Essentially the different converter types may be distinguished by the number of machines allowed per unit length of cordon and the particular scatter diagram of Hs, Tz applicable in each case. Thus the technically available resource **varies with the distribution of the theoretical resource**, **the converter characteristics and the number of such converters per unit length of cordon** that are allowable without mutual interference and degeneration of output.

5.3 Technical Resource Appraisal

Estimation of the technical resource requires projection of the electrical power and energy levels that the historical wave regimes would attain if they were allowed to act upon a cordon of real converters or converter groups. The reference converter chosen for this purpose at the outset was the OPD ‘Pelamis’.

Fig. 15 shows the mean annual technical power resource in terms of MWe/km for the Pelamis. This is derived by an hourly comparison of the forecast Hs, Tz values with the corresponding values on the power scatter diagram for that converter. It is assumed that electromechanical conversion efficiency for the units is 85%, based on information supplied by OPD the machines are spaced in a single cordon as described in 5.2 above. The figure shows that such a cordon would produce 4.5MWe/km along a line within 75km of the west coast. 3-3.5MW/km would be obtainable within 25km over large sections of coastline (Donegal, Mayo, Galway, Kerry and part of Co. Clare).

Table 5.1 summarises the technical power flux levels obtainable using the Pelamis cordon at different distances from the coast. The contour lengths are limited to those occurring in the ‘box’ of interest.

Table 5.1

Average Annual Technical Power Levels Crossing Contours (Pelamis)

(a) Ave Contour Level MWe/km	(b) Contour Length km	Ave. Elec. Power at Contour = (a.b. ÷1000) GWe
1	288	0.29
1.5	550	0.825
2	625	1.25
2.5	725	1.81
3	850	2.55
3.5	1175	4.1
4	850	3.4
4.5	450	2.02

Summing the output per km of wave front yields the Mean Annual Technical Energy Resource for Pelamis (Fig. No. 16). (It should be noted that in Figs. 15-24 Pelamis creates its own contours of power flux and energy based on passing the WAM wave records at different locations through the Pelamis scatter table. A different converter will in general produce a different set of outputs although in the longer term these would be expected to converge towards a best attainable value as the technologies mature). Fig. 16 shows that an unrestricted cordon of Pelamis converters could produce the following average energy outputs at different distances offshore. (Table 5.2)

An important feature highlighted here is that a wave converter will usually perform best when operating in waves that match a particular region of its scatter table. In the case of the Pelamis 750 this lies where 3m < Hz <5 m. and 5 < Tz < 8sec. Thus Fig. 15 shows 'high performance' areas off the Irish West Coast where waves of this type predominate and this converter is projected to perform well. Going further offshore into an area of higher waves of longer period results in a reduction in performance of this particular machine whose scatter table reflects the fact that it has been optimised for operation off Portugal.

A disappointing feature is that the implied annual capacity factors are somewhat on the low side. They are not however dissimilar to those experienced during the earlier stages of wind power development and could be expected to improve with refinement in converter tuning and design.

Considering the seasonal power outputs using the reference converter, Figs.17, 19 show (as is to be expected from the earlier figures) that Spring and Autumn outputs are rather similar. It is notable that the power production regime off the north west coasts is higher in Autumn than in Spring, while the reverse is true off the South West coast. There are no significant differences in power outputs at the south and east coasts. Again Fig. 20 the Winter power output increases significantly (20-30%) over the Autumn figures while the Summer (Fig. 18) falls by 40% from 3.5 to 2MWe/km within 25km of the west coast.

Table 5.2

Average Annual Technical Energy Resource (Pelamis)

Contour Level GWh/km	Nett Contour Length km	Annual Elec. Energy TWh	Implied Capacity Factor %
8	300	2.4	6.4
10	363	3.63	8.0
12	612.5	7.35	9.6
14	563	7.89	11.21
16	628	10.04	12.82
18	640	11.52	14.42
20	720	14.4	16.02
22	775	17.05	17.62
24	812.5	19.5	19.22
26	862.5	22.4	20.83
28	862.5	24.15	22.43
30	862.5	25.9	24.03
32	875	28.0	25.63
34	800	27.2	27.24
36	625	22.5	28.84
38	575	21.85	30.44
40	313	12.5	32.09

The corresponding mean seasonal technical energy resource utilising the Pelamis is shown in Figs. 21-24. The Winter levels of the resource (Fig. 24) show that 10-12GWh/km would be obtainable utilising a Pelamis cordon within 50km of the whole west coast (apart from Donegal and Galway Bays). In Summer this figure drops to 4-5GWh/km (Fig. 22) while in Spring and Autumn (Figs. 21, 23) it rises to 8-9GWh/km.

5.4 Seasonal Capacity Factors (Pelamis)

The implied capacity factors shown in Table 5.2 are calculated on an annual basis. Higher values may be reached seasonally or over the shorter term. Figures 21-24 show the occurrence of contours of 2 -12 GWhe/km of electrical energy. The possible maximum operating hours for the seasons Spring, Summer, Autumn and Winter are 2208, 2208, 2184, 2160 respectively. Multiplying these by the installed capacity, 14.25 MW/km, gives the maximum outputs that could be delivered as 31464, 31464, 31122, 30780 MWhe/km respectively. Dividing the contour values by these seasonal maxima provides the implied seasonal capacity factors of Table 5.5. Inspection of Figures 21-24 shows that Capacity Factors reach the following values quite close to the coast: Spring (31.7%), Summer (19%), Autumn (32.1%), Winter (39%).

Table 5.3
Seasonal Technical Power Resource (Pelamis) (GWe)

Season	Contour Level MW/km	Contour Length kM	Total Power Flux Crossing Contour GWe
Spring	1	315	0.32
(Fig. 17)	1.5	525	0.79
	2	600	1.2
	2.5	693	1.73
	3	788	2.36
	3.5	820	2.87
	4	550	2.2
	4.5	425	1.91
Summer	0.5	500	0.25
(Fig. 18)	1	538	0.54
	1.5	700	1.05
	2	763	1.53
	2.5	650	1.63
Autumn	1	300	0.3
(Fig. 19)	1.5	525	0.79
	2	600	1.2
	2.5	750	1.88
	3	813	2.44
	3.5	825	2.89
	4	745	2.98
	4.5	425	1.91
Winter	1	100	0.1
(Fig 20)	1.5	275	0.4
	2	450	0.9
	2.5	613	1.53
	3	713	2.14
	3.5	800	2.8
	4	850	3.4
	4.5	875	3.94
	5	700	4.2
	5.5	575	3.16
	6.0	400	2.4

Table 5.4
Seasonal Technical Energy Resource (Pelamis) (TWhe)

Season	Contour Level MW/km	Contour Length kM	Total Power Flux Crossing Contour TWhe
Spring	2	313	0.63
(Fig. 21)	4	538	2.15
	6	688	4.13
	8	850	6.8
	10	400	4.0
Summer	2	450	0.9
(Fig. 22)	4	725	2.9
	6	250	1.5
Autumn	2	213	0.43
(Fig. 23)	4	538	2.15
	6	750	4.5
	8	775	6.2
	10	275	2.75
Winter	2	50	0.1
(Fig 24)	4	350	1.4
	6	650	3.9
	8	788	6.3
	10	850	8.5
	12	276	3.31

Table 5.5
Ranges of Implied Seasonal Capacity Factors (%)

Contour GWhe/km	Season			
	Spring	Summer	Autumn	Winter
2	6.3	6.3	6.43	6.49
4	12.7	12.7	12.9	13.0
6	19.07	19.07	19.27	19.5
8	25.4*	25.4	25.7	25.99
10	31.78*	31.78*	32.1	32.5
12	38.1*	38.1*	38.6*	38.98

(*Not reached in Figs. 21-24)

6 The Mean Annual Practicable Energy Resource

6.1 Introduction

Areas associated with wrecks, overfalls, extreme currents where the wave pattern may be distorted and where severe drag or fatigue may occur on downcomers (power cables, anchor, mooring cables) leading to converter damping are deleted.

It is of course arguable that at a future time, if the wave pattern at particular overfall locations has been adequately characterised through prolonged in-situ measurements they will be found to be acceptably predictable (because of the tidal stream influence) or even desirable for particular converter types and will be able to yield unusually high output.

Bearing in mind, however, the probable difficulties of mooring and utilising service vessels under such conditions, these areas are deleted at this point in time. It may also be noted that Pelamis is designed to function in areas where current < 1 knot.

6.2 Practicable Resource Appraisal

The specific deletions made are listed in Table 6.1 and the results of these deletions are shown in Figs. (25,26) showing distribution of Practicable mean annual power and energy resources. These result in Tables 6.2 and 6.3.

Table 6.1

Deletions made to establish Practicable Resource

- Areas with depth < 50m
- Areas at Overfalls (minor areas easily avoided)
- Areas at Wrecks (minor areas easily avoided)
- Areas further than 100km from coast (defined as baseline of 12 mile limit) as practical economic limit of transmission cabling at scales envisaged
- Areas where surface current exceeds 1.0 knot (Pelamis). In general these are within 50m depth zone or in areas where the average power resource is relatively small (Irish sea, North Channel).

Table 6.2

Average Practicable Power Levels Crossing Contours

(a) Ave Power Contour Level MWe/km	(b) Nett Contour Length km	Ave. Elec. Power at Contour GWe
1	175	0.175
1.5	463	0.694
2	550	1.1
2.5	650	1.625
3	815	2.45
3.5	790	2.77
4	550	2.2
4.5	400	1.8

Table 6.3

Average Annual Practicable Energy Resource (Pelamis)

Energy Contour Level GWhe/km	Contour Length km	Annual Elec. Energy TWh	Implied Capacity Factor %
8	165	1.2	6.4
10	290	2.9	8.0
12	463	5.55	9.6
14	500	7.0	11.2
16	513	8.2	12.8
18	575	10.35	14.4
20	625	12.5	16.02
22	663	14.58	17.6
24	720	17.28	19.2
26	790	20.54	20.8
28	820	22.96	22.4
30	800	24.0	24.03
32	670	21.44	25.63
34	600	20.4	27.24
36	550	19.8	28.84
38	450	17.1	30.4
40	275	11.0	32.09

Thus the electrical energy produced by the above notional single cordon of Pelamis machines operating at the 32GWh/km contour within 10-50km of the coast (as defined by the baseline to the 12 mile limit) would yield up to 21 TWh per year on average, depending on location. The optimum location in terms of output at minimum transmission and servicing cost would appear to lie near the 38MWe/km contour about 15km off the N.W. Mayo coast. The implied capacity factor rises from about 24% to 32% with increasing distance from the coast across the higher energy contours.

7 The Mean Annual Accessible Energy Resource

7.1 Introduction

A further set of deletions is made to exclude mineral extraction zones, special fishing areas, navigation lanes, windfarm concessions, fish farms, pipelines and cables, current network capacity limits and notified environmental zones and the average annual energy output associated with these areas. This results in the residual accessible mean annual energy resource.

The distribution of this resource is shown on Figs. (27, 28) and is quantified in tables (7.1, 2). As noted earlier the accessible resource may be further broken down into three segments viz.

- Viable Open Market Segment
- Viable Managed Market Segment
- Non Viable Market Segment

depending on current or projected market conditions and status of technological development.

Although methodology for addressing these issues as a function of market conditions has been developed by ESBI (Ref. 2), it is outside the scope of the present report to discuss these issues in detail. Apart from the nature of the resource, technological improvement and relative capital costs of other renewables and fossil fuels are major determinants in this area.

7.2 Accessible Resource Appraisal

Table 7.2 summarises the overall accessible electrical power flow levels obtainable using the Pelamis cordon at different distances from the coast. For the purposes of this report the cordon is assumed to be continuous and to lie along the respective contours shown on Fig. 27. However it is to be expected that such a cordon would in reality consist of intermittent groups of converters staggered so as to allow maximum sea room for navigation and wave transfer between the groups. In fact in this case there is relatively little difference between the Practicable and Accessible resources as the scale of the deletions made at the accessible stage is rather small. The purpose of the exercise is to highlight potential interface areas rather than to postulate outright arbitrary development restrictions on wave conversion because particular areas have e.g. fishery connotations at present.

Most of the deletions are too close inshore to have a significant effect on the contours of power and energy. Deletions from the lengths of these contours are made where sea bed cables or notional approaches to ports are crossed. Two large fishing areas are shown edged in red on Figs. (27,28). It is assumed that an indicative 50% reduction in contour length is made on passing through these areas. Further deletions might need to be made in respect of established submarine exercise areas. These effects can be noted in the changed nett contour lengths of Tables 7.2, 3 relative to Tables 6.3, 3.

In calculating these reductions the following are taken into account as detailed on Table 7.1.

Table 7.1

Deletions made to establish Accessible Resource

- Cable + Pipeline corridor Width: 1km per corridor (green on Figs.)
- Shipping Corridor Width: 5km per port corridor (green on Figs.)
- Fishery Blocks: 0.5 x contour length within blocks shown on Figs. 27, 28
- Marine Traffic Separation zones: contour length within zone
- Submarine exercise areas not included. (See Admiralty Charts)

Table 7.2

Average Annual Accessible Power Levels Crossing Contours (Pelamis)

(a) Ave Power Contour Level MWe/km	(b) Nett Contour Length km	Ave. Elec. Power at Contour GWe
1	140	0.14
1.5	326	0.49
2	447	0.89
2.5	569	1.42
3	734	2.2
3.5	688	2.4
4	460	1.84
4.5	340	0.53

Thus the effect of reducing available contour lengths to facilitate other users is to reduce the averaged electrical power per contour somewhat from 1.6GW to 1.36GW or 15% (derived from Tables 6.2 and 7.2). The equivalent energy figures are considered on Table 7.3, derived from Fig. 28. Comparison with Table 6.3 shows a drop on mean energy per contour 13.93TWh to 11.72TWh or 16%.

Table 7.3

Average Annual Accessible Energy Resource (Pelamis)

Energy Contour Level GWhe/km	Contour Length km	Annual Elec. Energy TWh	Implied Capacity Factor % (Pelamis)
8	133	1.06	6.4
10	254	2.54	8
12	357.5	4.29	9.6
14	383	5.36	11.21
16	435.5	6.97	12.81
18	487	8.76	14.4
20	539	10.78	16.0
22	585.5	12.88	17.6
24	648	15.55	19.2
26	716	18.62	20.8
28	695	19.46	22.4
30	692	20.76	24.0
32	565	18.08	25.6
34	480	16.32	27.2
36	444	15.98	28.8
38	341	12.96	30.44
40	220	8.8	32.09

The importance of the North West Mayo, and Kerry areas in particular is evident from their proximity to contours where relatively high converter capacity factors are projected as being likely. The North West Donegal area is reasonably attractive. Unfortunately electrical network capacity is still relatively weak in those areas although it has been improving as part of a general strengthening of the system and because of the need to cater for planned wind farms.

This should not pose a major problem for small scale/demonstration level wave projects however.

The above analysis has been carried out based on figures available for the performance of Pelamis 750 as supplied for Portuguese conditions and which is currently available as a full scale converter. There are indications that projected scatter tables for other systems currently under development may give better energy recovery rates but this has still to be demonstrated in full scale.

7.3 Environmental Issues

It is necessary to recognise that in the final analysis each case for wave power development will be assessed on its merits against established objective criteria wherein the extent of impacts and mitigation measures alike are assessed in reaching decisions. It is important that the collection of relevant baseline information is put in hand so that its absence is not used as an excuse to delay the granting of necessary permissions associated with possible implementation of preliminary wave conversion demonstration projects.

7.4 Commercial Considerations

A standardised method of commercial analysis based on that used by the Commission for Energy Regulation in determining the cost/kW for the 'Best New Entrant' to the electricity market (usually a 400MW combined cycle gas turbine) has been developed in Ref. (2) and is applied in Appendix 8. The model is available to potential users on the S.E.I. website.

There is relatively little firm information publicly available on the projected costs of specific full size multi megawatt wavepower projects. However a contract for a pilot installation of three Pelamis units has been awarded in Portugal and these are being fabricated for installation in 2006. Based on the inevitably high cost of preproduction units as publicly quoted a scaled up 20MW installation might be expected to have a projected levelised break-even cost of the order of 18.5c/kWh.

It is emphasised that this must be considered a conservatively high preliminary figure reflecting the small scale and relatively low capacity factors obtained but the figures obtained are actually better than were obtained during early development of wind turbines. With improved capacity factors and quantity production of converters there is every expectation that corresponding reductions in cost would occur.

Based on costs quoted by the developers of Pelamis to the Electric Power Research Institute for 2004 and reported by the Institute (Ref. 31) the case of a 157MW installation located in the Irish wave regime about 28km off the coast has been considered in some detail in Appendix 8 using the model of Ref. (2). This suggests that a levelised break even cost of order 8.2c/km and a selling price of circa 10.5c/kWh might be achievable under favourable circumstances. The improvements primarily relate to economy of scale and improved capacity factor. Clearly many of the assumptions used may be further debated and remain to be proven in the hard world of offshore engineering but there are reasonable grounds for believing that wavepower, in the context of the Irish wave climate, is closing the gap on other renewables such as offshore windpower.

8 Conclusions

8.1 General

(1) The project has provided a preliminary assessment of the different levels of the mean annual wave power/energy resource that are available around Ireland. It amplifies earlier studies and quantifies the electrical resource in a way that allows recognition of particularly promising areas and comparison with other renewables.

Table 8.1

Summarised Results for Areas Considered

Average Annual Resource Type		Level
Theoretical Hydrodynamic Power Flow	GW	4.25 - 50
Theoretical Hydrodynamic Energy	TWh/yr	11.25 – 460
Technical Electrical Power Flow	GWe	0.29 – 4.1
Technical Electrical Energy	TWhe/yr	2.4 – 28
Practicable Electrical Power Flow	GWe	0.18 - 2.77
Practicable Electrical Energy	TWhe/yr	1.2 – 24
Accessible Electrical Power Flow	GWe	0.14 - 2.4
Accessible Electrical Energy	TWhr/yr	1.06 – 20.76

(2) The annual accessible electrical energy is broadly equivalent to that supplied annually by ESB at present.

(3) These levels are underwritten by reasonably good correlation between buoy measurements and hourly model data available for 724 offshore grid points over the period Sept. 2001 – Dec. 2004.

(4) These energy levels are very significant in the context of Ireland’s energy needs and in relation to the degree of intermittent energy that can be accepted on to the electrical network without storage.

(5) The distribution of the resource is extremely important. From the perspective of ease of access of the electrical network it is clear that particular areas are well favoured relative to others. Priority locations are on the west coast (Donegal, Mayo, Kerry) where the network is still relatively weak apart from nodes such as Clare (Moneypoint) where the network is strong but the nearshore resource is perhaps less than had been expected.

(6) Given the wave climate the key elements influencing the value of the accessible resource are the converter designs as reflected in their ‘scatter’ tables, the number and cost of machines that can be deployed per kilometre of cordon and the operating capacity factors. (It may be recalled that early wind farms had capacity factors below 0.2 but that large modern machines now operate in the vicinity of twice this figure with correspondingly improved economy.)

(7) Subject to assumptions listed in Appendix 8 it is suggested that a favourably located wave farm of157MW capacity of Pelamis units might be capable of delivering electricity at a price in the vicinity of 10.5-11.5 € cents/kWh.

8.2 Input Data

(1) The level of agreement obtained between this Atlas and earlier work is reasonable but there is an anomaly between buoy measurements and forecast values that resulted in some scaling down of the latter. This merits further investigation as it can have a significant impact on energy production, capacity factors and project competitiveness in particular areas.

(2) Because of the relatively short time periods over which buoy measurements and wave forecasts have been available and the area to be covered, it is to be expected that later repetition of the exercise in about five years time (utilising a decade of data) should bring significant improvement in the quality of results.

(3) Two particular areas for improvement would be

- quality of buoy data (continuity of measurement and accuracy of wave period measurement)
- Bathymetry for near shore modelling purposes

(4) A future analysis would usefully incorporate significant wave height and zero crossing period for simultaneous swell and wind sea conditions with directionality.

8.3 Shallow Waters

(1) In the absence of the SPECTRUM model an approximate method was successfully applied to estimate power levels in the transitional zone between the WAM grid points and the 20m bathymetric depth contour.

(2) A future more precise analysis, where justified, would involve the use of a second grid based model such as SWAN, RCPWAVE or other for estimation in this transitional area.

(3) It may be noted that the 20m depth limit means that most waves other than those in storms occur under deep water or transitional regimes.

8.4 Interfacing with Others

(1) The Law of the Sea Convention and Protocols provide mutual safeguards for users of the marine resource. During the course of this project preliminary liaison was successfully initiated with representatives of other users to minimise potential for misunderstandings in this area and to inform the development of the accessible resource.

8.5 Commercial Development

(1) The energy rich areas have been identified and while these may be refined in the future they are unlikely to vary significantly. It is therefore possible for these areas to be taken into account in future Strategic Planning to preclude the impositions of developments or restrictions that would hinder development of the resource in the national interest.

(2) Within these broad areas there is evidence from other sources of localised areas with favourable regimes closer to shore than is suggested by the large scale data. The exploration of these ‘hot spots’ was outside the scope of this report.

(3) Seasonality of power levels and variability within seasons are critical factors in terms of energy production in that they match the annual demand profile and access needs for converter maintenance.

(4) It may be appropriate that focussed measurement programmes are initiated in promising areas to more precisely underwrite and quantify the resource levels.

(5) It is essential that wave conversion costs are progressively reduced if the resource is to play a significant part in Ireland’s renewable resource portfolio. (International experience has shown that for renewable energy systems to become viable at all in the first instance, special developmental market conditions require to be established at least at demonstration level)

(6) The bivariate or ‘scatter’ table method is the appropriate one to use in estimating the different levels of power and energy that can be recovered by different converters. This places an onus on converter developers to supply reliable scatter tables.

(7) The method also permits implied capacity factors to be assessed for different converters and distances offshore. This is crucial to estimating of commercial viability of different converter installations.

9 Recommendations

1. Future renewable energy policy development (including electrical network enhancement) should have regard to the quantification and distribution of the wave power resource that has been identified in this report.
2. Coastal Zone Management Planning should reflect the existence of this resource and safeguard corridors that may be necessary to facilitate its economic development.
3. Work on the spacing and mutual interference of different types of converter should be put in hand to clarify the most effective patterns of cordon for both capturing wave energy and allowing the passage of energy to permit the use of secondary cordons or other purposes closer to the coast.
4. The value of in situ wave measurements for analysis and calibration purposes has been central to this project. Every effort should be made to maintain and enhance the measurement programmes operated by the Irish Marine Institute and others.
5. While every effort has been made, within the constraints of the project, to produce accurate preliminary mapping based on the currently available data, the process could usefully be revisited within a few years using later methods and additional data for updating purposes as the wave resource is inherently a dynamic one.

6. It is suggested that where state or semi-state or research agencies are collecting marine-environmental information for their own purposes and where it is possible to extend this work to include areas with high indicative wave resource at marginal or insignificant cost this should be done to build up an environmental data bank for strategic environmental assessment purposes.
7. It is important to ensure that reliable scatter tables and capital and operating cost figures are supplied by intending developers so that realistic cost and performance characteristics can be generated for planning purposes.

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