Economic Wave Energy Resource Assessment Methodology & European Assessment

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Executive Summary

This project presents a methodology for assessing the economic wave energy resource for a given area of ocean. The methodology is implemented to assess the economic wave energy resource in Europe, estimating the potential size of the future European wave energy market. The Pelamis Wave Energy Conversion System (WECS), currently being developed in Scotland, is selected as the baseline technology, applying the latest technical performance and cost data. A Geographic Information System (GIS) is developed to model and analyse the geographical wave resource data collected from the European Wave Energy Atlas (WERATLAS). The GIS resource model is divided into 10 km by 10 km cells. The internal rate of return (IRR) is calculated for potential arrays deployed within each cell throughout European waters. Cells that meet the required rate of return (RRR) are considered to be commercially viable. The total commercially viable sites constitute the economic resource. Two market scenarios are completed, firstly assuming a single electricity price and subsidy for all European countries (*internal*), and secondly, applying existing *regional* market prices and renewable policies. The methodology is designed to be consistent with the draft performance assessment standard for wave energy conversion systems presented by the European Marine Energy Centre.

Technology

The 750 kW Pelamis WECS is the selected device for the resource assessment. The WECS power matrix and the wave scatter diagram provide an efficient representation that allows a device's wave energy conversion performance to be estimated for a given site's wave conditions.

Methodology Design

The methodology shown in figure A provides a systematic and reusable approach to calculate the wave energy resource for a given area of sea based upon on the resource, technology and economic data input. The first and second step focus on energy related aspects of the assessment and the third and fourth performs the economic tasks.

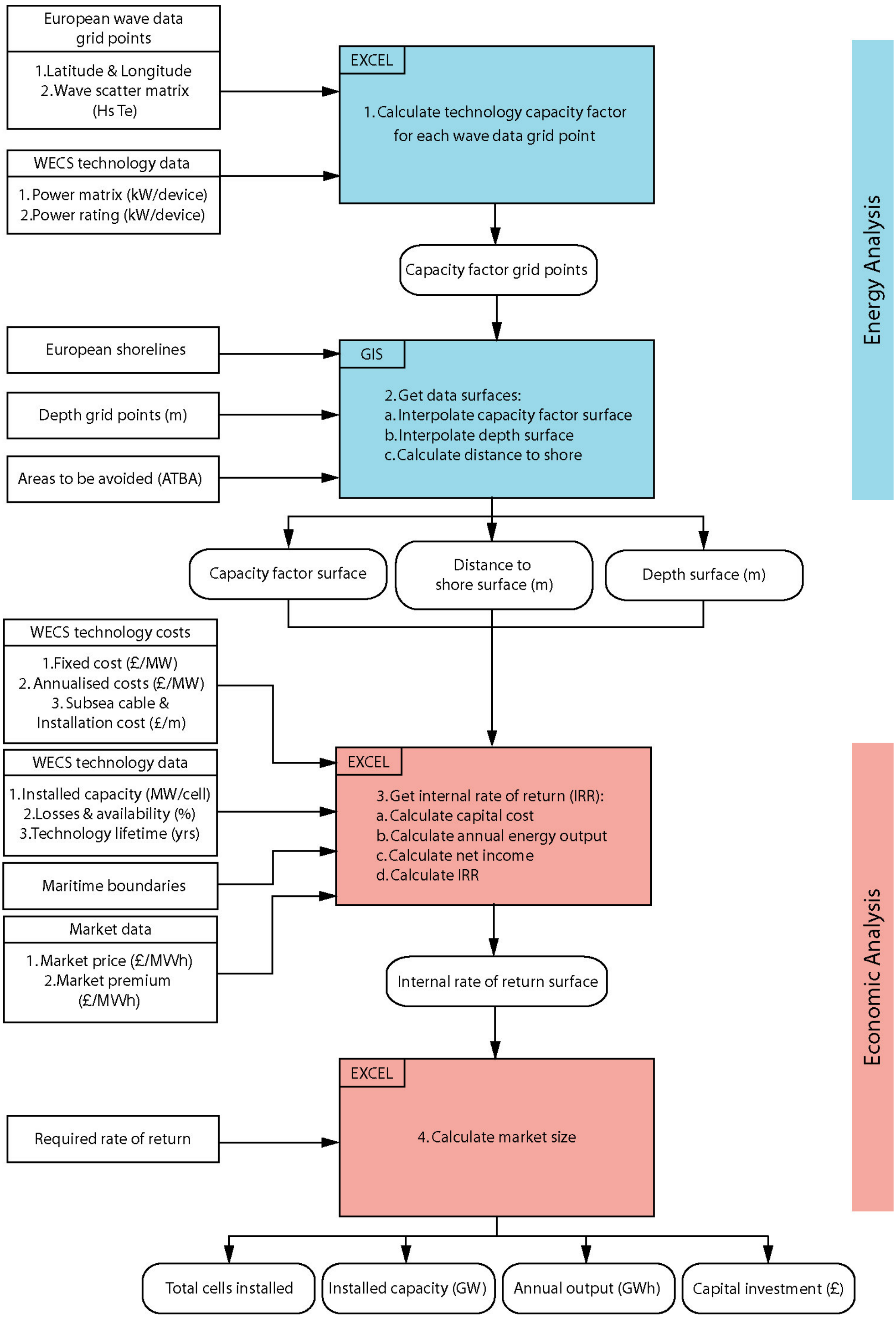


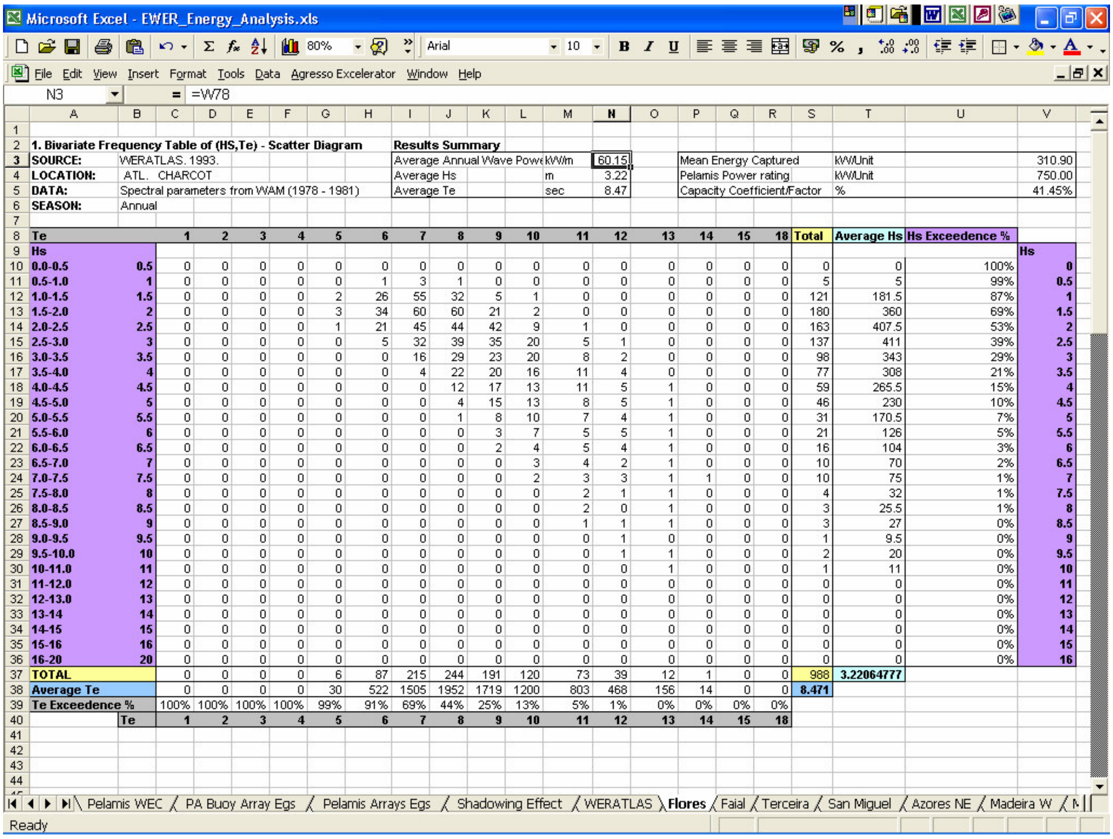
Figure A: Overview of the assessment methodology

Assessment of the European Wave Energy Resource

This project implements the methodology to assess the economic wave energy resource in European waters.

Energy Analysis using Excel

Microsoft Excel and the European Wave Energy Atlas are used to implement the first step in the methodology involving numerical analysis of the energy related data (included in the Excel model shown in figure B).



1. Bivariate Frequency Table of (HS,Te) - Scatter Diagram
SOURCE: WERATLAS. 1993.
LOCATION: ATL. CHARCOT
DATA: Spectral parameters from WAM (1978 - 1981)
SEASON: Annual

Results Summary		
Average Annual Wave Powe	kW/m	60.15
Average Hs	m	3.22
Average Te	sec	8.47
Mean Energy Captured	kW/Unit	310.90
Pelamis Power rating	kW/Unit	750.00
Capacity Coefficient/Factor	%	41.45%

Te		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	18	Total	Average Hs	Hs Exceedence %	
Hs																					Hs
0.0-0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	0
0.5-1.0	1	0	0	0	0	0	1	3	1	0	0	0	0	0	0	0	0	5	5	99%	0.5
1.0-1.5	1.5	0	0	0	0	2	26	55	32	5	1	0	0	0	0	0	0	121	181.5	87%	1
1.5-2.0	2	0	0	0	0	3	34	60	60	21	2	0	0	0	0	0	0	180	360	69%	1.5
2.0-2.5	2.5	0	0	0	0	1	21	45	44	42	9	1	0	0	0	0	0	163	407.5	53%	2
2.5-3.0	3	0	0	0	0	0	5	32	39	35	20	5	1	0	0	0	0	137	411	39%	2.5
3.0-3.5	3.5	0	0	0	0	0	0	16	29	23	20	8	2	0	0	0	0	98	343	29%	3
3.5-4.0	4	0	0	0	0	0	0	4	22	20	16	11	4	0	0	0	0	77	308	21%	3.5
4.0-4.5	4.5	0	0	0	0	0	0	0	12	17	13	11	5	1	0	0	0	59	265.5	15%	4
4.5-5.0	5	0	0	0	0	0	0	0	4	15	13	8	5	1	0	0	0	46	230	10%	4.5
5.0-5.5	5.5	0	0	0	0	0	0	0	1	8	10	7	4	1	0	0	0	31	170.5	7%	5
5.5-6.0	6	0	0	0	0	0	0	0	0	3	7	5	5	1	0	0	0	21	126	5%	5.5
6.0-6.5	6.5	0	0	0	0	0	0	0	0	2	4	5	4	1	0	0	0	16	104	3%	6
6.5-7.0	7	0	0	0	0	0	0	0	0	0	3	4	2	1	0	0	0	10	70	2%	6.5
7.0-7.5	7.5	0	0	0	0	0	0	0	0	0	2	3	3	1	1	0	0	10	75	1%	7
7.5-8.0	8	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	4	32	1%	7.5
8.0-8.5	8.5	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	3	25.5	1%	8
8.5-9.0	9	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	3	27	0%	8.5
9.0-9.5	9.5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	9.5	0%	9
9.5-10.0	10	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	20	0%	9.5
10-11.0	11	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	11	0%	10
11-12.0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	11
12-13.0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	12
13-14	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	13
14-15	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	14
15-16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	15
16-20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	16
TOTAL		0	0	0	0	6	87	215	244	191	120	73	39	12	1	0	0	988	3.22064777		
Average Te		0	0	0	0	30	522	1505	1952	1719	1200	803	468	156	14	0	0	8.471			
Te Exceedence %		100%	100%	100%	100%	99%	91%	69%	44%	25%	13%	5%	1%	0%	0%	0%	0%				
	Te	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	18				

Figure B: The wave scatter diagram representing the wave conditions for a deepwater location off the Portuguese coast.

Geographic Information System

The GIS model is developed to represent and analyse the geographical-based wave resource data. The model is summarised as:

- Model cell size: 10 km
- Projection: Geographic
- Area of analysis: 13°W to 10°E and 65°N to 30°N
- Total area: 8,524,800 km^2

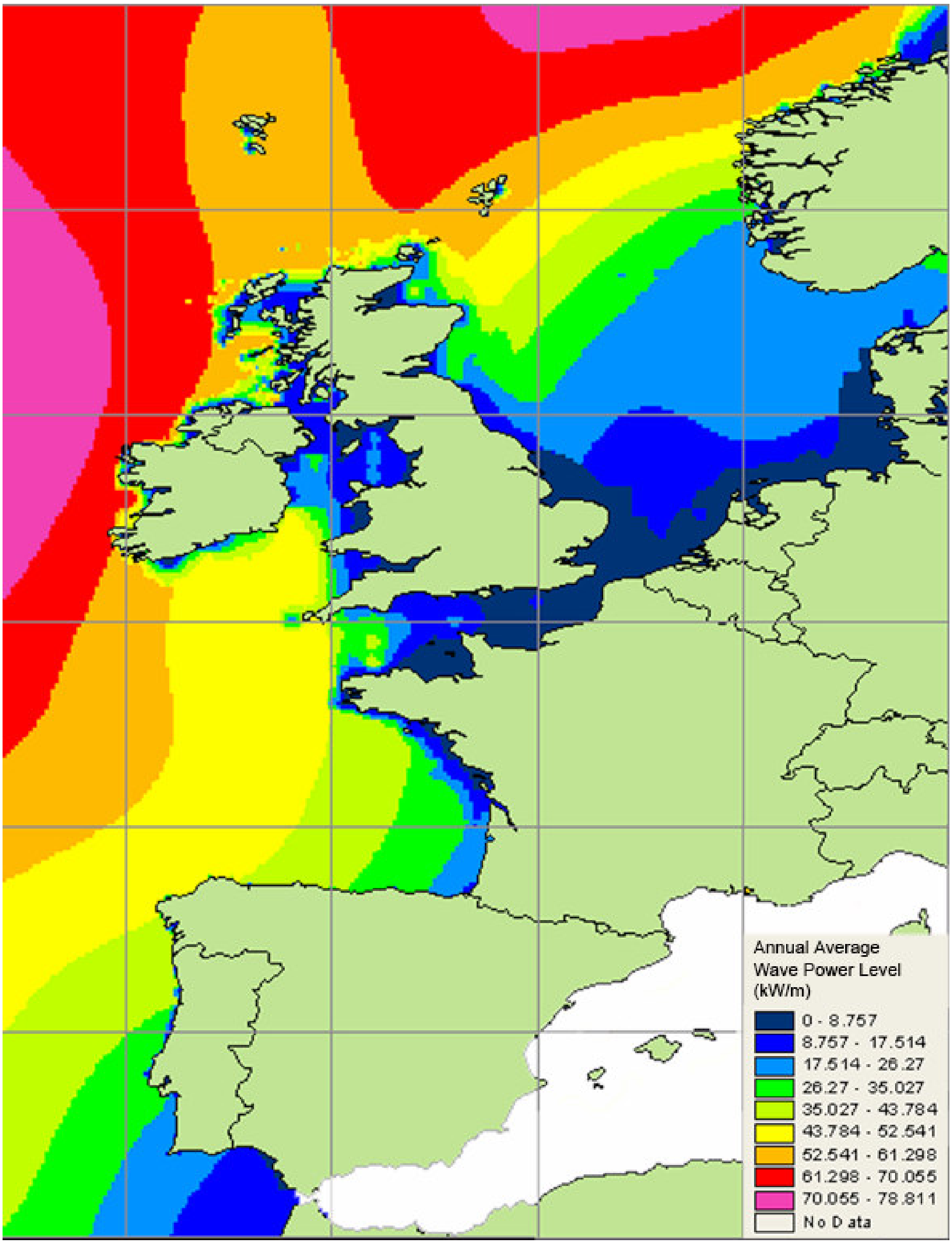


Figure C: The annual average wave energy resource is interpolated from the average annual wave power levels (in kW/m) for each gridded wave data point obtained from the WERATLAS. This surface displays the distribution of the wave resource around Europe.

The second step in the methodology generates the GIS data surfaces by interpolating wave data and depth coordinates, and calculating the distance to shore for each model cell. A GIS S*urface* provides an excellent tool for visualising the resource and allows the entire wave resource for the assessed area to be interpolated from a limited set of gridded wave data. An example of a surface is given in figure C.

Economic Analysis using Microsoft Excel

The third step in the methodology calculates the internal rate of return for potential wave energy arrays deployed in European waters. Figure D shows the economic model implemented using Microsoft Excel. The IRR is calculated for each cell in the model. Cells that meet the RRR are considered to be commercially viable. Two required rates of return for wave energy arrays are selected: 10% is considered optimistic and 13 % more realistic.

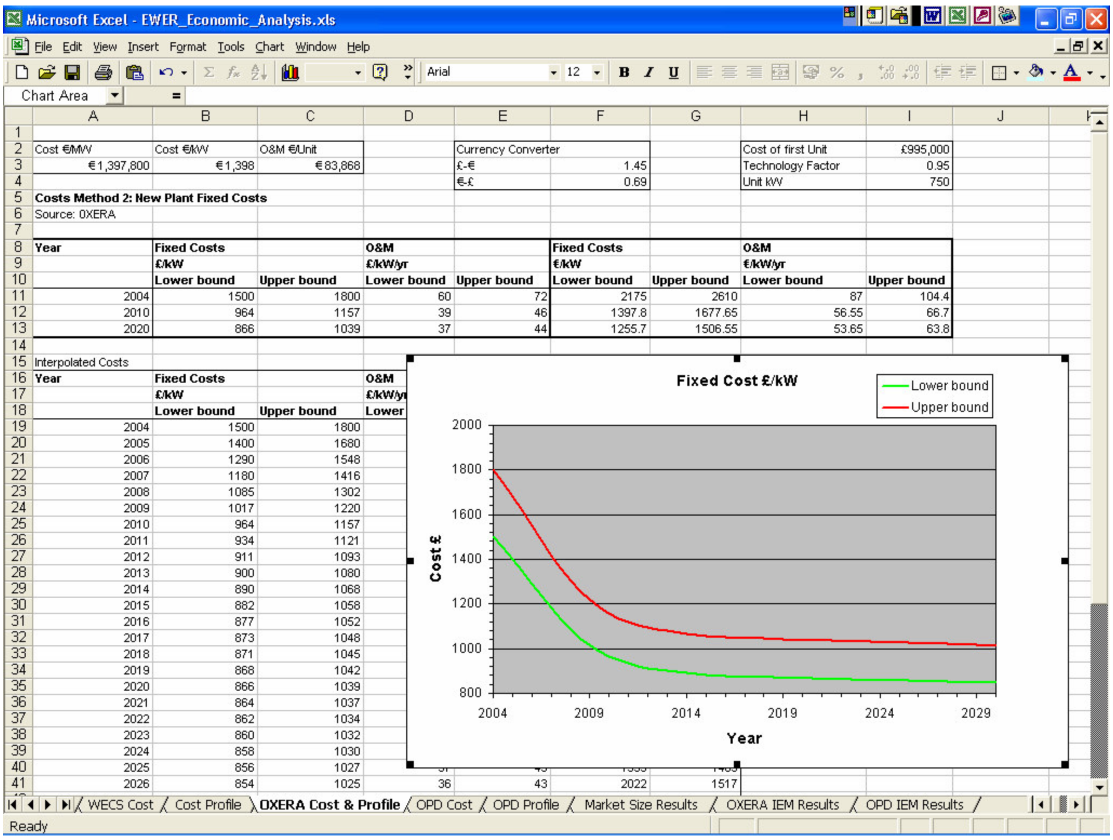


Figure D: The fixed cost estimates of the Pelamis WECS integrated within the economic analysis in the Excel model.

The final step in the methodology compares the IRR to the RRR in each model cell. The total commercially viable sites constitute the European economic wave resource and potential market. The Excel model identifies the potential market automatically using an algorithm implemented using Visual Basic and data output from the GIS model.

Results

Assuming the Internal Electricity Market scenario, WECS cost of 964 £/kW for 2010, and a RRR of 10 %, an electricity entry price (including wholesale price and premium) of just under 55 £/MWh is required to make wave energy devices commercially viable (illustrated in figure E). An entry price of exactly 55 £/MWh would generate an economic resource of some 1.5 GW capacity corresponding to a capital investment of £1.4 billion. This resource is located around the Irish west coast. For the realistic rate of 13 %, figure E indicates, the entry price for wave energy is higher at approximately 60 £/MWh. The results are displayed in table G.

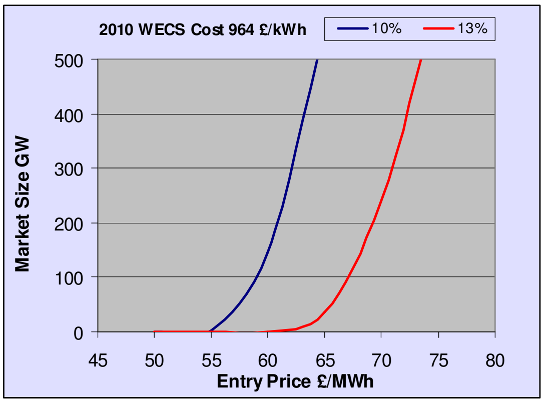


Figure E: Estimated market in 2010

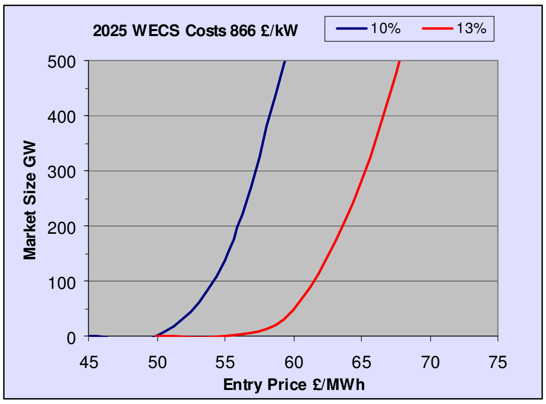


Figure F: Estimated market in 2025

For the Internal Electricity Market scenario and the WECS cost of 866 £/kW for 2025, the market entry price required for wave energy to become commercial viability is reduced to approximately 50 and 55 £/MWh for rates of return of 10 and 13 % respectively. Table G shows at 10 % RRR, the selected entry price of 55 £/MWh constitutes an economic resource of 137.4 GW corresponding to a market worth approximately £120 billion. The majority of this resource is located off the west coast of Ireland, the northwest region of Scotland and to the northwest of Norway. There is no market if investors require 13 % return.

Year	10% RRR			13% RRR		
	Cells	GW	£ Billion	Cells	GW	£ Billion
2010	5	1.5	1.4	0	0	0
2025	458	137.4	119	0	0	0

Table G: The economic wave energy resource, assuming an entry cost of 55 £/MWh.

Conclusions

The European wave energy resource is modelled using GIS. The resource model is interpolated from 23 wave data points obtained from the WERATLAS. This data is not ideal for assessing the European resource because the UK Met Office models underestimate swell waves which, in Western Europe, are an important contribution to the overall resource and of particular importance to wave energy conversion. The model is not accurate for intermediate depths due to the limited number of data points obtained.

The methodology divides the resource model into 100 km^2 cells. The cell size limits the accuracy of the modelled wave resource close to shore as the depth can range from 0 to as much as 500 metres. The equivalent unit of installed capacity of 300 MW (based on a device packing density of 3 MW/km^2) is too large. Instead, 1 km^2 cells could provide more accurate resource estimates.

The methodology estimates the potential economic wave energy resource for a given area of sea. The accuracy is dependent on the resolution of the wave energy resource model, the technology cost estimates, market entry costs and the transmission and array configuration assumptions. Using several assumed variables increases the level of uncertainty of the estimate. For this reason, a single resource estimate is not calculated; instead, estimates are generated for a range of optimistic and more realistic technology cost estimates. When the actual commercial cost of wave devices is established, a more accurate wave resource estimate could be generated using this methodology.

The European resource assessment could also be improved by obtaining a new data set of 50 or more, wave data grid points located in the Western European approaches of the Northern Atlantic Ocean and North Sea where wave power levels are most significant. The model cell size could be reduced to 1 km to allow the resource to be more accurately modelled and enable more sophisticated regional policy mechanisms, which react to the rate of market growth, to be applied. European Transmission Networks and grid supply points could be integrated into the model to allow the least cost route for the submarine grid connection to be determined. Hence, the capital cost estimated for each wave array would be more realistic.

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1 Introduction

1.1 Background

International awareness of the threat of “global warming” and “climate change” is influencing international energy policy which emphasise the importance of a “carbon free” and “sustainable” world economy. The problems that oil-dependent economies face in the future are becoming more evident as global oil prices rise and as production begins to dry out. Security of electricity supply is becoming increasingly important for the UK as fossil fuel resources decline – the UK become a net importer of gas by 2006. Nuclear energy is well known for being a carbon-free source of electricity. However, due to public environmental concerns, national security risks and the actual cost of decommissioning, the decision to build the next generation of UK’s nuclear industry is not straightforward. The success of wind turbines is helping accomplish EU renewable targets for 2010 [1]. However, problems incurred with planning consent are restricting onshore projects. For these reasons, alternative sources of renewable energy incorporated within a diverse energy mix are essential if energy demand is to be met and climate change addressed.

Wave energy is one of the most abundant sources of renewable energy available around the world that has not yet been harnessed to meet global energy demand. Europe’s western shores lie at the end of a long fetch of the Atlantic Ocean and are surrounded by stormy waters. The potential wave energy resource that could be exploited is vast – particular in countries such as Portugal, Ireland, United Kingdom and Norway. Previous attempts to harness the unpredictable power of ocean waves have either perished in the harsh marine environment[1] or proven too uneconomical[2]. However, new waves of innovative and competitive energy capture technologies are

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[1] Norwegian interest in wave energy diminished after the Oscillating Water Column prototype funded by the Norwegian government and built by engineering company Kvaerner was destroyed during a storm in 1988 [2].

[2] £15 Million was spent by the UK government on the wave energy program, which began in 1976 [3]. Several resource assessments and WECS designs were completed. The program concluded that wave energy devices could generate electricity for around 19 pence per kWh. This was deemed too expensive. Together with uncertainties surrounding “survivability” due to the harshness of the marine environment, the program was abandoned in 1982. Only one design reached the demonstration level.

nearing the final stages of development[3]. Provided the prototypes can survive demonstration at sea, a wave energy industry could be on the horizon.

1.2 Wave Energy Resource

The *Wave Energy Resource* is the entire amount of energy that is stored within the waves in an area of ocean in offshore or inshore waters. The *Accessible* resource is the amount of this resource that can be captured and converted into useful energy taking into account certain technical, economic and environmental constraints. The *Technical* wave energy resource is the total amount of electricity that can be converted from wave energy regardless of economics, taking into account technical factors. The *Economic* resource, which is lower than the Technical resource, incorporates whether the Wave Energy Conversion System (WECS) used to extract the energy is economically competitive with other forms of existing electricity generation.

Several studies have investigated the wave energy resource aiming to identify the best sites to deploy WECS technology and estimate the size of the resource, including:

- 120 GW located on the west and north coasts of the United Kingdom [6]
- 320 GW around Europe [7]
- 2 TW globally [8]

However, as yet no comprehensive strategy has been applied to assess the potential European wave energy market given the resource and technology data currently available. Additionally, the benefit of using Geographical Information Systems (GIS) to analyse the wave energy resource data has not yet been utilised for assessing the European market.

Wave conditions required for shoreline-based WECSs are restricted to certain "hotspots" where wave levels are unusually high. Wave power levels near to shore are limited by decreasing depth. Subsequently, the *shoreline* and *nearshore* wave energy resource is considered to be much lower than the *deepwater* resource [9]. This assessment focused on the deepwater resource located offshore.

[3] Ocean Power Delivery Ltd – based in Edinburgh – have secured around £5 million in DTI capital grants and venture capital and are nearing the final stages of demonstration of a full-scale version of the 750 kW Pelamis WECS [4]. Several other R&D programs are in progress around the world [5].

1.3 Motivation

This project is motivated by the following requirements and developments:

- The need for a comprehensive economic assessment of the European wave energy resource identifying the potential market, exploiting available GIS techniques.
- The increasing research and development into wave energy devices and increased availability of device performance data and economic information.
- The renewed support for potential wave energy industries within Europe in the form of market-pull measures implemented by European governments[4].
- The requirement for a generic resource assessment methodology that applies the latest WECS draft standards being developed, which can be reused as new technology, economic and resource data become available.

1.4 Aims and Objectives

This project completes the following tasks:

- Design a robust and reusable wave energy resource assessment methodology, consistent with the EMEC WECS draft standard [13].
- Collect the best available wave resource, technology and economic data.
- Assess the economic wave energy resource in Europe by implement the methodology to identify the size of the potential European market, based on selected WECS technology (the Pelamis WECS) incorporating technical, environmental and economic constraints.
- Analyse the deepwater offshore wave energy resource and model using GIS.
- Investigate different economic scenarios. For example, the *Internal Electricity Market* framework versus existing regional electricity markets in Europe and the effect of market fiscal mechanisms such as feed-in tariffs on market size.

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[4] The government's of Portugal and United Kingdom's latest attempts to encourage the growth of wave energy industries: £150M and £50M, respectively, in financial support to bridge the gap in public funding between the demonstration of WECS prototypes and the development of full-scale WECS schemes [10].

1.5 Approach

The resource assessment methodology incorporates technical parameters, including:

- Rated power of WECS
- Capture efficiency (capacity factor)
- System availability
- Losses in power chain including transmission losses
- Population density of WECS arrays
- Submarine transmission cabling required (length equivalent to depth and distance to shoreline)
- Lifetime period

Economic factors are also incorporated, including:

- Capital cost
- Annualised costs (operation and maintenance)
- Annual energy output
- Internal rate of return
- Market mechanisms such as taxes, subsidies and the ETS.

Environmental constraints are also taken into account:

- Depth
- Distance to shoreline
- *Areas To Be Avoided* at sea (ATBA) e.g. shipping channels, explosives dumping grounds

Wave data for Europe, WECS technology data and European market tariffs and prices are collected. However, access to this data is limited and expensive, commercially sensitive or may not even exist yet. Therefore it is important that the assessment methodology is clearly described and outlined so it can be applied when more information becomes available in the future.

2 Wave Energy

Oceans cover two thirds of the earth's surface and present a massive energy resource. The global energy resource stored within the ocean's waves is estimated at more that 2 TW [8]. Ocean waves could become an abundant source of renewable energy provided the technical and economical challenges of wave energy capture are overcome. The IEA have predicated that wave energy may eventually provide over 10% of the world's electricity supply [5].

Waves are energy in transition stored in the ocean's surface in the form of waves being carried away from their origin. Wave energy can be considered as a concentrated form of solar energy since the primary source of wind energy is the sun and the main source of wave energy is the wind. Winds are generated by the differential heating of earth giving rise to thermal air currents. As they pass over open stretches of water they transfer some of their energy to form waves. The precise mechanisms of energy transfer are complex and not yet fully understood. However, three main processes appear to be at work:

1. Air flowing over the ocean surface exerts a tangible stress, resulting in wave formation.
2. Turbulent airflow close to the waters surface creates rapidly varying shear stresses and pressure fluctuations. Waves develop where these oscillations are in phase with existing waves.
3. Wind can exert a stronger force on the upwind face of more developed waves causing increased wave growth. This process is maximised when the speeds of the winds and waves are equal.

Power intensity becomes more concentrated throughout this process of energy transformation. The size of waves generated depends on the wind speed, the length of time wind flows and the distance of water over which it blows – the *fetch*.

The basics of wave theory are described in this section to give a background on the subject and help understand the wave resource calculations performed within the assessment methodology detailed in section 5. For more on the mechanisms and theory behind wave energy refer to [11].

2.1 Wave Properties

2.1.1 Monochromatic Seas

Waves can be measured in terms of the *Wave Height* H (the distance from trough to crest) and the *Wave Period* T (the time between successive waves). The simplest theory used to describe the action of waves is the linear wave theory [11]. This is an approximation of real sea conditions, representative of simple monochromatic or sinusoidal waves. Linear theory characterises waves in terms of *Wavelength* λ (the distance between successive crests) and period T. The ocean can be classified according to depth d, as:

- Deepwater where $d \geq \lambda/2$
- Intermediate water where $\lambda/2 > d \geq \lambda/20$
- Shallow water where $d < \lambda/20$

For deep water, wavelength and period are related as follows:

$$\lambda = \frac{gT}{2\pi} \qquad \text{Equation 2.1}$$

where g is the acceleration due to gravity.

Individual waves travel at a *Phase Velocity* C, where:

$$C = \frac{\lambda}{T} \qquad \text{Equation 2.2}$$

The *Total Energy* E in a deepwater wave is equal to:

$$E\ (J/m) = E_p + E_k = \frac{\rho\, g^2 H^2 \lambda\, b}{8} \qquad \text{Equation 2.3}$$

where b is the width of the crest and ρ is the density of water. The total energy described by linear theory is equally composed of potential energy E_p and kinetic energy E_k.

The transfer of wave energy from point-to-point in the direction of wave travel is characterised by the *Energy Flux* or, more commonly, *Wave Power* P:

$$P\ (kW/m) = \frac{\rho\, g^2\, T}{32\, \pi} \qquad \text{Equation 2.4}$$

which represents the power level in kilowatts per metre of wave front (kW/m).

2.1.2 Random Seas

More detailed techniques are required to model real wave conditions that are random in height, period and direction. Statistical measurements of varying wave heights and energy period that occur at a location represent the variation in sea states. The most commonly used parameters are the *Root Mean Square* of wave height, H_{rms}, or *Significant Wave Height* – defined as the average of the one-third highest wave, H_s (~$4H_{rms}$) and the *Wave Energy Period* T_e (seconds between successive wave crests).

2.2 Wave Scatter Diagram

The *Scatter Diagram* (also referred to as a Wave Scatter Matrix) is used to represent the random wave conditions that occur in reality, recording the annual variation in sea states for a measured location [12]. This location is determined by a specific measure of Latitude and Longitude. The scatter diagram indicates how often a sea state with a particular combination of significant wave height H_s and wave energy period T_e occurs annually (recorded in parts per thousand). The scatter diagram is compatible with the wave device power conversion matrix, as outlined by the EMEC [13], allowing the annual energy that can be captured to be easily calculated (further detail is given section 3.2). Table 2.1 shows an example of a scatter diagram for a deepwater location close to Barra, off the Scottish west coast.

Significant Wave Height Hs (m)	Energy Period Te (secs)	4	5	6	7	8	9	10	11	12	13	14	15	18
0.0-0.5		0	0	0	0	0	0	0	0	0	0	0	0	0
0.5-1.0		0	2	11	12	3	0	0	0	0	0	0	0	0
1.0-1.5		0	15	38	44	35	10	2	0	0	0	0	0	0
1.5-2.0		0	11	37	38	45	30	8	2	1	0	0	0	0
2.0-2.5		0	1	25	35	32	30	17	3	1	0	0	0	0
2.5-3.0		0	0	8	25	27	23	19	8	2	0	0	0	0
3.0-3.5		0	0	0	15	21	22	16	12	2	1	0	0	0
3.5-4.0		0	0	0	4	18	19	14	11	5	1	0	0	0
4.0-4.5		0	0	0	1	11	16	12	9	6	3	0	0	0
4.5-5.0		0	0	0	0	4	15	13	9	7	3	1	0	0
5.0-5.5		0	0	0	0	1	7	11	8	5	2	1	0	0
5.5-6.0		0	0	0	0	0	3	8	7	4	2	1	0	0
6.0-6.5		0	0	0	0	0	1	5	5	4	2	1	0	0
6.5-7.0		0	0	0	0	0	0	3	4	2	2	1	0	0
7.0-7.5		0	0	0	0	0	0	1	3	2	2	1	0	0
7.5-8.0		0	0	0	0	0	0	0	2	2	2	1	0	0
8.0-8.5		0	0	0	0	0	0	0	1	2	2	0	0	0
8.5-9.0		0	0	0	0	0	0	0	0	2	1	1	0	0
9.0-9.5		0	0	0	0	0	0	0	0	1	1	0	0	0
9.5-10.0		0	0	0	0	0	0	0	0	1	1	0	0	0
10-11.0		0	0	0	0	0	0	0	0	0	1	1	1	0
11-12.0		0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2.1: Sea state scatter diagram representing the annual frequency of occurrence of each combination of significant wave height H_s (in half-metre intervals) and wave energy period T_e (in second intervals), plotted in parts per thousand. The matrix represents the conditions for a deepwater location in the west coast region of Scotland (57° N, 9° W).

2.3 Wave Power Level (kW/m)

The *Power* P within a particular sea state (combination of H_s and T_e) can be evaluated by substituting the H_s and T_e into equations similar to those describing monochromatic seas (Equation 2.4), giving:

$$P\ (\text{kW/m}) = 0.49\, H_s^2\, T_e \qquad \text{Equation 2.5}$$

The average annual power level for a location can be determined by using the power P within each sea state and it's *Weighting Factor* W which is the number of times that that particular sea state occurs:

$$P_{ave}\ (\text{kW/m}) = \frac{\sum P_i W_i}{\sum W_i} \qquad \text{Equation 2.6}$$

where sea states with power levels P_i occur W_i times per year. The annual average power level available in kilowatts per metre of wave front (kW/m) is commonly used to present wave energy resource. Table 2.2 indicates how the power level for a deep water location off the Scottish west coast is calculated using the wave scatter matrix in table 2.1 and equation 2.6.

Significant Wave Height Hs (m)	Wave Energy Period Te (secs)	4	5	6	7	8	9	10	11	12	13	14	15	18	Total
0.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0
1		0	5	32	41	12	0	0	0	0	0	0	0	0	90
1.5		0	83	251	340	309	99	22	0	0	0	0	0	0	1104
2		0	108	435	521	706	529	157	43	24	0	0	0	0	2523
2.5		0	15	459	750	784	827	521	101	37	0	0	0	0	3494
3		0	0	212	772	953	913	838	388	106	0	0	0	0	4181
3.5		0	0	0	630	1008	1188	960	792	144	78	0	0	0	4802
4		0	0	0	220	1129	1341	1098	949	470	102	0	0	0	5308
4.5		0	0	0	69	873	1429	1191	982	714	387	0	0	0	5646
5		0	0	0	0	392	1654	1593	1213	1029	478	172	0	0	6529
5.5		0	0	0	0	119	934	1630	1304	889	385	208	0	0	5470
6		0	0	0	0	0	476	1411	1358	847	459	247	0	0	4798
6.5		0	0	0	0	0	186	1035	1139	994	538	290	0	0	4182
7		0	0	0	0	0	0	720	1056	576	624	336	0	0	3313
7.5		0	0	0	0	0	0	276	910	662	717	386	0	0	2949
8		0	0	0	0	0	0	0	690	753	815	439	0	0	2697
8.5		0	0	0	0	0	0	0	389	850	920	0	0	0	2160
9		0	0	0	0	0	0	0	0	953	516	556	0	0	2024
9.5		0	0	0	0	0	0	0	0	531	575	0	0	0	1106
10		0	0	0	0	0	0	0	0	588	637	0	0	0	1225
11		0	0	0	0	0	0	0	0	0	771	830	889	0	2490
12		0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL		0	211	1390	3343	6284	9576	11451	11315	10165	8002	3463	889	0	66090
Average Annual Wave Power (kW/m)															66.6

Table 2.2: Displays the equivalent wave power level P_i for each sea state represented in the wave scatter matrix in Table 2.1 (calculated using equation 2.5) multiplied by its weighting factor W_i. The annual average wave power level (kW/m) for that location is then calculated by dividing the sum of products by the sum of all weighting factors giving a value of 66.6 kW/m (equation 2.6).

2.4 Wave Direction

The direction of the waves in real seas changes constantly according to the direction of weather systems and wind. In certain areas where a predominate wind blows, such as the prevailing westerly wind common to the British Isles, the waves will also move in a predominate direction.

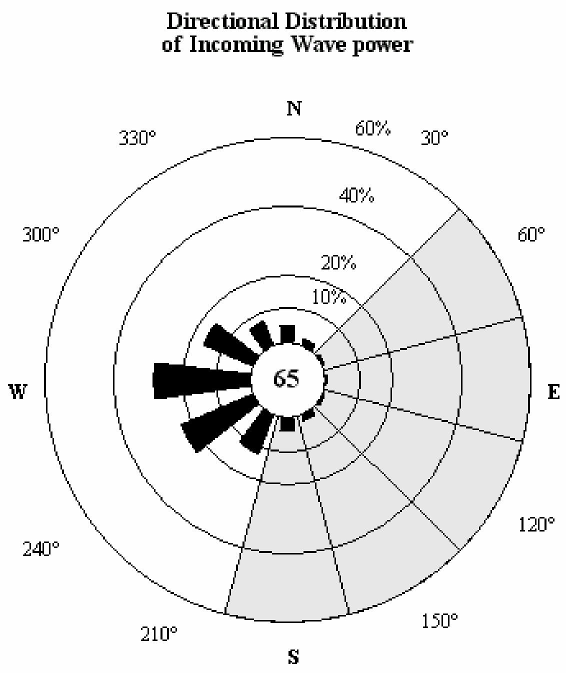


Figure 2.1 Annual Wave Direction Rose for a deepwater location off the west coast of Scotland (57°N, 9°W). Source: WERATLAS.

Wave direction can have a major effect on the design and captured efficiency of WECS. The Wave *Direction Rose* can be used to present the directional distribution of Incoming wave power for a certain location. For example, the direction rose in figure 2.1 presents the directional distribution for a deep water location which experiences an average of 65 kW/m of wave power. This indicates that over 75% of waves come from bearings between 240° to 300°. The same information is presented in tabular format in table 2.3.

The effect of the spread in wave direction on the amount of power that can be intercepted by a unidirectional WECS in random seas can be represented using a *Directionality Factor.* Multidirectional WECS installed in isolation, which are capable of changing their orientation or capturing waves from any direction, do not require directionality factors. However for arrays that are deployed in lines perpendicular to the predominate wave direction, a change in wave direction may effect the power output due to the *Shadowing Effect* of devices "up wave" (see section 3.5).

Direction (from)	Mean Direction %	Mean Power (kW/m)
0 deg(North)	4.8	3.09
30 deg	2.2	1.14
60 deg	0.9	0.46
90 deg(East)	0.6	0.27
120 deg	0.9	0.49
150 deg	1.2	1.12
180 deg(South)	2.9	2.54
210 deg	8.6	7.76
240 deg	22.3	14.96
270 deg(West)	35.3	18.53
300 deg	14.3	10
330 deg	7	4.77
All Directions	100	65.43

Table 2.3 Annual Directional Distribution of Mean Wave Power for deepwater location west of Scotland (57° N, 9° W). Source: WERATLAS.

2.5 Wave Energy Resource

The *Wave Energy Resource* is the entire amount of energy that is stored within the waves in an area of ocean in deep or coastal waters. The *Accessible* resource is the amount of this resource that can be captured and converted into useful energy taking into account technical, economic and environmental constraints. The *Technical* wave energy resource is the total amount of electricity that can be converted from wave energy regardless of economics, taking into account technical factors.

Several studies investigating the deepwater, nearshore and shoreline resources aiming to identify the best sites to deploy WECS technology and estimate the size, for example:

- 120 GW located on the west and north coasts of United Kingdom [6]
- 25 GW surrounding Ireland's north, west and south coasts [14]
- 10 GW around Portugal of which 5GW is exploitable [15]
- 320 GW around Europe [7]
- 2 TW globally [8].

The *Economic* resource, which is lower than the technical resource, incorporates whether the WECS used to extract the energy is economically competitive with other forms of existing electricity generation. So far a number of economic assessments have been completed, which identified the size of potential wave energy markets taking into account competing sources of electricity:

- Garrad Hassan assessed Scotland’s resource in 2001 [16]. The study concluded that 13.8 GW of generation could be installed for under 7 pence/kWh for both 2010 and 2025 unit costs at 8 % and 15 % discount rates.
- The global market is assessed by Thorpe in 1999 indicated that if the wave energy devices performed as predicted, then their economic contribution would be over 2000 TWh/year by the year 2025 [9]. This corresponds to a capital investment of over £500 billion based upon the economic assessments of shoreline, nearshore and offshore technology including the Islay Limpet, Osprey OWC and Salter Duck.

2.6 Global Resource

The global wave energy resource is taken to be to total power intercepted by a line along the coasts of countries facing major oceans. The deepwater resource is estimated at approximately 1.3 TW [17]. This estimate avoids assuming advanced arrays such as devices located in the mid-Atlantic ocean and ignores the small scale resource in seas such as the Baltic and Mediterranean. The annual average wave power levels (kW/m) measured for certain locations around the world show the resources distribution as in figure 2.2. The highest power level – the largest resource – exists along the parallels of latitude of approximately 55° North and South of the Equator.

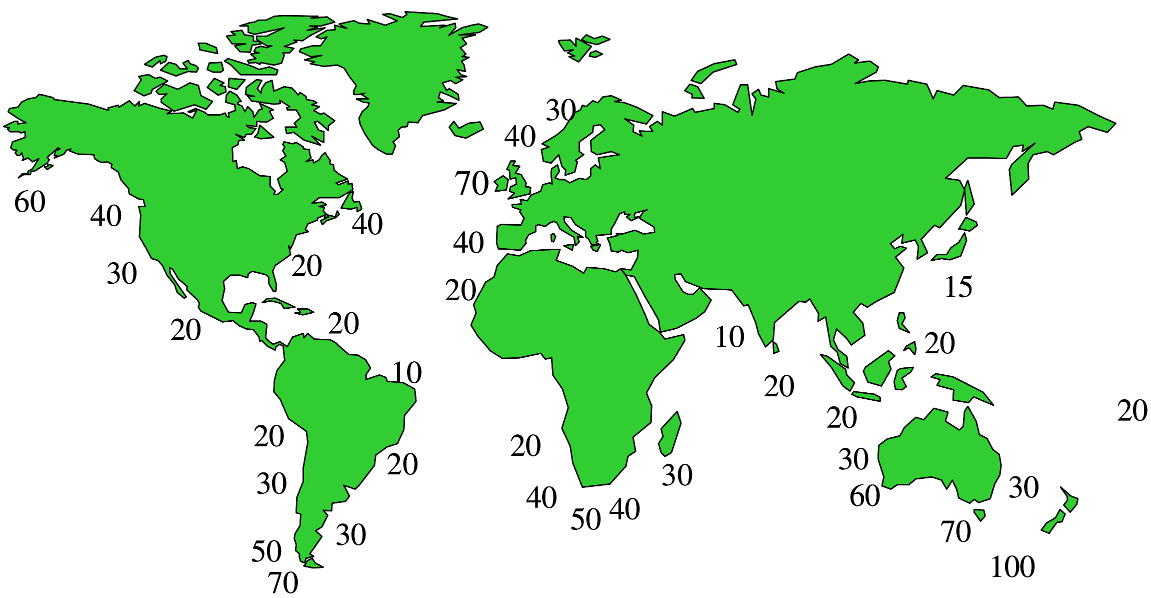


Figure 2.2: Global distribution of wave power levels in kW/m of wave crest length. Source: [18].

2.7 European Resource

Europe's western shores are positioned at the end of a long fetch of the Atlantic Ocean. The predominately westerly winds generate stormy wave conditions giving rise to a large European wave energy resource. The total resource has been estimated at some 320 GW [7]. Figure 2.3 indicates the average annual power levels around Europe. The west coast region of Ireland experiences some of the highest levels, Scotland and Iceland experience equally high levels and Norway and Portugal also have a sizeable resource.

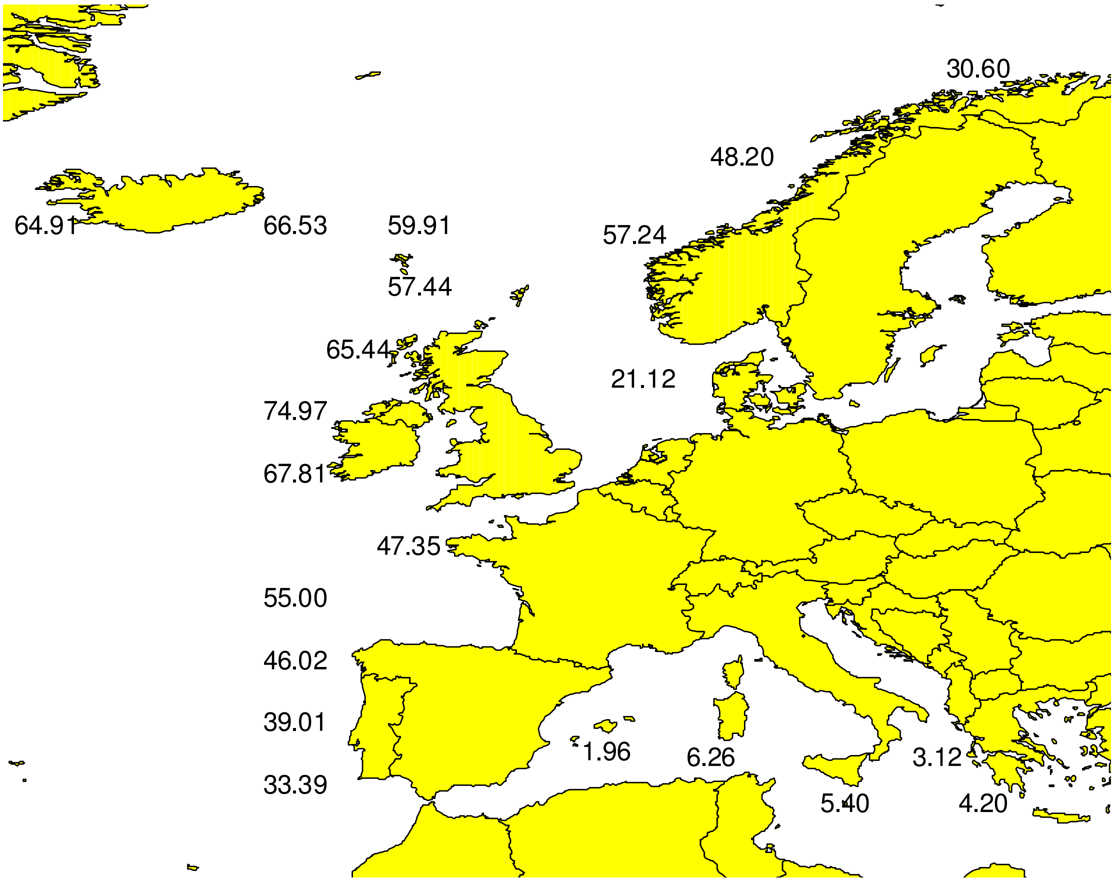


Figure 2.3: European distribution of wave power levels in kW/m of wave crest length. Source: WERATLAS. Averages are based upon on wave height and period measurements from 1987-to-1994 using the UK Met Office's European Wind-Wave Model.

2.8 Data Sources

To assess the economic wave energy resource for Europe, the European wave energy resource must be modelled. The available resource can be calculated by measuring and recording wave conditions – using wave scatter matrices and wave direction roses to present this data – at several locations over a period of time and then calculating annual average power levels – using techniques already described. The parameters required: wave height, wave period and wave direction, can be collected from a number of sources including:

- Physical measurement using *Waverider* buoys fixed into position using moorings and transmitting data in real time using radio or telecommunications.
- Wave condition estimates based upon models of wind speed and direction.
- More advanced theoretical techniques using weather models calibrated against Satellite-derived and in-situ data.

The frequency of the measurement and the overall period at which the data is collected, will effect accuracy and determine whether the data is representative of the wave climate at that location. Although, the data is averaged over an annual period, there is a degree of uncertainty because the actual sea state over the measured period may have been unusually calm or stormy compared to the climate in the years before or after the measurements are taken.

2.8.1 European Wave Energy Atlas (WERATLAS)

The WERATLAS [19] provides a comprehensive set of wave data for 85 grid point positions around Europe. Significant wave height, wave energy period and directional data are available in wave matrix, wave rose and tabular format, averaged over seasonal and annual periods. The wave data is from the UK Met Office Wind-Wave Model data set from 1987 to 1994. This data is not ideal for assessing the European resource because the UK Met Office models are thought to underestimate swell waves which, in Western Europe, are an important contribution to the overall resource and of particular importance to wave energy conversion. 23 of the 85 data points lie within the area analysed in this assessment outlined in section 6.1.

2.8.2 UK Met Office, European Wind-Wave Model (WAM)

The UK Met Office is requested for sets of wave height, period and directional data for 50 locations around Europe, summarised over a 4-year period, from their latest 3rd generation European Wind-Wave model [20]. The wave parameters are estimated using wind speed and direction measurements and advanced modelling techniques.

The cost for this data is considered too expensive for the purposes of this study [21]. For example, for 50 grid points for 5 years the cost equates to:

- 3-hourly data = £75,000
- 6-hourly data = £50,000
- 12-hourly data = £25,000

2.8.3 British Oceanographic Data Centre (BODC)

The BODC provided the complete data set of wave measurements from their Waverider buoys positioned around the British Isles. The data sets are made up of significant wave height, wave energy period and directional data measured over 2 to 5 year periods. Waverider buoys are thought to over estimate calm conditions. Unfortunately the data sets are largely incomplete and attempts to retrieve the complete data sets are unsuccessful. The data is not used to model the resource. For the location of these buoys and for more information on these service readers should refer to [22].

2.8.4 Oceanor, Eurowaves

The *Eurowaves* project completed in 2001 by Oceanor provides the wave data required for locations – selected by Oceanor – within the area on interest [23]. Eurowaves uses data from the European Centre for Medium-range Weather Forecast calibrated against Satellite-derived and in-situ data giving the most accurate wave data available for the European region. Eurowaves provides the preferred data source however the project budget could not justify the cost for the data requested [24]. For example, a set of data for 10 points would cost €3,490.

2.8.5 Selected Source

Access to wave data for Europe is expensive. Due to a limited budget, this assessment selected the WERATLAS to supply the wave data: significant wave height, energy period and directionality, averaged over an 8 year period (1987 to 1994) from the UK Met Office Wind-Wave Model. Wave Scatter Matrices for 85 grid points within European waters are collected.

2.9 Resource Assessment Methodologies

An assessment methodology outlines how something is assessed, in this case how the economic wave energy resource is assessed. Previous assessments, for example, Thorpe's 'Brief Review of Wave Energy' [9], have applied the simple technique of measuring the commercial viability of wave energy by predicting the cost of electricity generated by potential WECS in terms of pence/kWh. The steps taken to calculate this measure are outlined in figure 2.4. The methodology overview here is device independent; however, certain aspects must be performed using different techniques because of the design of the device (e.g. point absorber versus OWC). This methodology was applied to shoreline, nearshore and offshore devices being developed in the UK – the Islay Limpet, the Osprey OWC and the Salter Duck – using the latest information available at the time. The study concluded that, if the wave energy devices performed as predicted, then they could generate over 2000TWh/year by the year 2025. This corresponded to a capital investment of over £500 billion.

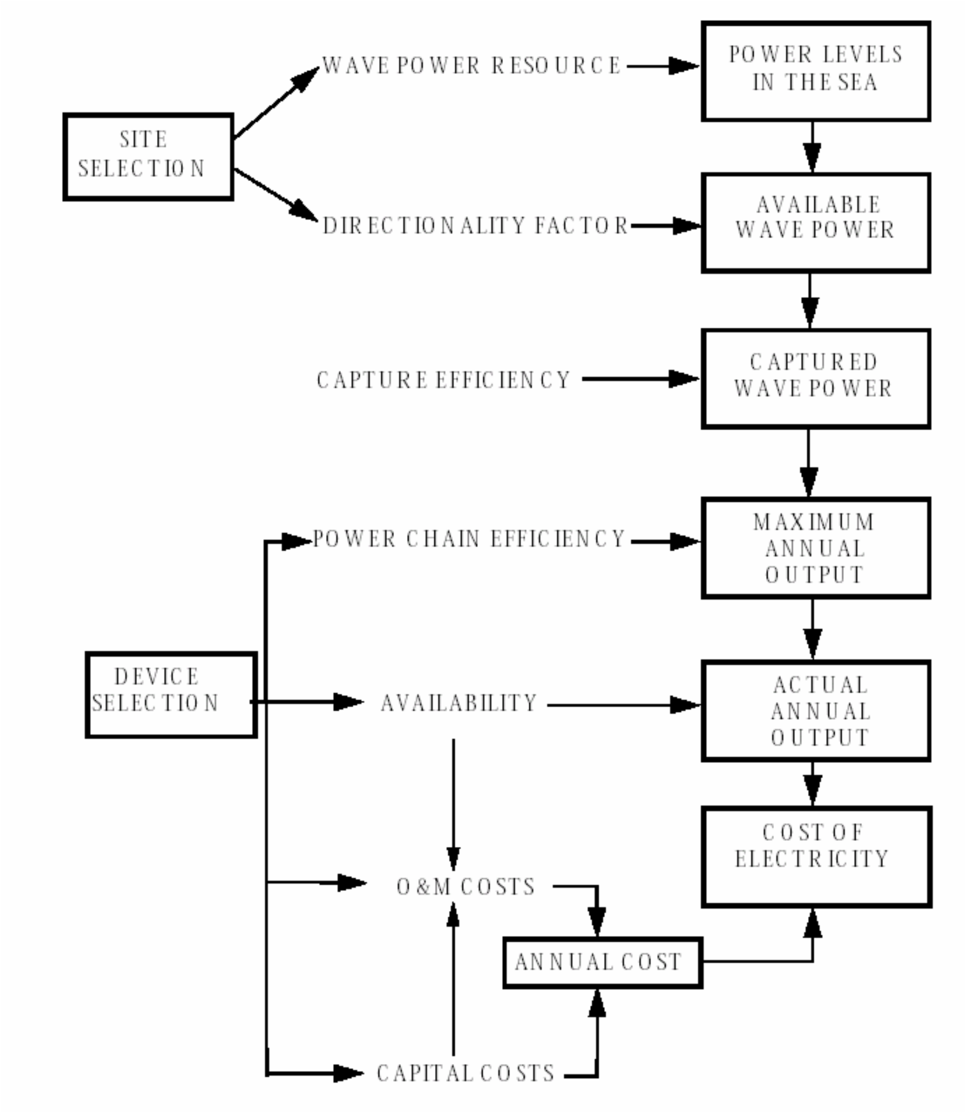


Figure 2.4: Example of a methodology for assessing the economic wave energy resource.

2.10 Resource Surface

A common technique to represent the wave energy resource is to construct a *Resource Surface*. This modelling technique bases the resource values on a set of gridded wave data (e.g. significant wave height, wave energy period, or average power levels) and interpolates these values using a GIS computer program to produce a GIS Raster surface, generating a value for each cell based upon its orientation to the original gridded data and the type of interpolation algorithm applied. Barriers and inner or outer bounds can also be incorporated to give a more realistic model, for example, to take into account shallow depths or coastline. The result is a graphical representation, as displayed in figure 2.5, which is very useful for visualising the wave energy resource and identifying the best locations to install devices.

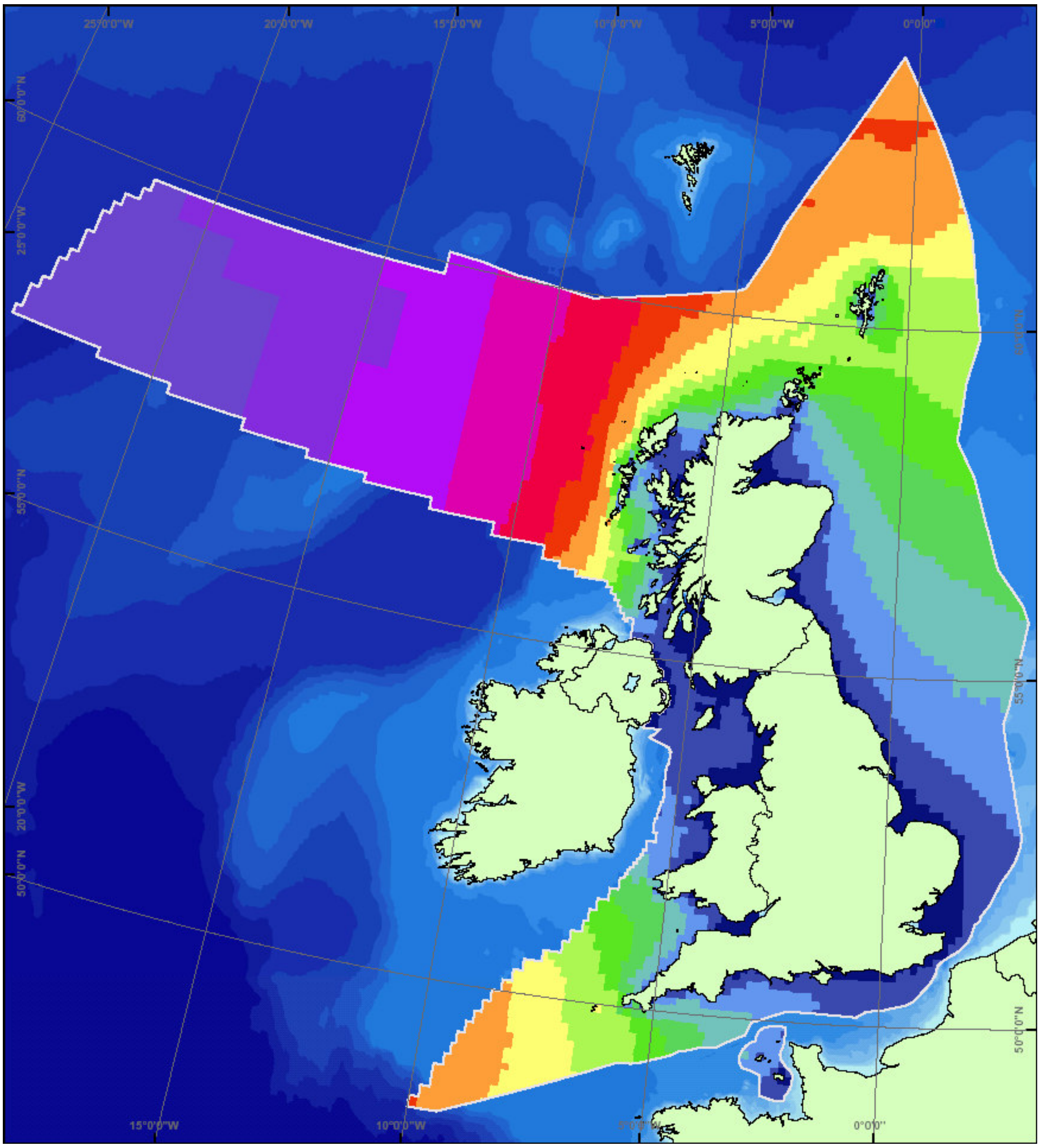


Figure 2.5: Wave Energy Resource surface representing the annual average power level in British waters. Published by the UK Department of Trade and Industry in 2004 as part of the Atlas of UK Marine Energy Resources [25].

3 Technology

3.1 Technology Selection

The Wave Energy Capture System (WECS) selected for this assessment is based upon the current stage of development at the time of this assessment and the availability of technical and economic data. Devices that are currently being demonstrated using full-scale prototypes are preferred due to the availability of measured data as opposed to estimated data. The availability of accurate data is also very important. Data presenting the device's energy conversion performance is required if the technical resource is to be accurately assessed. For the purposes of determining the amount of power converted by a device in different sea states, a WECS power conversion matrix is required for the assessment methodology proposed in this project (see section 3.2). Equally, capital and annualised cost estimates for the commercially manufactured design are required. Ideally, data should be independently verified to ensure soundness and where possible cost estimates from sources other than the developer should be obtained to provide realistic and optimistic cost scenarios. The technology considered in this study is summarised in this section.

3.1.1 Pelamis WECS

In 2004, Ocean Power Delivery Ltd began demonstrating a full-scale 750kW prototype of their *Pelamis* wave device [4]. An artist's impression of this wave device deployed at sea in multiple arrays is shown in figure 3.1. The grid-connected prototype is installed at EMEC in Orkney, Scotland. The device's estimated performance is represented using a power matrix [26] displayed in figure 3.2. Cost estimates for the commercial version are available which include a broad range of costs of components and array related costs [27, 16]. Aspects of the Pelamis R&D program have been independently verified by W.S. Atkins Ltd.

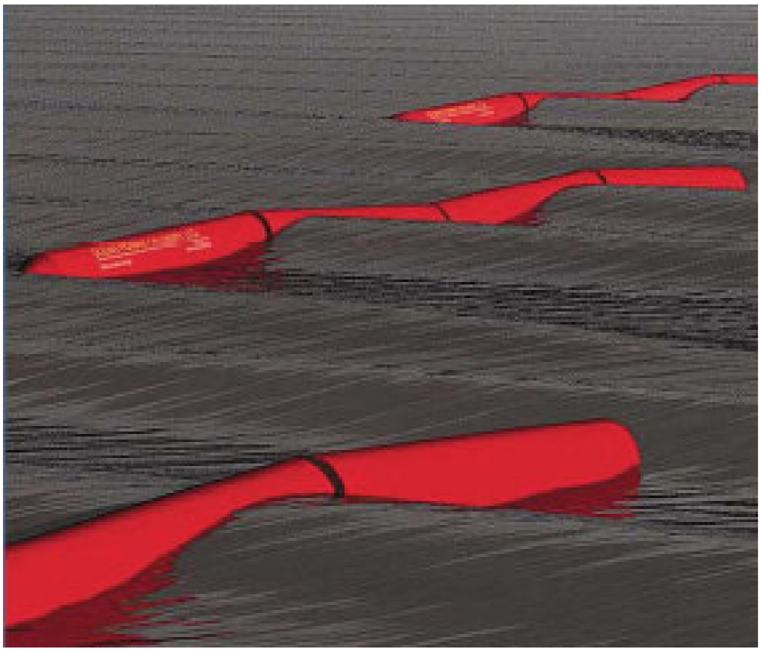


Figure 3.1: An artist's impression of Ocean Power Delivery's Pelamis wave device deployed at sea in multiple arrays.

The Pelamis is an *Attenuator* wave device. It is secured in position using a flexible mooring system. The flexible structure of four elements, each approximately 30 m long, connected by hydraulic joints allows the device to change direction with the waves. No directionality factor is applied to this multidirectional device. The Pelamis WECS is selected for this assessment because of its advanced stage of research, development and demonstration, the availability of a power conversion matrix. Estimates of the device's capital cost and operation and maintenance costs are obtained from the developer and from OXERA Consulting LTD, an independent consultant. The costs are included in section 3.8.

3.1.2 Wave Dragon

A full-scale prototype of the Wave Dragon WECS is being tested in Denmark [28]. No power matrix or detailed data representing the devices wave energy conversion behaviour is available at the time of this assessment. Only very general cost estimates are available.

3.1.3 WavePlane

The WavePlane is an overtopping WECS, which creates a water vortex to turn turbines [29]. WavePlane International AS has developed the device over the past 7 years in Denmark. A full-scale prototype is being developed by Caley Ocean Systems who aimed to test the device at the EMEC in August 2004. No power matrix or detailed data representing the devices wave energy conversion behaviour is available at the time of this assessment. Required cost estimates are not available.

3.1.4 Archimedes Wave Swing (AWS)

The Archimedes Wave Swing (AWS) is a large device fixed to the seabed using a buoyant air filled chamber to bob up and down with the waves, which in turn generates electricity [30]. Initially developed in the Netherlands, a full-scale prototype is being tested in Portugal. Due difficulties experienced with installation onto the seabed, demonstration has been delayed. No power matrix or detailed data representing the devices wave energy conversion performance is available at the time of this assessment. Only general cost estimates are available.

3.1.5 Limpet OWC

The demonstration of the Limpet OWC has shown that the cost involved with shoreline wave energy conversion greatly outweighs the potential economic benefits [31]. The *shoreline* and *nearshore* wave energy resource around Europe's shores is considered to be much lower than the deepwater resource [32]. Therefore, this assessment focused on deep water WECSs.

3.2 Power Matrix

The actual amount of available wave power that can be captured using a WECS can be established using the *Power Matrix* representation presented by the EMEC [13]. The Pelamis WECS power matrix is shown in figure 3.1. The matrix presents the amount of electricity that can be converted by an individual WECS unit (kW) in different sea states (different combinations H_s and T_e).

Significant wave height (H_{sig}, m) \ Power period (T_{pow}, s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Figure 3.2: The Pelamis 750kW WECS power matrix represents the amount of power generated for different sea states (different combinations of significant wave height and wave energy period). Source: [26].

3.3 Average Annual Power Capture

Therefore, the average annual power captured per unit, P_{ave} (kW/Unit) for a specific location can be determined by multiplying each weighting factor, W, in its wave scatter diagram (section 2.2) by the corresponding captured power value, P, in the WECS power matrix and then dividing the sum of all products by the sum of all weighting factors:

$$P_{ave}\ (\text{kW/Unit}) = \frac{\sum P_i W_i}{\sum W_i} \qquad \text{Equation 3.1}$$

where sea states where power capture equals P_i occur W_i times per year. To ensure compatibility, both matrices must use the wave data using similar ranges.

3.4 Shadowing effect and shadow zone

WECS will be deployed in arrays made up of parallel rows of devices, perpendicular to the predominate wave direction – similar to offshore wave farms. In a simple wave model neglecting three-dimensional scattering of waves, the line of WECSs at the front of the array will absorb energy from the waves and thus reduce the power flux available to the WECS behind. For example, if a Pelamis WECS is assumed to capture 40% of incoming energy, and the spacing is 40 times the devices diameter, then only 1% of the incoming energy will be absorbed by each row. For the n^{th} row in a array subjected to unidirectional waves, the available power flux will be attenuated by 0.99^{n-1}. Therefore, the second row in the array will receive 99% of the incoming energy. For ideal unidirectional wave conditions with sinusoidal waves, a 10-row-array will capture approximately 10% of the total available power flux. To minimise this *shadowing effect,* the line of devices must be perpendicular to the predominate direction of incoming swell. Changes in wave direction may increase the effect of shadowing. For example, arrays configured in long rectangles positioned perpendicular to predominate wave direction would be significantly affected by a 90° shift in direction. Different layouts such as circular arrays arranged in hexagonal patterns may reduce shadowing effects [33].

As wave fields pass over a WECS, energy is absorbed, reflected and deflected creating a *shadow zone* in the immediate wake of the device. If devices are located too close together so devices lie in the shadow zone of other "up wave" devices, then the energy captured decreases. Therefore spacing of adjacent devices must be sufficient to allow this area of wave inactivity to dissipate due to the process of wave diffraction.

3.5 Wave Regeneration

European waters experience prevailing westerly winds, therefore WECS arrays deployed up wave over the ocean surface will shadow the ones behind them in the same way that lines of WECS may shadow other devices within individual arrays. However, this additional shadowing effect can be countered by leaving a sufficient distance between arrays to regenerate waves from wind – the primary source of wave energy. Assuming, arrays are positioned in straight rows perpendicular to a constant wind direction, the distance required for wave regeneration can be calculated using a relation between the significant wave height, H_s, wind speed, V and the length of fetch, F [34]:

$$H_s = \frac{0.91x\ V^{1.175}\ x\ F^{0.41}}{1000} \quad \text{for } 0.5 < \frac{F}{V^2} < 2000 \qquad \text{Equation 3.2}$$

For example, assume an initial significant wave height of 3.5 m is reduced to 3 m immediately behind the first row of WECS arrays. For a wind speed of 12 m/s, the required fetch to achieve 3.5 m waves in deep water is 208 km. The corresponding fetch for a significant wave height of 3 m is 178 km. Thus the attenuated waves need a distance of 30 km to regenerate.

3.6 Population Density and Array Configuration

To assess the annual output of multiple Pelamis WECS deployed in arrays, the population density – the number of devices that can operate within a specified area – must be determined. Devices must not be too densely packed or shadow zones may affect the overall output. On the other hand, density should be minimised to reduce array footprint and conflicts with other sea users. Also, longer lengths of transmission cabling would be necessary to interconnect the array, thus raising the cost of electricity produced.

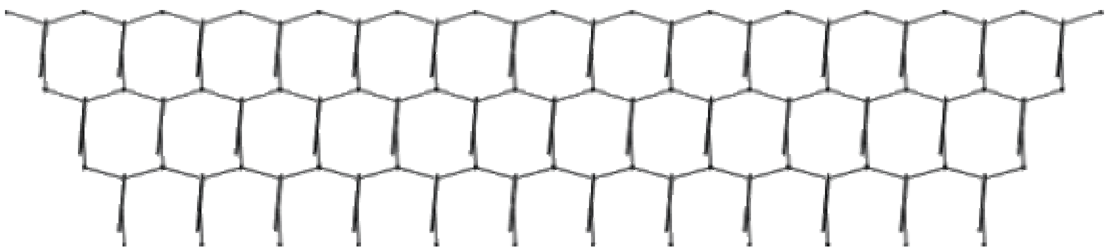


Figure 3.2: OPDs planned configuration for 30 MW Pelamis WECS arrays.

OPD plan to deploy arrays of 39 Pelamis WECSs in three parallels perpendicular to the wave direction. This configuration, shown in figure 3.2, constitutes arrays of approximately 30 MW in capacity. Devices would be spaced 200 m apart to prevent devices shadowing other devices [35]. As the Pelamis is 120 m in length, irrespective of wave direction the minimum distance to the next device is 80 m. This is considered enough to allow shadow zones, which occur in the wake of the device, to dissipate due to wave diffraction and allow any variation in wave power directly behind the line of device to disperse, becoming constant. Subsequently, ~30 MW arrays would be 2600 m by 400 m giving a population density of approximately 30 MW/km^2.

Row	Units	Width
		m
1	14	2600
2	13	2400
3	12	2200

Table 3.1: OPD Pelamis configuration

Spacing	m	200
Units		39
Rows		3
Breadth	m	400
Area	km^2	1.04

Table 3.2: Pelamis array properties

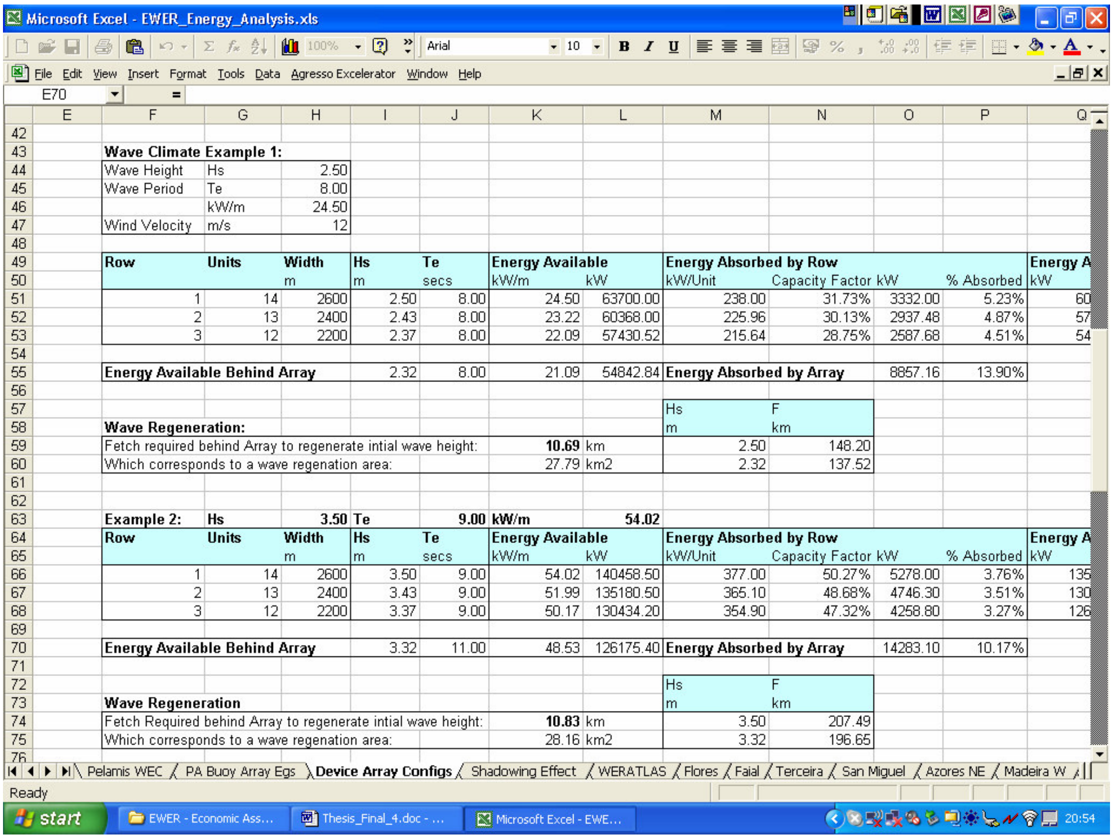


Figure 3.3: The shadowing effect is investigated for different wave conditions and assuming the OPD array layout to determine the array density to be using in the European resource assessment.

To determine the array density to be selected for the assessment, the shadowing effect is investigated for different wave conditions assuming a constant wind speed of 12 m/s and the OPD array layout. The analysis is completed using Microsoft Excel as illustrated in figure 3.3 and is included in Appendix 14.4. Due to the predominant wind direction experienced in European waters and the flexibility of the Pelamis device that allows energy to be captured from different wave directions, the required fetch is estimated assuming unidirectional wave conditions. Neglecting array effects on wave period, the effect of wave height and equivalent wave power capture is identified. The power captured per unit is estimated using a linear interpolation of the Pelamis power matrix included in Appendix 14.4. The following scenarios assume constant wave power received across the width of each line of WECS.

3.6.1 2.5 m significant wave height, 8 sec wave period, 24.5 kW/m wave power

Row	Units	Width	Hs	Te	Energy Available		Energy Absorbed by Row				Energy behind Row	
		m	m	secs	kW/m	kW	kW/Unit	Capacity factor	kW	% Absorbed	kW	kW/m
1	14	2600	2.50	8.00	24.50	63700	238.00	31.73%	3332	5.23%	60368	23.22
2	13	2400	2.43	8.00	23.22	60368	225.96	30.13%	2937	4.87%	57431	22.09
3	12	2200	2.37	8.00	22.09	57431	215.64	28.75%	2588	4.51%	54843	21.09

In this sea state, immediately behind the array, the wave height is 2.32 m and wave power is 21 kW/m. Of the 24.5 kW/m – 63700 kW – of original energy flux, 8857 kW is absorbed or 14 %. The fetch required to regenerate the wave height of 2.5 metres is 10.7 km.

3.6.2 3.5 m significant wave height, 9 sec wave period, 54.02 kW/m wave power

Row	Units	Width	Hs	Te	Energy Available		Energy Absorbed by Row				Energy behind Row	
		m	m	secs	kW/m	kW	kW/Unit	Capacity Factor	kW	% Absorbed	kW	kW/m
1	14	2600	3.50	9.00	54.02	140459	377.00	50%	5278	3.76%	135181	51.99
2	13	2400	3.43	9.00	51.99	135181	365.10	49%	4746	3.51%	130434	50.17
3	12	2200	3.37	9.00	50.17	130434	354.90	47%	4259	3.27%	126175	48.53

In these conditions, the wave height is 3.32 m and wave power is 48.5 kW/m immediately behind the array. 14283 kW is absorbed – 10.2 % – of the original 54 kW/m of energy flux – 140459 kW. The fetch required to regenerate the wave height of 3.5 metres is 10.8 km.

3.6.3 4.5 m significant wave height, 7.5 sec wave period, 74.4 kW/m wave power

Row	Units	Width	Hs	Te	Energy Available		Energy Absorbed by Row				Energy behind Row	
		m	m	secs	kW/m	kW	kW/Unit	Capacity Factor	kW	% Absorbed	kW	kW/m
1	14	2600	4.50	7.50	74.42	193489	648.00	86.40%	9072	4.69%	184417	70.93
2	13	2400	4.39	7.50	70.93	184417	625.56	83.41%	8132	4.41%	176284	67.80
3	12	2200	4.30	7.50	67.80	176284	607.20	80.96%	7286	4.13%	168998	65.00

In this wave climate, the wave height is 4.2 m and wave power is 65 kW/m immediately behind the array. 24491 kW is absorbed – 12.6 % – of the original 74.2 kW/m of energy flux – 193489 kW. The fetch required to regenerate the wave height of 4.5 metres is 17.5 km.

3.6.4 7 m significant wave height, 11 sec wave period, 264.1 kW/m wave power

Row	Units	Width	Hs	Te	Energy Available		Energy Absorbed by Row				Energy behind Row	
		m	m	secs	kW/m	kW	kW/Unit	Capacity Factor	kW	% Absorbed	kW	kW/m
1	14	2600	7.00	11.00	264.11	686686	750.00	100%	10500	1.53%	676186	260.07
2	13	2400	6.95	11.00	260.07	676186	740.80	99%	9630	1.42%	666556	256.37
3	12	2200	6.90	11.00	256.37	666556	731.60	98%	8779	1.32%	657776	252.99

In this sea state, the wave height is 6.85 m and wave power is 253 kW/m immediately behind the array. 28910 kW is absorbed, 4.2 % of the total 686686 kW wave power available – 264.1 kW/m. The fetch required to regenerate the height of 7 metres is 8.8 km.

3.7 Selected Configuration and Device Density

The scenarios above show the OPD configuration would only absorb between 4% and 14% of the available energy flux for a range of sea states. The distances required to regenerate the wave heights range from around 9 to 18 km. However, the shadowing effect on arrays located behind is insignificant with 96 to 84 % of wave power still available. Therefore, a wave regeneration distance of 9 km in front of each array is considered adequate for the assessment. Assuming each 30 MW array takes up approximately 1 km^2, each 10 km cell contains 10 arrays. This gives a total installed capacity of 300 MW/cell and an overall cell population density of 3 MW/km^2. This density would leave 9 km free in front of the devices within each cell to allow shipping vessels to safely navigate. The selected array layout for the model is shown in figure 3.4.

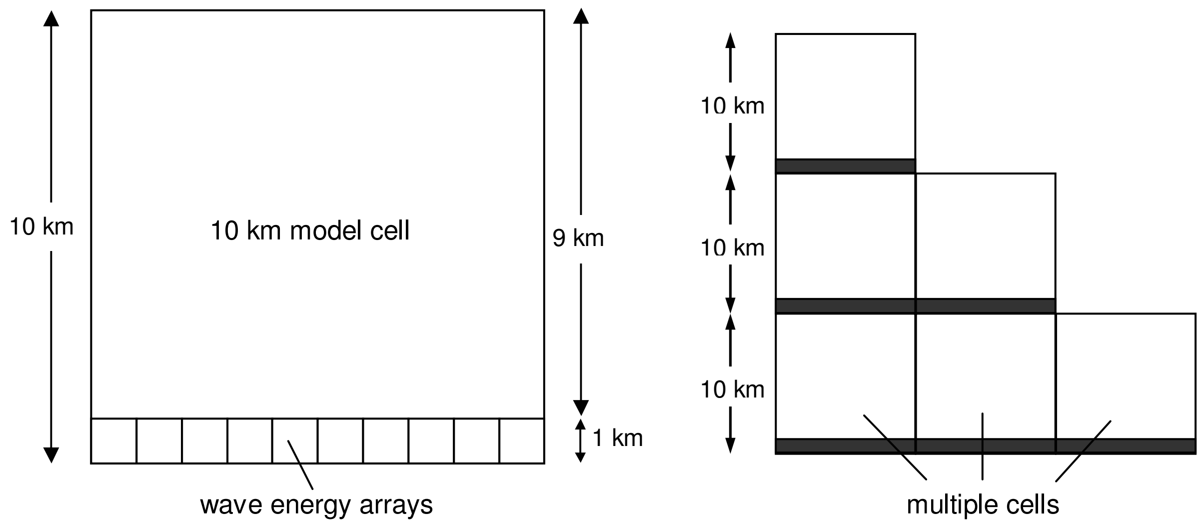


Figure 3.4: The selected device density and distance between arrays.

3.8 Technology Costs

Cost estimates are collected from OPD and OXERA consultants. These provided a lower and upper bound cost scenarios for the economic assessment respectively. The OPD estimates are considered optimistic, therefore, more weight is given to the OXERA costs as they are considered to be more representative [39]. The fixed costs included:

- Planning and approval
- Pelamis WECS
- Mooring System
- Array electrical interconnection
- Installation
- Connection to the onshore grid

3.8.1 OPD Costs

OPDs more ambitious cost estimates [16] assume the "learning by doing" principle of cost reduction, where the capital cost per unit is reduced by half when the number of units produced doubles. The estimates are based upon a project size of 250MW and the best information available to OPD.

Year	Capital £/kW	O&M £/kw/yr
2010	750	37.5
2025	500	25

Table 3.1: OPD capital and annualised operation and maintenance costs

3.8.2 OXERA Costs

OXERA cost estimates displayed in table 3.2 are more conservative [40]. The lower bound is selected to represent the Pelamis WECS.

Year	Capital £/kW Lower bound	Upper bound	O&M £/kW/yr Lower bound	Upper bound
2004	1500	1800	60	72
2010	964	1157	39	46
2020	866	1039	37	44
2025*	856	1027	37	43

Table 3.2: OXERA wave device cost profile. *Costs for 2025 are extrapolated.

3.8.3 Submarine Cable Costs

The cost of additional transmission infrastructure required to connect WECS arrays together and transfer the energy ashore is not included in the above costs. It is assumed that HVDC transmission technology rated at 440kV would be utilized. Cost estimates shown in table 3.3 for the purchase and installation of submarine cable per metre are obtained from EConnect Ltd [42].

kV	£ Cost/m	Installation cost/m†
33	100	250
132	300	250
440	500*	250

Table 3.3: Cost estimates for Submarine cable. * Costs for 440kV are extrapolated. † Installation costs may vary by ±50% based upon the nature, depth and slope of the seabed.

4 Economics and Finance

4.1 Electricity Markets

Based upon the European wave energy resource outlined in 2.7, wave energy generation could develop within the electricity markets of several countries, including: Denmark, France, Germany, United Kingdom, Iceland, Ireland, Norway, Netherlands, Portugal and Spain.

The extent of growth and share within these separate markets will depend on the:

1. Competitiveness of the cost of electricity compared to other generation
2. Feed-in tariffs and subsidies available

Separate market mechanisms are already available within these countries that are helping Renewables to penetrate these markets and reduce the cost of generation, in particular wind [42]. The current status of available subsidies is outlined by the European Renewable Energy Foundation who identified the market price and premium for a range of Renewables throughout Europe based upon 2003 market data [43]. The prices and premiums available for marine energy are detailed in table 4.1.

	€ / MWh			£ / MWh		
Country	Market Price	Premium	Total	Market Price	Premium	Total
Belgium	31.00	90.0	121	21.4	62.1	83.5
Denmark	34.60	48.0	82.60	23.9	33.1	57.0
United Kingdom	28.00	66.0	94	19.3	45.5	64.9
France			83.8			57.8
Germany			88			60.7
Ireland			60			41.4
Netherlands			68			46.9
Norway*	34.6	29.0	63.6	23.9	20.0	43.9
Portugal			225			155.3
Spain	35.4	26.7	62.1	24.4	18.4	42.8
Sweden	34.6	29.0	63.6	23.9	20.0	43.9
Average	33.0	48.1	92.0	22.8	33.2	63.5

Table 4.1: The prices and premiums available for marine energy in 2003. Where no premium or price is available for wave energy, the values are taken for offshore wind. *No value for Norway is available, so values from Sweden are used.

There are also plans within Europe to harmonise policy and unite individual electricity markets into a single Internal Electricity Market (IEM) by 2010 where a single price and premium framework is in place for all European countries [44].

For the purposes of this assessment two market scenarios are investigated:

1. Internal Electricity Market with a single price and subsidy for wave energy
2. Regional Electricity Market using existing separate prices and premium frameworks

4.1.1 Internal Electricity Market (IEM) – Price and Premium

The IEM electricity price selected is based upon OXERA consultant's UK market price profile from 2004 to 2025 displayed in table 4.2 [40]. The total price includes the *EU Emission Trading Scheme* the embedded benefits and *Climate Change Levy* exception certificates. This is considered to be a conservative representation of market mechanism throughout Europe. The selected European renewable price, which is slightly lower than the average of 2003 European prices in table 4.1, is considered to be around 20% lower than the wholesale price [39].

Year	Wholesale Price (inc. ETS)	Embedded benefits	CCL Excemption Certificates	Total UK Price		Selected Renewable Price*	
	£/MWh	£/MWh	£/MWh	£/MWh	€/MWh	£/MWh	€/MWh
2004	20	2.5	3.87	26	38	22	32
2005	23	2.5	3.87	29	43	25	36
2006	23	2.5	3.87	29	43	25	36
2007	23	2.5	3.87	29	43	25	36
2008	23	2.5	3.87	29	43	25	36
2009	24	2.5	3.87	30	44	26	37
2010	24	2.5	3.87	30	44	26	37
2011	25	2.5	3.87	31	45	26	38
2012	25	2.5	3.87	31	45	26	38
2013	25	2.5	3.87	31	45	26	38
2014	25	2.5	3.87	31	45	26	38
2015	25	2.5	3.87	31	45	26	38
2016	25	2.5	3.87	31	45	26	38
2017	25	2.5	3.87	31	45	26	38
2018	25	2.5	3.87	31	45	26	38
2019	25	2.5	3.87	31	45	26	38
2020	25	2.5	3.87	31	45	26	38
2021	25	2.5	3.87	31	45	26	38
2022	25	2.5	3.87	31	45	26	38
2023	25	2.5	3.87	31	45	26	38
2024	25	2.5	3.87	31	45	26	38
2025	25	2.5	3.87	31	45	26	38

Table 4.2: UK electricity price profile from 2004 to 2005. Source: [40]. *Current wholesale electricity prices for Renewable energy source are approximately 20% lower than the figure given by OXERA.

The UK total price for electricity generated from offshore wind, including subsidy, is approximately £50/MWh in 2004. Therefore, an entry price of £55/MWh is considered conservative and achievable for wave energy [39]. The selected price and premium is displayed in table 4.3. Selecting an accurate subsidy is very difficult as this depends on several factors such as current market share, competitiveness of the cost of electricity supplied compared to other generation, the level of market pull necessary to create the market size desired, objections from existing generator companies and the effect on the existing electricity market. The influence of different levels of subsidy on the potential market is presented in the Sensitivity Analysis in section 8.

4.1.2 Regional Electricity Market – Price and Premium

The separate prices and premiums for wave energy in the countries listed above are based on the EREF RES-E Market prices and frameworks available in 2003 for marine energy as detailed in table 4.1. Where no premium or price is available for wave generation, the values are taken for offshore wind, which is considered to be representative for wave energy.

4.2 Transmission tariffs

The cost of transferring electricity across the existing transmission system to the customer is included within a transmission tariff, which generator companies must pay to the utility that own the transmission infrastructure. Tariffs may vary from country to country and from region to region within a country in relation their distance from centres of load population. In some countries, generators may not pay any tariff such as in Spain and Portugal, or, actually receive funds if located close to load centres such as in the United Kingdom.

Country	Transmission Tariff
Belgium	0
Denmark	1.076
United Kingdom	2.32
France	0
Germany	0
Ireland	1.253
Netherlands	0.979
Norway	1.943
Portugal	0
Spain	0
Sweden	1.077
Average	0.8

Table 4.4: Transmission tariffs in €/MWh based upon consuming a constant load of 15 MW during 16 hours (from 0800 to 2400) in working days, and no load in the weekends (approximately 4200 hours per year), for European countries in 2002.

Transmission tariffs can be charged per unit of electricity generated per hour. Tariffs, displayed in table 4.4, are obtained from a European Union study, which collected the tariff data for all European countries in 2002 [45].

4.3 Internal Rate of Return

The Internal Rate of Return (IRR) of a Capital Budgeting project is the discount rate at which the Net Present Value (NPV) of a project equals zero. The IRR decision rule specifies that all *independent* wave energy projects with an IRR greater than the cost of capital should be accepted. When choosing among *mutually exclusive* projects, the project with the highest IRR should be selected (as long as the IRR is greater than the cost of capital).

The determination of the IRR for a project, typically, involves trial and error or a numerical technique. (The IRR function within Microsoft Excel is used to calculate the IRR for wave energy projects throughout in this assessment).

The Net Present Value (NPV) of a Capital Budgeting project indicates the expected impact of the project on the value of the company. Projects with a positive NPV are expected to increase the value of the company. Thus, the NPV decision rule specifies that all "independent" projects with a positive NPV should be accepted. When choosing among "mutually exclusive" projects, the project with the largest (positive) NPV should be selected.

4.4 Required Rate of Return

The Required Rate of Return (RRR) is the financial return on an investment required to attract investors. If this return is too low then investors will invest elsewhere. RRR can be estimated by taking into account the risk associated with the technology and the project. Financial analysis of wave energy projects by WAVENet recommend that real after-tax RRR should be no less than 10 % [46]. The current RRR for offshore wind projects in the United Kingdom is around 12.5 %. As more technical risk is associated with the untested offshore wave technology compared to offshore wind, a RRR of 13% is considered realistic for wave power [39]. Therefore, the RRR used in this assessment to calculate the potential market – the areas of the European ocean where WECS arrays are commercially viable – are as follows:

- 10% optimistic rate
- 13% realistic rate

4.5 RRR and discount rate

Discount rates are used to estimate the present value of a project based on the perceived risk of a project. Normally, discount rates of 8 % apply to project using mature technology, whilst 15 % apply to developments with technical risk such as wave power projects. The discount rate that should be selected to compare technology cost should be based on the RRR associated with the technology's risk. Therefore, discount rates close to 10 % should be applicable to wave energy cost estimates.

4.6 Currency

Sterling (GBP, £) and Euro (EUR, €) currency are both used during the economic analysis. A fixed rate exchange is applied:

- 1.45 GBP-EUR
- 0.69 EUR-GBP

Sterling is used to represent monies in the project report.

5 Methodology Design

The methodology is required to provide a systematic and reusable approach to calculate the wave energy resource for a given area of sea based upon on the resource, technology and economic data input.

The overview of the methodology is outlined in figure 5.1. The methodology is made up of data input, the necessary step to calculate the market size and data output. The data input is denoted by clear rectangles with a black outline. Each step in the methodology performs operations on the given input, represented by grey rectangles with black outlines. The output of each operation is presented by a rectangular oval with black outline. Operations located within blue areas are performed for each grid cell within the assessment model. Data input is displayed on the left-hand side and linked to one of the four steps that run from top to bottom. Data parameters are transferred between steps in the methodology.

The methodology consists of the following steps and are explained in this section:

1. **Get Technology Capacity Factor for each Wave Data Grid Point**
2. **Get Data Surfaces**
    a. Interpolate Capacity Factor Surface
    b. Interpolate Depth Surface
    c. Calculate Distance to Shore Surface
3. **Get Internal Rate of Return (IRR)**
    a. Calculate Capital Cost
    b. Calculate Annual Energy Output
    c. Calculate Net Income
    d. Calculated IRR
4. **Get Market Size**

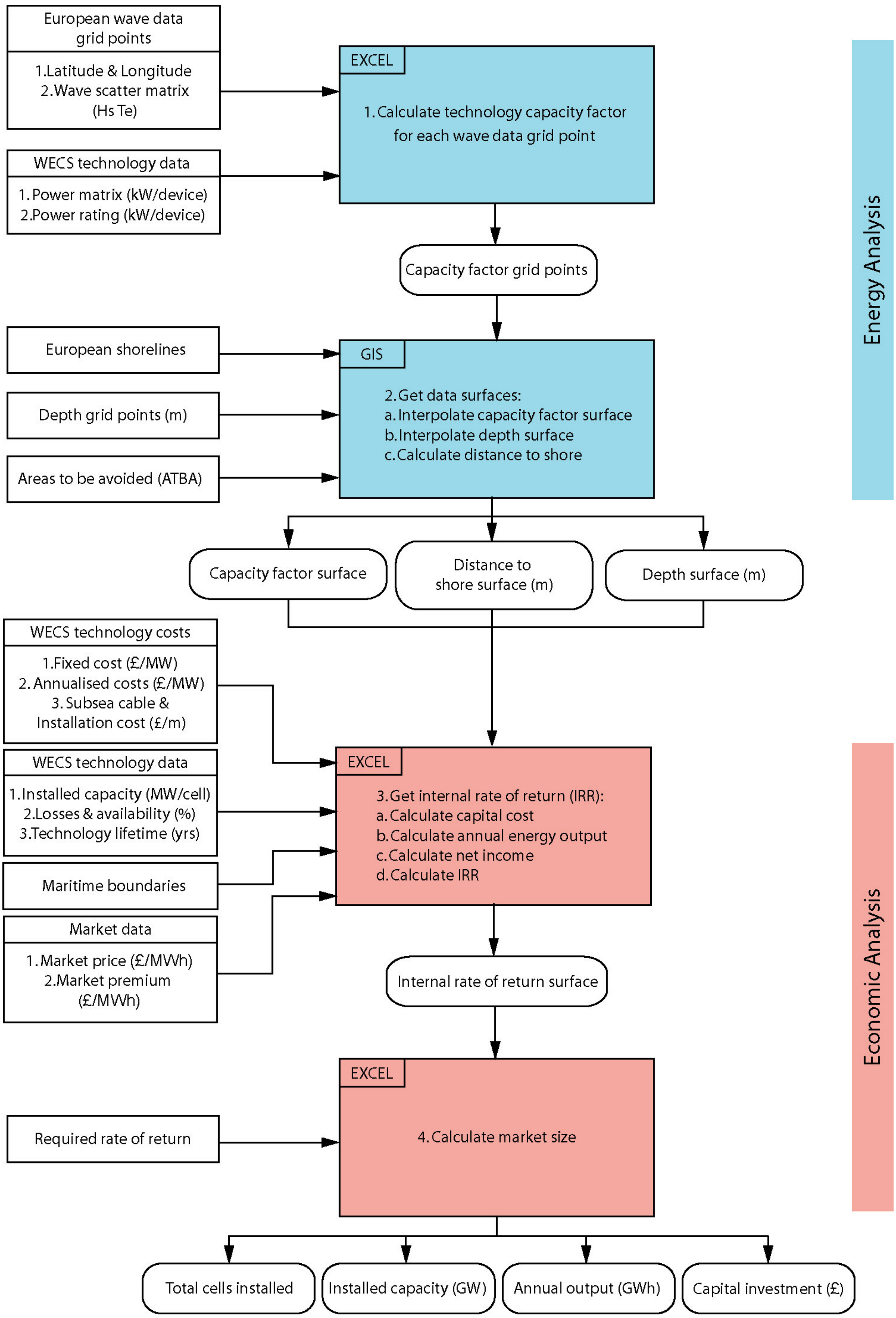


Figure 5.1: Overview of the assessment methodology. The first and second step focus on energy related aspects of the assessment and the third and fourth performs the economic tasks.

5.1 Calculate technology capacity factor

The first procedure calculates the WECS capacity factor (also known as load factor or capacity coefficient) for each gridded wave data point displayed in section 7.6. The procedure is outlined in figure 5.2. The capacity factor is calculated by dividing the actual energy captured by the devices *Rated Power*.

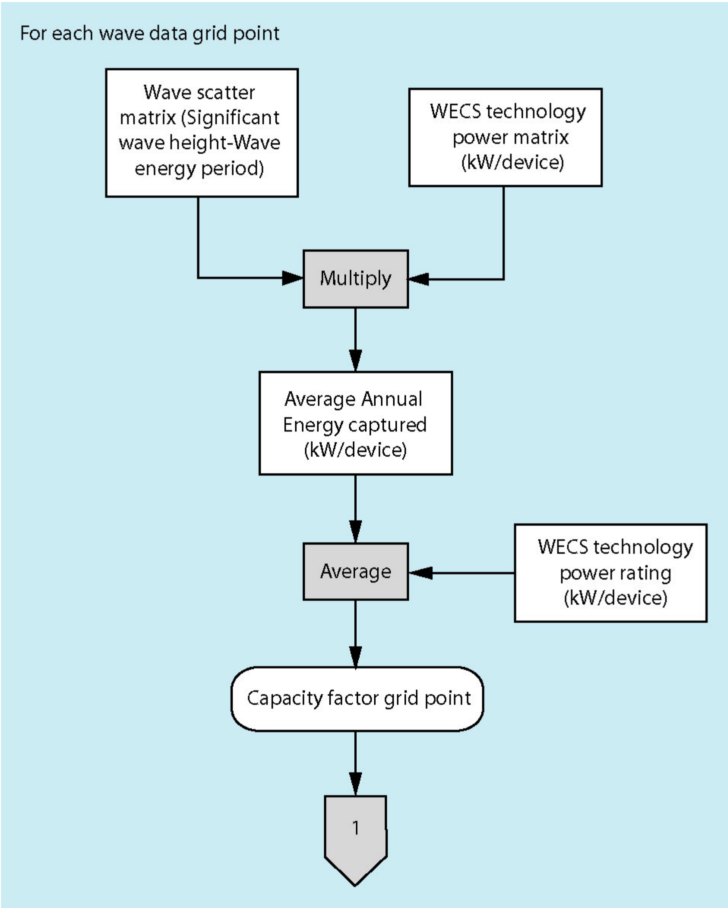


Figure 5.2: The first step in the methodology calculates the technology capacity factor for the wave device if installed at the location of the wave data.

5.1.1 Data Input - Wave Data

Explained in section 2, the wave data should comprise of measurements of significant wave height wave period recorded for a specific location of latitude and longitude. This data should be annualised over the total period of measurement to represent the sea state of a typical year. The number of data points will affect the quality of the GIS model generated in the next step of the methodology. Hence, the obvious importance of using as many data points as possible to improve the accuracy of the overall economic assessment. An example of the data points obtained from the WERATLAS utilised to assess the European wave energy resource in this study is displayed in table 5.1.

Point Code	Name	Latitude Coordinate	Longitude Coordinate	Mean Energy Available (kW/m)	Standard Deviation (kW/m)	Variation Coefficient (%)	Data Source
ATL.12	GORRINGE BK	36.00	-12.00	33.39	6.34	19	WAM 1987 – 2005
ATL.13	LISBOA	39.00	-12.00	39.01	7.33	19	WAM 1987 – 2006
ATL.14	VIGO	42.00	-12.00	46.02	9.54	21	WAM 1987 – 2007
ATL.15	CHARCOT	45.00	-12.00	55	11.72	21	WAM 1987 – 2008
ATL.16	LA CORUNA	45.00	-9.00	50.22	11.83	24	WAM 1987 – 2009
ATL.17	GIJON	45.00	-6.00	44.15	10.85	25	WAM 1987 – 2010
ATL.18	ARCACHON	45.00	-3.00	32.59	8.22	25	WAM 1987 – 2011
ATL.19	OUESSANT	48.00	-6.00	47.35	11.84	25	WAM 1987 – 2012
ATL.20	LUNDY	51.00	-6.00	46.05	10.17	22	WAM 1987 – 2013
ATL.21	FASTNET	51.00	-9.00	53.4	11.91	22	WAM 1987 – 2014
ATL.22	SHANNON	51.00	-12.00	67.81	14.46	21	WAM 1987 – 2015
ATL.23	BELMULLET	54.00	-12.00	74.97	16.33	22	WAM 1987 – 2016
ATL.24	BARRA	57.00	-9.00	65.44	17.04	26	WAM 1987 – 2017
ATL.25	FAIR ISLE	60.00	-3.00	61.47	13.61	22	WAM 1987 – 2018
ATL.26	NORTH RONA	60.00	-6.00	57.44	12.17	21	WAM 1987 – 2019
ATL.27	FAEROES	63.00	-6.00	59.91	11.72	20	WAM 1987 – 2020
ATL.32	AUK	56.23	2.03	21.3	5.95	28	Directional buoy 1984 – 1994
ATL.33	K13	53.13	3.13	10.67	1.4	13	Directional buoy 1984 – 1995
ATL.34	GORM	55.58	4.75	21.12	7.04	33	Non-directional buoy 1981-
ATL.35	UTSIRA	59.30	4.82	23.12	5.52	24	Frequency buoy 1974 – 1986
ATL.36	STAD	62.50	4.37	57.24	Insuf. Data	Insuf. Data	Directional buoy 1990 – 1991
ATL.37	HALTENBANKEN	65.10	7.40	42.37	8.51	20	Directional buoy 1980 – 1988
ATL.38	TRAENABANKEN	66.30	9.53	48.2	Insuf. Data	Insuf. Data	Directional buoy 1981 – 1984

Table 5.1: Wave data for 23 measured locations in the Northern Atlantic and the North Sea.

5.1.2 Data Input – Wave Scatter Diagrams

For each wave data point, the wave height measurements and energy period data should be represented using a sea state scatter diagram (or matrix) characterising the variation in sea state for each location in a typical year (the method for displaying wave energy data as outlined in section 2.2). In this study, these are obtained from the WERATLAS, an example of which is shown in table 5.2.

Significant Wave Height Hs (m)	**Energy Period Te (secs)**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**18**
0.0-0.5		0	0	0	0	0	0	0	0	0	0	0	0	0
0.5-1.0		0	2	11	12	3	0	0	0	0	0	0	0	0
1.0-1.5		0	15	38	44	35	10	2	0	0	0	0	0	0
1.5-2.0		0	11	37	38	45	30	8	2	1	0	0	0	0
2.0-2.5		0	1	25	35	32	30	17	3	1	0	0	0	0
2.5-3.0		0	0	8	25	27	23	19	8	2	0	0	0	0
3.0-3.5		0	0	0	15	21	22	16	12	2	1	0	0	0
3.5-4.0		0	0	0	4	18	19	14	11	5	1	0	0	0
4.0-4.5		0	0	0	1	11	16	12	9	6	3	0	0	0
4.5-5.0		0	0	0	0	4	15	13	9	7	3	1	0	0
5.0-5.5		0	0	0	0	1	7	11	8	5	2	1	0	0
5.5-6.0		0	0	0	0	0	3	8	7	4	2	1	0	0
6.0-6.5		0	0	0	0	0	1	5	5	4	2	1	0	0
6.5-7.0		0	0	0	0	0	0	3	4	2	2	1	0	0
7.0-7.5		0	0	0	0	0	0	1	3	2	2	1	0	0
7.5-8.0		0	0	0	0	0	0	0	2	2	2	1	0	0
8.0-8.5		0	0	0	0	0	0	0	1	2	2	0	0	0
8.5-9.0		0	0	0	0	0	0	0	0	2	1	1	0	0
9.0-9.5		0	0	0	0	0	0	0	0	1	1	0	0	0
9.5-10.0		0	0	0	0	0	0	0	0	1	1	0	0	0
10-11.0		0	0	0	0	0	0	0	0	0	1	1	1	0
11-12.0		0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.2: The wave scatter diagram representing the wave conditions for a deepwater location 57°N 9°W off the Scottish west coast obtained from the WERATLAS.

5.1.3 Data Input – WECS Power Conversion Matrix

The actual amount of available energy that can be captured using the wave device unit can be calculated using a *Power Conversion Matrix* (see section 3.2). The estimated power conversion performance of the Pelamis device for typical wave conditions is given in table 5.3.

Hs (metres)	**Te (seconds)**																
	5.0	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**	**9.0**	**9.5**	**10.0**	**10.5**	**11.0**	**11.5**	**12.0**	**12.5**	**13.0**
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	0	0	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	0	0	0	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	0	0	0	0	0	750	750	750	750	750	750	750	750	676	613	584	525
7.5	0	0	0	0	0	750	750	750	750	750	750	750	750	750	686	622	593
8.0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

Table 5.3: The Pelamis 750kW WECS power matrix representing the amount of energy generated for different sea states. These figures are estimated values based upon mathematical modelling and scale model tank testing.

5.1.4 Calculate average power captured and technology capacity factor

The WECS power conversion matrix indicates the power that can be captured for different seas states. Therefore, the average annual energy captured per unit, P_{ave} (kW/Unit) for an offshore location can be estimated by multiplying each weighting factor, W, in the wave scatter diagrams for that location by the corresponding converted power value, P, in the WECS power matrix and then dividing the sum of all products by the sum of all weighting factors:

$$P_{ave}\ (\text{kW/Unit}) = \frac{\sum P_i W_i}{\sum W_i} \qquad \text{Equation 3.1}$$

To ensure compatibility, the scatter diagram and power matrix must represent the wave data using similar ranges of wave height and wave period.

5.1.5 Data Output – Capacity factor grid points

The wave device capacity factor is then calculated by dividing P_{ave} by the devices power rating. This is repeated for each wave data location. The complete list of wave data including position of latitude and longitude, the average annual energy captured (kW/unit) and capacity factors are then transferred to the GIS model.

5.2 Get Data Surfaces

The methodology uses gridded geographical data – data for a particular position of latitude and longitude, for example measurements of sea depth or wave height. These data sets are often limited in size due to the cost of acquisition. To represent the entire area to be analysed, data surfaces can be interpolated from the original data sets using Geographical Information Systems (GIS) interpolation techniques. A GIS model is developed to represent and analyse the geographical-based wave resource data. The GIS resource model is divided into grid cells. The GIS analysis is explained in section 7.

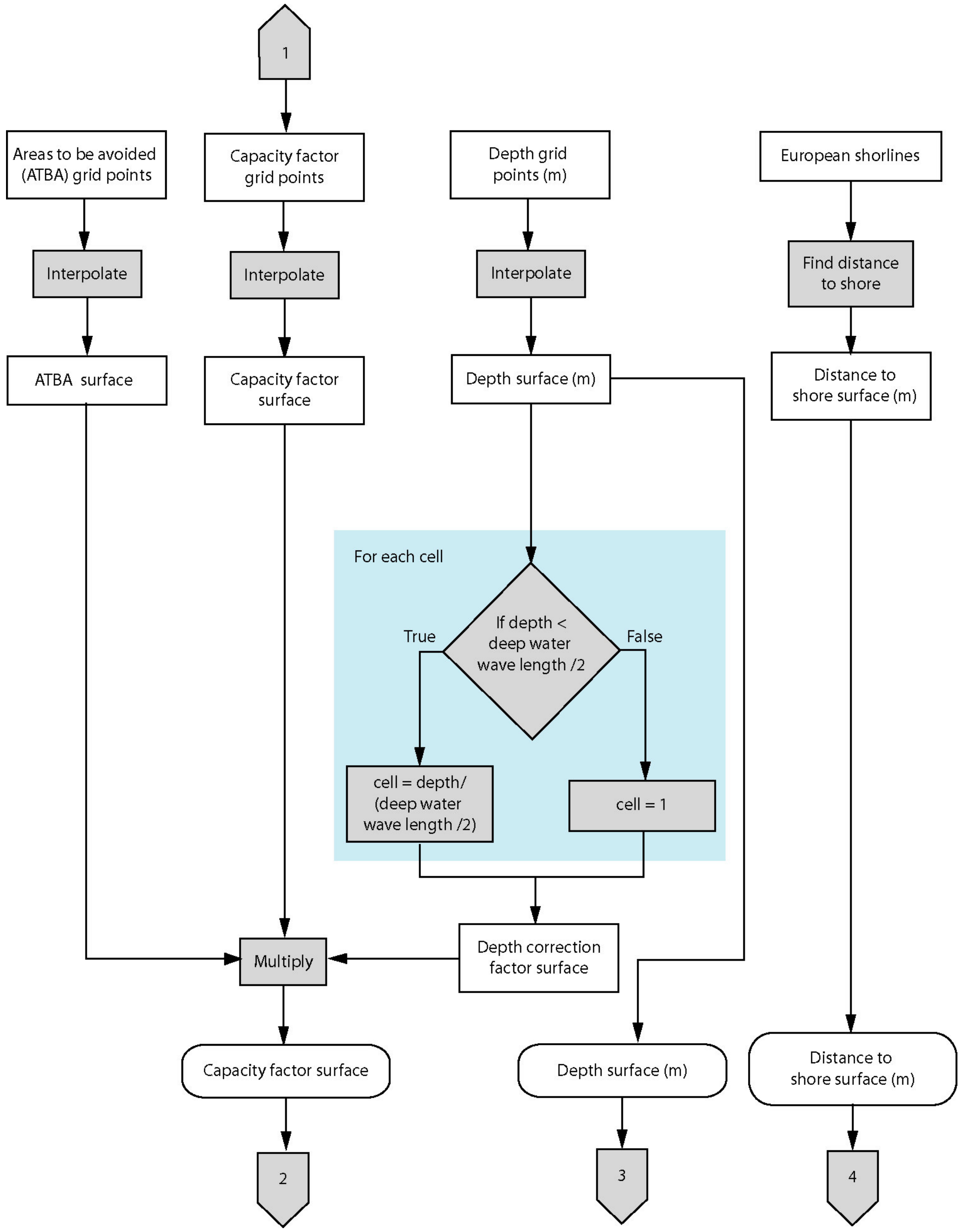


Figure 5.3: The second procedure in the methodology generates the GIS data surfaces by interpolating capacity factors and depth, and calculating the distance to shore for each cell in the resource model.

5.2.1 Interpolate Capacity Factor Surface

The second step in the methodology uses the GIS model to take the capacity factor values calculated for each wave data grid point in the first step and interpolate values for all cells within the GIS model. The GIS interpolation operation creates a surface representing the capacity factors. An average capacity factor is interpolated for each model cell based upon its position relative to the original grid points and the type of interpolation algorithm executed. This surface allows the energy captured by wave energy arrays deployed within any cell to be estimated using the interpolated capacity factor.

5.2.1.1 Data Input – Capacity factor grid points

The gridded WECS capacity factors calculated in the first step are input into the GIS model.

5.2.1.2 Data Input – Areas to be Avoided (ATBA)

Environmental constraints that may restrict the deployment of WECS in certain areas are incorporated. Any area that is designated by a European maritime authority is avoided and excluded from the economic assessment. Areas to be avoided (ATBA) including:

- Deep water shipping channels
- Traffic routing measures
- Inshore traffic zones
- Traffic Separation Arrays
- Explosives dumping grounds

The navigational risk associated with the amount of shipping activity in a particular area is not included in this assessment. Areas of scientific interest are also not incorporated.

5.2.2 Interpolate Depth Surface

The average depth must be calculated for each cell within the resource model so that the cost of transferring the captured power onshore using submarine cable can be calculated. The GIS depth surface can be interpolated from a gridded data set of depths measurements, obtained from sources such as Admiralty Charts.

5.2.2.1 Data Input - Depth points (metres)

The number of gridded depth measurements input into the GIS model will affect the accuracy of the GIS depth surface.

5.2.3 Calculate Distance to Shore Surface

The distance to shore must be calculated for each cell within the resource model so the cost of transferring the captured power onshore can be determined. A GIS map of the area of shoreline to be assessed should be input into the GIS model so the distance to the nearest shoreline for each cell can be calculated.

5.2.3.1 Data Input – European shorelines

A GIS map of Europe is input into the GIS model included in section 7.6.

5.3 Get Internal Rate of Return

The third step in the methodology calculates the internal rate of return for potential wave energy arrays as shown in figure 5.4.

5.3.1 Calculate Capital Cost

The total cost to deploy WECS arrays is calculated for every cell within the resource model. The fixed cost per MW is multiplied by the installed capacity (MW/cell) to give the total fixed cost for each cell. The cells fixed cost is then added together with the variable cost of submarine transmission cable to give the total capital cost for every cell. The fixed costs (Cost/MW) included:

- Planning and approval
- Pelamis WECS
- Mooring System
- Array electrical interconnection
- Installation
- Grid connection onshore

The total submarine cable cost is calculated by multiplying the cost of purchasing and installing per metre length of cable by the distance to shore and the depth of each cell.

5.3.1.1 Data Input

- Fixed costs (£)
- Depth surface (m)
- Distance to nearest shore surface (m)
- Submarine cable costs (£)
- WECS Population density (MW/Cell)

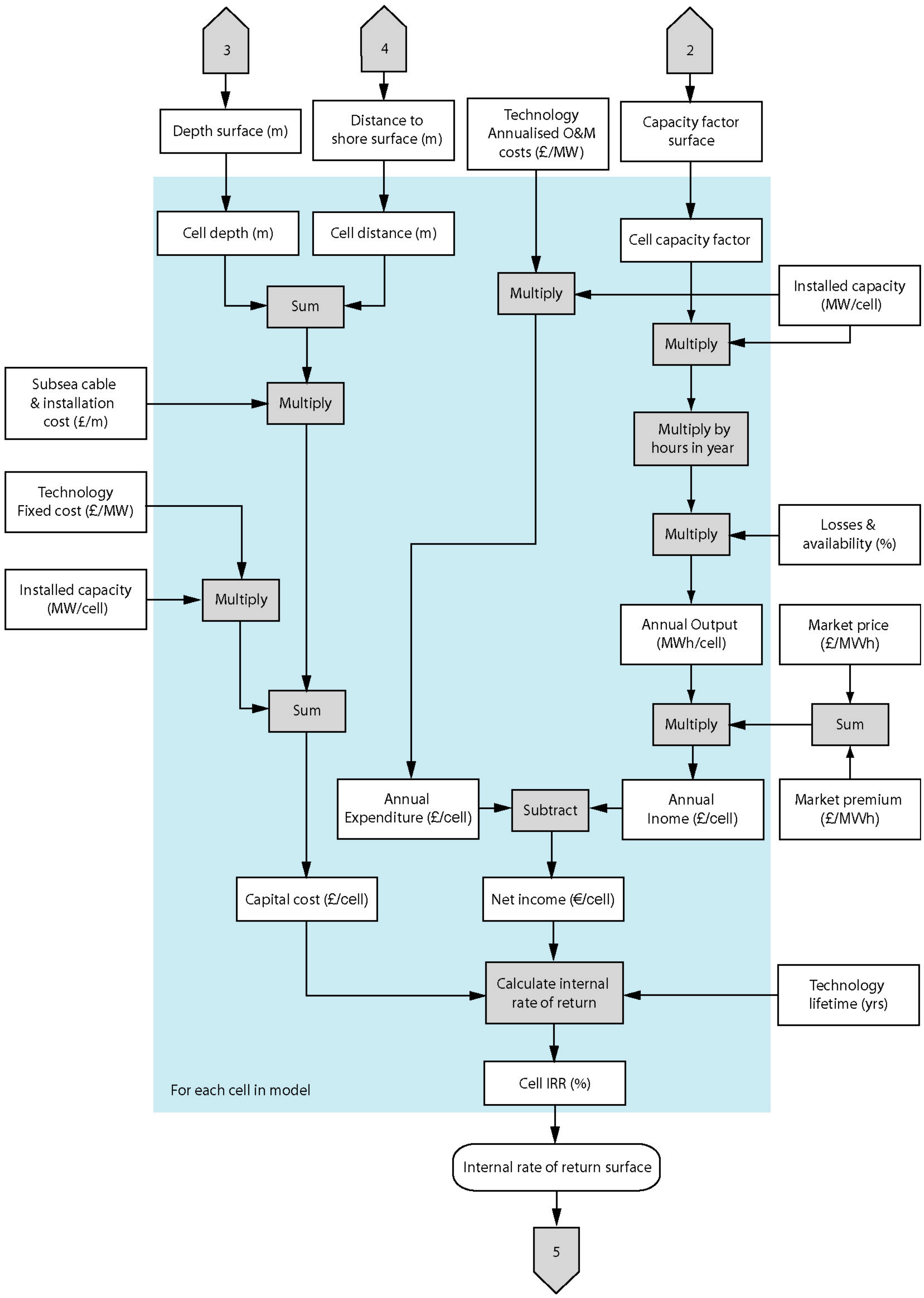


Figure 5.4: The third step in the methodology calculates the internal rate of return for potential wave energy arrays deployed in the selected area.

5.3.2 Calculate Annual Energy Output (MWh)

The annual energy that could be generated by WECS arrays must be calculated for each cell so the potential income can be estimated. The capacity factor for every 100 km^2 cell is obtained from the inputted capacity factor surface. This is multiplied by the cell's installed capacity (MW) and then by the hours in a year – 24 x 365.25 = 8766. To account for transmission losses, the annual output is multiplied by a factor. To incorporate when the plant is not generating electricity due to maintenance work, a system availability factor is also included, giving the total annual energy output in MWh.

5.3.2.1 Data Input

- Capacity factor surface
- WECS Population density (MW/km)
- Losses and availability factor (%)

5.3.3 Calculate Net Income

The net income is required to calculate the Internal Rate of Return (IRR) described in section 4.3. The annualised costs of operating the device array is input. The annualised cost per MW is multiplied by the WECS population density, giving the annual expenditure for each cell. The annual income is then calculated by multiplying the annual output by the selected market price and subsidy displayed in section 4.1. The expenditure is then subtracted from the income to give the net income.

5.3.3.1 Data Input

- Annual Output (MWh)
- Market Price (£/MWh)
- Market Premium (£/MWh)
- Technology Annualised O&M Cost (£/MW)

5.3.4 Calculate Internal Rate of Return (IRR)

The IRR described in section 4.3 is calculated for the WECS arrays that could be deployed within each resource cell. Calculating the IRR allows all sites to be considered, commercially viable cells to be identified based upon the Required Rate of Return (RRR) and the potential market to be determined. To calculate the IRR the

Capital Cost and annual cash flow for the arrays lifetime is required. The annual income is based upon an estimated electricity price averaged over the developments lifetime. The IRR is calculated for every cell within the resource model giving the IRR surface. No form of tax is included in the methodology.

5.3.4.1 Data Input

- Capital Cost
- Annual Output (MWh)
- Net Income (£/cell)
- Technology lifetime (yrs)

5.3.4.2 Data Output

- Internal Rate of Return Surface

5.4 Get Market Size

Comparing the IRR to the RRR in each cell identifies the potential market. If the IRR is greater than or equal to the RRR, then the cell is considered to be a commercially viable area to install wave energy arrays. The total annual output, market capacity and capital investment equivalent to the number of commercially viable cells is then counted giving the market parameters required. This process is illustrated in figure 5.5.

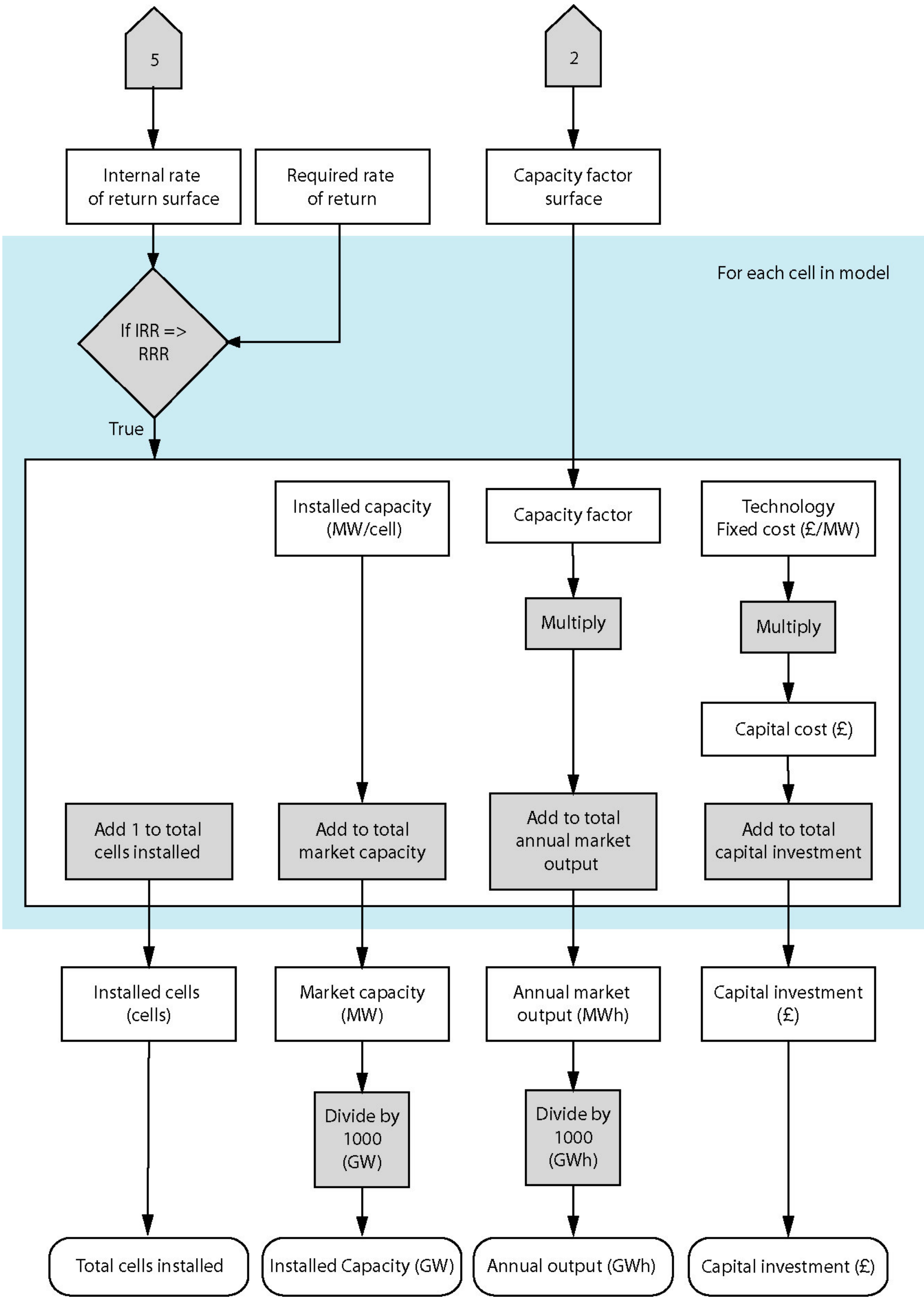


Figure 5.5: The fourth procedure in the methodology determines the number of cells within the resource model that are commercially viable if the IRR is greater than or equal to the RRR, thus identifying the economic wave energy resource and potential market.

5.4.1 Data Input

- Internal Rate of Return (IRR)
- Required Rate of Return (RRR)
- WECS Population density (MW/km)

5.4.2 Data Output

- Installed Capacity (GW)
- Installed Cells
- Total Annual Output (GWh)
- Capital Investment (£)

6 Methodology Implementation – Assessment of the European Wave Energy Resource

The methodology presented in section 5 is implemented using Microsoft Excel to analysis the numerical data and a Geographical Information System (GIS) to model the geographical data. This assessment applies the methodology to the European wave resource; however it can assess the economic viability of arrays installed in any ocean area. This assessment also uses Ocean Power Delivery's 750kW Pelamis wave device; however any device can be applied provided a power conversion matrix is available or similar data describing the device's performance for a range of sea conditions as required. The methodology design is independent of the implementation and can be implemented using different tools and techniques to those applied in this assessment.

As explained in Section 6, the methodology consists of the following steps:

1. **Get Technology Capacity Factor for each Wave Data Grid Point**
   (Implemented using Microsoft Excel. The Energy Analysis Excel model is included in Appendix 14.4)
2. **Get Data Surfaces**
   a. Interpolate Capacity Factor Surface
   b. Interpolate Depth Surface
   c. Calculate Distance to Shore Surface

   (Implemented using ARC View GIS. The GIS Model is included in Appendix 4.4)
3. **Get Internal Rate of Return (IRR)**
   a. Calculate Capital Cost
   b. Calculate Annual Energy Output
   c. Calculate Net Income
   d. Calculated IRR

   (Implemented in Microsoft Excel. The economic Analysis Excel model is included in Appendix 14.2)
4. **Get Market Size**
   (Implemented in Microsoft Excel. The Economic Analysis Excel model is included in Appendix 14.2)

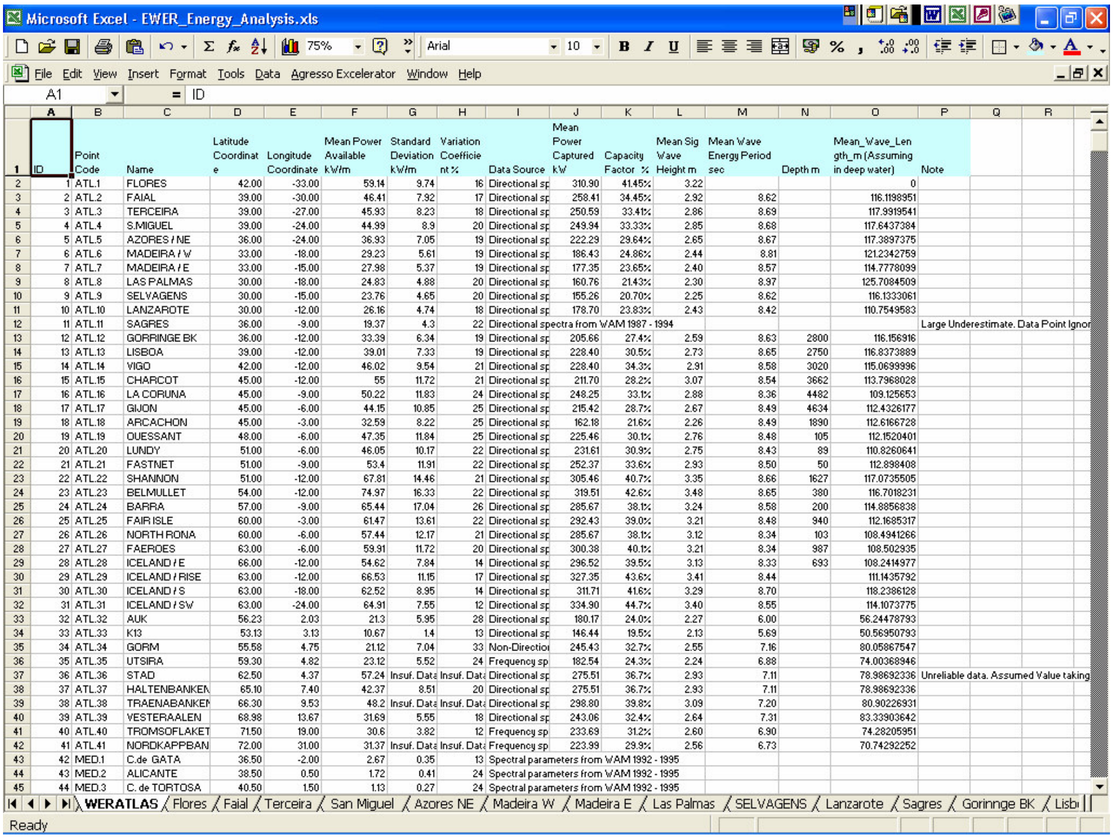
The first and second step focus on energy related aspects of the assessment and the third and fourth performs the economic tasks. Microsoft Excel and Visual Basic are used for the mathematical operations and data analysis in steps 1, 2 and 4. A GIS tool is used in step 2 to model the wave energy resource and geographical data.

6.1 Calculate technology capacity factor

The first procedure calculates the WECS capacity factor for each gridded wave data point displayed in section 7.6. The capacity factor is calculated by dividing the actual energy captured by the devices *Rated Power*. Microsoft Excel and the European Wave Energy Atlas are used to implement this step in the assessment. The energy related data analysis is included in the Excel model in Appendix 14.4.

6.1.1 Data Input - European Wave Data

The wave data is taken from the European Wave Energy Atlas described in section 2.8.1. Wave data for 23 locations within the area of analysis acquired from the WERATLAS. The data is exported from the WERATLAS in *text tab-delimited* format and then imported into the Excel model, as displayed in figure 6.1. The location of these measurements is illustrated in section 7.6 of the GIS resource model.

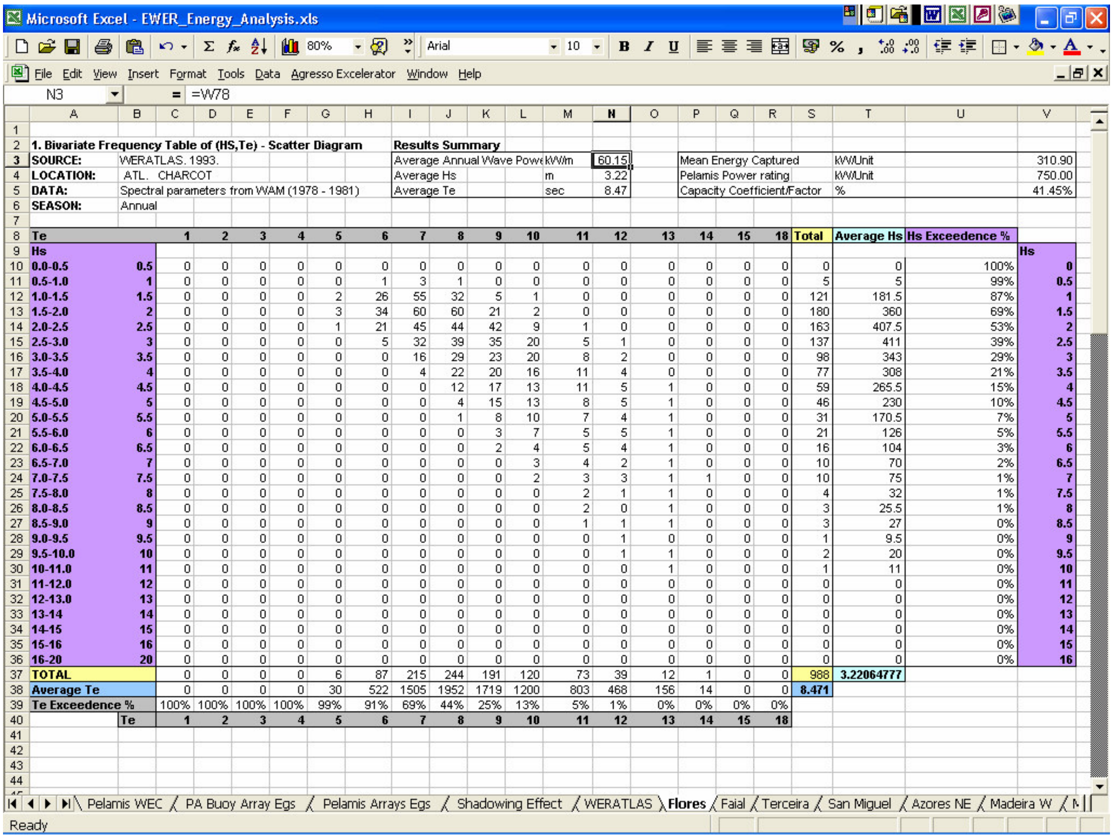


ID	Point Code	Name	Latitude Coordinate	Longitude Coordinate	Mean Power Available kW/m	Standard Deviation kW/m	Variation Coefficient %	Data Source	Mean Power Captured kW	Capacity Factor %	Mean Sig Wave Height m	Mean Wave Energy Period sec	Depth m	Mean_Wave_Length_m (Assuming in deep water)	Note
1	ATL.1	FLORES	42.00	-33.00	59.14	9.74	16	Directional sp	310.90	41.45%	3.22			0	
2	ATL.2	FAIAL	39.00	-30.00	46.41	7.92	17	Directional sp	258.41	34.45%	2.92	8.62		116.1198951	
3	ATL.3	TERCEIRA	39.00	-27.00	45.93	8.23	18	Directional sp	250.59	33.41%	2.86	8.69		117.9919541	
4	ATL.4	S.MIGUEL	39.00	-24.00	44.99	8.9	20	Directional sp	249.94	33.33%	2.85	8.68		117.6437384	
5	ATL.5	AZORES / NE	36.00	-24.00	36.93	7.05	19	Directional sp	222.29	29.64%	2.65	8.67		117.3897375	
6	ATL.6	MADEIRA / W	33.00	-18.00	29.23	5.61	19	Directional sp	186.43	24.86%	2.44	8.81		121.2342759	
7	ATL.7	MADEIRA / E	33.00	-15.00	27.98	5.37	19	Directional sp	177.35	23.65%	2.40	8.57		114.7778099	
8	ATL.8	LAS PALMAS	30.00	-18.00	24.83	4.88	20	Directional sp	160.76	21.43%	2.30	8.97		125.7084509	
9	ATL.9	SELVAGENS	30.00	-15.00	23.76	4.65	20	Directional sp	155.26	20.70%	2.25	8.62		116.1333061	
10	ATL.10	LANZAROTE	30.00	-12.00	26.16	4.74	18	Directional sp	178.70	23.83%	2.43	8.42		110.7549583	
11	ATL.11	SAGRES	36.00	-9.00	19.37	4.3	22	Directional spectra from WAM 1987 - 1994							Large Underestimate. Data Point Ignor
12	ATL.12	GORRINGE BK	36.00	-12.00	33.39	6.34	19	Directional sp	205.66	27.4%	2.59	8.63	2800	116.156916	
13	ATL.13	LISBOA	39.00	-12.00	39.01	7.33	19	Directional sp	228.40	30.5%	2.73	8.65	2750	116.8373889	
14	ATL.14	VIGO	42.00	-12.00	46.02	9.54	21	Directional sp	228.40	34.3%	2.91	8.58	3020	115.0699996	
15	ATL.15	CHARCOT	45.00	-12.00	55	11.72	21	Directional sp	211.70	28.2%	3.07	8.54	3662	113.7968028	
16	ATL.16	LA CORUNA	45.00	-9.00	50.22	11.83	24	Directional sp	248.25	33.1%	2.88	8.36	4482	109.125653	
17	ATL.17	GIJON	45.00	-6.00	44.15	10.85	25	Directional sp	215.42	28.7%	2.67	8.49	4634	112.4326177	
18	ATL.18	ARCACHON	45.00	-3.00	32.59	8.22	25	Directional sp	162.18	21.6%	2.26	8.49	1890	112.6166728	
19	ATL.19	OUESSANT	48.00	-6.00	47.35	11.84	25	Directional sp	225.46	30.1%	2.76	8.48	105	112.1520401	
20	ATL.20	LUNDY	51.00	-6.00	46.05	10.17	22	Directional sp	231.61	30.9%	2.75	8.43	89	110.8260641	
21	ATL.21	FASTNET	51.00	-9.00	53.4	11.91	22	Directional sp	252.37	33.6%	2.93	8.50	50	112.898408	
22	ATL.22	SHANNON	51.00	-12.00	67.81	14.46	21	Directional sp	305.46	40.7%	3.35	8.66	1627	117.0735505	
23	ATL.23	BELMULLET	54.00	-12.00	74.97	16.33	22	Directional sp	319.51	42.6%	3.48	8.65	380	116.7018231	
24	ATL.24	BARRA	57.00	-9.00	65.44	17.04	26	Directional sp	285.67	38.1%	3.24	8.58	200	114.8856838	
25	ATL.25	FAIR ISLE	60.00	-3.00	61.47	13.61	22	Directional sp	292.43	39.0%	3.21	8.48	940	112.1685317	
26	ATL.26	NORTH RONA	60.00	-6.00	57.44	12.17	21	Directional sp	285.67	38.1%	3.12	8.34	103	108.4941266	
27	ATL.27	FAEROES	63.00	-6.00	59.91	11.72	20	Directional sp	300.38	40.1%	3.21	8.34	987	108.502935	
28	ATL.28	ICELAND / E	66.00	-12.00	54.62	7.84	14	Directional sp	296.52	39.5%	3.13	8.33	693	108.2414977	
29	ATL.29	ICELAND / RISE	63.00	-12.00	66.53	11.15	17	Directional sp	327.35	43.6%	3.41	8.44		111.1435792	
30	ATL.30	ICELAND / S	63.00	-18.00	62.52	8.95	14	Directional sp	311.71	41.6%	3.29	8.70		118.2386128	
31	ATL.31	ICELAND / SW	63.00	-24.00	64.91	7.55	12	Directional sp	334.90	44.7%	3.40	8.55		114.1073775	
32	ATL.32	AUK	56.23	2.03	21.3	5.95	28	Directional sp	180.17	24.0%	2.27	6.00		56.24478793	
33	ATL.33	K13	53.13	3.13	10.67	1.4	13	Directional sp	146.44	19.5%	2.13	5.69		50.56950793	
34	ATL.34	GORM	55.58	4.75	21.12	7.04	33	Non-Directio	245.43	32.7%	2.55	7.16		80.05867547	
35	ATL.35	UTSIRA	59.30	4.82	23.12	5.52	24	Frequency sp	182.54	24.3%	2.24	6.88		74.00368946	
36	ATL.36	STAD	62.50	4.37	57.24	Insuf. Data	Insuf. Data	Directional sp	275.51	36.7%	2.93	7.11		78.98692336	Unreliable data. Assumed Value taking
37	ATL.37	HALTENBANKEN	65.10	7.40	42.37	8.51	20	Directional sp	275.51	36.7%	2.93	7.11		78.98692336	
38	ATL.38	TRAENABANKEN	66.30	9.53	48.2	Insuf. Data	Insuf. Data	Directional sp	298.80	39.8%	3.09	7.20		80.90226931	
39	ATL.39	VESTERAALEN	68.98	13.67	31.69	5.55	18	Directional sp	243.06	32.4%	2.64	7.31		83.33903642	
40	ATL.40	TROMSOFLAKET	71.50	19.00	30.6	3.82	12	Frequency sp	233.69	31.2%	2.60	6.90		74.28205951	
41	ATL.41	NORDKAPPBAN	72.00	31.00	31.37	Insuf. Data	Insuf. Data	Frequency sp	223.99	29.9%	2.56	6.73		70.74292252	
42	MED.1	C.de GATA	36.50	-2.00	2.67	0.35	13	Spectral parameters from WAM 1992 - 1995							
43	MED.2	ALICANTE	38.50	0.50	1.72	0.41	24	Spectral parameters from WAM 1992 - 1995							
44	MED.3	C. de TORTOSA	40.50	1.50	1.13	0.27	24	Spectral parameters from WAM 1992 - 1995							

Figure 6.1: Wave data for 23 measured locations in the Northern Atlantic and the North Sea imported from the WERATLAS into the Excel model.

6.1.2 Data Input – Wave Scatter Diagrams

Wave Scatter Diagrams (explained in section 2.2), obtained from the WERATLAS, represent the variation in sea state at a specific site. For each of the 23 locations, a wave scatter diagram is exported from the WERATLAS in *text tab-delimited* format and then imported into the Excel model, as shown in figure 6.2. The complete set of wave scatter diagrams for each site is included in the Excel model in Appendix 14.4.



1. Bivariate Frequency Table of (HS,Te) - Scatter Diagram

SOURCE:	WERATLAS. 1993.
LOCATION:	ATL. CHARCOT
DATA:	Spectral parameters from WAM (1978 - 1981)
SEASON:	Annual

Results Summary

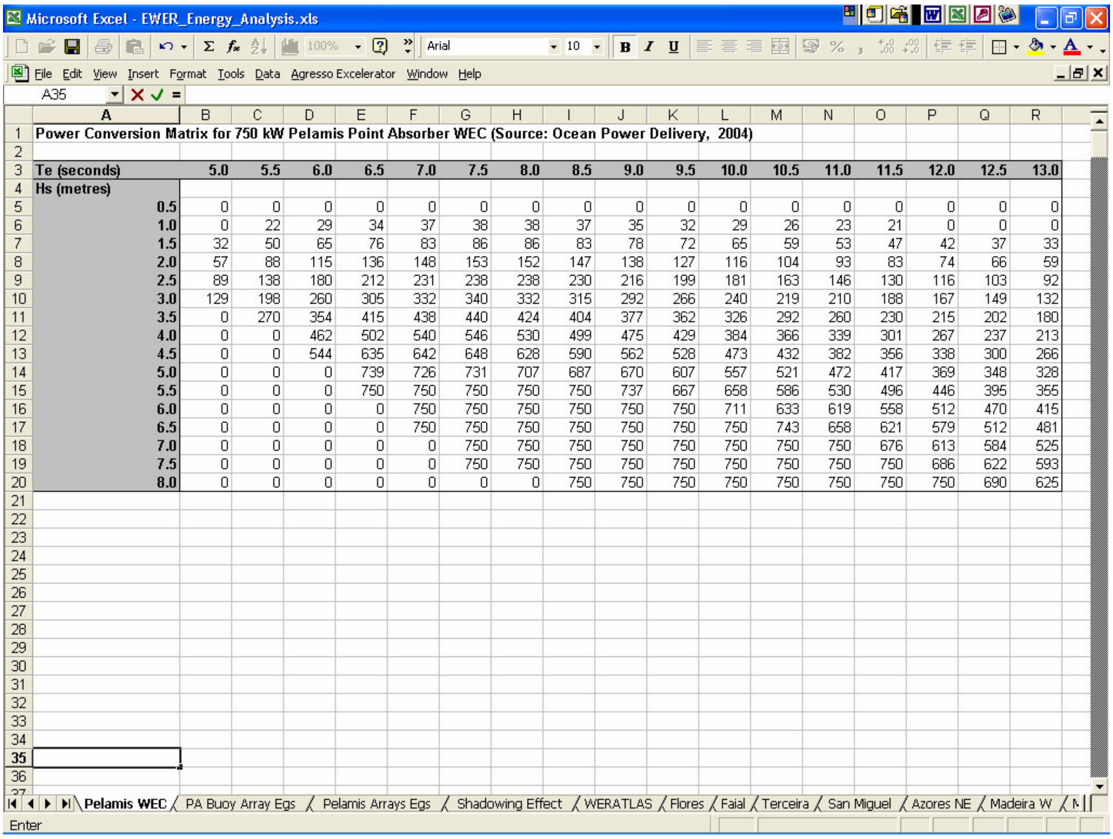
Average Annual Wave Powe	kW/m	60.15
Average Hs	m	3.22
Average Te	sec	8.47
Mean Energy Captured	kW/Unit	310.90
Pelamis Power rating	kW/Unit	750.00
Capacity Coefficient/Factor	%	41.45%

Te		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**18**	**Total**	**Average Hs**	**Hs Exceedence %**	
Hs																					**Hs**
0.0-0.5	**0.5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	**0**
0.5-1.0	**1**	0	0	0	0	0	1	3	1	0	0	0	0	0	0	0	0	5	5	99%	**0.5**
1.0-1.5	**1.5**	0	0	0	0	2	26	55	32	5	1	0	0	0	0	0	0	121	181.5	87%	**1**
1.5-2.0	**2**	0	0	0	0	3	34	60	60	21	2	0	0	0	0	0	0	180	360	69%	**1.5**
2.0-2.5	**2.5**	0	0	0	0	1	21	45	44	42	9	1	0	0	0	0	0	163	407.5	53%	**2**
2.5-3.0	**3**	0	0	0	0	0	5	32	39	35	20	5	1	0	0	0	0	137	411	39%	**2.5**
3.0-3.5	**3.5**	0	0	0	0	0	0	16	29	23	20	8	2	0	0	0	0	98	343	29%	**3**
3.5-4.0	**4**	0	0	0	0	0	0	4	22	20	16	11	4	0	0	0	0	77	308	21%	**3.5**
4.0-4.5	**4.5**	0	0	0	0	0	0	0	12	17	13	11	5	1	0	0	0	59	265.5	15%	**4**
4.5-5.0	**5**	0	0	0	0	0	0	0	4	15	13	8	5	1	0	0	0	46	230	10%	**4.5**
5.0-5.5	**5.5**	0	0	0	0	0	0	0	1	8	10	7	4	1	0	0	0	31	170.5	7%	**5**
5.5-6.0	**6**	0	0	0	0	0	0	0	0	3	7	5	5	1	0	0	0	21	126	5%	**5.5**
6.0-6.5	**6.5**	0	0	0	0	0	0	0	0	2	4	5	4	1	0	0	0	16	104	3%	**6**
6.5-7.0	**7**	0	0	0	0	0	0	0	0	0	3	4	2	1	0	0	0	10	70	2%	**6.5**
7.0-7.5	**7.5**	0	0	0	0	0	0	0	0	0	2	3	3	1	1	0	0	10	75	1%	**7**
7.5-8.0	**8**	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	4	32	1%	**7.5**
8.0-8.5	**8.5**	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	3	25.5	1%	**8**
8.5-9.0	**9**	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	3	27	0%	**8.5**
9.0-9.5	**9.5**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	9.5	0%	**9**
9.5-10.0	**10**	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	20	0%	**9.5**
10-11.0	**11**	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	11	0%	**10**
11-12.0	**12**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	**11**
12-13.0	**13**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	**12**
13-14	**14**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	**13**
14-15	**15**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	**14**
15-16	**16**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	**15**
16-20	**20**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	**16**
TOTAL		0	0	0	0	6	87	215	244	191	120	73	39	12	1	0	0	988	3.22064777		
Average Te		0	0	0	0	30	522	1505	1952	1719	1200	803	468	156	14	0	0	8.471			
Te Exceedence %		100%	100%	100%	100%	99%	91%	69%	44%	25%	13%	5%	1%	0%	0%	0%	0%				
	Te	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**18**				

Figure 6.2: The wave scatter diagram representing the wave conditions for a deepwater location off the Portuguese coast obtained from the WERATLAS and input into the Excel model.

6.1.3 Data Input – Pelamis WECS Power Matrix

The actual amount of available energy that can be captured using the Pelamis 750 kW WECS unit is established using the power matrix (explained in section 3.2). This is also integrated into the Excel model as shown in figure 6.3.



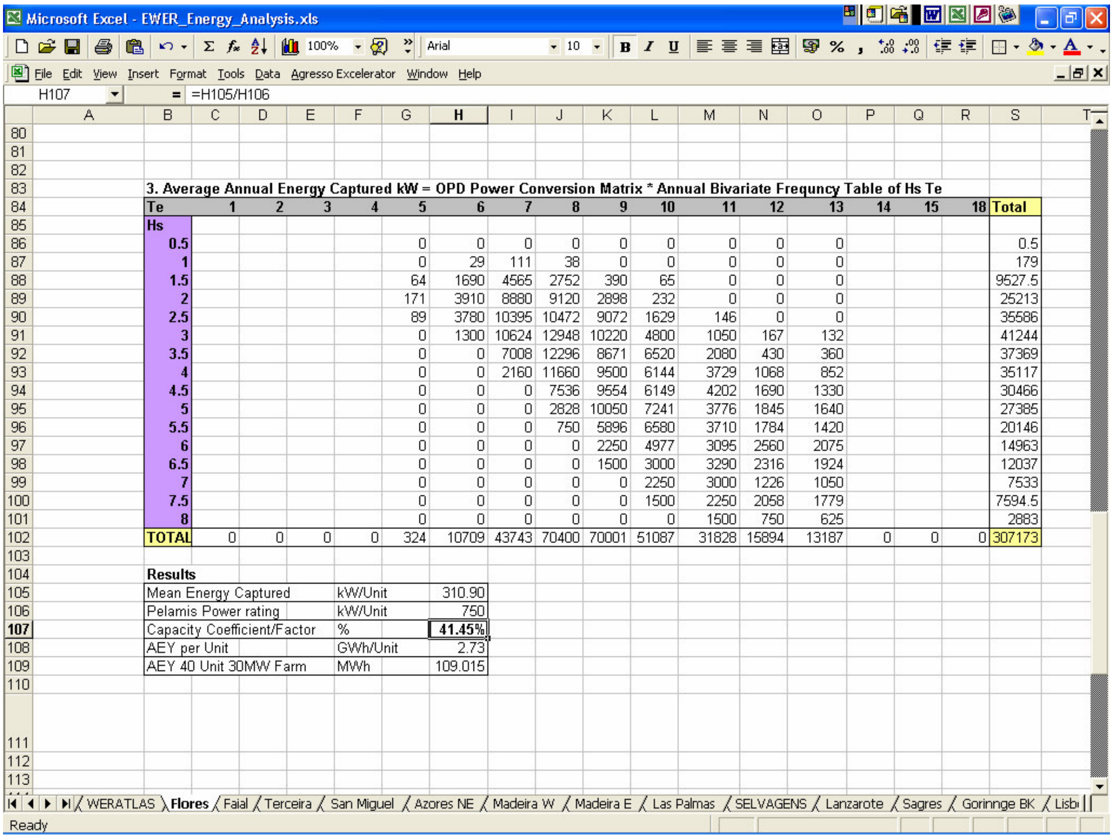
Power Conversion Matrix for 750 kW Pelamis Point Absorber WEC (Source: Ocean Power Delivery, 2004)

Te (seconds)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
Hs (metres)																	
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	0	0	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	0	0	0	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	0	0	0	0	0	750	750	750	750	750	750	750	750	676	613	584	525
7.5	0	0	0	0	0	750	750	750	750	750	750	750	750	750	686	622	593
8.0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

Figure 6.3: The Pelamis 750kW WECS Power Matrix representing the amount of energy generated for different sea states within the Excel model.

6.1.4 Calculate average annual power capture and technology capacity factor

The Pelamis WECS power matrix determines the energy captured in different seas states. Applying equation 3.1 outlined in section 5.1.1, the average annual energy capture per device for a specific location is calculated within the Excel model as shown in figure 6.4.



3. Average Annual Energy Captured kW = OPD Power Conversion Matrix * Annual Bivariate Frequncy Table of Hs Te

Te	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	18	Total
Hs																	
0.5					0	0	0	0	0	0	0	0	0				0.5
1					0	29	111	38	0	0	0	0	0				179
1.5					64	1690	4565	2752	390	65	0	0	0				9527.5
2					171	3910	8880	9120	2898	232	0	0	0				25213
2.5					89	3780	10395	10472	9072	1629	146	0	0				35586
3					0	1300	10624	12948	10220	4800	1050	167	132				41244
3.5					0	0	7008	12296	8671	6520	2080	430	360				37369
4					0	0	2160	11660	9500	6144	3729	1068	852				35117
4.5					0	0	0	7536	9554	6149	4202	1690	1330				30466
5					0	0	0	2828	10050	7241	3776	1845	1640				27385
5.5					0	0	0	750	5896	6580	3710	1784	1420				20146
6					0	0	0	0	2250	4977	3095	2560	2075				14963
6.5					0	0	0	0	1500	3000	3290	2316	1924				12037
7					0	0	0	0	0	2250	3000	1226	1050				7533
7.5					0	0	0	0	0	1500	2250	2058	1779				7594.5
8					0	0	0	0	0	0	1500	750	625				2883
TOTAL	0	0	0	0	324	10709	43743	70400	70001	51087	31828	15894	13187	0	0	0	307173

Results

Mean Energy Captured	kW/Unit	310.90
Pelamis Power rating	kW/Unit	750
Capacity Coefficient/Factor	%	41.45%
AEY per Unit	GWh/Unit	2.73
AEY 40 Unit 30MW Farm	MWh	109.015

Figure 6.4: Calculating the average annual power capture and technology capacity factor for the Pelamis device located at a location off the Portuguese coast within the Excel model.

6.1.5 Data Output – Capacity factor grid points

The Pelamis capacity factor is then calculated within the Excel model by dividing the average annual power capture by the devices power rating – 750 kW. This is repeated for each site. The complete list of wave data sites including the average annual power capture (kW/unit) and capacity factors are shown in figure 6.5. This data is then exported from Excel in text tab-delimited format and transferred to the GIS model. The capacity factors calculated are included together with the other energy data in the energy related analysis Excel model in Appendix 14.4.

Microsoft Excel - EWER_Energy_Analysis.xls

M17 = ='La Coruna'!I5

	B	C	D	E	F	G	H	I	J	K	L	M	N	
1	Point Code	Name	Latitude Coordinate	Longitude Coordinate	Mean Power Available kW/m	Standard Deviation kW/m	Variation Coefficient %	Data Source	Mean Power Captured kW	**Capacity Factor %**	Mean Sig Wave Height m	Mean Wave Energy Period sec	Depth m	Mean_W gth_m in deep
13	ATL.12	GORRINGE BK	36.00	-12.00	33.39	6.34	19	Directional s	205.66	**27.4%**	2.59	8.63	2800	1
14	ATL.13	LISBOA	39.00	-12.00	39.01	7.33	19	Directional s	228.40	**30.5%**	2.73	8.65	2750	11
15	ATL.14	VIGO	42.00	-12.00	46.02	9.54	21	Directional s	228.40	**34.3%**	2.91	8.58	3020	11
16	ATL.15	CHARCOT	45.00	-12.00	55	11.72	21	Directional s	211.70	**28.2%**	3.07	8.54	3662	11
17	ATL.16	LA CORUNA	45.00	-9.00	50.22	11.83	24	Directional s	248.25	**33.1%**	2.88	8.36	4482	1
18	ATL.17	GIJON	45.00	-6.00	44.15	10.85	25	Directional s	215.42	**28.7%**	2.67	8.49	4634	11
19	ATL.18	ARCACHON	45.00	-3.00	32.59	8.22	25	Directional s	162.18	**21.6%**	2.26	8.49	1890	11
20	ATL.19	OUESSANT	48.00	-6.00	47.35	11.84	25	Directional s	225.46	**30.1%**	2.76	8.48	105	11
21	ATL.20	LUNDY	51.00	-6.00	46.05	10.17	22	Directional s	231.61	**30.9%**	2.75	8.43	89	11
22	ATL.21	FASTNET	51.00	-9.00	53.4	11.91	22	Directional s	252.37	**33.6%**	2.93	8.50	50	1
23	ATL.22	SHANNON	51.00	-12.00	67.81	14.46	21	Directional s	305.46	**40.7%**	3.35	8.66	1627	11
24	ATL.23	BELMULLET	54.00	-12.00	74.97	16.33	22	Directional s	319.51	**42.6%**	3.48	8.65	380	11
25	ATL.24	BARRA	57.00	-9.00	65.44	17.04	26	Directional s	285.67	**38.1%**	3.24	8.58	200	11
26	ATL.25	FAIR ISLE	60.00	-3.00	61.47	13.61	22	Directional s	292.43	**39.0%**	3.21	8.48	940	11
27	ATL.26	NORTH RONA	60.00	-6.00	57.44	12.17	21	Directional s	285.67	**38.1%**	3.12	8.34	103	10
28	ATL.27	FAEROES	63.00	-6.00	59.91	11.72	20	Directional s	300.38	**40.1%**	3.21	8.34	987	1
29	ATL.28	ICELAND / E	66.00	-12.00	54.62	7.84	14	Directional s	296.52	**39.5%**	3.13	8.33	693	10
30	ATL.29	ICELAND / RISE	63.00	-12.00	66.53	11.15	17	Directional s	327.35	**43.6%**	3.41	8.44		11
31	ATL.30	ICELAND / S	63.00	-18.00	62.52	8.95	14	Directional s	311.71	**41.6%**	3.29	8.70		11
32	ATL.31	ICELAND / SW	63.00	-24.00	64.91	7.55	12	Directional s	334.90	**44.7%**	3.40	8.55		11
33	ATL.32	AUK	56.23	2.03	21.3	5.95	28	Directional s	180.17	**24.0%**	2.27	6.00		56
34	ATL.33	K13	53.13	3.13	10.67	1.4	13	Directional s	146.44	**19.5%**	2.13	5.69		50
35	ATL.34	GORM	55.58	4.75	21.12	7.04	33	Non-Directior	245.43	**32.7%**	2.55	7.16		80
36	ATL.35	UTSIRA	59.30	4.82	23.12	5.52	24	Frequency s	182.54	**24.3%**	2.24	6.88		74
37	ATL.36	STAD	62.50	4.37	57.24	Insuf. Data	Insuf. Dat	Directional s	275.51	**36.7%**	2.93	7.11		78
38	ATL.37	HALTENBANKEN	65.10	7.40	42.37	8.51	20	Directional s	275.51	**36.7%**	2.93	7.11		78
39	ATL.38	TRAENABANKEN	66.30	9.53	48.2	Insuf. Data	Insuf. Dat	Directional s	298.80	**39.8%**	3.09	7.20		80
40	ATL.39	VESTERAALEN	68.98	13.67	31.69	5.55	18	Directional s	243.06	**32.4%**	2.64	7.31		83
41	ATL.40	TROMSOFLAKET	71.50	19.00	30.6	3.82	12	Frequency s	233.69	**31.2%**	2.60	6.90		74
42	ATL.41	NORDKAPPBANI	72.00	31.00	31.37	Insuf. Data	Insuf. Dat	Frequency s	223.99	**29.9%**	2.56	6.73		70
43	MED.1	C.de GATA	36.50	-2.00	2.67	0.35	13	Spectral parameters from WAM 1992 - 1995						
44	MED.2	ALICANTE	38.50	0.50	1.72	0.41	24	Spectral parameters from WAM 1992 - 1995						

Pelamis WEC / PA Buoy Array Egs / Pelamis Arrays Egs / Shadowing Effect / **WERATLAS** / Flores / Faial / Terceira / San Miguel / Azores NE / Madeira W / M

Ready

Figure 6.5: The Excel model showing the complete list of wave data including the average annual power captured (kW/unit) and technology capacity factor for the Pelamis device located at 23 sites within European waters.

6.2 Get Data Surfaces

The second step in the methodology generates the GIS data surfaces by interpolating capacity factors and depth and calculating the distance to shore for each model cell using a GIS.

6.2.1 Interpolate Capacity Factor Surface

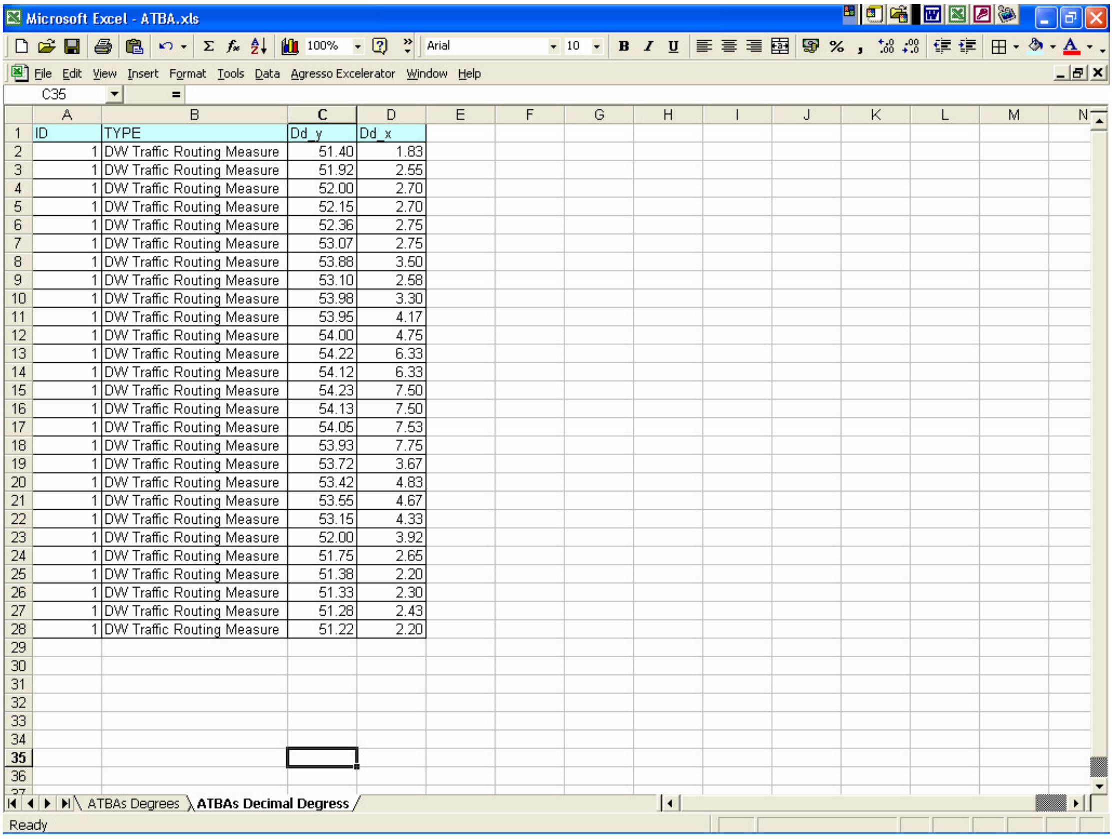
The Pelamis capacity factors calculated for each wave data grid point in the first step are imported into the GIS model. Capacity factors for all locations in European waters are then estimated from the original 23 capacity factors data points using a GIS interpolation operation. An average capacity factor is interpolated for each cell in the model based upon its position relative to the original data points and the type of interpolation algorithm executed (the *Spline* interpolation algorithm is selected in this case). The interpolated surface generated allows the energy captured by wave energy arrays deployed within any cell to be estimated using the interpolated capacity factor. The interpolated GIS surface is displayed in section 7.12.

6.2.1.1 Data Input – Capacity factor grid points

The gridded Pelamis WECS capacity factors calculated in the first step are input into the GIS model.

6.2.1.2 Data Input – Areas to be Avoided (ATBA)

The ATBA within the area of analysis are acquired from UKHO Admiralty Charts [44]. Coordinates outlining these areas are obtained and input into the GIS resource model. The format of this data set is shown in figure 6.6. A GIS surface is generated representing the ATBA included in section 7.9. If a surface cell is within an ATBA then it is given a value of 0, else the cell is set to 1. The capacity factor surface is then multiplied by the ATBA surface so any cells within an ATBA are set to zero. The navigational risk associated with the amount of shipping activity in a particular area is not included in this assessment. Areas of scientific interest are also not incorporated. The ATBA coordinates are included in Appendix 14.1.

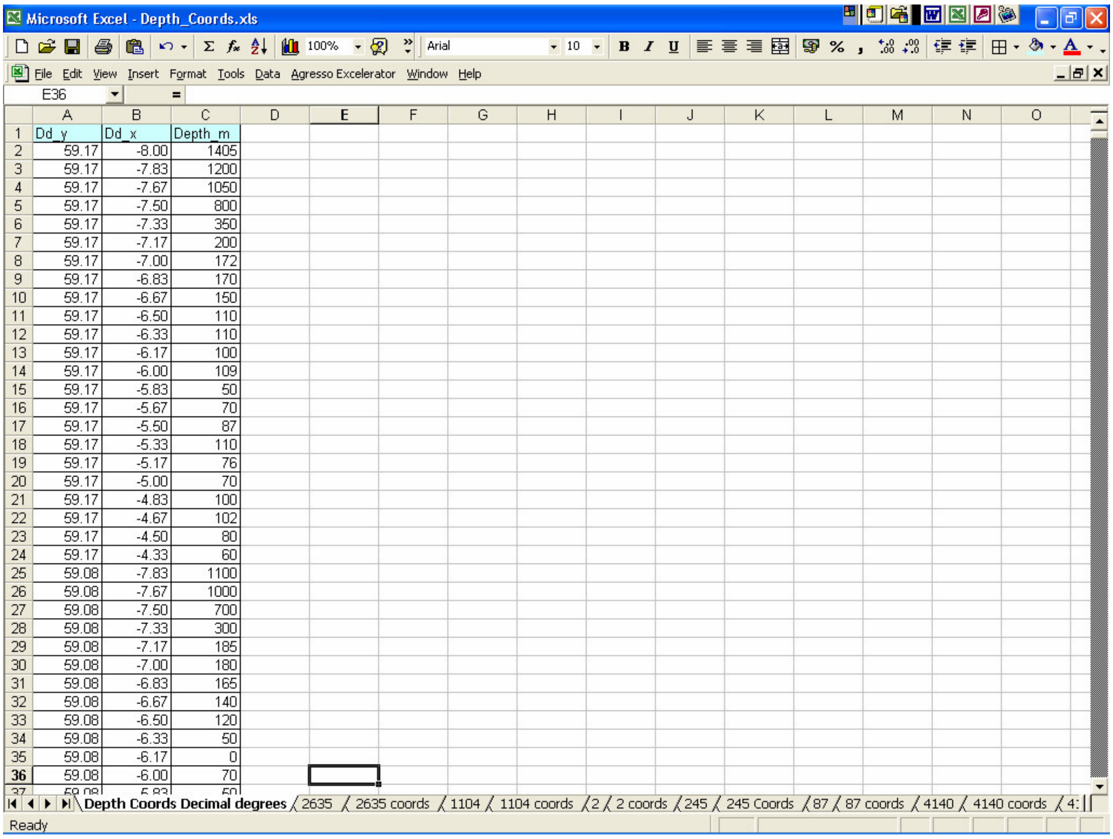


ID	TYPE	Dd_y	Dd_x
1	DW Traffic Routing Measure	51.40	1.83
1	DW Traffic Routing Measure	51.92	2.55
1	DW Traffic Routing Measure	52.00	2.70
1	DW Traffic Routing Measure	52.15	2.70
1	DW Traffic Routing Measure	52.36	2.75
1	DW Traffic Routing Measure	53.07	2.75
1	DW Traffic Routing Measure	53.88	3.50
1	DW Traffic Routing Measure	53.10	2.58
1	DW Traffic Routing Measure	53.98	3.30
1	DW Traffic Routing Measure	53.95	4.17
1	DW Traffic Routing Measure	54.00	4.75
1	DW Traffic Routing Measure	54.22	6.33
1	DW Traffic Routing Measure	54.12	6.33
1	DW Traffic Routing Measure	54.23	7.50
1	DW Traffic Routing Measure	54.13	7.50
1	DW Traffic Routing Measure	54.05	7.53
1	DW Traffic Routing Measure	53.93	7.75
1	DW Traffic Routing Measure	53.72	3.67
1	DW Traffic Routing Measure	53.42	4.83
1	DW Traffic Routing Measure	53.55	4.67
1	DW Traffic Routing Measure	53.15	4.33
1	DW Traffic Routing Measure	52.00	3.92
1	DW Traffic Routing Measure	51.75	2.65
1	DW Traffic Routing Measure	51.38	2.20
1	DW Traffic Routing Measure	51.33	2.30
1	DW Traffic Routing Measure	51.28	2.43
1	DW Traffic Routing Measure	51.22	2.20

Figure 6.6: Coordinates outlining the ATBA within the area of analysis are obtained from UKHO Admiralty Charts. The position of latitude and longitude are converted into decimal degrees and input into the GIS.

6.2.2 Interpolate Depth Surface

The average depth must be calculated for each cell within the resource model so that the cost of transferring the captured power onshore using submarine cable can be calculated. Over 2700 depth measurements (metres) covering the area of analysis of the Northern Atlantic Ocean and North Sea are obtained from UKHO Admiralty Charts [44]. The depth surface is interpolated from the gridded depth data within the GIS model. The depth surface is made up interpolated values contained within each 10 km model cell, as illustrated in section 6.7. Appendix 14.7 gives the depth data set.



	Dd_y	Dd_x	Depth_m
2	59.17	-8.00	1405
3	59.17	-7.83	1200
4	59.17	-7.67	1050
5	59.17	-7.50	800
6	59.17	-7.33	350
7	59.17	-7.17	200
8	59.17	-7.00	172
9	59.17	-6.83	170
10	59.17	-6.67	150
11	59.17	-6.50	110
12	59.17	-6.33	110
13	59.17	-6.17	100
14	59.17	-6.00	109
15	59.17	-5.83	50
16	59.17	-5.67	70
17	59.17	-5.50	87
18	59.17	-5.33	110
19	59.17	-5.17	76
20	59.17	-5.00	70
21	59.17	-4.83	100
22	59.17	-4.67	102
23	59.17	-4.50	80
24	59.17	-4.33	60
25	59.08	-7.83	1100
26	59.08	-7.67	1000
27	59.08	-7.50	700
28	59.08	-7.33	300
29	59.08	-7.17	185
30	59.08	-7.00	180
31	59.08	-6.83	165
32	59.08	-6.67	140
33	59.08	-6.50	120
34	59.08	-6.33	50
35	59.08	-6.17	0
36	59.08	-6.00	70

Figure 6.7: Depth measurements (in metres) covering the area of analysis are obtained from UKHO Admiralty Charts. The position of latitude and longitude are converted into decimal degrees and input into the GIS.

The capacity factor grid points are mostly located in deepwater (3 are located in intermediate depths approximately less than 60m in the North Sea). Therefore the interpolation for the Northern Atlantic waters does not incorporate intermediate or shallow waters (see section 2.1). To correct the surface cells that lie within areas of intermediate or shallow waters, a depth correction factor surface is calculated to correct the device capacity factors (and the wave energy resource model). For each cell in the model, if the cell depth is less than half of the average wavelength (~60 m) then the cell is defined as not being located in deepwater and the depth correction is set from between 1 and 0 by dividing the depth by 60. If the cell is in deepwater the factor is set to 1. The capacity factor surface is then factored by the depth correction surface. This approach is not exact but allowed more realistic capacity factors to be calculated for shallower waters. Corrected values are tested against a number of capacity factors for locations in intermediate depth using wave scatter diagrams from separate wave resource studies. The deviation is as little as 20% which is considered acceptable due to the European scale of this assessment. When assessing a smaller region such as the UK resource a more precise method is recommended. It should be noted that any attempt to incorporate shallower depths is limited because of the 10 km model cell size. The accuracy of the model within this region is imperfect because the depth often increases from 0 to over 200 metres over a 10 km distance from shore. This could be improved by increasing the resolution of analysis, for example, by using 1 km^2 cells as in [16].

6.2.2.1 Data Input - Depth points (metres)

Over 2700 gridded depth measurements are input into the GIS model.

6.2.3 Calculate Distance to Shore Surface

The distance to shore must be calculated for each cell within the resource model so the cost of transferring the captured power onshore can be determined. A GIS map of Europe is input into the GIS model and the distance to the nearest shoreline for each cell is calculated using the *Find Distance* GIS operation. The corresponding *Distance to Shore* surface generated is included in section 7.8.

This methodology only considers distances to landmasses with transmission grid rated at 132 kV or above, therefore discarding islands with lower voltage distribution networks. Also, the distance to the nearest shoreline, i.e. the shortest distance to shore, added to the depth would determine the length of submarine cable required to transmit the power ashore from each cell. Separate studies have successfully applied GIS techniques to marine energy-related tasks, such as optimising the integration of marine energy stations into the electricity network by determining the *Least Cost*

Route [45]. However, this methodology does not take into account the nature of the sea or attempt to select the least cost route for submarine cable.

6.2.3.1 Data Input – European shorelines

A GIS map of Europe is input into the GIS model included in section 7.6.

6.3 Get Internal Rate of Return

The third step in the methodology calculates the IRR for potential wave energy arrays deployed in European waters. The economic analysis Excel model implemented to calculate the IRR for each cell within the model is included in Appendix 14.2.

6.3.1 Calculate Capital Cost

The total cost to deploy arrays of the Pelamis device is calculated for every cell within the resource model by adding the fixed costs per MW of capacity together with the variable cost of the submarine transmission cable for each cell.

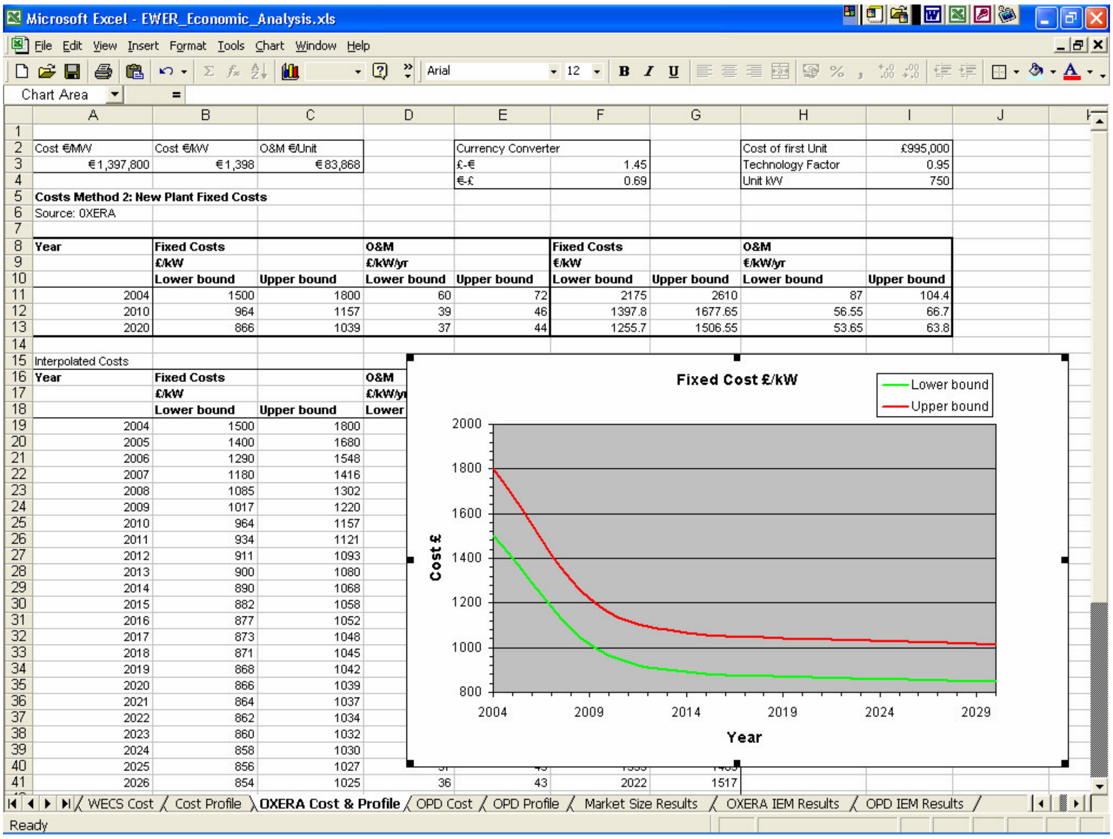
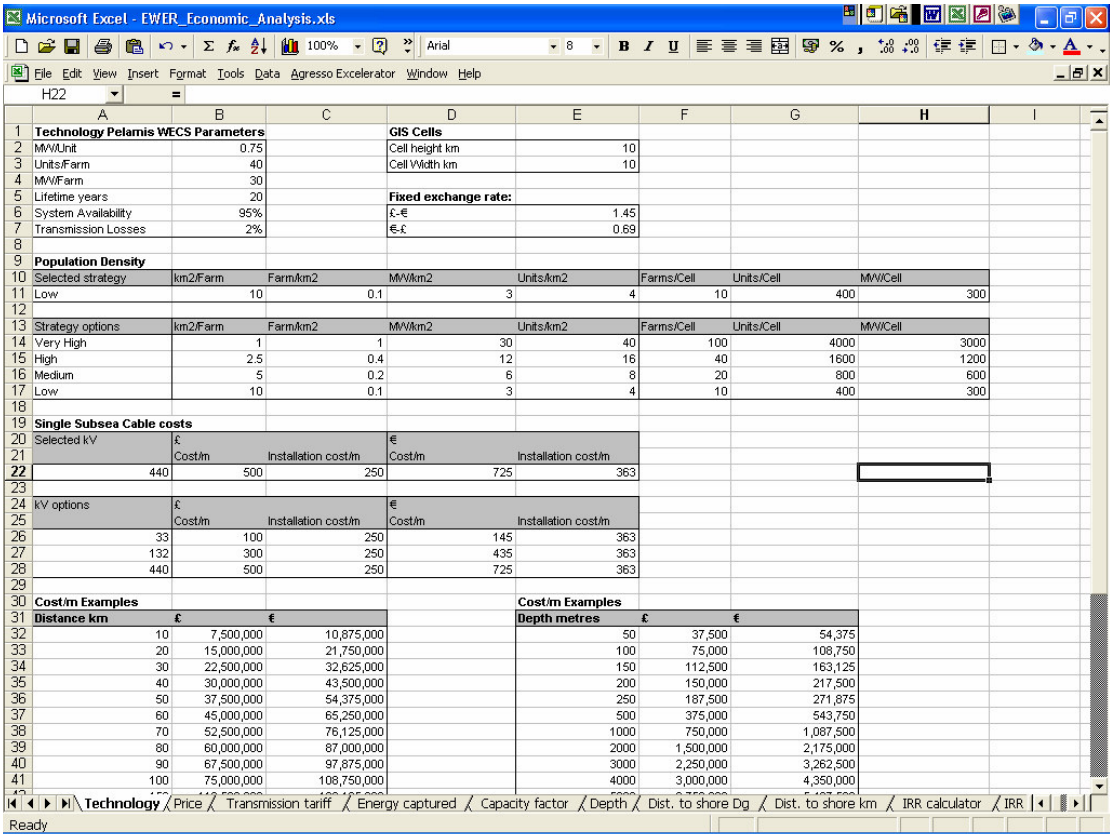


Figure 6.8: The fixed cost estimates of the Pelamis WECS obtained from OXERA Consulting integrated within the economic analysis in the Excel model.

The technology related parameters selected for this assessment in the Excel model are shown in figures 6.9. The selected device population density (explained in section 3.5) specifies that each 100 km^2 cell contains a total installed capacity of 300 MW.



	A	B	C	D	E	F	G	H
1	**Technology Pelamis WECS Parameters**			**GIS Cells**				
2	MW/Unit	0.75		Cell height km	10			
3	Units/Farm	40		Cell Width km	10			
4	MW/Farm	30						
5	Lifetime years	20		**Fixed exchange rate:**				
6	System Availability	95%		£-€	1.45			
7	Transmission Losses	2%		€-£	0.69			
8								
9	**Population Density**							
10	Selected strategy	km2/Farm	Farm/km2	MW/km2	Units/km2	Farms/Cell	Units/Cell	MW/Cell
11	Low	10	0.1	3	4	10	400	300
12								
13	Strategy options	km2/Farm	Farm/km2	MW/km2	Units/km2	Farms/Cell	Units/Cell	MW/Cell
14	Very High	1	1	30	40	100	4000	3000
15	High	2.5	0.4	12	16	40	1600	1200
16	Medium	5	0.2	6	8	20	800	600
17	Low	10	0.1	3	4	10	400	300
18								
19	**Single Subsea Cable costs**							
20	Selected kV	£		€				
21		Cost/m	Installation cost/m	Cost/m	Installation cost/m			
22	440	500	250	725	363			
23								
24	kV options	£		€				
25		Cost/m	Installation cost/m	Cost/m	Installation cost/m			
26	33	100	250	145	363			
27	132	300	250	435	363			
28	440	500	250	725	363			
29								
30	**Cost/m Examples**				**Cost/m Examples**			
31	**Distance km**	**£**	**€**		**Depth metres**	**£**	**€**	
32	10	7,500,000	10,875,000		50	37,500	54,375	
33	20	15,000,000	21,750,000		100	75,000	108,750	
34	30	22,500,000	32,625,000		150	112,500	163,125	
35	40	30,000,000	43,500,000		200	150,000	217,500	
36	50	37,500,000	54,375,000		250	187,500	271,875	
37	60	45,000,000	65,250,000		500	375,000	543,750	
38	70	52,500,000	76,125,000		1000	750,000	1,087,500	
39	80	60,000,000	87,000,000		2000	1,500,000	2,175,000	
40	90	67,500,000	97,875,000		3000	2,250,000	3,262,500	
41	100	75,000,000	108,750,000		4000	3,000,000	4,350,000	

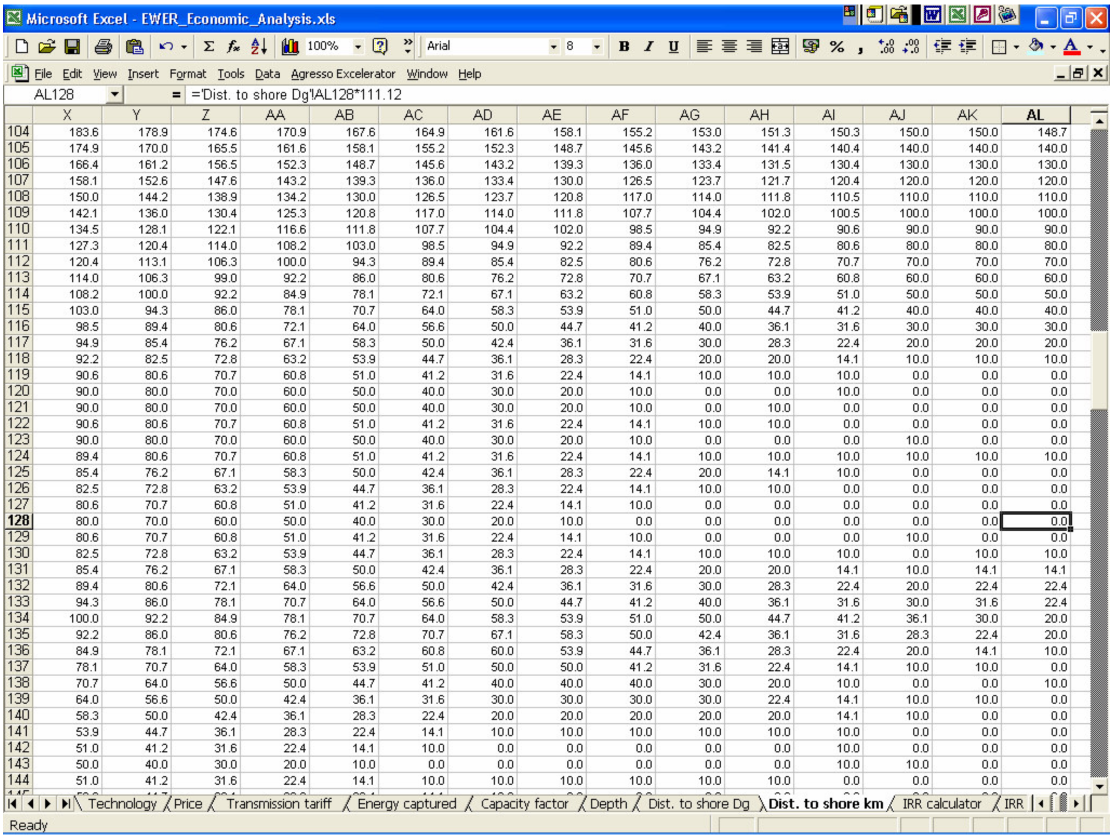
Figure 6.9: The selected technology parameters and variables in the Excel model used to calculate the internal rate of return for arrays of Pelamis devices deployed in each cell in the assessment model.

The total submarine cable cost is calculated by multiplying the cost of purchasing and installing per metre length of cable by the distance to shore and the depth of each cell. The depth and distance to shore is included in the Excel model as illustrated in Figure 9.10 and 9.11. For example, using costs estimates based on the OPD cost estimates for the Pelamis WECS in 2010 and the cable costs outlined in 3.7:

- 500 £/kW Pelamis WECS fixed cost
- 750 £/m 440 kV submarine cable costs

Hence, a 300 MW array 10 km from shore would cost approximately £160 M:

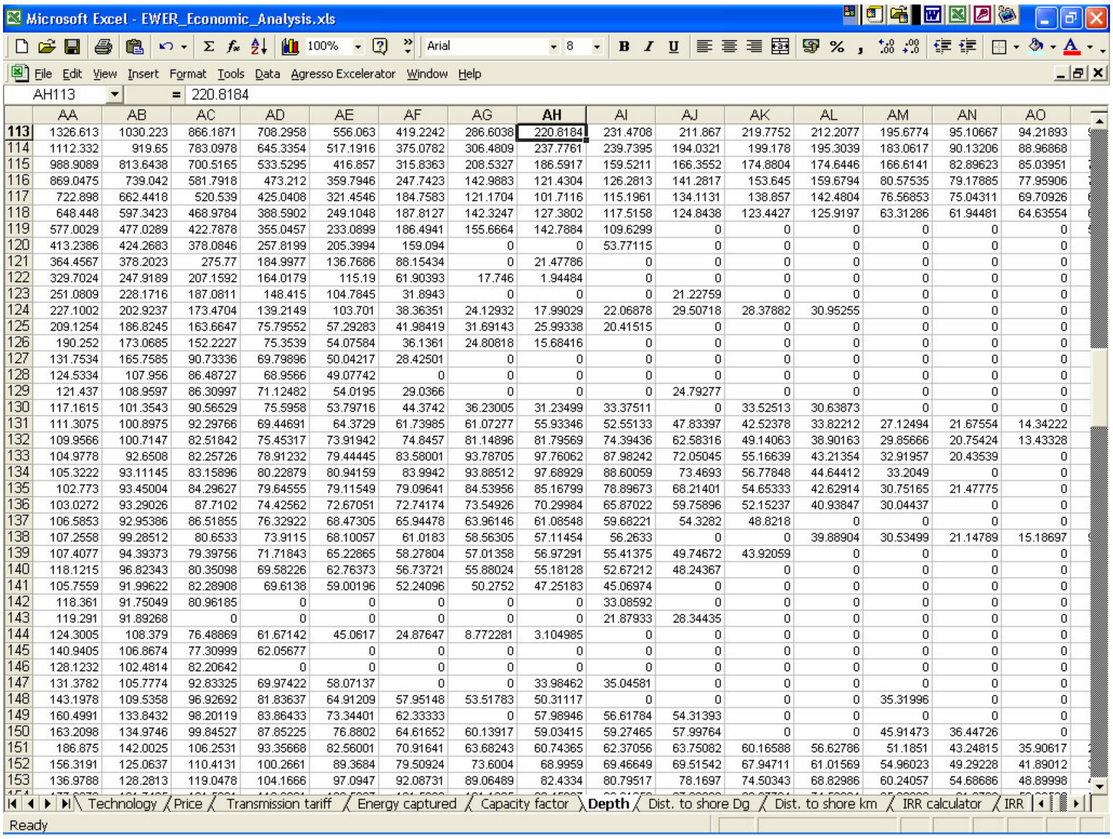
- (300 x 500,000) + (10 x 1000 x 750) = 157,500,000



AL128 = ='Dist. to shore Dg'!AL128*111.12

	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL
104	183.6	178.9	174.6	170.9	167.6	164.9	161.6	158.1	155.2	153.0	151.3	150.3	150.0	150.0	148.7
105	174.9	170.0	165.5	161.6	158.1	155.2	152.3	148.7	145.6	143.2	141.4	140.4	140.0	140.0	140.0
106	166.4	161.2	156.5	152.3	148.7	145.6	143.2	139.3	136.0	133.4	131.5	130.4	130.0	130.0	130.0
107	158.1	152.6	147.6	143.2	139.3	136.0	133.4	130.0	126.5	123.7	121.7	120.4	120.0	120.0	120.0
108	150.0	144.2	138.9	134.2	130.0	126.5	123.7	120.8	117.0	114.0	111.8	110.5	110.0	110.0	110.0
109	142.1	136.0	130.4	125.3	120.8	117.0	114.0	111.8	107.7	104.4	102.0	100.5	100.0	100.0	100.0
110	134.5	128.1	122.1	116.6	111.8	107.7	104.4	102.0	98.5	94.9	92.2	90.6	90.0	90.0	90.0
111	127.3	120.4	114.0	108.2	103.0	98.5	94.9	92.2	89.4	85.4	82.5	80.6	80.0	80.0	80.0
112	120.4	113.1	106.3	100.0	94.3	89.4	85.4	82.5	80.6	76.2	72.8	70.7	70.0	70.0	70.0
113	114.0	106.3	99.0	92.2	86.0	80.6	76.2	72.8	70.7	67.1	63.2	60.8	60.0	60.0	60.0
114	108.2	100.0	92.2	84.9	78.1	72.1	67.1	63.2	60.8	58.3	53.9	51.0	50.0	50.0	50.0
115	103.0	94.3	86.0	78.1	70.7	64.0	58.3	53.9	51.0	50.0	44.7	41.2	40.0	40.0	40.0
116	98.5	89.4	80.6	72.1	64.0	56.6	50.0	44.7	41.2	40.0	36.1	31.6	30.0	30.0	30.0
117	94.9	85.4	76.2	67.1	58.3	50.0	42.4	36.1	31.6	30.0	28.3	22.4	20.0	20.0	20.0
118	92.2	82.5	72.8	63.2	53.9	44.7	36.1	28.3	22.4	20.0	20.0	14.1	10.0	10.0	10.0
119	90.6	80.6	70.7	60.8	51.0	41.2	31.6	22.4	14.1	10.0	10.0	10.0	0.0	0.0	0.0
120	90.0	80.0	70.0	60.0	50.0	40.0	30.0	20.0	10.0	0.0	0.0	10.0	0.0	0.0	0.0
121	90.0	80.0	70.0	60.0	50.0	40.0	30.0	20.0	10.0	0.0	10.0	0.0	0.0	0.0	0.0
122	90.6	80.6	70.7	60.8	51.0	41.2	31.6	22.4	14.1	10.0	10.0	0.0	0.0	0.0	0.0
123	90.0	80.0	70.0	60.0	50.0	40.0	30.0	20.0	10.0	0.0	0.0	0.0	10.0	0.0	0.0
124	89.4	80.6	70.7	60.8	51.0	41.2	31.6	22.4	14.1	10.0	10.0	10.0	10.0	10.0	10.0
125	85.4	76.2	67.1	58.3	50.0	42.4	36.1	28.3	22.4	20.0	14.1	10.0	0.0	0.0	0.0
126	82.5	72.8	63.2	53.9	44.7	36.1	28.3	22.4	14.1	10.0	10.0	0.0	0.0	0.0	0.0
127	80.6	70.7	60.8	51.0	41.2	31.6	22.4	14.1	10.0	0.0	0.0	0.0	0.0	0.0	0.0
128	80.0	70.0	60.0	50.0	40.0	30.0	20.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
129	80.6	70.7	60.8	51.0	41.2	31.6	22.4	14.1	10.0	0.0	0.0	0.0	10.0	0.0	0.0
130	82.5	72.8	63.2	53.9	44.7	36.1	28.3	22.4	14.1	10.0	10.0	10.0	0.0	10.0	10.0
131	85.4	76.2	67.1	58.3	50.0	42.4	36.1	28.3	22.4	20.0	20.0	14.1	10.0	14.1	14.1
132	89.4	80.6	72.1	64.0	56.6	50.0	42.4	36.1	31.6	30.0	28.3	22.4	20.0	22.4	22.4
133	94.3	86.0	78.1	70.7	64.0	56.6	50.0	44.7	41.2	40.0	36.1	31.6	30.0	31.6	22.4
134	100.0	92.2	84.9	78.1	70.7	64.0	58.3	53.9	51.0	50.0	44.7	41.2	36.1	30.0	20.0
135	92.2	86.0	80.6	76.2	72.8	70.7	67.1	58.3	50.0	42.4	36.1	31.6	28.3	22.4	20.0
136	84.9	78.1	72.1	67.1	63.2	60.8	60.0	53.9	44.7	36.1	28.3	22.4	20.0	14.1	10.0
137	78.1	70.7	64.0	58.3	53.9	51.0	50.0	50.0	41.2	31.6	22.4	14.1	10.0	10.0	0.0
138	70.7	64.0	56.6	50.0	44.7	41.2	40.0	40.0	40.0	30.0	20.0	10.0	0.0	0.0	10.0
139	64.0	56.6	50.0	42.4	36.1	31.6	30.0	30.0	30.0	30.0	22.4	14.1	10.0	10.0	0.0
140	58.3	50.0	42.4	36.1	28.3	22.4	20.0	20.0	20.0	20.0	20.0	14.1	10.0	0.0	0.0
141	53.9	44.7	36.1	28.3	22.4	14.1	10.0	10.0	10.0	10.0	10.0	10.0	0.0	0.0	0.0
142	51.0	41.2	31.6	22.4	14.1	10.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0
143	50.0	40.0	30.0	20.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	10.0	0.0	0.0
144	51.0	41.2	31.6	22.4	14.1	10.0	10.0	10.0	10.0	10.0	10.0	0.0	0.0	0.0	0.0

Figure 6.10: The distance to shore (in km) of each cell as included in the Excel model.



AH113 = 220.8184

	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
113	1326.613	1030.223	866.1871	708.2958	556.063	419.2242	286.6038	220.8184	231.4708	211.867	219.7752	212.2077	195.6774	95.10667	94.21893
114	1112.332	919.65	783.0978	645.3354	517.1916	375.0782	306.4809	237.7761	239.7395	194.0321	199.178	195.3039	183.0617	90.13206	88.96868
115	988.9089	813.6438	700.5165	533.5295	416.857	315.8363	208.5327	186.5917	159.5211	166.3552	174.8804	174.6446	166.6141	82.89623	85.03951
116	869.0475	739.042	581.7918	473.212	359.7946	247.7423	142.9883	121.4304	126.2813	141.2817	153.645	159.6794	80.57535	79.17885	77.95906
117	722.898	662.4418	520.539	425.0408	321.4546	184.7583	121.1704	101.7116	115.1961	134.1131	138.857	142.4804	76.56853	75.04311	69.70926
118	648.448	597.3423	468.9784	388.5902	249.1048	187.8127	142.3247	127.3802	117.5158	124.8438	123.4427	125.9197	63.31286	61.94481	64.63554
119	577.0029	477.0289	422.7878	355.0457	233.0899	186.4941	155.6664	142.7884	109.6299	0	0	0	0	0	0
120	413.2386	424.2683	378.0846	257.8199	205.3994	159.094	0	0	53.77115	0	0	0	0	0	0
121	364.4567	378.2023	275.77	184.9977	136.7686	88.15434	0	21.47786	0	0	0	0	0	0	0
122	329.7024	247.9189	207.1592	164.0179	115.19	61.90393	17.746	1.94484	0	0	0	0	0	0	0
123	251.0809	228.1716	187.0811	148.415	104.7845	31.8943	0	0	0	21.22759	0	0	0	0	0
124	227.1002	202.9237	173.4704	139.2149	103.701	38.36351	24.12932	17.99029	22.06878	29.50718	28.37882	30.95255	0	0	0
125	209.1254	186.8245	163.6647	75.79552	57.29283	41.98419	31.69143	25.99338	20.41515	0	0	0	0	0	0
126	190.252	173.0685	152.2227	75.3539	54.07584	36.1361	24.80818	15.68416	0	0	0	0	0	0	0
127	131.7534	165.7585	90.73336	69.79896	50.04217	28.42501	0	0	0	0	0	0	0	0	0
128	124.5334	107.956	86.48727	68.9566	49.07742	0	0	0	0	0	0	0	0	0	0
129	121.437	108.9597	86.30997	71.12482	54.0195	29.0366	0	0	0	24.79277	0	0	0	0	0
130	117.1615	101.3543	90.56529	75.5958	53.79716	44.3742	36.23005	31.23499	33.37511	0	33.52513	30.63873	0	0	0
131	111.3075	100.8975	92.29766	69.44691	64.3729	61.73985	61.07277	55.93346	52.55133	47.83397	42.52378	33.82212	27.12494	21.67554	14.34222
132	109.9566	100.7147	82.51842	75.45317	73.91942	74.8457	81.14896	81.79569	74.39436	62.58316	49.14063	38.90163	29.85666	20.75424	13.43328
133	104.9778	92.6508	82.25726	78.91232	79.44445	83.58001	93.78705	97.76062	87.98242	72.05045	55.16639	43.21354	32.91957	20.43539	0
134	105.3222	93.11145	83.15896	80.22879	80.94159	83.9942	93.88512	97.68929	88.60059	73.4693	56.77848	44.64412	33.2049	0	0
135	102.773	93.45004	84.29627	79.64555	79.11549	79.09641	84.53956	85.16799	78.89673	68.21401	54.65333	42.62914	30.75165	21.47775	0
136	103.0272	93.29026	87.7102	74.42562	72.67051	72.74174	73.54926	70.29984	65.87022	59.75896	52.15237	40.93847	30.04437	0	0
137	106.5853	92.95386	86.51855	76.32922	68.47305	65.94478	63.96146	61.08548	59.68221	54.3282	48.8218	0	0	0	0
138	107.2558	99.28512	80.6533	73.9115	68.10057	61.0183	58.56305	57.11454	56.2633	0	0	39.88904	30.53499	21.14789	15.18697
139	107.4077	94.39373	79.39756	71.71843	65.22865	58.27804	57.01358	56.97291	55.41375	49.74672	43.92059	0	0	0	0
140	118.1215	96.82343	80.35098	69.58226	62.76373	56.73721	55.88024	55.18128	52.67212	48.24367	0	0	0	0	0
141	105.7559	91.99622	82.28908	69.6138	59.00196	52.24096	50.2752	47.25183	45.06974	0	0	0	0	0	0
142	118.361	91.75049	80.96185	0	0	0	0	0	33.08592	0	0	0	0	0	0
143	119.291	91.89268	0	0	0	0	0	0	21.87933	28.34435	0	0	0	0	0
144	124.3005	108.379	76.48869	61.67142	45.0617	24.87647	8.772281	3.104985	0	0	0	0	0	0	0
145	140.9405	106.8674	77.30999	62.05677	0	0	0	0	0	0	0	0	0	0	0
146	128.1232	102.4814	82.20642	0	0	0	0	0	0	0	0	0	0	0	0
147	131.3782	105.7774	92.83325	69.97422	58.07137	0	0	33.98462	35.04581	0	0	0	0	0	0
148	143.1978	109.5358	96.92692	81.83637	64.91209	57.95148	53.51783	50.31117	0	0	0	0	35.31996	0	0
149	160.4991	133.8432	98.20119	83.86433	73.34401	62.33333	0	57.98946	56.61784	54.31393	0	0	0	0	0
150	163.2098	134.9746	99.84527	87.85225	76.8802	64.61652	60.13917	59.03415	59.27465	57.99764	0	0	45.91473	36.44726	0
151	186.875	142.0025	106.2531	93.35668	82.56001	70.91641	63.68243	60.74365	62.37056	63.75082	60.16588	56.62786	51.1851	43.24815	35.90617
152	156.3191	125.0637	110.4131	100.2661	89.3684	79.50924	73.6004	68.9959	69.46649	69.51542	67.94711	61.01569	54.96023	49.29228	41.89012
153	136.9788	128.2813	119.0478	104.1666	97.0947	92.08731	89.06489	82.4334	80.79517	78.1697	74.50343	68.82986	60.24057	54.68686	48.89998

Figure 6.11: The depth (in metres) of each cell as included in the Excel model.

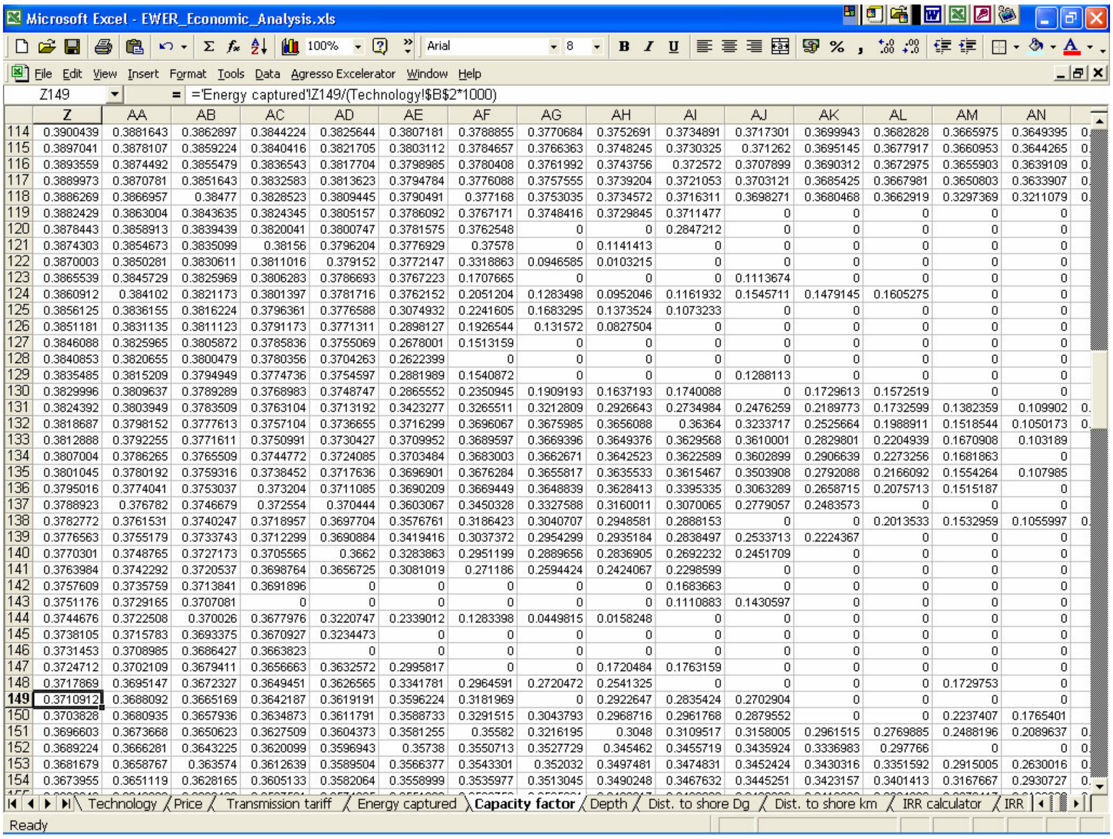
This simple capital cost model assumes that there is a point of connection to the onshore grid at the nearest shoreline and includes a flat grid connection charge within the fixed cost. In reality, connecting to the nearest Grid Supply Point (GSP) once onshore could require laying additional transmission equipment, upgrading the existing grid infrastructure to manage the additional power levels and dealing with associated planning restriction. The existing grid and planned upgrades would greatly affect the least cost route for the submarine cable. Therefore the shortest route to shore, utilised in this model, may not be the least cost route. The methodology does not model the existing European transmission systems hence it is not possible to account for the cost involved with onshore transmission (a major limitation of this implementation).

6.3.1.1 Data Input

- Fixed costs – the assumed fixed costs are selected in the Excel model as shown in figure 6.9 (as explained in section 3.8).
- Distance to nearest shore surface in metres –input into the Excel model shown in figure 6.10
- Depth surface in metres – shown in the Excel model figure 6.11
- Submarine cable costs – assumed in the Technology parameters worksheets of the Excel Model shown in figure 6.9 (as detail in 3.8.3)
- WECS Population density – 300 MW deployed in each cell (as explained in section 3.6)

6.3.2 Calculate Annual Energy Output (MWh)

The annual energy that could be generated by Pelamis WECS arrays is calculated for each cell so the potential income can be estimated. The capacity factor surface is exported from the GIS model and imported into the Excel model (as shown in figure 9.12) giving the capacity factor for every 10 km^2 site. This is multiplied by the cell's installed capacity (MW) and then by the hours in a year – 24 x 365.25 = 8766. To account for transmission losses, the annual output is then multiplied by a factor of 98 % a factor (assuming losses of 2 %). To incorporate when the plant is not generating electricity due to maintenance work, a system availability of 95 % is also included, giving the total annual energy output in MWh.



	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	
114	0.3900439	0.3881643	0.3862897	0.3844224	0.3825644	0.3807181	0.3788855	0.3770684	0.3752691	0.3734891	0.3717301	0.3699943	0.3682828	0.3665975	0.3649395	0
115	0.3897041	0.3878107	0.3859224	0.3840416	0.3821705	0.3803112	0.3784657	0.3766363	0.3748245	0.3730325	0.371262	0.3695145	0.3677917	0.3660953	0.3644265	0
116	0.3893559	0.3874492	0.3855479	0.3836543	0.3817704	0.3798985	0.3780408	0.3761992	0.3743756	0.372572	0.3707899	0.3690312	0.3672975	0.3655903	0.3639109	0
117	0.3889973	0.3870781	0.3851643	0.3832583	0.3813623	0.3794784	0.3776088	0.3757555	0.3739204	0.3721053	0.3703121	0.3685425	0.3667981	0.3650803	0.3633907	0
118	0.3886269	0.3866957	0.38477	0.3828523	0.3809445	0.3790491	0.377168	0.3753035	0.3734572	0.3716311	0.3698271	0.3680468	0.3662919	0.3297369	0.3211079	0
119	0.3882429	0.3863004	0.3843635	0.3824345	0.3805157	0.3786092	0.3767171	0.3748416	0.3729845	0.3711477	0	0	0	0	0	
120	0.3878443	0.3858913	0.3839439	0.3820041	0.3800747	0.3781575	0.3762548	0	0	0.2847212	0	0	0	0	0	
121	0.3874303	0.3854673	0.3835099	0.38156	0.3796204	0.3776929	0.37578	0	0.1141413	0	0	0	0	0	0	
122	0.3870003	0.3850281	0.3830611	0.3811016	0.379152	0.3772147	0.3318863	0.0946585	0.0103215	0	0	0	0	0	0	
123	0.3865539	0.3845729	0.3825969	0.3806283	0.3786693	0.3767223	0.1707665	0	0	0	0.1113674	0	0	0	0	
124	0.3860912	0.384102	0.3821173	0.3801397	0.3781716	0.3762152	0.2051204	0.1283498	0.0952046	0.1161932	0.1545711	0.1479145	0.1605275	0	0	
125	0.3856125	0.3836155	0.3816224	0.3796361	0.3776588	0.3074932	0.2241605	0.1683295	0.1373524	0.1073233	0	0	0	0	0	
126	0.3851181	0.3831135	0.3811123	0.3791173	0.3771311	0.2898127	0.1926544	0.131572	0.0827504	0	0	0	0	0	0	
127	0.3846088	0.3825965	0.3805872	0.3785836	0.3755069	0.2678001	0.1513159	0	0	0	0	0	0	0	0	
128	0.3840853	0.3820655	0.3800479	0.3780356	0.3704263	0.2622399	0	0	0	0	0	0	0	0	0	
129	0.3835485	0.3815209	0.3794949	0.3774736	0.3754597	0.2881989	0.1540872	0	0	0	0.1288113	0	0	0	0	
130	0.3829996	0.3809637	0.3789289	0.3768983	0.3748747	0.2865552	0.2350945	0.1909193	0.1637193	0.1740088	0	0.1729613	0.1572519	0	0	
131	0.3824392	0.3803949	0.3783509	0.3763104	0.3713192	0.3423277	0.3265511	0.3212809	0.2926643	0.2734984	0.2476259	0.2189773	0.1732599	0.1382359	0.109902	0.
132	0.3818687	0.3798152	0.3777613	0.3757104	0.3736655	0.3716299	0.3696067	0.3675985	0.3656088	0.36364	0.3233717	0.2525664	0.1988911	0.1518544	0.1050173	0.
133	0.3812888	0.3792255	0.3771611	0.3750991	0.3730427	0.3709952	0.3689597	0.3669396	0.3649376	0.3629568	0.3610001	0.2829801	0.2204939	0.1670908	0.103189	
134	0.3807004	0.3786265	0.3765509	0.3744772	0.3724085	0.3703484	0.3683003	0.3662671	0.3642523	0.3622589	0.3602899	0.2906639	0.2273256	0.1681863	0	
135	0.3801045	0.3780192	0.3759316	0.3738452	0.3717636	0.3696901	0.3676284	0.3655817	0.3635533	0.3615467	0.3503908	0.2792088	0.2166092	0.1554264	0.107985	
136	0.3795016	0.3774041	0.3753037	0.373204	0.3711085	0.3690209	0.3669449	0.3648839	0.3628413	0.3395335	0.3063289	0.2658715	0.2075713	0.1515187	0	
137	0.3788923	0.376782	0.3746679	0.372554	0.370444	0.3603067	0.3450328	0.3327588	0.3160011	0.3070065	0.2779057	0.2483573	0	0	0	
138	0.3782772	0.3761531	0.3740247	0.3718957	0.3697704	0.3576761	0.3186423	0.3040707	0.2948581	0.2888153	0	0	0.2013533	0.1532959	0.1055997	0
139	0.3776563	0.3755179	0.3733743	0.3712299	0.3690884	0.3419416	0.3037372	0.2954299	0.2935184	0.2838497	0.2533713	0.2224367	0	0	0	
140	0.3770301	0.3748765	0.3727173	0.3705565	0.3662	0.3283863	0.2951199	0.2889656	0.2836905	0.2692232	0.2451709	0	0	0	0	
141	0.3763984	0.3742292	0.3720537	0.3698764	0.3656725	0.3081019	0.271186	0.2594424	0.2424067	0.2298599	0	0	0	0	0	
142	0.3757609	0.3735759	0.3713841	0.3691896	0	0	0	0	0	0.1683663	0	0	0	0	0	
143	0.3751176	0.3729165	0.3707081	0	0	0	0	0	0	0.1110883	0.1430597	0	0	0	0	
144	0.3744676	0.3722508	0.370026	0.3677976	0.3220747	0.2339012	0.1283398	0.0449815	0.0158248	0	0	0	0	0	0	
145	0.3738105	0.3715783	0.3693375	0.3670927	0.3234473	0	0	0	0	0	0	0	0	0	0	
146	0.3731453	0.3708985	0.3686427	0.3663823	0	0	0	0	0	0	0	0	0	0	0	
147	0.3724712	0.3702109	0.3679411	0.3656663	0.3632572	0.2995817	0	0	0.1720484	0.1763159	0	0	0	0	0	
148	0.3717869	0.3695147	0.3672327	0.3649451	0.3626565	0.3341781	0.2964591	0.2720472	0.2541325	0	0	0	0	0.1729753	0	
149	0.3710912	0.3688092	0.3665169	0.3642187	0.3619191	0.3596224	0.3181969	0	0.2922647	0.2835424	0.2702904	0	0	0	0	
150	0.3703828	0.3680935	0.3657936	0.3634873	0.3611791	0.3588733	0.3291515	0.3043793	0.2968716	0.2961768	0.2879552	0	0	0.2237407	0.1765401	
151	0.3696603	0.3673668	0.3650623	0.3627509	0.3604373	0.3581255	0.35582	0.3216195	0.3048	0.3109517	0.3158005	0.2961515	0.2769885	0.2488196	0.2089637	0
152	0.3689224	0.3666281	0.3643225	0.3620099	0.3596943	0.35738	0.3550713	0.3527729	0.345462	0.3455719	0.3435924	0.3336983	0.297766	0	0	0
153	0.3681679	0.3658767	0.363574	0.3612639	0.3589504	0.3566377	0.3543301	0.352032	0.3497481	0.3474831	0.3452424	0.3430316	0.3351592	0.2915005	0.2630016	0
154	0.3673955	0.3651119	0.3628165	0.3605133	0.3582064	0.3558999	0.3535977	0.3513045	0.3490248	0.3467632	0.3445251	0.3423157	0.3401413	0.3167667	0.2930727	0.

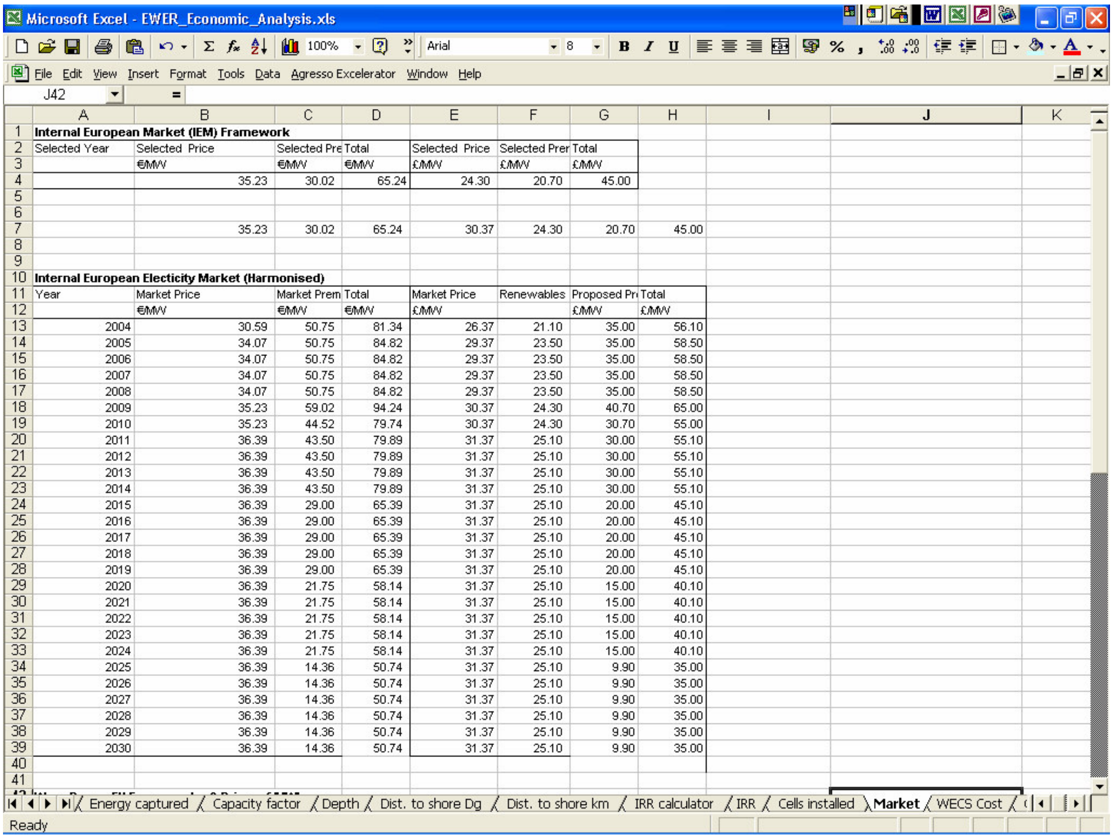
Figure 6.11: The capacity factor for every cell in the Excel model.

6.3.2.1 Data Input

- Capacity factor for each cell – see figure 6.11
- WECS Population density –300 MW deployed in each cell
- Losses and availability factor – 98% and 95%

6.3.3 Calculate Net Income

The annualised cost per MW is multiplied by the Pelamis population density of 300MW per cell, giving the annual expenditure for each cell. The annual income is then calculated by multiplying the annual output by the selected market price and subsidy (as show in the Excel model in figure 6.12). The expenditure is then subtracted from the income to give the net income for device arrays deployed in each cell.


Microsoft Excel - EWER_Economic_Analysis.xls

	A	B	C	D	E	F	G	H
1	**Internal European Market (IEM) Framework**							
2	Selected Year	Selected Price	Selected Pre	Total	Selected Price	Selected Prer	Total	
3		€/MW	€/MW	€/MW	£/MW	£/MW	£/MW	
4		35.23	30.02	65.24	24.30	20.70	45.00	
5								
6								
7		35.23	30.02	65.24	30.37	24.30	20.70	45.00
8								
9								
10	**Internal European Electicity Market (Harmonised)**							
11	Year	Market Price	Market Prem	Total	Market Price	Renewables	Proposed Pr	Total
12		€/MW	€/MW	€/MW	£/MW		£/MW	£/MW
13	2004	30.59	50.75	81.34	26.37	21.10	35.00	56.10
14	2005	34.07	50.75	84.82	29.37	23.50	35.00	58.50
15	2006	34.07	50.75	84.82	29.37	23.50	35.00	58.50
16	2007	34.07	50.75	84.82	29.37	23.50	35.00	58.50
17	2008	34.07	50.75	84.82	29.37	23.50	35.00	58.50
18	2009	35.23	59.02	94.24	30.37	24.30	40.70	65.00
19	2010	35.23	44.52	79.74	30.37	24.30	30.70	55.00
20	2011	36.39	43.50	79.89	31.37	25.10	30.00	55.10
21	2012	36.39	43.50	79.89	31.37	25.10	30.00	55.10
22	2013	36.39	43.50	79.89	31.37	25.10	30.00	55.10
23	2014	36.39	43.50	79.89	31.37	25.10	30.00	55.10
24	2015	36.39	29.00	65.39	31.37	25.10	20.00	45.10
25	2016	36.39	29.00	65.39	31.37	25.10	20.00	45.10
26	2017	36.39	29.00	65.39	31.37	25.10	20.00	45.10
27	2018	36.39	29.00	65.39	31.37	25.10	20.00	45.10
28	2019	36.39	29.00	65.39	31.37	25.10	20.00	45.10
29	2020	36.39	21.75	58.14	31.37	25.10	15.00	40.10
30	2021	36.39	21.75	58.14	31.37	25.10	15.00	40.10
31	2022	36.39	21.75	58.14	31.37	25.10	15.00	40.10
32	2023	36.39	21.75	58.14	31.37	25.10	15.00	40.10
33	2024	36.39	21.75	58.14	31.37	25.10	15.00	40.10
34	2025	36.39	14.36	50.74	31.37	25.10	9.90	35.00
35	2026	36.39	14.36	50.74	31.37	25.10	9.90	35.00
36	2027	36.39	14.36	50.74	31.37	25.10	9.90	35.00
37	2028	36.39	14.36	50.74	31.37	25.10	9.90	35.00
38	2029	36.39	14.36	50.74	31.37	25.10	9.90	35.00
39	2030	36.39	14.36	50.74	31.37	25.10	9.90	35.00

Energy captured / Capacity factor / Depth / Dist. to shore Dg / Dist. to shore km / IRR calculator / IRR / Cells installed / Market / WECS Cost

Ready

Figure 6.12: The IEM electricity market price used within the economic Excel model. These prices are based upon OXERA consultant's UK market price profile from 2004 to 2025 explained in section 4.1.1.

6.3.3.1 Data Input

- Annual Output (MWh)
- Market Price (£/MWh)
- Market Premium (£/MWh)
- Technology Annualised O&M Cost (£/MW)

6.3.4 Calculate Internal Rate of Return (IRR)

The IRR described in section 4.3 is calculated for arrays of the Pelamis device deployed within each resource cell. The IRR is generated within the Excel model using the Excel IRR function as shown in figure 6.13. The detailed algorithm used to calculate the IRR automatically for every model cell is implemented using Visual Basic within Excel. The algorithm inputs the capital cost, annual energy output (shown in figure 6.14) and net income, and the lifetime of the Pelamis device (assumed to be 20 years) in the *Technology Parameters* worksheets in the Excel model shown in figure 6.9. The result is shown in figure 6.15. This can be examined in greater detail in Appendix 14.2.

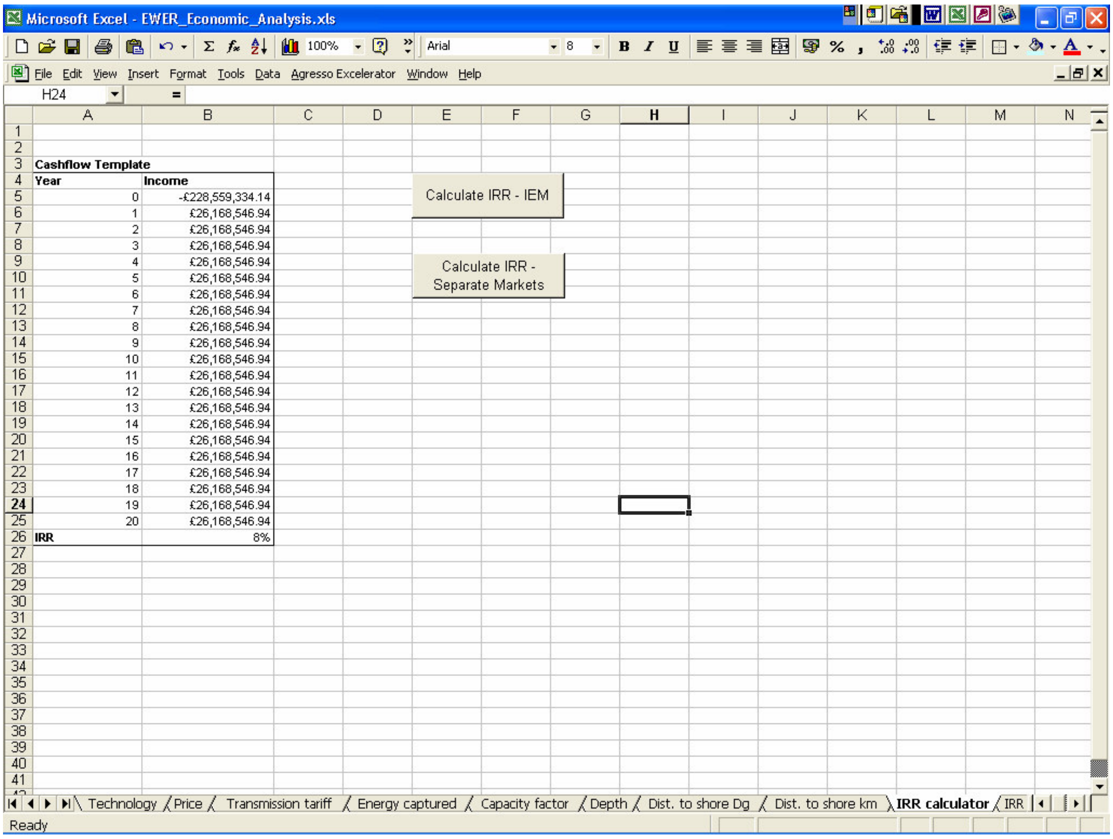
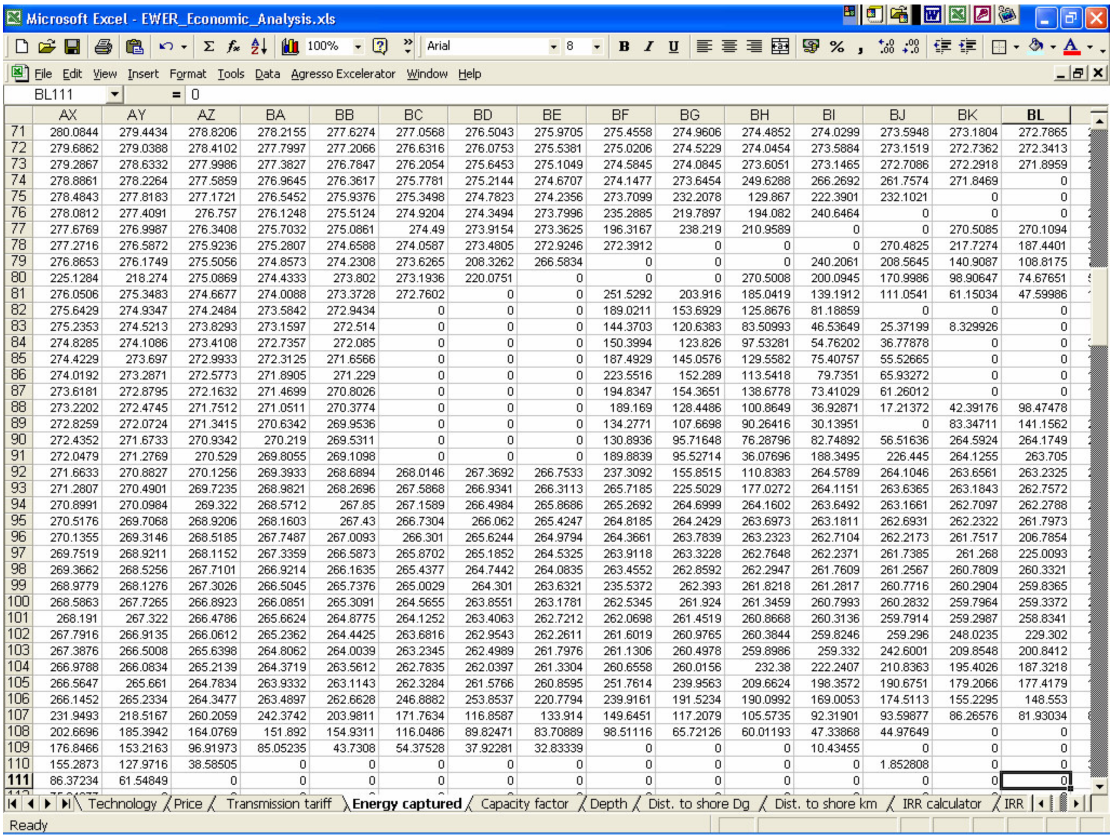


Figure 6.13: Comparing the IRR to the RRR in each cell identifies the potential market. Selecting the appropriate button initiates the Visual Basic algorithm, which automatically calculates the rate of return for each cell (using the Excel IRR function). Two different algorithms are required to calculate the IRR under the *IEM* market scenario and the *Regional* market scenario as explained in section 4.

6.3.4.1 Data Input

- Capital Cost
- Annual Output (MWh)
- Net Income (£/cell)
- Technology lifetime (yrs)



	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL
71	280.0844	279.4434	278.8206	278.2155	277.6274	277.0568	276.5043	275.9705	275.4558	274.9606	274.4852	274.0299	273.5948	273.1804	272.7865
72	279.6862	279.0388	278.4102	277.7997	277.2066	276.6316	276.0753	275.5381	275.0206	274.5229	274.0454	273.5884	273.1519	272.7362	272.3413
73	279.2867	278.6332	277.9986	277.3827	276.7847	276.2054	275.6453	275.1049	274.5845	274.0845	273.6051	273.1465	272.7086	272.2918	271.8959
74	278.8861	278.2264	277.5859	276.9645	276.3617	275.7781	275.2144	274.6707	274.1477	273.6454	249.6288	266.2692	261.7574	271.8469	0
75	278.4843	277.8183	277.1721	276.5452	275.9376	275.3498	274.7823	274.2356	273.7099	232.2078	129.867	222.3901	232.1021	0	0
76	278.0812	277.4091	276.757	276.1248	275.5124	274.9204	274.3494	273.7996	235.2885	219.7897	194.082	240.6464	0	0	0
77	277.6769	276.9987	276.3408	275.7032	275.0861	274.49	273.9154	273.3625	196.3167	238.219	210.9589	0	0	270.5085	270.1094
78	277.2716	276.5872	275.9236	275.2807	274.6588	274.0587	273.4805	272.9246	272.3912	0	0	0	270.4825	217.7274	187.4401
79	276.8653	276.1749	275.5056	274.8573	274.2308	273.6265	208.3262	266.5834	0	0	0	240.2061	208.5645	140.9087	108.8175
80	225.1284	218.274	275.0869	274.4333	273.802	273.1936	220.0751	0	0	0	270.5008	200.0945	170.9986	98.90647	74.67651
81	276.0506	275.3483	274.6677	274.0088	273.3728	272.7602	0	0	251.5292	203.916	185.0419	139.1912	111.0541	61.15034	47.59986
82	275.6429	274.9347	274.2484	273.5842	272.9434	0	0	0	189.0211	153.6929	125.8676	81.18859	0	0	0
83	275.2353	274.5213	273.8293	273.1597	272.514	0	0	0	144.3703	120.6383	83.50993	46.53649	25.37199	8.329926	0
84	274.8285	274.1086	273.4108	272.7357	272.085	0	0	0	150.3994	123.826	97.53281	54.76202	36.77878	0	0
85	274.4229	273.697	272.9933	272.3125	271.6566	0	0	0	187.4929	145.0576	129.5582	75.40757	55.52665	0	0
86	274.0192	273.2871	272.5773	271.8905	271.229	0	0	0	223.5516	152.289	113.5418	79.7351	65.93272	0	0
87	273.6181	272.8795	272.1632	271.4699	270.8026	0	0	0	194.8347	154.3651	138.6778	73.41029	61.26012	0	0
88	273.2202	272.4745	271.7512	271.0511	270.3774	0	0	0	189.169	128.4486	100.8649	36.92871	17.21372	42.39176	98.47478
89	272.8259	272.0724	271.3415	270.6342	269.9536	0	0	0	134.2771	107.6698	90.26416	30.13951	0	83.34711	141.1562
90	272.4352	271.6733	270.9342	270.219	269.5311	0	0	0	130.8936	95.71648	76.28796	82.74892	56.51636	264.5924	264.1749
91	272.0479	271.2769	270.529	269.8055	269.1098	0	0	0	189.8839	95.52714	36.07696	188.3495	226.445	264.1255	263.705
92	271.6633	270.8827	270.1256	269.3933	268.6894	268.0146	267.3692	266.7533	237.3092	155.8515	110.8383	264.5789	264.1046	263.6561	263.2325
93	271.2807	270.4901	269.7235	268.9821	268.2696	267.5868	266.9341	266.3113	265.7185	225.5029	177.0272	264.1151	263.6365	263.1843	262.7572
94	270.8991	270.0984	269.322	268.5712	267.85	267.1589	266.4984	265.8686	265.2692	264.6999	264.1602	263.6492	263.1661	262.7097	262.2788
95	270.5176	269.7068	268.9206	268.1603	267.43	266.7304	266.062	265.4247	264.8185	264.2429	263.6973	263.1811	262.6931	262.2322	261.7973
96	270.1355	269.3146	268.5185	267.7487	267.0093	266.301	265.6244	264.9794	264.3661	263.7839	263.2323	262.7104	262.2173	261.7517	206.7854
97	269.7519	268.9211	268.1152	267.3359	266.5873	265.8702	265.1852	264.5325	263.9118	263.3228	262.7648	262.2371	261.7385	261.268	225.0093
98	269.3662	268.5256	267.7101	266.9214	266.1635	265.4377	264.7442	264.0835	263.4552	262.8592	262.2947	261.7609	261.2567	260.7809	260.3321
99	268.9779	268.1276	267.3026	266.5045	265.7376	265.0029	264.301	263.6321	235.5372	262.393	261.8218	261.2817	260.7716	260.2904	259.8365
100	268.5863	267.7265	266.8923	266.0851	265.3091	264.5655	263.8551	263.1781	262.5345	261.924	261.3459	260.7993	260.2832	259.7964	259.3372
101	268.191	267.322	266.4786	265.6624	264.8775	264.1252	263.4063	262.7212	262.0698	261.4519	260.8668	260.3136	259.7914	259.2987	258.8341
102	267.7916	266.9135	266.0612	265.2362	264.4425	263.6816	262.9543	262.2611	261.6019	260.9765	260.3844	259.8246	259.296	248.0235	229.302
103	267.3876	266.5008	265.6398	264.8062	264.0039	263.2345	262.4989	261.7976	261.1306	260.4978	259.8986	259.332	242.6001	209.8548	200.8412
104	266.9788	266.0834	265.2139	264.3719	263.5612	262.7835	262.0397	261.3304	260.6558	260.0156	232.38	222.2407	210.8363	195.4026	187.3218
105	266.5647	265.661	264.7834	263.9332	263.1143	262.3284	261.5766	260.8595	251.7614	239.9563	209.6624	198.3572	190.6751	179.2066	177.4179
106	266.1452	265.2334	264.3477	263.4897	262.6628	246.8882	253.8537	220.7794	239.9161	191.5234	190.0992	169.0053	174.5113	155.2295	148.553
107	231.9493	218.5167	260.2059	242.3742	203.9811	171.7634	116.8587	133.914	149.6451	117.2079	105.5735	92.31901	93.59877	86.26576	81.93034
108	202.6696	185.3942	164.0769	151.892	154.9311	116.0486	89.82471	83.70889	98.51116	65.72126	60.01193	47.33868	44.97649	0	0
109	176.8466	153.2163	96.91973	85.05235	43.7308	54.37528	37.92281	32.83339	0	0	0	10.43455	0	0	0
110	155.2873	127.9716	38.58505	0	0	0	0	0	0	0	0	0	1.852808	0	0
111	86.37234	61.54849	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6.14: The estimated annual energy output for each cell within the Excel model.

6.3.4.2 Data Output

- IRR – calculated for arrays of the Pelamis device deployed within each cell shown in figure 6.15.

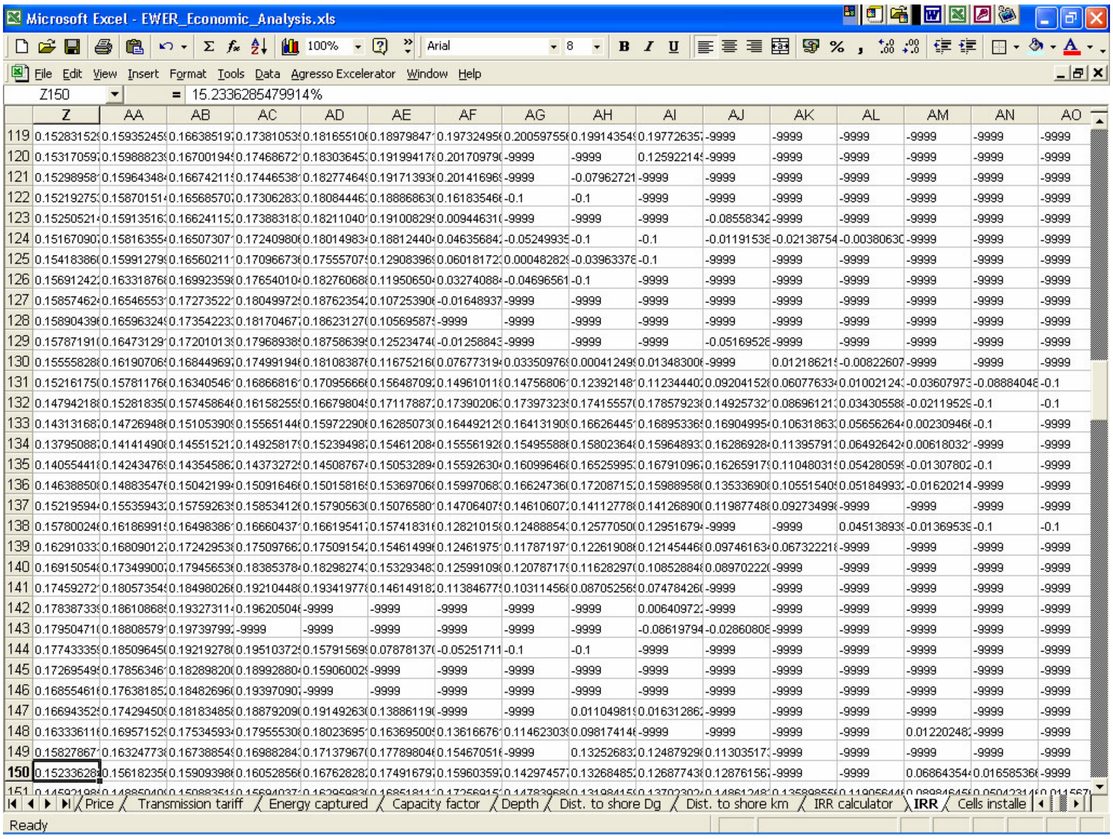


Figure 6.15: The IRR calculated for arrays of the Pelamis device deployed within each cell within the economic analysis Excel model.

6.4 Get Market Size

Comparing the IRR to the RRR in each model cell identifies the potential market and thus gives the economic European wave energy resource. Two required rates of rates of return are selected: an optimistic RRR of 10 % and a more realistic RRR of 13%. This is explained in greater detail in section 4.4. The implementation can be examined in greater detail in the economic analysis Excel model included in Appendix 14.2.

The Excel model compares the IRR to the RRR in each cell to identify the potential market automatically using an algorithm implemented within the Excel model using Visual Basic. If the IRR is greater than or equal to the RRR, then the cell is considered to be a commercially viable area to install wave energy arrays. The total annual output, market capacity and capital investment equivalent to the number of commercially viable cells is then counted giving the market size in annual energy output, installed capacity and capital invested as shown in figure 6.16.

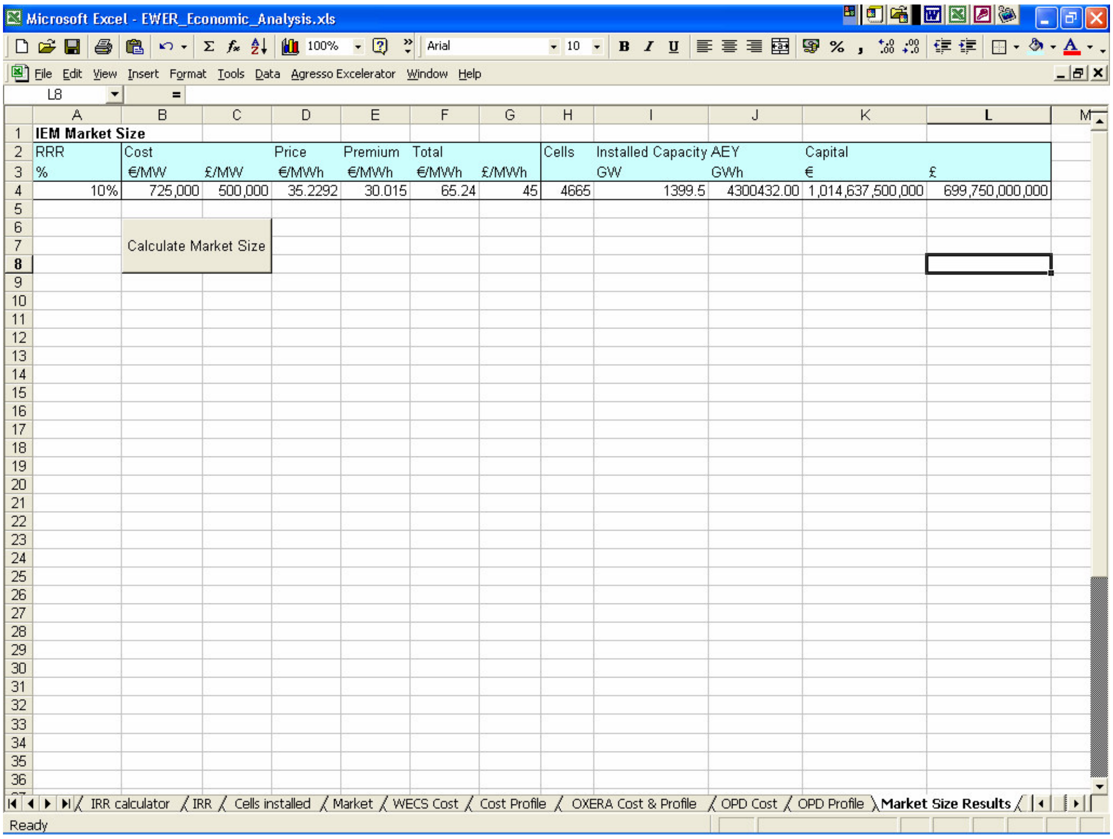


Figure 6.16: The potential European market is calculated algorithm by pressing the button within the Excel model.

6.4.1 Data Input

- Internal Rate of Return – shown in figure 6.15.
- Required Rate of Return – an optimistic 10 % and a more realistic 13%.
- WECS Population density – 30 MW/km (or 300 MW installed per cell).

6.4.2 Data Output

- Installed Capacity (GW)
- Installed Cells
- Total Annual Output (GWh)
- Capital Investment (£)

IEM Market Size

Year	RRR	Cost		Price	Premium	Total		Cells	Installed Cap	AEY	Capital	
	%	€/MW	£/MW	€/MWh	€/MWh	€/MWh	£/MWh		GW	GWh	€	£
2010	10%	1,397,800	964,000	35.2	66.3	101.5	70	3847	1154.1	3750362	1,613,200,980,000	1,112,552,400,000
2010	10%	1,397,800	964,000	35.2	59.0	94.2	65	1854	556.2	1825656	777,456,360,000	536,176,800,000
2010	10%	1,397,800	964,000	35.2	51.8	87.0	60	487	146.1	485571	204,218,580,000	140,840,400,000
2010	10%	1,397,800	964,000	35.2	44.5	79.7	55	5	1.5	5115	2,096,700,000	1,446,000,000
2010	10%	1,397,800	964,000	35.2	37.3	72.5	50	0	0.0	0	0	0
2010	13%	1,397,800	964,000	35.2	73.5	108.7	75	2065	619.5	2027943	865,937,100,000	597,198,000,000
2010	13%	1,397,800	964,000	35.2	66.3	101.5	70	802	240.6	795266	336,310,680,000	231,938,400,000
2010	13%	1,397,800	964,000	35.2	59.0	94.2	65	116	34.8	116288	48,643,440,000	33,547,200,000
2010	13%	1,397,800	964,000	35.2	51.8	87.0	60	0	0.0	0	0	0
2010	13%	1,397,800	964,000	35.2	44.5	79.7	55	0	0.0	0	0	0
2010	13%	1,397,800	964,000	35.2	37.3	72.5	50	0	0.0	0	0	0
2025	10%	1,255,700	866,000	35.2	51.8	87.0	60	1823	546.9	1787387	686,742,330,000	473,615,400,000
2025	10%	1,255,700	866,000	35.2	44.5	79.7	55	458	137.4	455355	172,533,180,000	118,988,400,000
2025	10%	1,255,700	866,000	35.2	37.3	72.5	50	1	0.3	1024	376,710,000	259,800,000
2025	10%	1,255,700	866,000	35.2	30.0	65.2	45	0	0	0	0	0
2025	13%	1,255,700	866,000	35.2	66.3	101.5	70	2302	690.6	2245918	867,186,420,000	598,059,600,000
2025	13%	1,255,700	866,000	35.2	59.0	94.2	65	944	283.2	930496	355,614,240,000	245,251,200,000
2025	13%	1,255,700	866,000	35.2	51.8	87.0	60	156	46.8	155983	58,766,760,000	40,528,800,000
2025	13%	1,255,700	866,000	35.2	44.5	79.7	55	0	0	0	0	0
2025	13%	1,255,700	866,000	35.2	37.3	72.5	50	0	0	0	0	0

6.16: The economic wave energy resource assessment results for the *Internal European Market* scenario. The market results are explained in section 9.1.

7 GIS Assessment Model

The Geographical Information System (GIS) model is developed to represent the wave energy resource and related geographical data. The model is summarised as:

- Model cell size: 10 km
- Projection: Geographic
- Area of analysis: 13°W to 10°E and 65°N to 30°N
- Total area: 8,524,800 km^2

Developing a GIS model optimised data analysis, allowing:

- Analysis of data dependent on geographical position.
- Interpolation of gridded wave data points, depth data points and ATBA data.
- Representation of resource, environmental and economic data using surfaces.
- Calculation of the distance of potential sites and the cost of transmission.
- Areas, where potential wave energy arrays would be commercially viable, to be represented graphically.

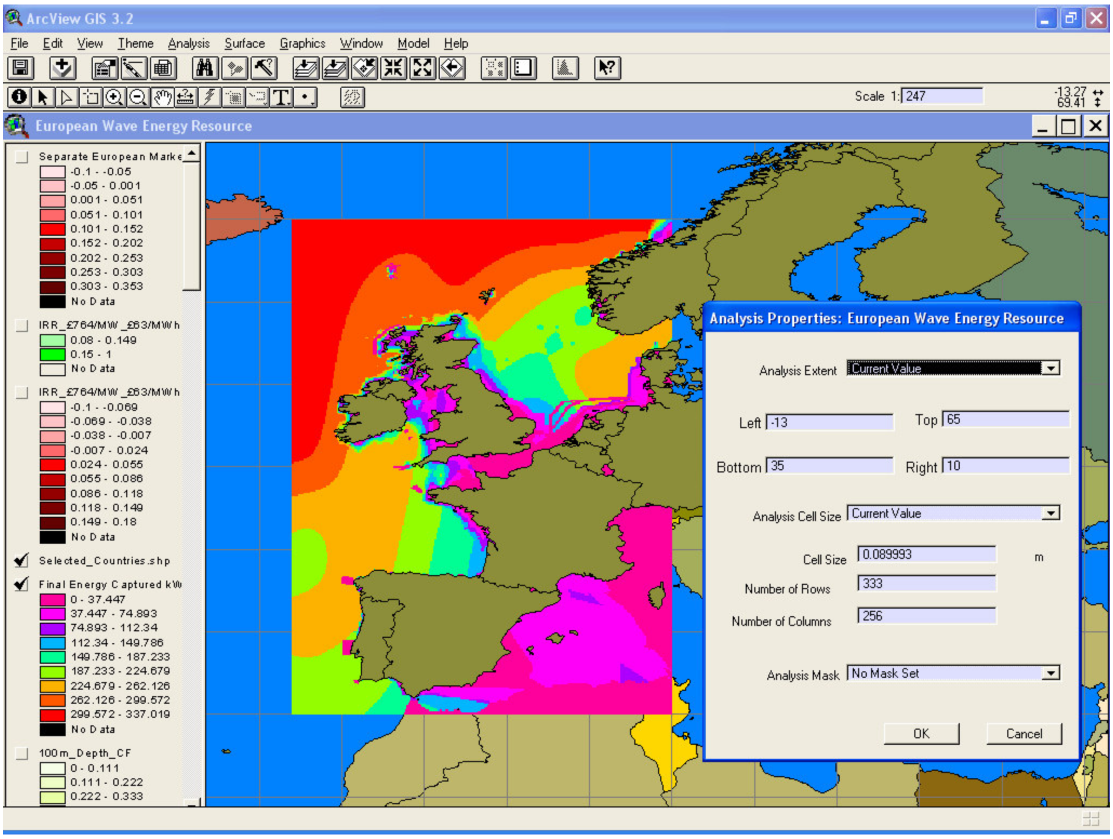


Figure 7.1: ARC View 3.2 GIS within the Microsoft XP computer environment.

ARC View 3.2 GIS [46], illustrated in figure 7.1, is used to develop the GIS model. For more on ARC View and GIS refer to [47]. A world map together with the parallels of latitude and meridians of longitude are imported from a supplied GIS library to form the default view.

7.1 Area of Analysis

Initial analysis of the European wave resource identified the area to be analysed. Due to limitations in resources this area is restricted to the Western European approaches of the northern Atlantic Ocean and the North Sea. This area experiences high wave power levels because of the long fetch of Atlantic Ocean that runs from the Gulf of Mexico up to Western Europe combined with the prevailing westerly winds. The Baltic and Mediterranean seas are discarded, as the available wave energy is negligible in comparison due to the shelter of surrounding landmasses, shorter fetches and shallower depths. The area selected is from 13°W to 10°E longitude left to right and from 65°N to 30°N latitude top to bottom as highlighted in figure 6.2.

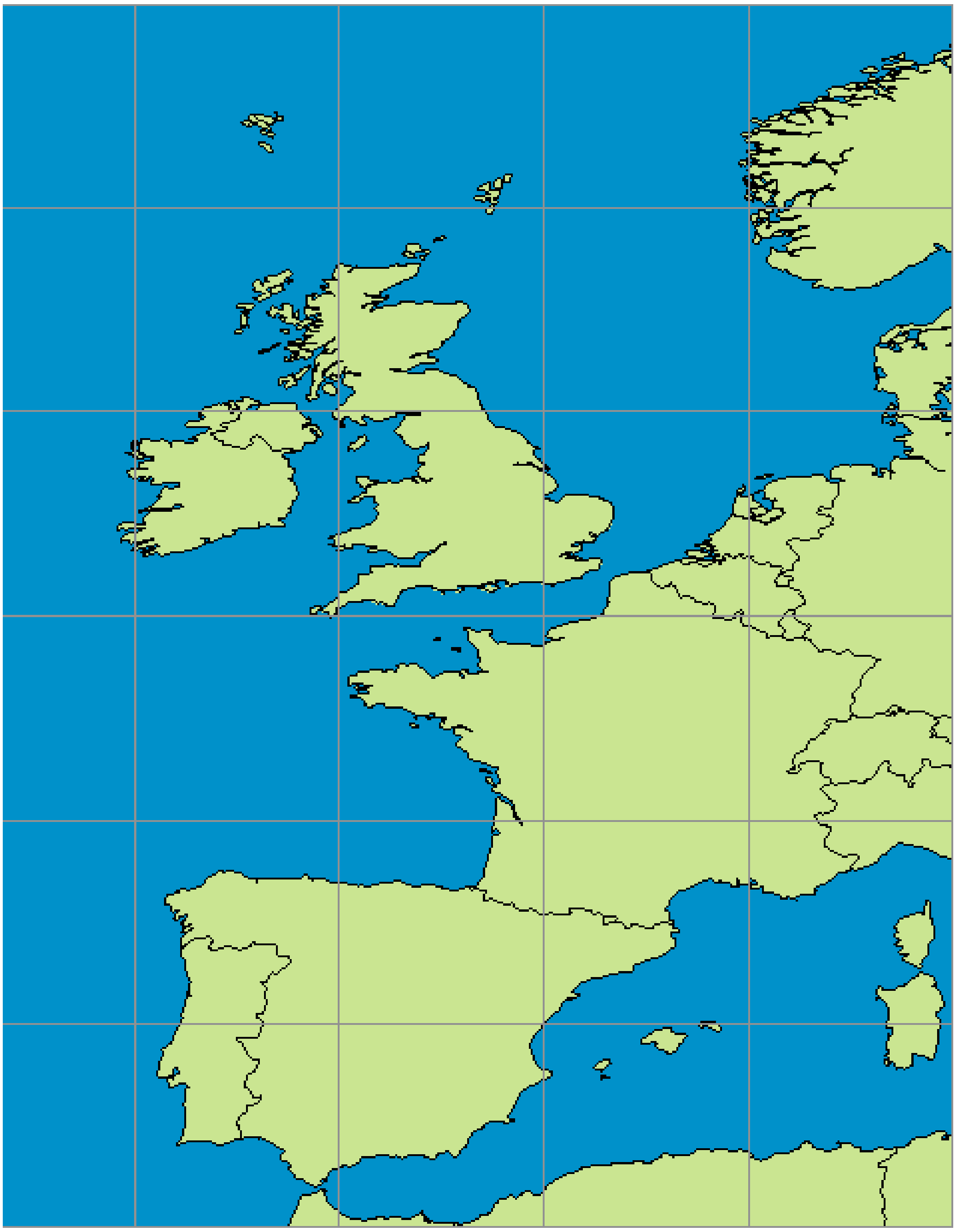


Figure 7.2: Selected area of analysis from 13°W to 10°E and from 65°N to 30°N.

This gave an area of 8,524,800 km^2 of Europe to be analysed. The selected area did not include all European maritime territory. For example, the maritime territory of United Kingdom extends beyond 20°W of the Greenwich meridian and Norway's waters extend beyond 20°E. However, these waters are too far away from load centres and any wave energy projects, using current transmission technology, would require uneconomical lengths of cable to connect to onshore grids.

7.2 GIS Raster Grids and Surfaces

For the purposes of analysis a *GIS Raster Grid* is initialised. This format allows for geographical grid-based data i.e. data which is identified by its position with respect to the specified datum – in this case latitude and longitude – to be represented and manipulated within the GIS computer environment. For example:

- Sets of gridded data such as average wave heights can be interpolated into *data surfaces* – interpolating values for each grid cell – thus giving a wave height for all locations within the area assessed.
- Geographical data sets such as coordinates of sea depth to be displayed as depth surfaces.
- Data surfaces such as the distances to nearest coastlines can be to be exported from the GIS in tab-delimited table format.

For more information on using ARC View GIS and Raster Grids refer to [48].

7.3 Cell Size

The resource model is divided into 10 km cells size using a GIS raster grid consisting of 333 rows and 256 columns. This is selected because Microsoft Excel worksheets are limited to 256 columns. This allowed the surfaces to be exported from the GIS model – as a tab-delimited text file – and imported into the Excel model using one worksheet. Transfer of data transfer between the GIS and Excel environment is made easier when working within this limit. If the raster grid exceeded these limits then the grid must be displayed on multiple worksheets. This is a rudimentary and is very slow process. Also, performing economic analysis on a raster grid within Excel, for example using Visual Basic scripts, is much more practical when working on a single worksheet.

7.4 Interpolation of gridded resource data points into surfaces

This assessment selected the WERATLAS to supply the wave data for 23 grid points within European waters. The GIS program enabled surfaces of wave data to be interpolated from the original data in the form of GIS Raster surface. The value for any location within the area of interest is represented by the equivalent interpolated cell value. The gridded wave resource grid points within the area assessed are illustrated in 7.6 and the equivalent interpolated surface representing the wave energy resource is displayed in section 7.11.

7.5 Projection

The Geographic Projection is used to display the GIS model. Difficulties experienced with ARC View GIS 3.2 prevented selecting the favoured Mercator projection used in UKHO Admiralty Charts.

7.6 WERATLAS Wave Data (23 grid points)

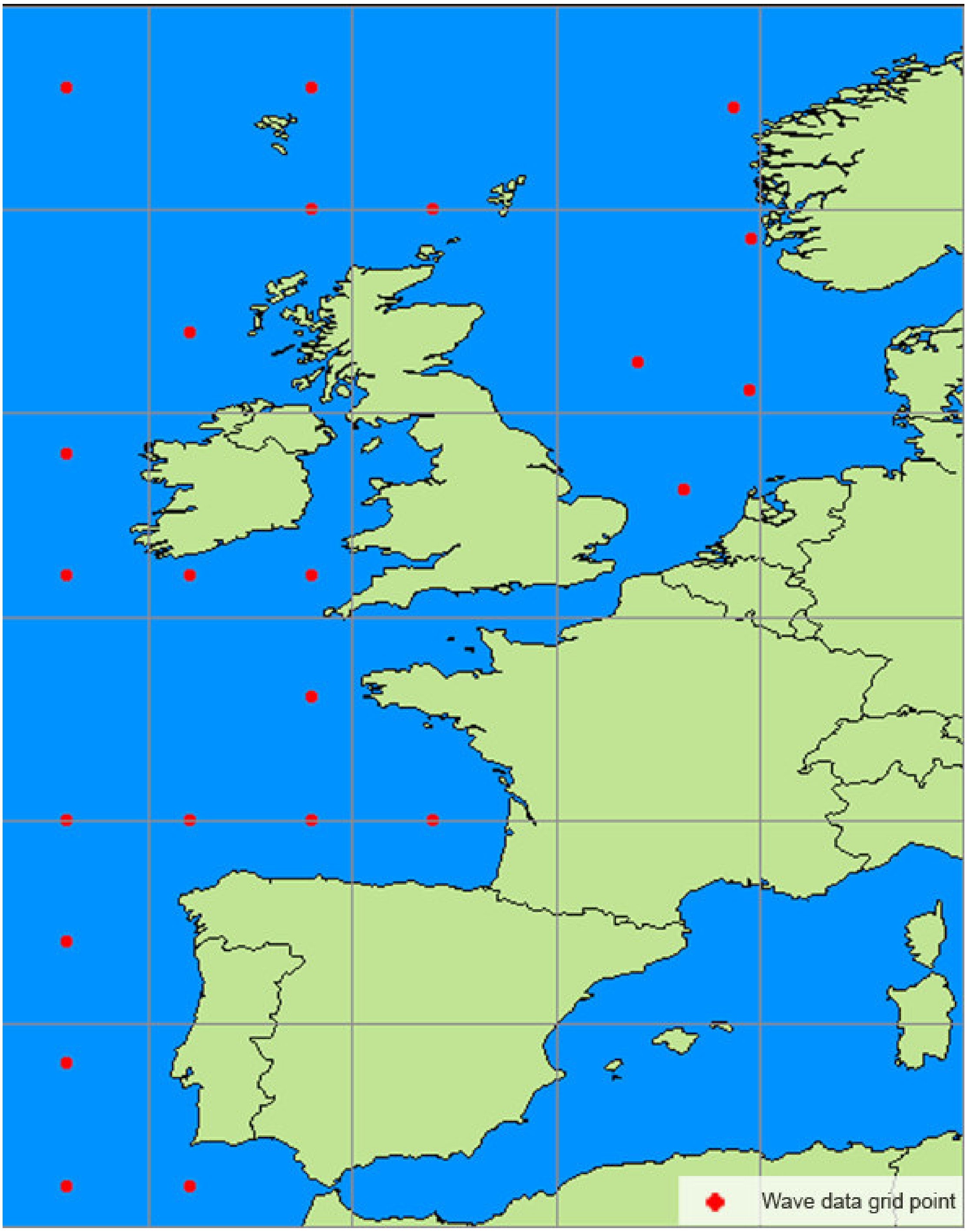


Figure 7.3: The WERATLAS [18] provides a comprehensive set of wave data for 85 positions around Europe. Significant wave height, wave energy period and directional data are available in wave matrix, tabular and wave rose format, averaged over seasonal and annual periods. The wave data is from the UK Met Office Wind-Wave Model data set from 1987-to-1994. 23 of the 85 data points lie within the area analysed. The wave data is represented in the GIS resource model as gridded data points displayed as red points.

7.7 Bathymetry (depth in metres)

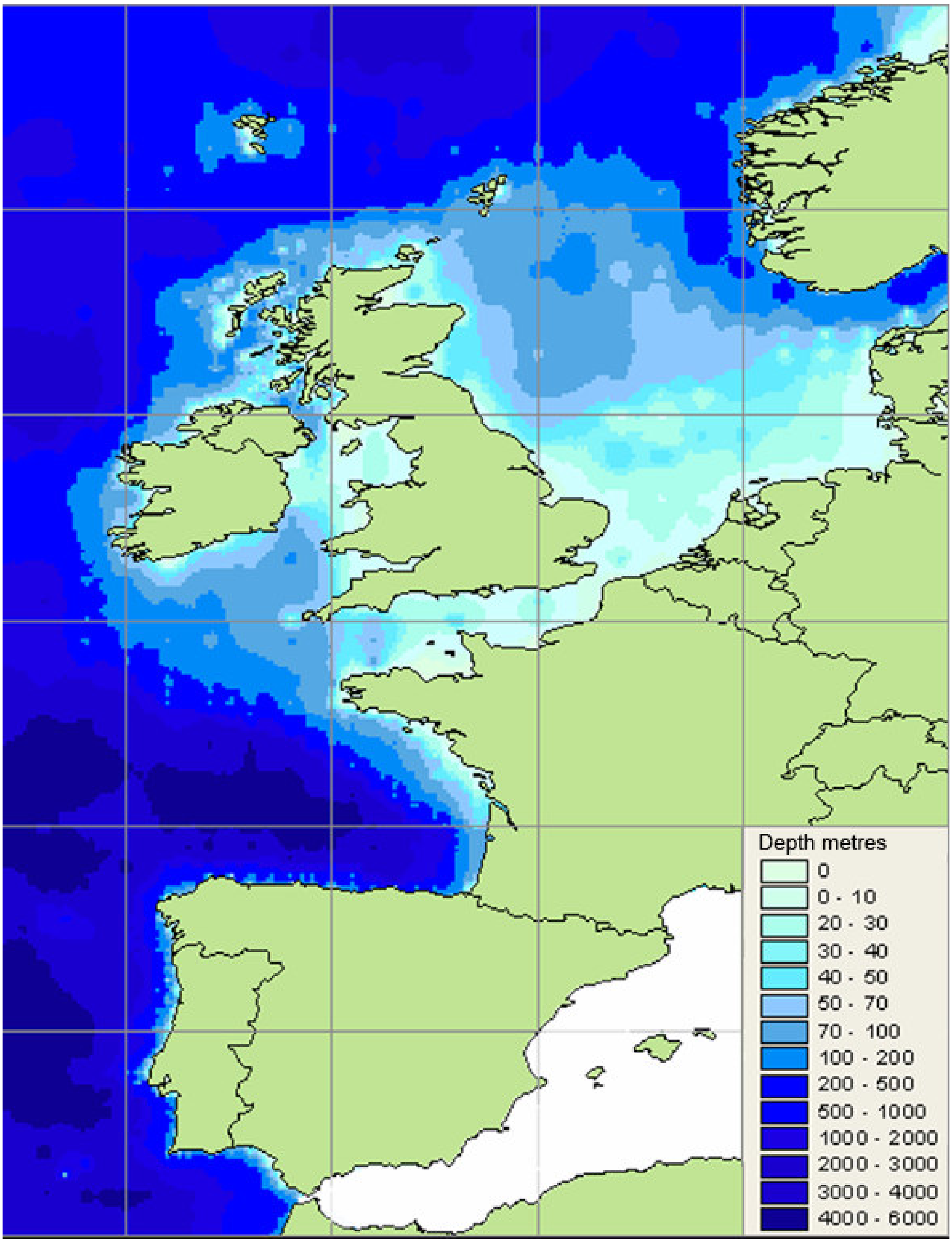


Figure 7.4: The GIS bathymetry surface, in metres, is interpolated from the gridded depth data input into the GIS model. Over 2700 depth measurements covering the Northern Atlantic Ocean and North Sea are obtained from UKHO Admiralty Charts [44]. The average depth must be calculated for each cell within the resource model, combined with the distance to shore, so that the cost of transferring the captured power onshore using submarine cable can be calculated.

7.8 Distance to Shore (kilometres)

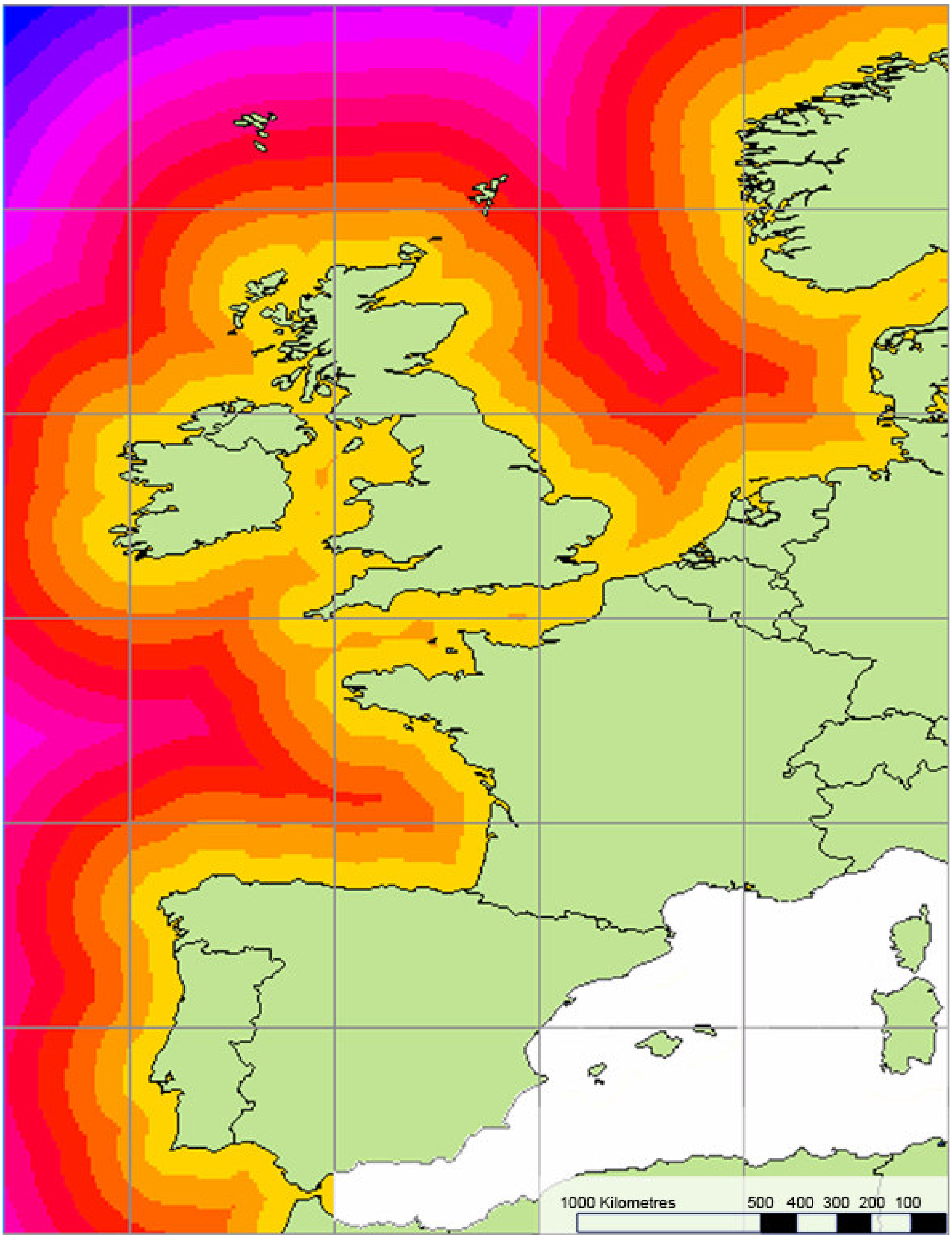


Figure 7.5: The distance to shore must be calculated for each cell within the resource model so that the cost of transferring the captured power onshore can be determined. A GIS map of Europe is input into the GIS model and the distance to the nearest shoreline for each cell is calculated in decimal degrees and then converted into metres to generate the *Distance to shore* GIS surface.

7.9 Areas to be avoided (ATBA)

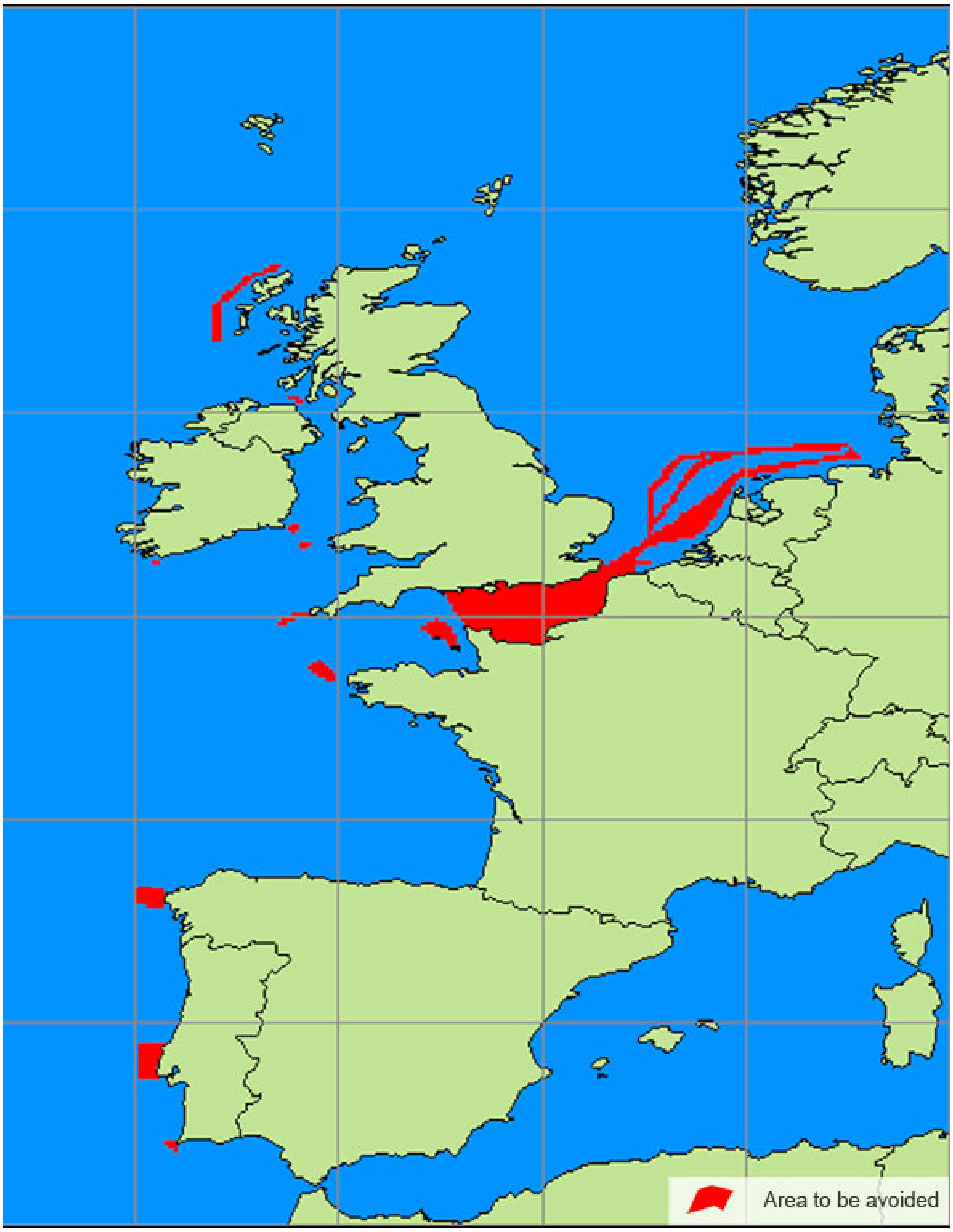


Figure 7.6: Environmental constraints that may restrict the deployment of WECS in certain areas are incorporated. Any area that is designated by a European maritime authority is avoided and excluded from the economic assessment. Areas to be avoided (ATBA) include deep water shipping channels, traffic routing measures, inshore traffic zones, traffic separation arrays and explosives dumping grounds. The ATBA are acquired from UKHO Admiralty Charts [44]. Coordinates outlining and identifying these areas are input into the GIS resource model. The equivalent GIS surface represents the ATBA as red zones.

7.10 European Maritime Territories

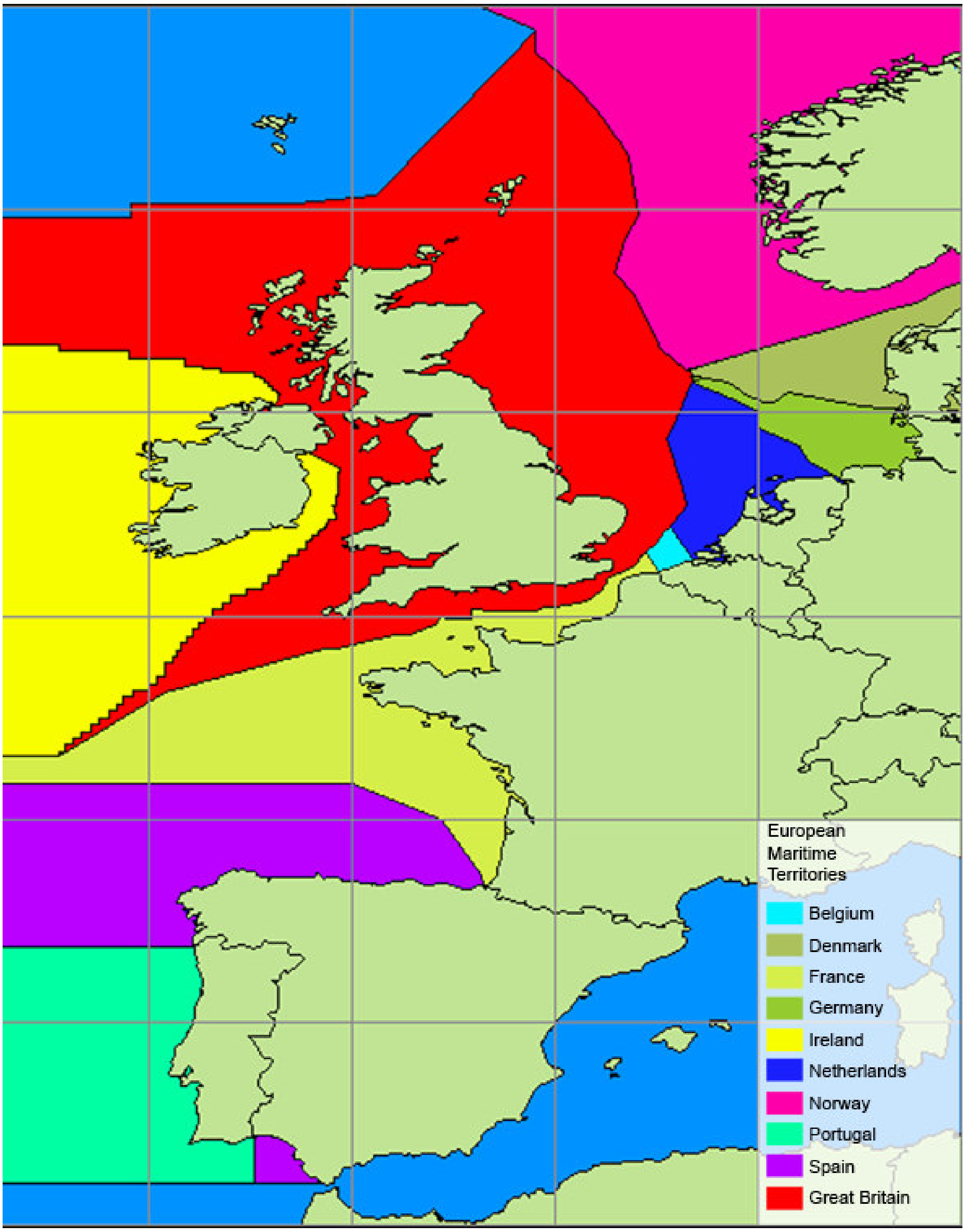


Figure 7.7: For the purposes of the regional electricity market scenario, the nationality of each potential site must be known so the market price and subsidy applicable ca be determined. The Maritime boundary GIS surface is interpolated based upon international maritime territorial coordinates of the included countries. The correct market data is identified using this surface.

7.11 Annual Average Wave Energy Resource

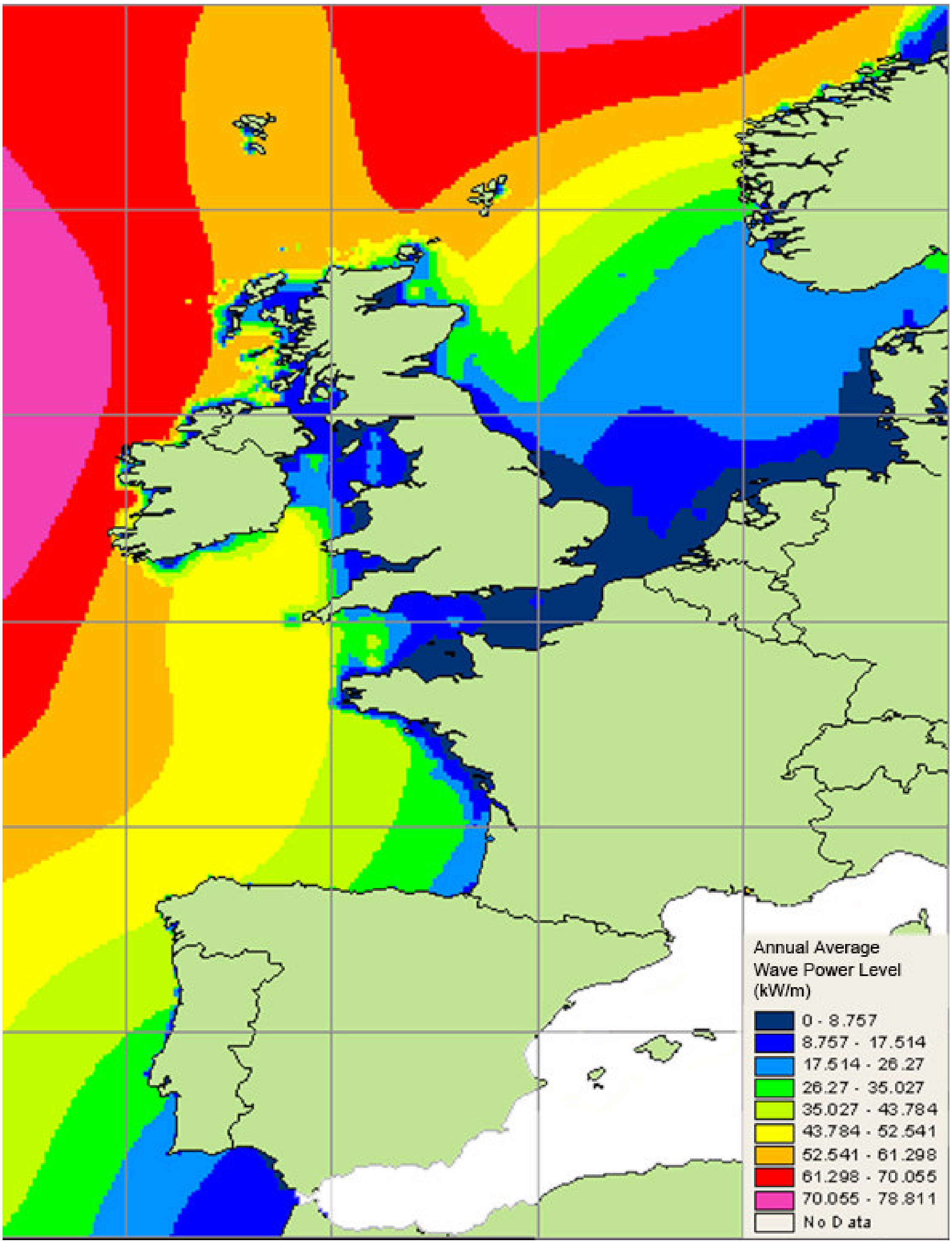


Figure 7.8: The annual average wave energy resource is interpolated from the average annual wave power levels (in kW/m) for each gridded wave data point obtained from the WERATLAS. The annual average power level available in kilowatts per metre of wave front (kW/m) is commonly used to present wave energy resource. This surface displays the distribution of the wave resource around Europe.

7.12 Pelamis WECS Average Annual Capacity Factor (%)

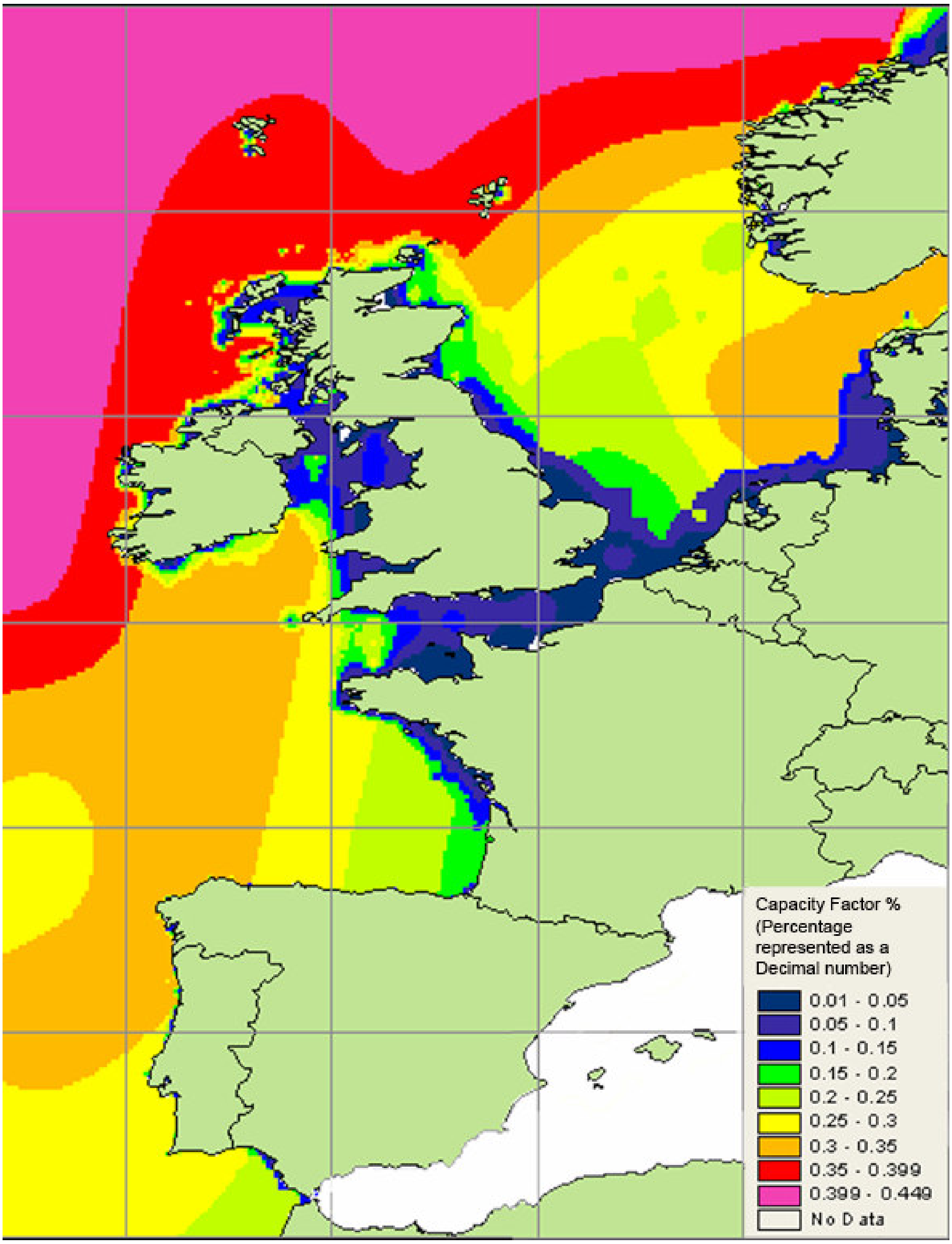


Figure 7.9: The WECS average annual capacity factor (also known as load factor or capacity coefficient) is calculated for each wave data point included in section 7.6. The capacity factor is calculated by dividing the actual energy captured by the devices *Rated Power*, outlined in section 5.1 of the methodology. The GIS surface is interpolated from the individual data points, allowing the annual average power captured to be estimated for all areas assessed. The capacity factor is represented as a decimal percentage.

8 Sensitivity Analysis

The methodology is tested to determine the effect of changing economic variables on the estimated wave energy market, including:

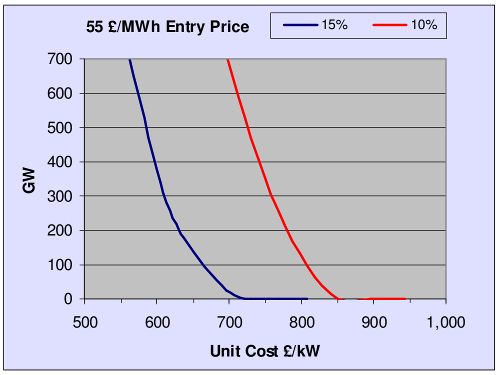
- WECS unit cost (£/kW)
- Electricity markets entry price, including wholesale price, benefits and premium (£/MWh)

The methodology implementation in tested extensively using a wide range of required rates of return, unit costs and different entry prices to identify any errors and make amendments where necessary. After successful testing, the wave energy market is estimated using two different RRR to show the effect on optimistic rate of 10 % and a conservative of 15 % (see section 4.4). The analysis showed the unit costs required for wave energy generation to become commercially viable for a range of entry prices.

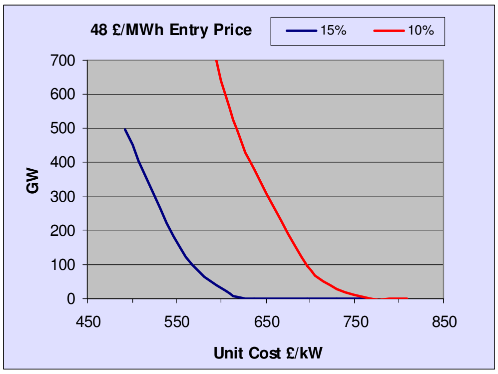
Graphs 8.1 to 8.4 show the estimated market trends for a range of entry prices from 55 £/MWh down to 34 £/MWh. The expected behaviour is observed:

- Market capacity increases in size as the cost of the WECS technology decreases.
- Lower entry prices require lower technology costs for a market to develop.
- If investors require a return of 15 % the potential market is considerably lower compared to a 10 % RRR.

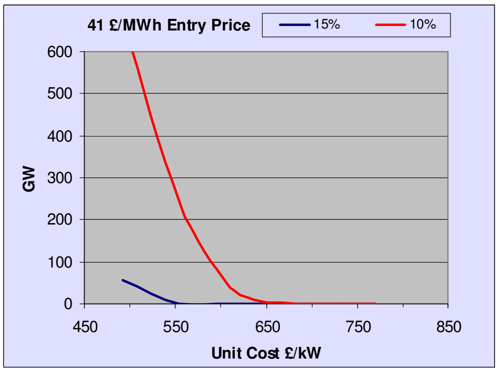
For an entry price of 55 £/MWh, based upon 10 % RRR a market would develop when the WECS cost drops to ~850 £/kW. For a 15 % RRR, wave generation becomes commercially viable for technology costs less than and equal to ~720 £/kW. A lower entry price of 48 £/MWh, requires WECS costs of ~760 and ~560 £/kW at 10 and 15 % RRR, respectively, for commercial viability.



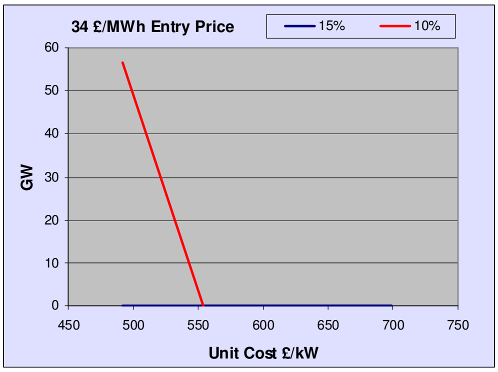
Graph 8.1: 55 £/MWh entry price 10 and 15 % RRR.



Graph 8.2: 48 £/MWh entry price and 10 and 15 % RRR.



Graph 8.3: 41 £/MWh entry price and 10 and 15 % RRR.



Graph 8.4: 34 £/MWh entry price and 10 and 15 % RRR.

Dropping to 41 £/MWh, the technology costs required are ~650 and ~540 £/kW for 10 and 15 % RRR, respectively. At market prices in the region of 34 £/MWh – including no significant premium, only 10 % RRR with unit costs less than or equal to ~550 £/MWh stimulate market growth. Graph 7.4 indicates wave energy would not penetrate the electricity market at this price if a 15 % rate of return is required.

9 Results of the European Assessment

The economic assessment of the European wave energy resource undertaken in this study investigates two different market scenarios:

1. *Internal Electricity Market* with a single price and premium for wave energy
2. *Regional Electricity Market* using existing prices and premium frameworks

9.1 Internal Electricity Market Scenario

The Internal Electricity Market scenario assumes European electricity market harmonisation which applies a single electricity entry price – including wholesale price and premium – for wave energy projects throughout Europe (detailed in section 4.1). The methodology is executed using a variable entry price to identify the level of subsidy required for wave energy to penetrate the market and produce market trends. The scenario is applied to two different estimates of probable WECS costs for 2010 and 2025. The OXERA and OPD WECS cost estimates applied are summarised in section 3.10. The equivalent economic wave energy resource and potential market for a range subsidy of entry prices are given. The complete results are included in Appendix 14.9.

9.1.1 OXERA WECS Costs

Assuming the Internal Electricity Market scenario and the WECS cost of 964 £/kW for 2010, wave energy would penetrate the market at just under 55 £/MWh for the optimistic RRR of 10 %. This is shown in graph 9.2 by the point at which the market curve crosses the x-axis (i.e. what entry price is required for the market to develop under the given RRR). The required entry prices are displayed in table 9.1. Table 9.4 shows the economic wave energy resource based on 2010 OXERA cost estimates, assuming an entry cost of 55 £/MWh. This entry price would generate an economic resource of some 1.5 GW capacity – 5 cells – corresponding to a capital investment of £1.4 billion. This resource is located around the Irish west coast. For the realistic rate of 13 %, the entry price for wave energy is higher at approximately 60 £/MWh. Graph 9.2 also indicates that no market would develop at the selected entry price of 55 £/MWh at 13% RRR.

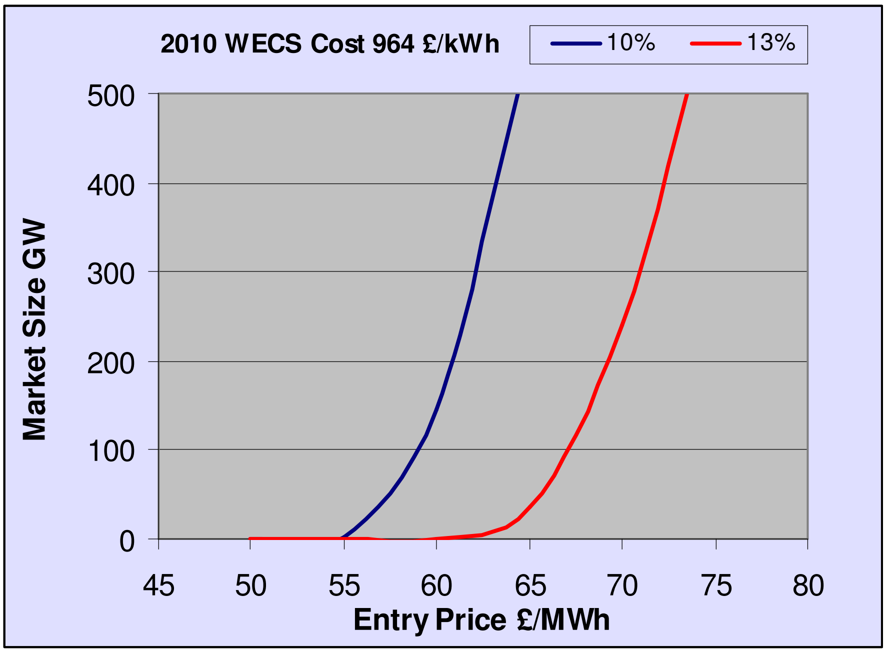
Under the Internal Electricity Market scenario and the device cost of 866 £/kW for 2025, the market entry price required for wave energy to become commercial viability is reduced to approximately 50 and 55 £/MWh for rates of return of 10 and 13 % respectively, as indicated by graph 9.3. Table 9.4 displays the economic wave energy resource based on 2025 OXERA cost estimates, assuming an entry cost of 55 £/MWh. At 10 % RRR, this selected entry price gives an economic resource of 137.4 GW – 458 cells – corresponding to a market worth approximately £120 billion. The majority of this resource is located off the west coast of Ireland, the northwest region of Scotland and to the northwest of Norway illustrated in figure 9.5. There is no market if investors require a 13 % return.

9.1.1.1 Required Entry Price (£/MWh)

Year	RRR 10%	13%
2010	55	60
2025	50	55

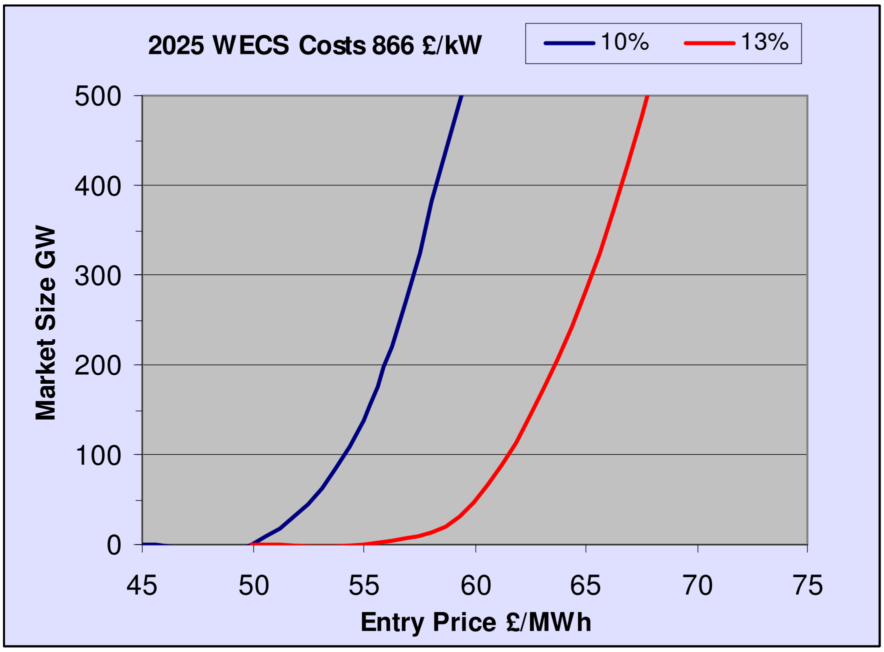
Table 9.1: The wave energy entry price (£/MWh) based on OXERA WECS unit cost estimates for 2010 and 2025.

9.1.1.2 2010 Market Trend



Graph 9.2: The 2010 WECS cost is estimated at 964 £/kW. The equivalent economic resource is displayed against the electricity entry price.

9.1.1.3 2025 Market Trend



Graph 9.3: The 2025 WECS cost is estimated at 866 £/kW. The equivalent market size is plotted against the electricity entry price.

9.1.1.4 Market Size

Year	10% RRR			13% RRR		
	Cells	GW	£ Billion	Cells	GW	£ Billion
2010	5	1.5	1.4	0	0	0
2025	458	137.4	119	0	0	0

Table 9.4: The economic wave energy resource based on 2010 and 2025 OXERA cost estimates, assuming an entry cost of 55 £/MWh.

9.1.1.5 2025 Economic Resource

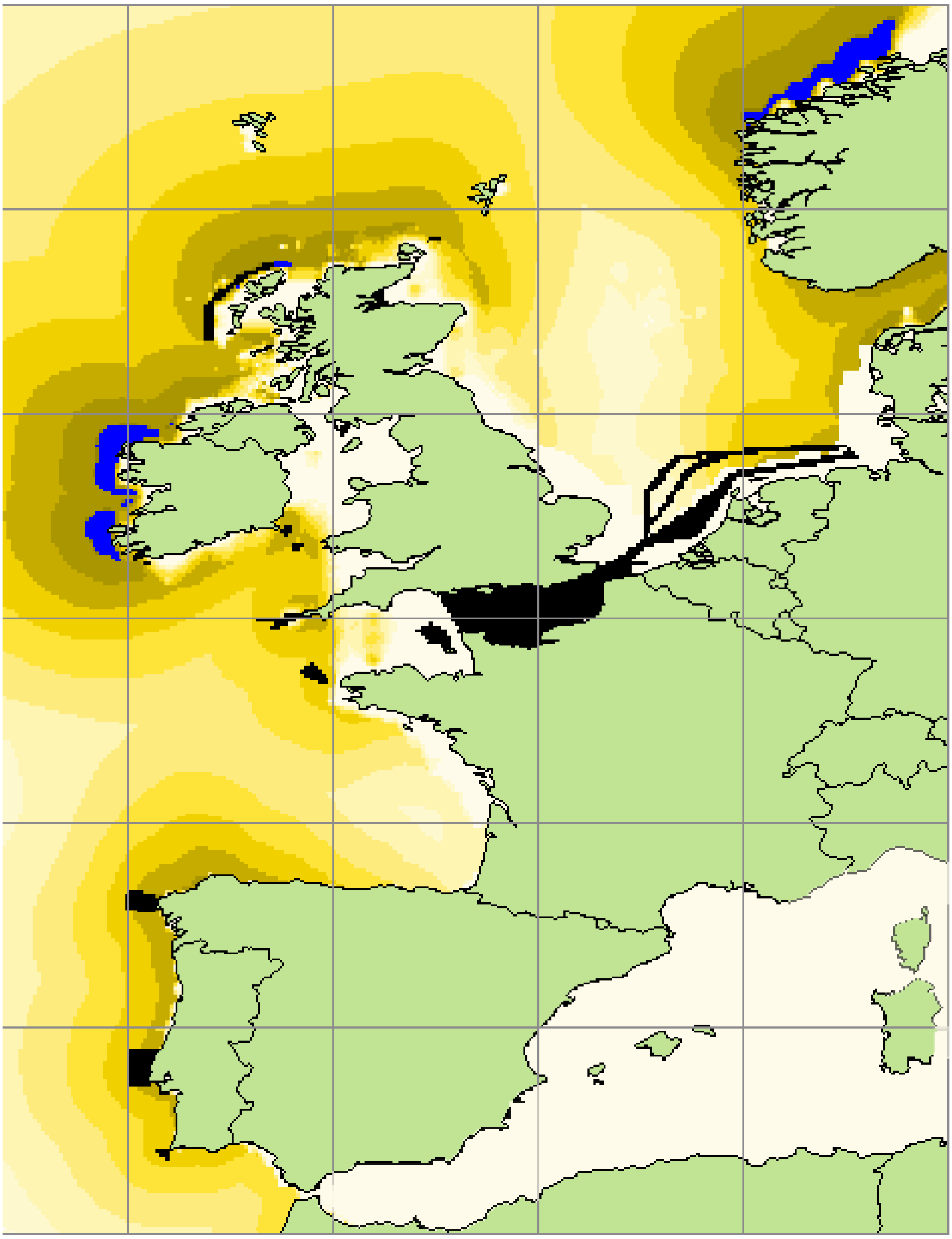


Figure 9.5: The internal rate of return GIS surface representing the economic wave energy resource based on 2025 OXERA WECS unit cost estimate of 866 £/kW, assuming an entry cost of 55 £/MWh. The commercially viable cells are coloured blue where the internal rate of return is equal to or greater than the required 10 % return.

9.1.2 OPD WECS Costs

Assuming the Internal Electricity Market scenario and the optimistic device cost of 750 £/kW for 2010, wave energy would penetrate the market at just under 45 and 50 £/MWh for the RRR of 10 % and 13 % respectively (see table 9.6 and graph 9.7). Table 9.8 shows the wave energy market for 2010 OPD cost, assuming these entry costs. At 10% RRR, an entry price of exactly 45 £/MWh would generate an economic resource of some 541 GW capacity corresponding to a capital investment of over £400 billion. The majority of this resource is located off the west coast of Ireland, the northwest region of Scotland and to the northwest of Norway as illustrated in figure 9.9. For the more realistic rate of 13 %, the entry price for wave energy is higher at approximately 50 £/MWh. This would generate an economic resource of some 65 GW corresponding to a market worth approximately £49 billion (shown in table 9.8).

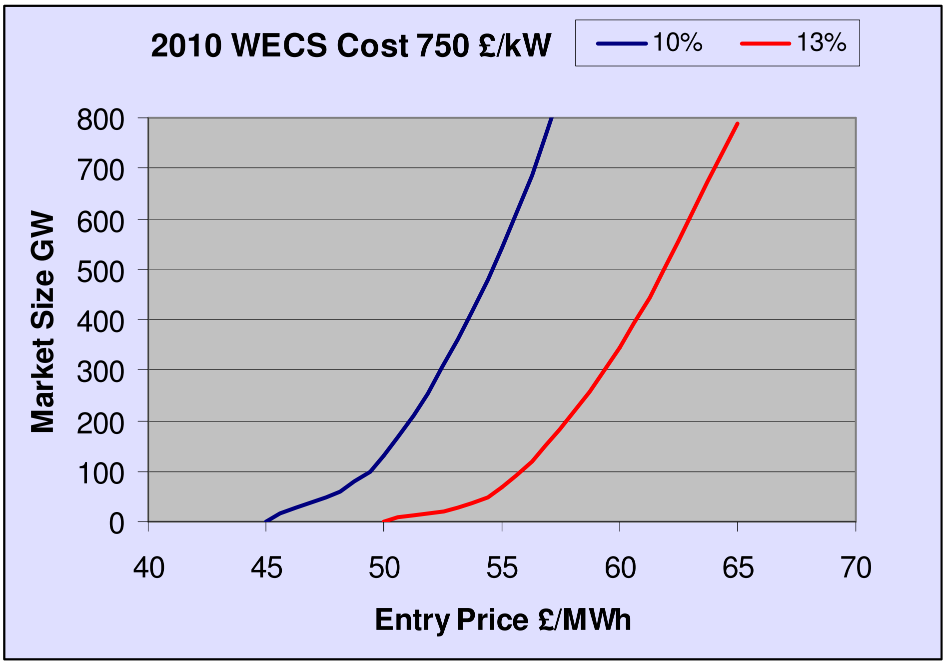
Assuming a device cost of 500 £/kW for 2025, the market entry price required for wave energy to become commercial viability is reduced to approximately 30 and 35 £/MWh for rates of return of 10 and 13 % respectively (see table 9.6 and graph 9.10). At 10 % RRR, the selected entry price of 30 £/MWh constitutes an economic resource of 135 GW – 452 cells – corresponding to a market worth approximately £68 billion (see table 9.11). For the realistic rate of 13 %, the entry price for wave energy is higher at approximately 35 £/MWh. This would generate an economic resource of 2.1 GW corresponding to a market worth approximately £1 billion as detailed in table 9.11.

9.1.2.1 Required Entry Price (£/MWh)

Year	RRR	
	10%	13%
2010	45	50
2025	30	35

Table 9.6: The entry costs (£/MWh) for wave energy projects assuming OPD WECS unit cost estimates for 2010 and 2025.

9.1.2.2 2010 Market Trend



Graph 9.7: The 2010 WECS cost is estimated at 750 £/kW. The equivalent market size is displayed against the electricity entry price.

9.1.2.3 2010 Market Size

Year	10% RRR			13% RRR		
	Cells	GW	£ Billion	Cells	GW	£ Billion
2010	1804	541.2	406	219	65.7	49

Table 9.8: The estimated wave energy market for 2010 OPD cost estimate.

9.1.2.4 2010 Economic Resource

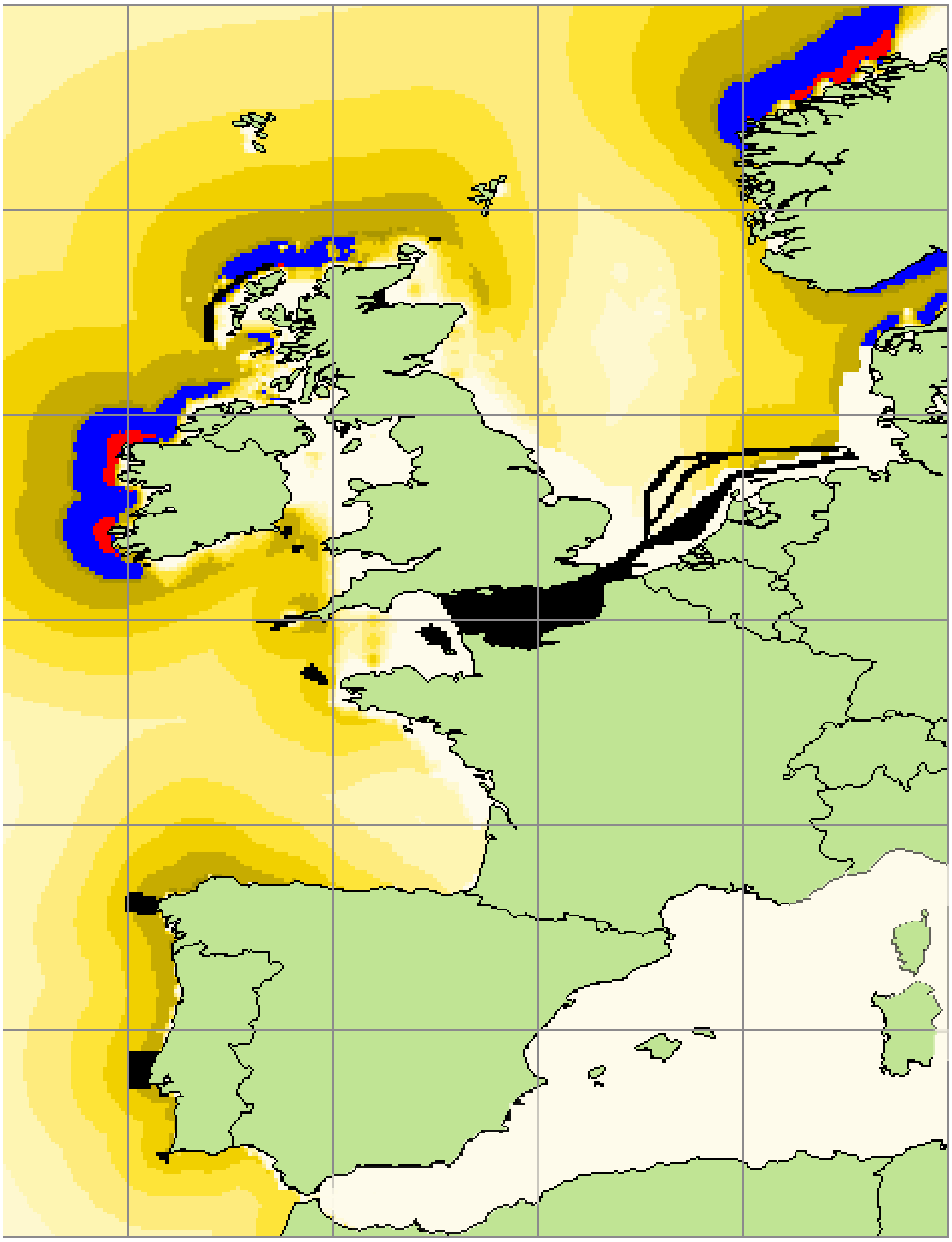
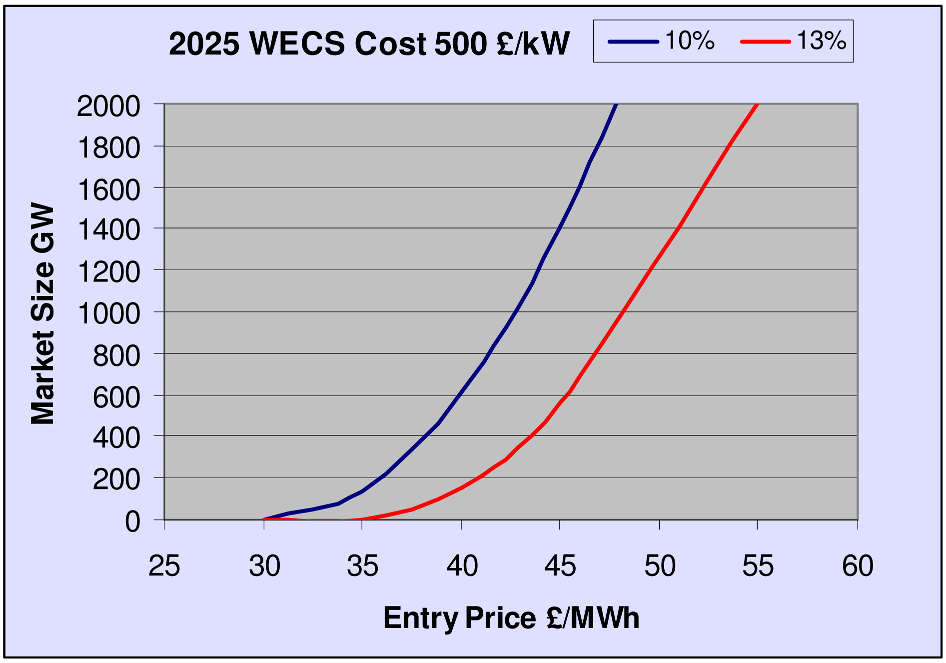


Figure 9.9: The internal rate of return GIS surface representing the estimated wave energy market for 2010 OPD WECS unit cost estimate of 750 £/kW, assuming an entry cost of 55 £/MWh. The commercially viable cells are coloured red where the internal rate of return is equal to or greater than the more realistic 13 % RRR. Both the blue and red cells indicate the equivalent market based on the optimistic return of 10 %.

9.1.2.5 2025 Market Trend



Graph 9.10: The 2010 WECS cost is estimated at 500 £/kW. The equivalent market size is displayed against the electricity entry price.

9.1.2.6 2025 Market Size

The OPD cost estimates for 2025 are very optimistic and thus would not receive a subsidy of 55 £/MWh in the European market. Therefore, an entry price of 35 £/MWh is selected for 2025 including a lower more realistic premium of approximately 10 £/MWh.

Year	10% RRR			13% RRR		
	Cells	GW	£ Billion	Cells	GW	£ Billion
2025	452	135.6	68	7	2.1	1

Table 9.11: The estimated wave energy market assuming the 2025 OPD cost estimate.

9.2 Regional Electricity Market Scenario

The Regional Electricity Market Scenario uses existing electricity prices and renewable subsidies available within the European countries presented in section 4.1. The methodology is modified to allocate each resource cell with the corresponding market price and feed-in tariff available for wave energy projects in that country. The nationality of each cell is determined using international maritime boundaries coordinates [52] input into the GIS model as illustrated in section 7.10.

Unfortunately, this scenario could not be completed because the methodology implementation is not advanced to manage technology feed-in tariffs that change according to the level of capacity installed. For example, the initial subsidy for wave project developed in Portugal is 225 €/MWh only applies to the first 50 MW installed [43]. The implemented methodology would not take this 50 MW limit into account. Subsequently, the assessment overestimates the potential market size to a large degree. However, the GIS market representation displayed in figure 9.12, gives an indication of which country offers the most lucrative market. For example, although the Portuguese energy resource is not as large as the Irish or British resource, the available subsidy of 225 €/MWh for wave energy generation makes the Portuguese market worth much more. Therefore, WECS array would be developed in Portugal until the subsidy limit of 50 MW of installed capacity is reached.

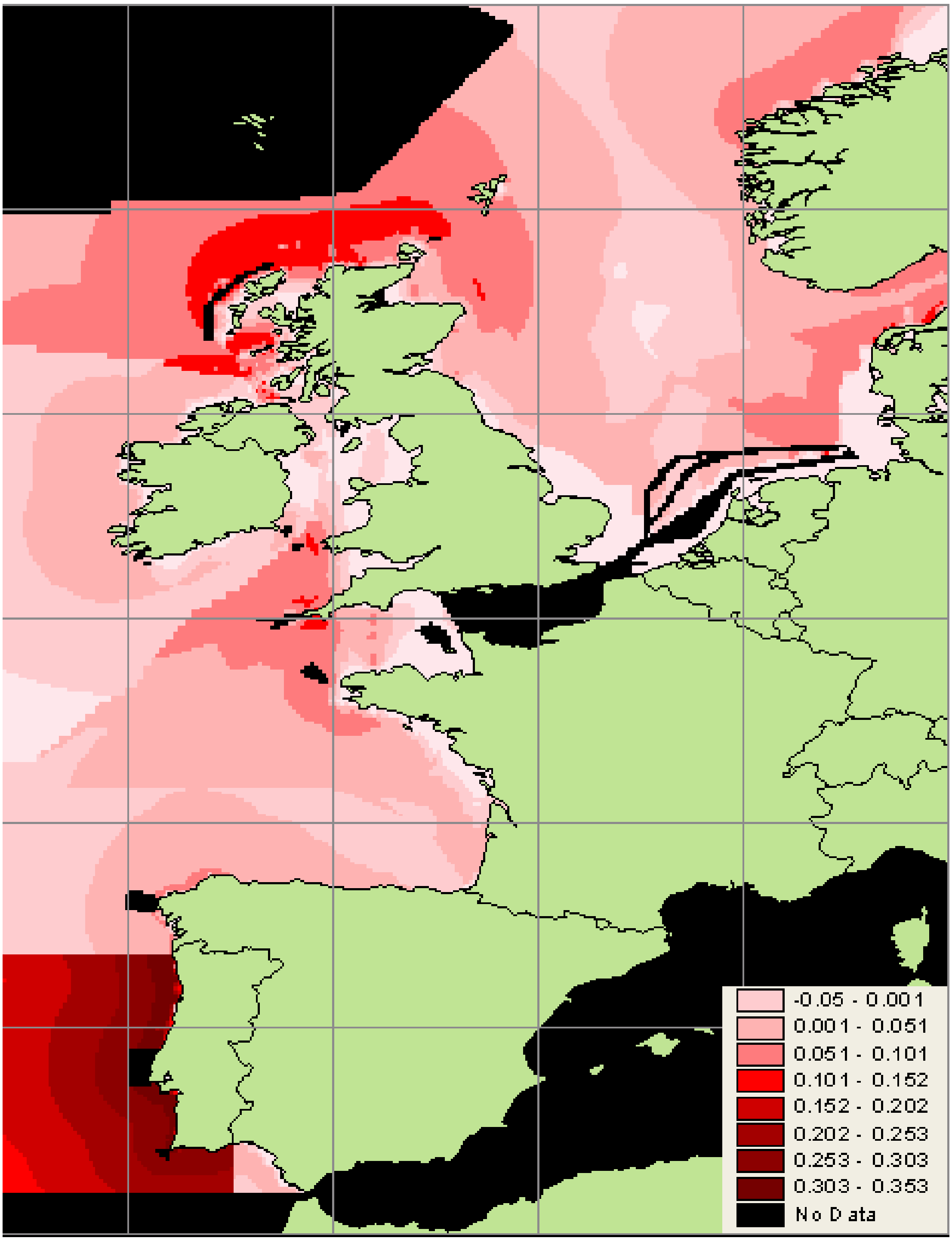


Figure 9.12: The internal rate of return GIS surface representing for the Regional Electricity Market scenario. The darker red cells located within Portuguese maritime territory indicates that a much higher rate of return is available. The IRR percentage is represented as a decimal number in the above figure.

10 Conclusions

10.1 Europe's western shores lie at the end of a long fetch of the Atlantic Ocean and are surrounded by stormy waters. The potential renewable wave energy resource that could be exploited is vast.

10.2 The economic wave resource assessment methodology design presented in this project can assess the resource for an given location of water provided wave measurements are available in the form of a wave scatter diagram, and for any device provided it has a power matrix representing conversion performance.

10.3 The methodology utilises the Internal Rate of Return economic analysis mechanism together with GIS modelling techniques.

10.4 This project implements the methodology to assess the economic wave energy resource in European waters.

10.5 The GIS model is developed to represent and analyse the geographical-based wave resource data. GIS *surfaces* provide an excellent method of visualising the resource and allows the entire wave resource model for the assessed area of sea to be interpolated from a limited set of gridded wave data.

10.6 The European wave energy resource is modelled using GIS. The resource model is interpolated from 23 wave data points obtained from the WERATLAS. This data is not ideal for assessing the European resource because the UK Met Office models underestimate swell waves which, in Western Europe, are an important contribution to the overall resource and of particular importance to wave energy conversion. The model is not accurate for intermediate depths due to the limited number of data points obtained. 50 to 100 gridded wave data points would be preferred for further European assessments. Oceanor's *Eurowaves* project would provide more precise data and thus much more accurate results; however commercial costs would apply.

10.7 The methodology divides the resource model into 100 km^2 cells. The cell size limits the accuracy of the modelled wave resource close to shore as the depth can range from 0 to as much as 500 metres. The equivalent unit of installed capacity of 300 MW (dependent on a device packing density of 3 MW/km^2) is too large. 1 km cells could provide more accurate resource estimates. However, resource models applying a higher resolution of analysis increase the complexity of the analysis which requires more computation.

10.8 The 750 kW Pelamis Wave Energy Conversion System (WECS) is selected as the baseline device for the assessment. The WECS power matrix and the wave scatter matrix provide an efficient representation that allows a device's wave energy conversion performance for a given site's wave conditions to be estimated.

10.9 The methodology estimates the potential economic wave energy resource for a given area of sea. The accuracy is dependent on the resolution of the wave energy resource model, the technology cost estimates, market entry costs and the transmission and array configuration assumptions. Using several assumed variables increases the level of uncertainty of the estimate. For this reason, a single resource estimate is not calculated; instead, estimates are generated for a range of optimistic and more realistic technology cost estimates. When the actual commercial cost of wave devices is established, a more accurate wave resource estimate could be generated using this methodology.

10.10 Due the shadowing effect, the capture efficiency of a single WECS array, and multiple arrays of devices, is dependent on array configuration and population density. Due to the long fetches required to regenerate waves, WECS should be deployed in single lines of arrays, with each array consisting of multiple rows of devices. The wave power levels available would determine the number of rows. For example, for a wave resource of power levels of 55 kW/m, with predominate direction and assuming device spacing of 200m, Pelamis WECS could be deployed in arrays of up to 10 rows before the devices located at the back are significantly affected. WECS located towards the rear of the array would receive less energy flux, thus they could be built smaller with lower power ratings to make the overall array more economical. The hexagonal layout may also neglect the effects of waves changing direction.

10.11 Dividing the wave energy resource into 100 km^2 cells for the purpose of the assessment required a deployment strategy of installing a certain capacity in each cell. A cell population density of 300 MW is selected to allow for wave regeneration and sea vessels to navigate around the arrays. However, this is unrealistic due to the additional transmission and installation expense of sites further from shore located in greater depths. In reality, much larger arrays would be developed in a single line perpendicular to predominate wave direction. Therefore, WECS arrays would not be shadowed by other "up wave" arrays and submarine cable length would be minimised. . This GIS based methodology does not take this principle into account as it does not apply an "intelligent" deployment strategy.

10.12 The assessment considered a single HVDC Submarine transmission cabled connection, rated at 440 kV, to be suitable for each 300 MW of installed capacity. This provides no redundancy.

10.13 The capital cost included in the methodology assumed that there is a *Point of Connection* (POC) to the onshore grid at the nearest shoreline and included a flat grid connection. In reality, connection costs may vary because connecting to the nearest *Grid Supply Point* (GSP) once onshore may require additional transmission lines, upgrading the existing grid infrastructure or resolving additional planning problems. The existing grid and planned upgrades would greatly affect the least cost route for the submarine cable. Therefore the shortest route to shore, utilised in this model, may not be the *Least Cost Route*. The methodology does not model the existing European transmission systems hence it is not possible to account for the cost involved with onshore transmission.

10.14 Two required rates of return for wave energy arrays are selected: 10% is considered optimistic and 13 % more realistic.

10.15 The market capacity estimated by the methodology is not limited by demand. For example, the Internal Electricity Market scenario estimated the Irish economic resource to be over 20 GW. However, this is unrealistic because it outweighs domestic electricity demand. On the other hand, the energy surplus could be exported to the UK or other European markets.

10.16 Assuming the more realistic technology cost estimates, for the Internal Electricity Market scenario, a required entry price – made up of wholesale price and subsidy – of £55/MWh for 2010 for wave energy devices to become commercially viable. Selecting an accurate subsidy is very difficult because it depends on several factors such as current market share, competitiveness compared to other generation, the level of market pull necessary to create the market size desired and the effect on the existing electricity market. The methodology can be used to help identify the required entry price.

10.17 Assuming the Internal Electricity Market scenario and the WECS cost of 964 £/kW for 2010, wave energy would penetrate the market at just under 55 £/MWh for the optimistic RRR of 10 %. An entry price of exactly 55 £/MWh would generate an economic resource of some 1.5 GW capacity – 5 cells – corresponding to a capital investment of £1.4 billion. This resource is located around the Irish west coast. For the realistic rate of 13 %, the entry price for wave energy is higher at approximately 60 £/MWh. No market would develop at the selected entry price of 55 £/MWh.

10.18 For the Internal Electricity Market scenario and the WECS cost of 866 £/kW for 2025, the market entry price required for wave energy to become commercial viability is reduced to approximately 50 and 55 £/MWh for rates of return of 10 and 13 % respectively. At 10 % RRR, the selected entry price of 55 £/MWh constitutes an economic resource of 137.4 GW – 458 cells – corresponding to a market worth approximately £120 billion. The majority of this resource is located off the west coast of Ireland, the northwest region of Scotland and to the northwest of Norway. There is no market if investors require 13 % return.

10.19 Scenario were also completed for assuming technology costs of 750 £/kW for 2010 and 500 £/kW for 2025, however the resource estimates were considered to be too optimistic.

10.20 Under the Internal Electricity Market conditions, the location of the commercially viable resource is located where the highest levels of wave energy are located. This is because of the single IEM market price assumed for each

European County. For markets to develop in other countries, a separate wave energy policy is required which provides a higher subsidy to offset the lower wave energy levels available.

10.21 To apply separate electricity prices and policy frameworks for each European country, the nationality of each cell is determined using international maritime boundaries. However, feed-in tariffs for renewable technologies decrease as the capacity increase. The methodology implementation cannot accommodate this dynamic. Also, several of the capacity limits are below the minimum capacity of 300 MW that is installed in each commercially viable cell. To solve this, the methodology must be perfected to accept technology subsidy profiles that allocate the corresponding subsidy to each level of generation capacity installed. However, this level of detail does not yet exist for wave energy within European renewable policy framework. The analysis cell size could also be reduced to identify when the different levels of capacity are installed so the correct feed-in tariff can be applied.

10.22 Under current market prices and subsidies available for wave energy projects, the Portuguese market is the most attractive to potential developers. Although the resource around Portugal is not as large as the Irish or UK resource, the available feed-in tariff of 225 €/MWh would subsidise the lower levels of energy generated. Therefore, the first WECS arrays will be developed in Portugal until the subsidy limit of 50 MW installed capacity is reached, unless other European countries propose more competitive wave energy policies.

10.23 The European resource assessment could be improved by obtaining a new data set of 50 or more, wave data grid points located in the Western European approaches of the Northern Atlantic Ocean and North Sea where wave power levels are most significant. The cell size could be reduced to 1 km^2 to allow the resource to be more accurately modelled and enable more sophisticated regional policy mechanisms, which react to the rate of market growth, to be applied. European Transmission Networks and grid supply points could be integrated into the model to allow the least cost route for the submarine grid connection to be determined. Hence, the capital cost estimated for each wave array would be more realistic.

11 Acknowledgements

The project was supervised by Dr Gary Connor of the Scottish Energy and Environment Foundation, and Dr Andrew Grant from the Energy Systems Research Unit, University of Strathclyde, who both provided superb input and guidance.

The author is very grateful for the helpful support from Nicola Owen and Chris McKenzie of the Special Needs department, the Interlibrary-loan library staff, Professor Gorman of the Mechanical Engineering department and Janet Harbidge, all whom are from the University of Strathclyde.

The project received key input from Claire Herdman of EConnect Ltd, Mike Collee of Ocean Power Delivery Ltd, Sarah Frowde of the United Kingdom Hydrographical Office, Polly Hadziabdic of the British Oceanographic Data Centre, Stephen Barstow of Oceanor, Robert Currie from the Institute of Energy and the Environment, University of Strathclyde and Francis Akwensive.

The author dedicates this work to Pete McNeil and Maisie Grant and thanks them dearly for their friendship and inspiration.

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13 Glossary of Abbreviations

ATBA	Areas To Be Avoided
AWS	Archimedes Wave Swing
BODC	British Oceanographic Data Centre
EMEC	European Marine Energy Centre
EREF	European Renewable Energy Foundation
EWER	European Wave Energy Resource
GIS	Geographical Information System
GSP	Grid Supply Point
HVDC	High Voltage Direct Current
IEM	Internal European Market
IRR	Internal Rate of Return
kV	Kilovolt
kW	Kilowatt
MW	Megawatt
MWh	Megawatt hours
OPD	Ocean Power Delivery Ltd
OXERA	Oxford Economic Research Associates
OWC	Oscillating Water Column
POC	Point Of Connection
RRR	Required Rate of Return
REM	Regional Electricity Market
TW	Terawatt
UKHO	United Kingdom Hydrographical Office
UKMO	United Kingdom Met Office
WECS	Wave Energy Conversion System
WERATLAS	Wave Energy Resource Atlas

14 Appendix

The following data files collected and created during the project are included on the project CD-ROM which can be requested from the author by email at robin.murray@aeat.co.uk:

14.1 ATBA Coordinates (Microsoft Excel)

14.2 EWER Economic Analysis (Microsoft Excel)

14.3 EWER Economic Assessment Methodology Figures (Adobe Illustrator)

14.4 EWER Energy Analysis (Microsoft Excel)

14.5 EWER GIS Model (ARC View GIS 3.2)

14.6 EWER Sensitivity Analysis (Microsoft Excel)

14.7 Depth Coordinates (Microsoft Excel)

14.8 Coordinates defining European Maritime Boundaries (Microsoft Excel)

14.9 Scenario Results – IRR (Microsoft Excel)