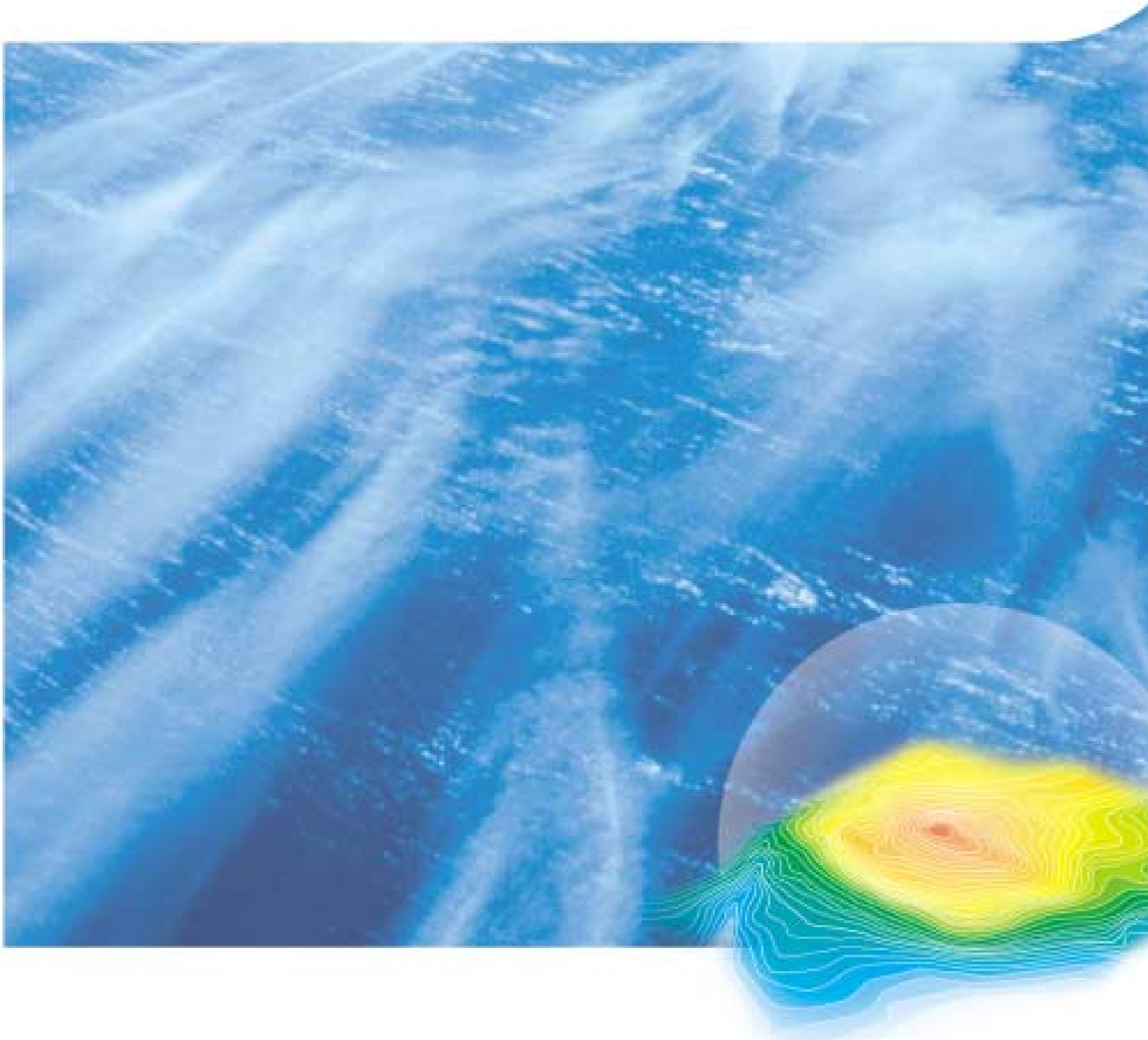
SUSTAINABLE
ENERGY
IRELAND



Tidal & Current Energy Resources in Ireland

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EXECUTIVE SUMMARY

Introduction

The European Union, the Republic of Ireland and the Northern Ireland Governments have each produced policies in respect of electricity generation which are intended to promote an increase in the amount of electricity being generated from renewable energy sources.

The European Union and its member states have set targets for electricity generation from renewable energy sources and the purpose of this study has been to investigate the tidal and marine current energy resource in Irish waters.

For the purpose of this study, Ireland and Irish waters are geographical terms relating to the island of Ireland.

Study Objectives

- To identify areas which have the potential for cost effective exploitation of the tidal stream and marine current energy resource.
- To prepare detailed analyses of areas considered to have the greatest potential for the extraction of tidal energy.
- To calculate the tidal and marine current energy resource available with existing technology and to assess the additional contribution which future technology is expected to make.
- To compare current evaluation of the energy resource with previous estimates.
- To evaluate deep water areas (exceeding 40m) which have high current velocities for the purpose of developing second-generation deep water devices.
- To extend the methodology for estimating the renewable energy resource in Ireland to provide a medium term development potential (or estimated contribution) for the years 2010 and 2020, including the anticipated resource/cost curve per unit of energy produced.

Methodology

For the calculation of tidal and marine current energy resource the generic renewable energy resource ranking system as used in previous studies has been adopted to provide consistency with these studies. The resource categories and the corresponding values are set out in the following table.

Resource category	Definition of resource category (Abbreviated)	Resource Total (TWh/yr)	% Electrical Consumption (2010)
Theoretical	Gross energy content between 10m depth contour and 12 nautical mile territorial limit	230	500
Technical	Theoretical resource limited by existing turbine support structure technology and to minimum current of 2.0m/sec	10.46	25
Practical	Technical resource limited by wave exposure, sea bed conditions, shipping lanes, military zones and disposal sites	2.63	6.27
Accessible	Practical resource limited by environmental constraints specific to each site. Constraint indeterminate at report stage	2.63	6.27
Viable	Accessible resource limited by commercial constraints including development costs and market reward	0.92	2.18

Energy Resource Categories

The predicted electricity demand for the Republic of Ireland and Northern Ireland in the year 2010 currently stands at 42 TWh/year.

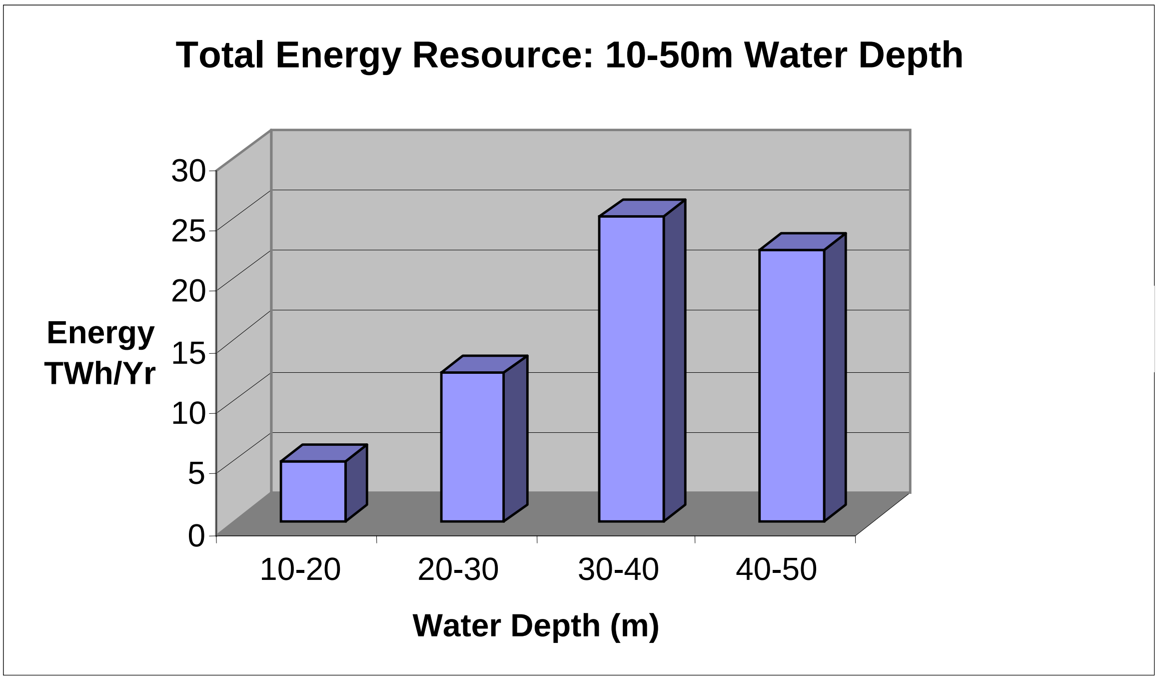
Theoretical Resource

The gross energy content of tidal and marine currents in the zone between the 10m depth contour and the 12 nautical mile territorial limit is referred to as the Theoretical Resource.

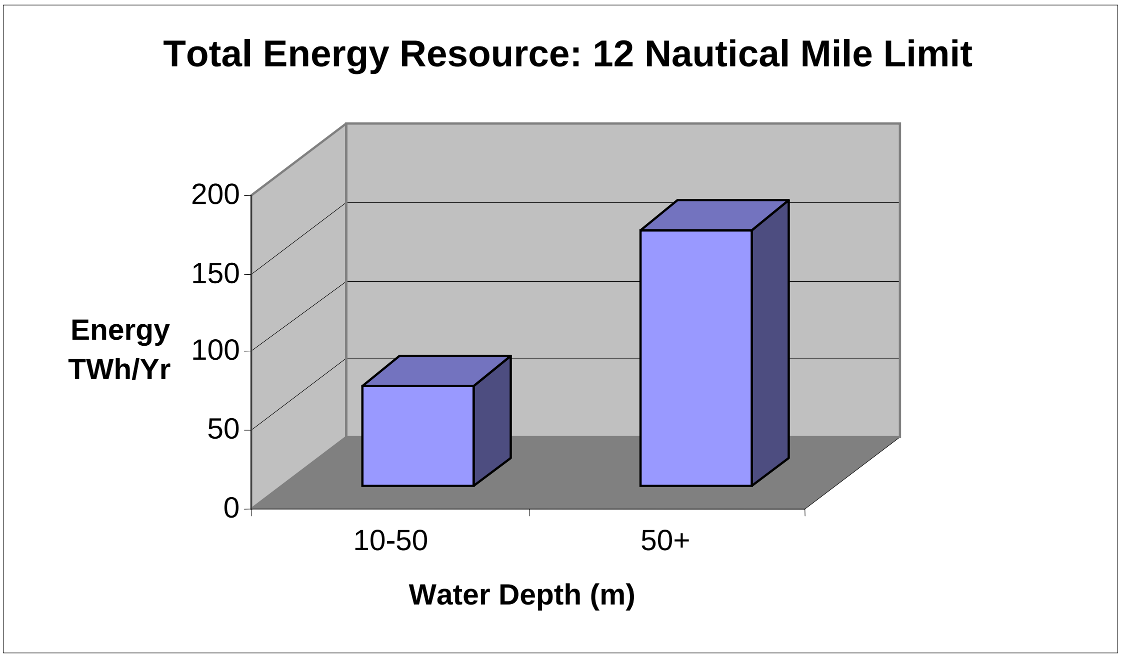
The theoretical tidal energy resource has been determined using computational modelling of current flows around Ireland. The accuracy of the models has been verified using current meter data taken at four locations around the coastline.

The theoretical resource has been calculated from the formula, $P_{(mean)} = 1/2\,\rho\,K_s\,K_n\,V^3_{(peak)}$ to be 230 TWh/year which represents over 5 times the predicted electricity consumption in Ireland for the year 2010. However, technological limitations, physical, environmental and commercial constraints make it impracticable to extract all of this energy.

When the technological limitations are applied to the Theoretical Resource, the resultant resource is referred to as the Technical Resource.



Total Energy Resource 10-50m Water Depth



Total Energy Resource: 12 Nautical Mile Limit

Technical Resource

The technical resource was calculated in a similar way to the theoretical resource, but only areas where the peak tidal velocities are greater than 1.5m/s have been included. Based on existing technology the device efficiency has been limited to 39% and the resource has been calculated between the 10m water depth contour and the 12 nautical mile territorial limit.

Tidal energy technology is in the early stages of development with various generating systems currently being researched. Fourteen variations of the four basic turbine configurations have been reviewed and their generating efficiency has been assessed. Supporting structures for the generating devices and the electrical power transmission system for shore connection have also been reviewed.

Although currently limited by support structure technology to a depth of 40m, turbines in the “horizontal axis rotational group” were found to be the most advanced. With existing technology, turbines become uneconomic with tidal currents below 2.0m/sec but with further development economic generation at lower velocities should be practicable. It is anticipated that these constraints will be overcome with future research.

Research indicates that existing electrical and subsea cabling technology as used in offshore wind power development is sufficiently advanced and should be directly applicable to tidal current farms without major modification.

Assuming that present technical restraints, such as water depth, can be overcome the Technical Resource has been calculated to be 10.46 TWh/year which represents approximately 25% of the predicted electrical consumption for the year 2010. This Technical Resource is however constrained by practical, physical and other interference. The resultant resource is referred to as the Practical Resource.

Practical Resource

The practical resource was determined by limiting the Technical Resource by the following constraints: water depth between 10m and 40m, peak tidal velocity greater than 1.5m/s, outside shipping lanes, military zones, disposal sites and outside areas containing pipelines and cables.

Detailed modelling of seven sites chosen for further study was carried out to determine the practical resource. For this purpose the type and number of turbines were chosen for each site after examination of water depth and physical constraints. The practical resource was then calculated in a similar way to the theoretical resource and this amounted to 2.633 TWh/year. This represents 6.27% of the predicted electrical consumption for the year 2010.

The Practical Resource is however restricted by man-made, institutional and regulatory constraints giving a further reduction in the resource and this is referred to as the Accessible Resource.

Accessible Resource

The constraints which have lead to the Accessible Resource are mainly environmental in nature. The research included a desk study carried out with statutory bodies to determine the possible environmental issues which could arise from the development of tidal power.

Benthic ecology, fishing grounds, marine mammals, visual impact and affect on recreational use of coastal waters were found to be the primary issues.

The environmental constraints will be specific to each site and a generic reduction in the resource has not been estimated as a full environmental impact assessment will be required for each individual site.

For the purpose of this study, the accessible and practical resource are therefore the same at 2.633 TWh/year.

The final constraints on the Theoretical Resource which have been investigated are those concerning commercial viability. These and previous constraints have lead ultimately to the Viable Resource.

Viable Resource

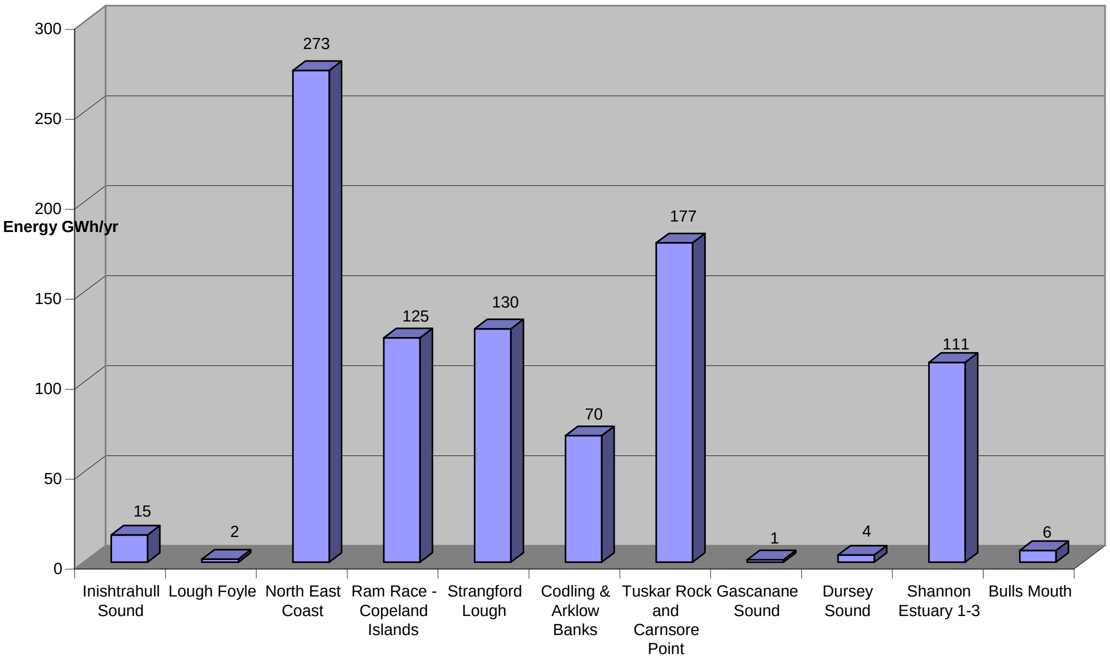
The viable resource was determined by limiting the Technical Resource by the following constraints: water depth between 10m and 40m, mean maximum spring tide current exceeding 2.5m/s and turbine rotor size of 7m less than average water depth.

The commercial constraints include development costs, scale, resource distribution, market reward, timing and other risk which will be variable over time. The techno-economic model developed by Marine Current Turbines Ltd was used to determine the viable tidal energy resource and provide costings for particular sites.

The model was validated against known industrial costs including cost functions for a range of bought-in components. Lifecycle costs based on a discounted cash flow analysis using a discount rate of 8% over 20 years was calculated by the model.

Levellised costs varied widely around the coast from 4.5 cent/kwh to 19.6 cent/kwh.

The viable tidal energy resource was calculated to be 0.915 TWh/yr which represents 2.18% of the predicted electricity consumption for the year 2010. It was concluded that the technology is nearing a level of maturity which will accommodate this level of energy extraction by around 2010.



Viable Energy Resource

Status of Technology

There are many similarities between wind and tidal current generating systems both in terms of devices and the nature of the driving force. Compared to wind technology, tidal systems are in their infancy and there have been only a small number of prototype scale demonstrations of plant with an installed capacity of over 100kW. It is expected to take several years before items of equipment are produced for purchase and installation.

Three of the most significant technology demonstrations have taken place during the past two years and two of these are ongoing. None of the demonstration units is a pre-production prototype and all research teams plan to build and test larger systems before going into production. Tidal current generators are not yet developed at the size necessary for large scale exploitation of the resource. Companies with small scale demonstration prototypes are expected to develop these to sufficient size to generate from the resource by 2010.

First generation devices will be limited to water depths between 10m and 50m. Second generation devices should appear after a period of approximately ten years and should be capable of operating in depths exceeding 50m.

Typical Site Installation and Turbine Spacing

At present research is still required on the spacing of tidal energy devices. Although it is considered best to place devices in a close spaced linear array across the flow as a 'tidal fence'. It is not always possible to extract the tidal stream resource in a single close spaced 'tidal fence' and successive lines of units may have to be considered. However, there is no published data from model experiments to verify predictions and prototype arrays have yet to be built.

Although there are significant differences, wind energy is the closest existing technology to that of tidal energy and here tower spacing of five rotor diameters is often used. With tidal streams it is appropriate to consider blockage factor in a line perpendicular to the main flow direction and device spacing in the direction of the flow. Prior to detailed scientific work being undertaken it is proposed that a blockage coefficient of between 10% and 15% be used with an upstream/downstream spacing of 10-20 diameters. Closer longitudinal spacing may be possible if the location of units is staggered on successive lines.

There are a variety of installation systems including gravity, piled and moored. The most suitable system will be dependent on sea bed conditions and degree of exposure at the site.

Schematic

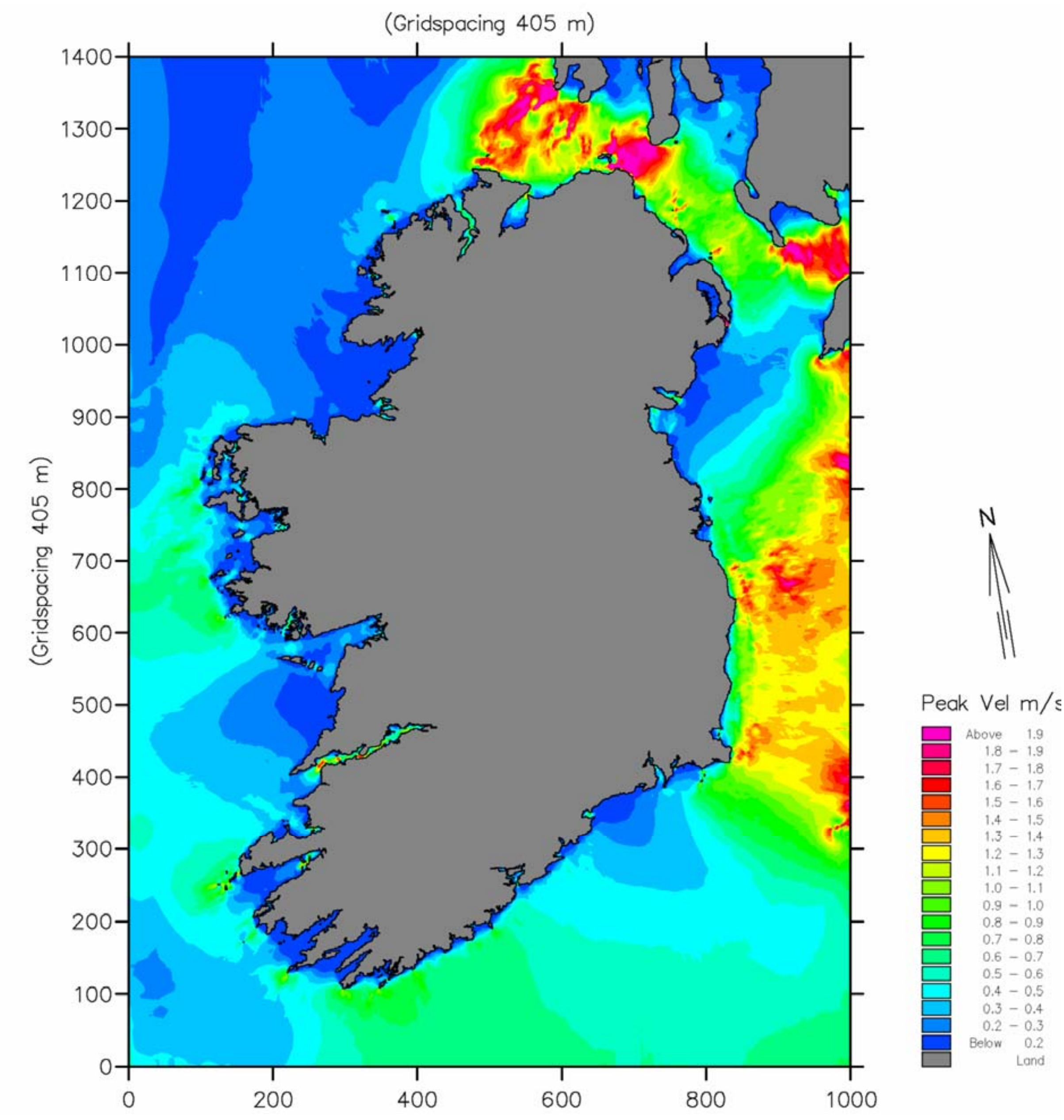
Operational mode

Rotor raised for servicing

Schematic of Seaflow Project

Tidal Pattern

The tidal currents are generally low along the west and south coasts, are relatively strong in the St George's and North Channels and are moderate along much of the east coast. The current strengths are considerably influenced by the local bathymetry. One part of the flood travels up the west coast and around the north of Ireland, whilst the other part floods north up the Irish Sea. The tidal streams meet in the area of St John's Point. A consequence of the way the tides flow around Ireland is that there is a phase difference in the times of high and low water along different parts of the coast.



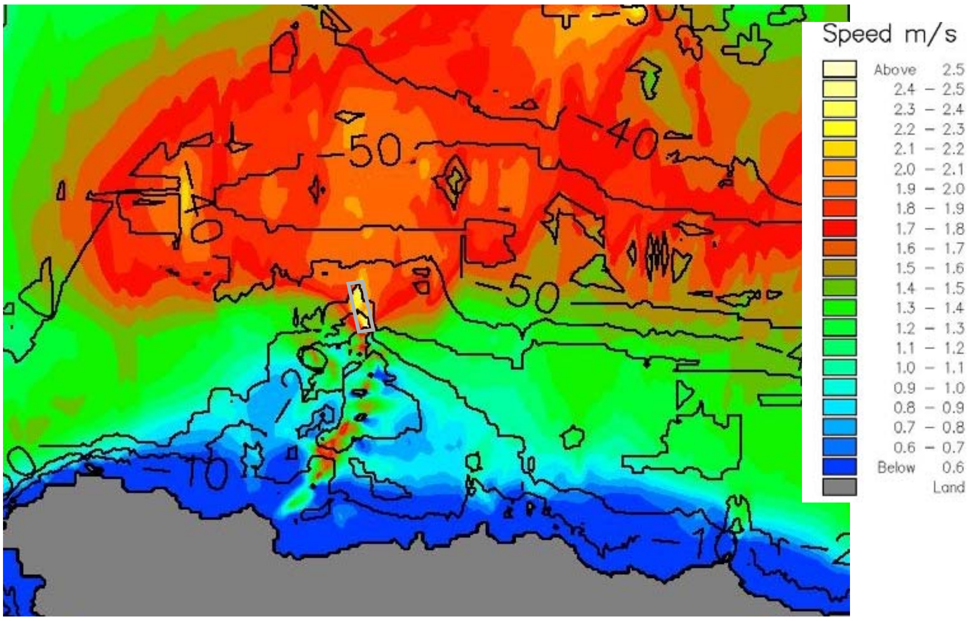
Depth Averaged Peak Spring Tidal Currents

Measurements and Modelling

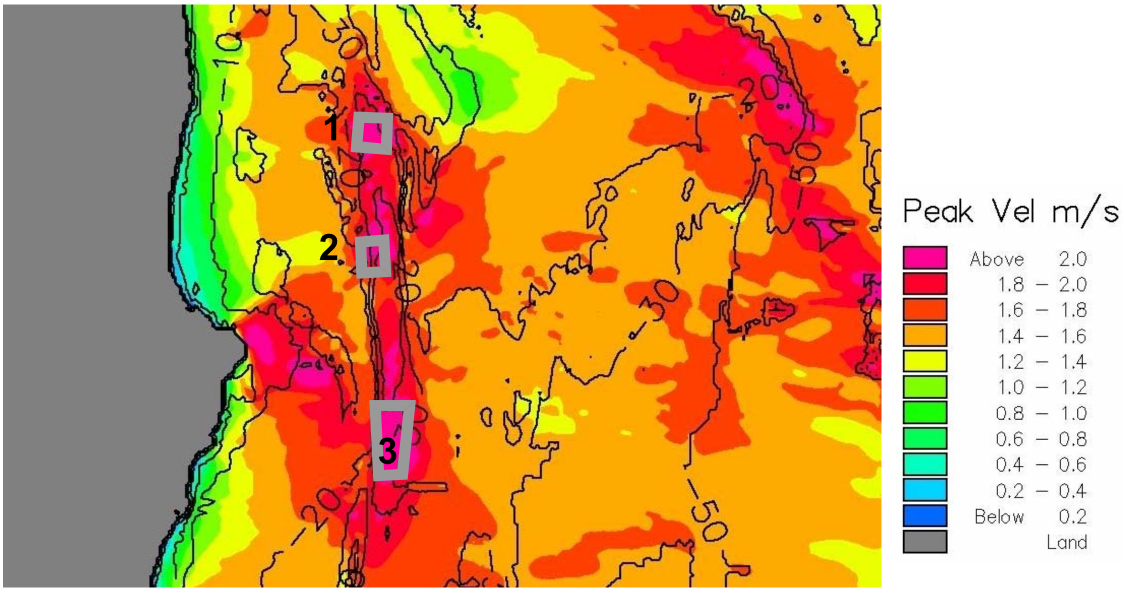
RPS Kirk McClure Morton have modelled the tidal energy resource around Ireland using the 2-D depth integrated flow model. The main tidal model covering the whole of the Irish Coast has a grid spacing of 405m. This model is driven by boundaries derived from a larger 1215m grid model that covers an area from south of Ireland to the north of Scotland and extends westward to the edge of the continental shelf. Nested within the main 405m grid Irish coast model are various detailed 135m and 45m grid sub-models covering sections of the coast, sea loughs and estuaries. These detailed tidal models have been used to simulate the tidal flows in areas that have potential for the development of tidal stream energy such as around the east coast banks, the Tuskar Rock, the Shannon Estuary and Inishstrahull Sound.

Generally the detailed computational models were verified using tidal height and current meter data previously recorded in the specific area of interest. As part of this project ADCP (Acoustic Doppler Current Profilers) devices were installed at two locations on the west coast of Ireland, one in the Shannon Estuary and one at the Bull's Mouth, both for a period of one month. Good correlation between the ADCP results and the depth averaged tidal models, was achieved.

The following are examples of turbine array locations where detailed modelling was carried out in order to determine the practicable, accessible and viable resource.



Inishtrahull Sound



Codling and Arklow Banks

Conclusions

- A significant proportion of the tidal and marine current energy resource is to be found on the east coast of Ireland. The resource on the west coast is concentrated in the Shannon Estuary.

- Tidal energy technology is in the early stages of development and stream velocities of at least 2.0m/sec are required for efficient generation. With further technological development, efficient generation from stream velocities of 1.5m/sec should be practicable by the year 2015.

- When technical, physical, institutional and commercial viability constraints are applied the resultant energy resource, referred to as the Viable Resource, reduces to approximately 0.915 TWh/year and this represents 2.18% of the predicted electricity consumption for the year 2010. This figure could rise to 6.27% of the predicted electricity consumption between 2010 and 2015.

- Environmental constraints, specific to each site, may also apply and in such cases exploitation of the viable resource may be affected.

- Many devices are in their infancy as development remains at an early stage. Largely due to commercial confidentiality, detailed information on test results is not widely available.

- A re-assessment of generating viability after a period when further test data should be available is recommended.

1.0 INTRODUCTION

The increase in global demand for electricity, especially in the densely populated countries, is expected to continue. In recognition of the pollution associated with generation from fossil fuels many countries have pledged their commitment to reduce greenhouse gas emissions. Renewable sources of energy, including tidal stream energy, will play an important role in reducing these emissions. The EU and its member states are currently setting targets for renewable energy generation.

Generally, the velocity of the mass movements of seawater caused by the rise and fall of the tides is in most places too low to provide a viable energy resource. However, in certain places a combination of the seabed bathymetry and the shape of coastline is such that tidal flows are concentrated and attain velocities that could provide cost-effective power generation. In many cases these velocities are sufficient to generate an unusually intense renewable energy resource, often with ten times or more energy concentration than that which would be available at a highly rated wind energy site. Moreover, a major advantage to be gained from utilisation of this resource is that the energy availability is not dependent on random weather variations, but has the accurate predictability of tidal movement.

The primary objectives of the study are as follows:-

(i) To determine the theoretical tidal marine current energy resource in Irish waters and to calculate the theoretical power available from this resource. This will be referred to as the "Theoretical Resource".

(ii) To identify and investigate sites which have the potential for efficient resource using existing and anticipated generating technology. This will be referred to as the "Technical Resource".

(iii) To identify and investigate sites which , after taking physical constraints into account, have the greatest potential for exploitation. This will be referred to as the "Practical Resource".

(iv) To identify and investigate sites which, after taking environmental and legislative constraints into account, have the greatest potential for exploitation. This will be referred to as the "Accessible Resource".

(v) To identify and investigate sites which, after taking commercial viability constraints into account, have the greatest potential for exploitation. This will be referred to as the "Viable Resource".

In pursuit of the primary objectives the following matters have also been investigated:-

(vi) To deploy new current meter installations for model verification. Initially two specific locations will be selected for detailed monitoring to establish flow characteristics for enhanced current regimes.

(vii) To evaluate deep water areas (exceeding 40m) which have high current velocities for the purpose of developing second-generation deep water devices.

(viii) To investigate the use of horizontal axis, vertical axis and oscillating flap devices which have been developed by Marine Current Turbines, Engineering Business, Gorlov Turbine, and Blue Energy Systems and use these as the basis for the evaluation of the “Technical Resource”.

(ix) To address the impact of non-uniform current flow and other relevant issues in Irish waters, for example, blockage, wave interaction, depth profile and race stability.

(x) To extend the methodology for estimating the renewable energy resource in Ireland to provide a medium term development potential (or estimated contribution) for the years 2010 and 2020, including the anticipated resource/cost curve per unit of energy produced.

(xi) To convert production costs per unit of energy from the resource analysis to ‘selling price’ allowing for project financing and an adequate return to the developer.

(xii) To compare latest technology and assessment of the energy resource with those obtained from previous evaluations.

1.1 Strategic Targets

A total of 38 industrialised countries were committed to the ‘Kyoto Protocol’ in December 1997. These countries agreed to reduce their emissions of greenhouse gases to levels that are 5.2% below 1990 levels, between the period 2008 and 2012.

In 2001 the European Parliament and Council adopted a directive requiring member states to adopt national targets for renewables that are consistent with reaching the Commissions’ overall target of 12% electricity generation from renewables by 2010. The indicative target for the Republic of Ireland is 13.2%.

The ESBI-SEI report ‘Updating the Renewable Energy Resource In Ireland (2004)’ concluded that it should be possible to meet CO_2 emission targets set for 2010 however the 2020 situation will be much more difficult unless measures are put in place to facilitate the entry of an increased element of intermittent power to the system.

1.2 Electricity Consumption

The electricity market is driven by the integrated demand for electricity. Based on demographic and other studies carried out by Economic and Social Research Institute (ESRI), load demand growth curves have been projected forward to 2020. Electricity demand projections, **Figure 1.1**, have been developed by ESBI[1] for the Republic of Ireland on the basis of ESRI's economic forecasts and the historic relationship between electricity demand and economic activity. The methodology used has been developed and refined over a fifteen year period and has proved to be consistently reliable over that period.

Figure 1.2 shows that electricity sales for the Republic of Ireland are projected to increase almost linearly from 2003 to 2020, with overall sales projected to increase at an average annual growth rate of 3%.

The maximum electricity demand and annual electricity consumption for Northern Ireland are given in **Figure 1.3**. Electricity consumption for Northern Ireland is set to grow at a rate of 1.5%-2.0% per annum.

The total electricity demand for the island of Ireland is estimated to be 42TWh in 2010. This increase in demand will require an increase in generation capacity which may be provided in part by renewable energy resources including tidal current energy.

1.3 Report Format

The format of this report has been based on the ESBI Generic Renewable Energy Resource Ranking Diagram, **Figure 1.4**, which identifies the resource under the following headings;

Theoretical Resource
The gross energy content of tidal stream energy existing within a given space.

Technical Resource
The technical resource is the theoretical resource constrained by the efficiency of currently available technology to extract renewable energy from the resource.

Practical Resource
The practical resource is the technical resource constrained by practical, physical or other incompatibilities.

Accessible Resource
The accessible resource is the practical resource constrained by institutional/regulatory matters that limit energy extraction e.g. environmental, energy policy, planning zonation etc.

Viable Resource
The viable resource is the accessible resource constrained by commercial viability at a particular time in the managed or supported market in terms of development cost, scale, resource distribution , market reward level, timing or other risk.

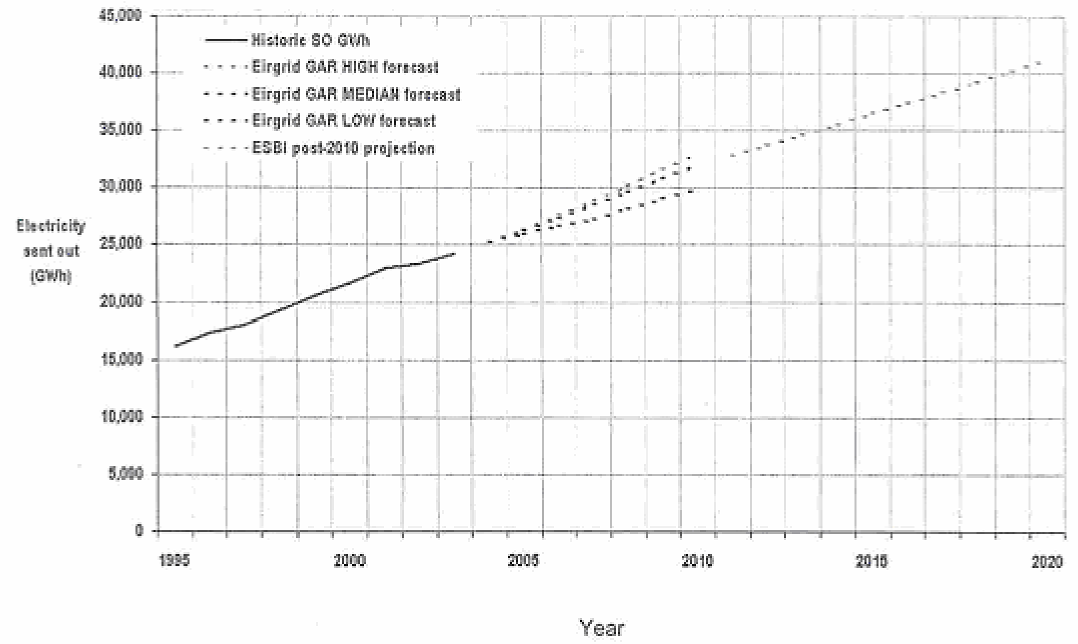


Figure 1.1 Historic and projected electricity demand for the Republic of Ireland

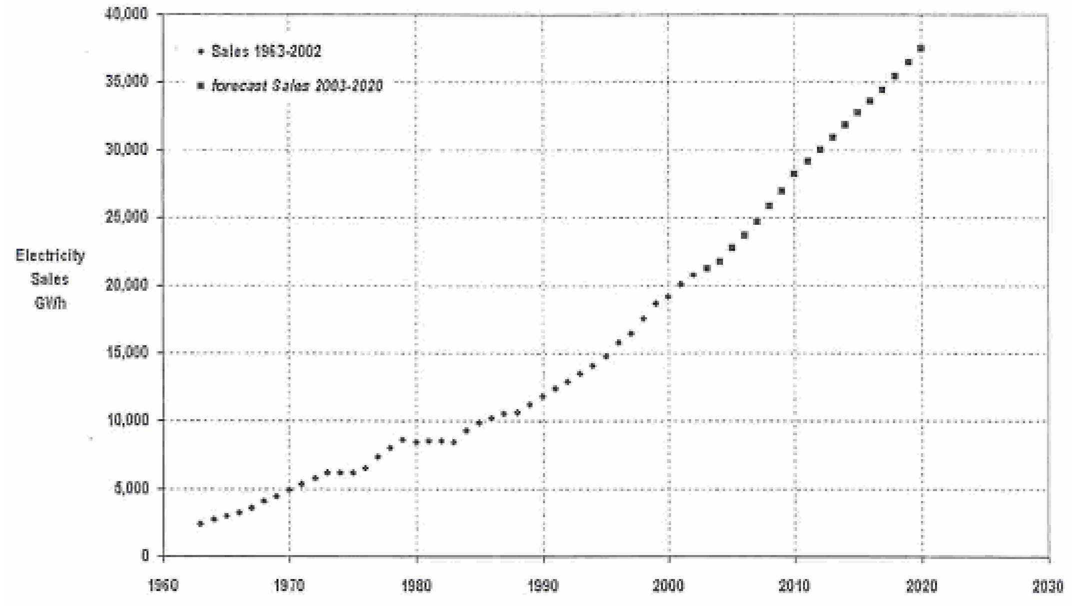


Figure 1.2 Historic and projected electricity sales for the Republic of Ireland

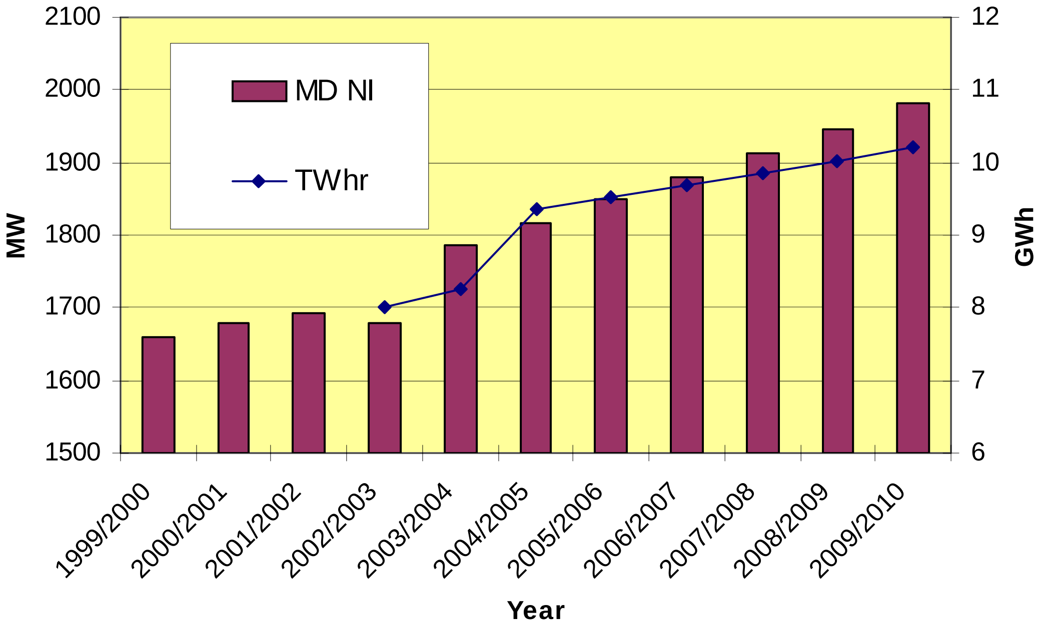


Figure 1.3 Maximum Demand (MD) and Annual Electricity Consumption NI

(MD from 'Seven Year Transmission Statement' NIE)

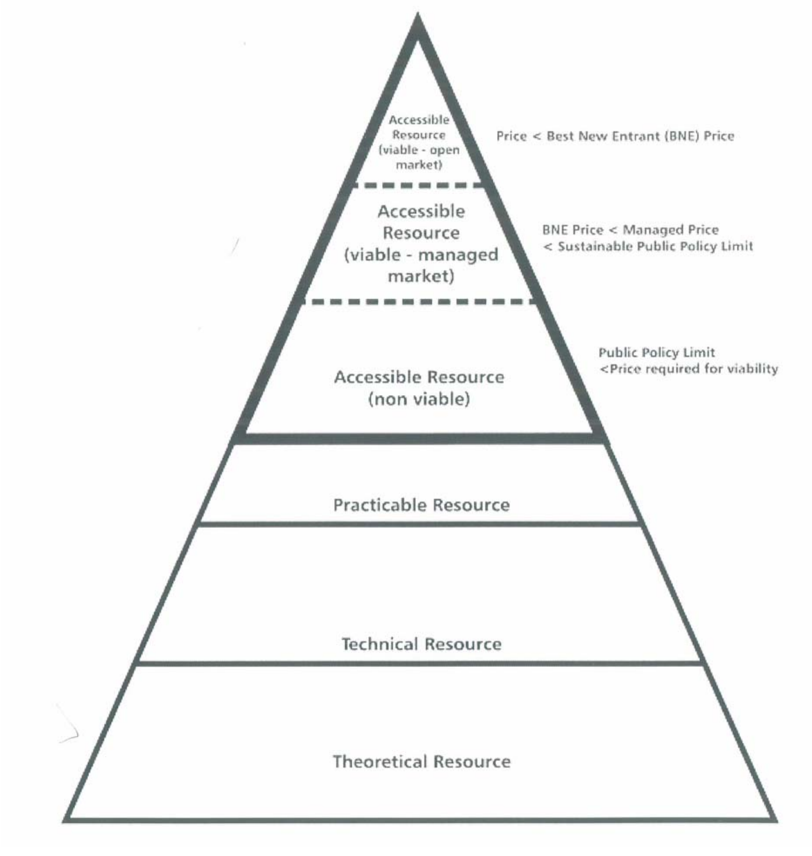


Figure 1.4 ESBI Generic Renewable Energy Resource Ranking Diagram

2.0 THEORETICAL RESOURCE

The “theoretical resource” is the gross energy content of tidal and marine currents within the 12 mile zone around Ireland.

In this chapter the total theoretical energy resource for Ireland has been calculated and a detailed description of the computational models, model verification and methodology used to determine these figures is given.

The main sources of tidal stream data which were used to identify sites around the coast of Ireland with high tidal stream velocities are discussed.

2.1 Tidal Regime

Tidal currents exist due to the movement of water resulting from the rotation of the Earth, relative to the bulges in the water surfaces of the oceans and seas caused by the gravitational attraction of the Moon and the Sun. The tidal waves produced have an amplitude of approximately 1m in mid-ocean and this is augmented by the sea bed topography and the shape of the coastlines of the land masses.

The two mechanisms which cause amplification are funnelling and resonant coupling to natural frequencies of water movement in coastal areas. In most parts of the world there is a diurnal ebb and flow cycle with a period of about 12.4 hours superimposed on a fortnightly variation of tidal range, with spring tides being maximum and neap tides minimum. This results from the variation in gravitational attraction due to the relative positions of the Sun and Moon.

Figure 2.1 illustrates the tide flow round Ireland having two distinct parts. One part of the flood travels up the west coast and around the north of Ireland, whilst the other part floods north up the Irish Sea. The tidal streams meet in the area of St John’s Point.

There are two points at which there is no variability in depth due to tidal activity (amphidromic points) in the tidal flow around Ireland. One is off the north coast near the Mull of Kintyre, and the second, a degredated point, is on the land near Courtown, Co. Wexford. Thus, the tidal range at spring tide around the Irish Coast varies between about 0.6 metres at Courtown and 4.5 metres at Galway. The typical range along the coastline is approximately 3 metres.

The depth averaged peak spring tidal currents are shown in **Figure 2.2**.

A consequence of the way the tides flow around Ireland is that there is a phase difference in the times of high and low water along different parts of the coast, as shown in **Figure 2.3**.

The tidal currents are generally low along the west and south coasts, are relatively strong in the St George's and North Channels and are moderate along much of the east coast. The current strengths are considerably influenced by the local bathymetry as set out in more detail in Section 2.4 below.

2.2 Sources of Tidal Stream Data

Information regarding the tidal stream velocities around Ireland is available from a number of sources including:-

- UK Admiralty Charts
    - Tidal Diamonds
    - Flood and ebb arrows.

- UK Admiralty Tidal Stream Atlases
    - NP 218 covering the north and north east coasts
    - NP216 covering the east and south east coasts
    - No tidal atlases available for south and west coasts

- Irish Coast Pilot

- Irish Cruising Sailing Directions
    - East and North Coast
    - South and West Coast

- Direct Current Meter Readings
    - British Oceanographic Data Centre
    - Marine Institute Databases
    - Department of Communications, Marine and Natural Resources
    - Local Authorities or other Institutions
    - Universities

The UK Admiralty Charts and Tidal Atlases give a good overall view of the tidal streams but they are mainly based on historical surface current measurements and whilst there is good coverage for the Irish Sea, the North Channel and St George's Channel, very little data is available for the south west and west coast of Ireland.

The Irish Coast Pilot, the Sailing Directions and other publications give useful information, particularly about local tidal streams around headlands, banks and channels, though this information tends to be qualitative rather than quantitative.

Current meter reading data is available from the sources noted above. While there are a reasonable number of readings in the Irish Sea and on parts of the north and south coasts, information for the west coast is very sparse. While current meter readings provide very useful information, the data tends to be very site-specific.

2.3 Computational Models

Computational models provide a useful tool for assessing the current flows around Ireland. Models that simulate the tidal flows over large areas such as the whole of the Irish Coast are typically 2 dimensional depth averaged models, *i.e.* they assume a uniform flow across the whole depth of the water column and are applicable to sea areas where the water column is well mixed and where density currents are not a significant feature of the hydraulic regime. Two-dimensional depth integrated tidal models are generally based on shallow water wave equations and therefore are really only applicable to continental shelf areas.

The models require hydraulic information at the boundaries of the model to drive the tidal flow within the model area. As noted above, tidal information off the west coast of Ireland is sparse, which until the advent of satellite technology made it difficult to have accurate boundary conditions in this area. However it is now possible to establish the tidal constituents in the open seas using satellite derived water surface elevations and these may be used for model boundary conditions where traditional tidal measurements are not available.

Existing 2-D models that cover the whole of the continental shelf around Britain, Ireland and northern Europe typically have grid spacing between 5 km and 12 km. **Figure 2.4** shows a velocity plot from the UK shelf model. At this resolution the general flow patterns can be seen but the grid spacing is such that important local bathymetric features are not represented accurately in these types of models.

Depth averaged computational models covering the whole of the Irish coast will typically have a grid spacing in excess of 400 metres. This grid spacing gives good definition of the main features but does not accurately represent the flow into some of the loughs, estuaries and narrow channels. Similarly the important changes in the local bathymetry around banks and headlands are not correctly modelled at this scale.

Most modern computational models allow either the inclusion of fine grid sub-models within the main model area or alternatively a variable grid system within the model area. This allows a finer resolution to be used for specific parts of the coast, such as estuaries, loughs and channels giving better resolution of the flow regime for these specific features.

RPS Kirk McClure Morton have modelled the tidal energy resource around Ireland using the 2-D depth integrated flow model. This model, which was developed by The Danish Hydraulics Institute, simulates water level variations and flows in response to forcing functions around the boundary of the modelling area. The water levels and flows are resolved on a rectangular grid covering the area of interest. The main inputs to the modelling zone are bathymetry, seabed resistance and hydrodynamic boundary conditions. The system solves the full time-dependent non-linear equations of continuity and conservation of momentum. The solution is obtained using an implicit ADI finite difference scheme of second order accuracy.

The main tidal model covering the whole of the Irish Coast has a grid spacing of 405m. This model is driven by boundaries derived from a larger 1215m grid model that covers an area from south of Ireland to the north of Scotland and extends westward to the edge of the continental shelf. The boundary conditions for the model have been calculated using a tool developed by the Danish National Survey and Cadastre Department (KMS) based on the results from the TOPEX satellite altimetry project. The surface elevation measured by the satellites offers an accuracy of +/-20mm.

Nested within the main 405m grid Irish coast model are various detailed 135m and 45m grid sub models covering sections of the coast, sea loughs and estuaries. These detailed tidal models have been used to simulate the tidal flows in areas that have potential for the development of tidal stream energy such as around the east coast banks, the Tuskar Rock, the Shannon Estuary and Inishstrahull Sound.

2.4 Model Verification

Generally the detailed computational models were verified using tidal height and current meter data previously recorded in the specific area of interest.

As part of this project ADCP (Acoustic Doppler Current Profilers) devices were installed at two locations on the west coast of Ireland, one in the Shannon Estuary and one at the Bull’s Mouth, both for a period of one month. Good correlation between the ADCP results and the depth averaged tidal models was achieved.

2.5 Hydraulic Constraints

Unlike wind energy where the turbines occupy only a small fraction of the depth of the wind field, tidal energy devices may occupy up to 70% of the depth of the flow field. Thus, the extraction of energy from tidal currents may affect the resource as local tidal currents are often a function of a resonance system which can be reduced or destroyed by the energy extraction process. Extraction between 10% and 15% of the resource in a particular area can usually be accepted but higher levels are likely to be detrimental with the effect increasing in an exponential manner.

Strong tidal currents occur in some of the shallower estuaries and channels around the coast. However, the typical tidal range is approximately 3 metres, meaning that unless the water depth is greater than 6 metres at low water, it is unlikely that significant useful energy can be extracted from the site.

The nature of the seabed itself also has an influence on the potential energy available from the tidal flow field at certain sites. The roughness of the bed affects the flow field in two ways. Firstly, a rough bed increases the vertical velocity gradient, reducing the velocities in the lower part of the water column. Secondly, a rough or undulating bed can set up significant vertical eddies which make the flow field unstable, significantly reducing the amount of energy that can be extracted.

As noted above, swell waves may influence the particle velocities over the whole of the water column in coastal waters. When the wave direction and the current direction are in phase or 180° out of phase then the wave orbital velocities will increase or reduce the current velocities over the wave period. When the swell wave direction is at 90° to the tidal current direction then the effect of the swell will be to cause an oscillation in the tidal stream direction over the depth of the water column over the period of the wave. In addition, the effect of the waves is to increase the apparent bed roughness experienced by the current with a resulting increase in the vertical velocity gradient.

2.6 Theoretical Power

Tidal current systems exploit the kinetic energy due to the flow of water in the tidal cycle which is proportional to the cross sectional area of the device and the cube of the stream velocity. Thus if velocity is doubled the power increases by a factor of 8.

By assuming the tidal cycle to be sinusoidal and the neap spring variation to be sinusoidal as well, the mean power level in a cross of flow is given by:

$$P_{(mean)} = 1/2\, \rho\, K_s\, K_n\, V^3_{(peak)}$$

- $V_{(peak)}$ is the maximum spring tide velocity
- K_s is the velocity shape factor = 0.424,
- K_n is the neap/spring factor (neap 60% of spring) = 0.57,
- r is the density of water (t/m^3)

There is also a variation in the velocity profile throughout the water column. A 1/7 power law is frequently used to describe the velocity profile which varies from zero at the sea bed to a maximum at the surface.

The depth-average velocity can be assumed to give a reasonable representation of the velocity over the tidal energy device, thus the theoretical power can be determined by using the Fraenkel formula with the depth average peak velocity.

While the above gives the energy in the tidal stream, not all this energy can be extracted by a machine. When energy is extracted from a stream tube in a moving body of fluid, there is a loss of linear momentum.

The power in a stream tube of cross sectional area A is:

$$P = 1/2\, \rho\, AV^3$$

where V is the average velocity in the stream tube.

The Betz model of an expanding stream tube assumes a cross sectional area upstream A_u increasing to A_t at the turbine and increasing further to A_d downstream. There is a corresponding reduction in velocity to maintain continuity. The power extraction device is treated as an actuator disc across which there is a change in pressure and a decrease in linear momentum as energy is extracted.

It can be shown that maximum power which can be extracted from the flow is 59% as the fluid must have sufficient kinetic energy to leave the power extraction region. This is known as the Betz criterion and applies to all free stream turbines whether operating in air or water. It applies to shrouded turbines both vertical and horizontal axis and oscillating hydrofoils. In the case of the shrouded turbine the extraction area is the frontal area of the shroud and turbine combined (while that of the hydrofoil is the swept area).

Although there are many similarities between wind and tidal stream energy one of the most significant differences is that the largest wind turbines occupy less than 0.1%, a very small percentage, of the depth of the atmosphere. The devices have a close lower boundary at ground level but the upper boundary is several hundred kilometres away. Consequently wind energy extraction is barely noticeable compared to the total kinetic energy in the atmosphere.

However, tidal stream devices are different in that there is an upper and lower boundary formed by the water surface and the sea bed respectively in close proximity to the devices. The tidal generator occupies a much greater proportion of the stream and could be in excess of 70% of the water column depth. The presence of both upper and lower boundaries modifies the simplistic Betz's model and increase the maximum theoretical capture above 59%.

As previously noted, the extraction of energy from a tidal stream may affect the resource itself. Thus extraction of 10% to 15% of the theoretical resource in a particular area is generally the accepted maximum level.

2.7 Device spacing

Further research is still required on the spacing of tidal energy devices, however some numerical work has been undertaken by the Roberts Gordon Institute, Bryden et al[3]. At present it is considered best to place devices in a close spaced linear array across the flow as a 'tidal fence'. Unfortunately it is not always possible to extract the tidal stream resource in a single close spaced 'tidal fence' and successive lines of units have to be considered. However, there is no published data from model experiments to verify predictions and prototype arrays have yet to be built.

Although there are significant differences, wind energy is the closest existing technology to that of tidal energy and here tower spacing of five rotor diameters is often used. With tidal streams it is appropriate to consider blockage factor in a line perpendicular to the main flow direction and device spacing in the direction of the flow. Prior to detailed scientific work being undertaken it is proposed that a blockage coefficient of between 10% and 15% be used with an upstream/downstream spacing of 10-20 diameters. Closer longitudinal spacing might be possible if the location of units is staggered on successive lines. It is noted that horizontal axis machines with a diameter of 70% of the mean water depth and a lateral spacing of 5 diameters would give a blockage coefficient of 11%.

2.8 Theoretical Resource Evaluation

The theoretical tidal energy resource was calculated using the RPS Kirk McClure Morton 405m grid model which produced the potential power per cross-section of flow using the power equation given in Section 2.6. The total cross-sectional area of flow which could be used to harness tidal energy was then calculated as a function of the cross-sectional area of the turbines and turbine spacing.

The cross-sectional area of a turbine rotor was calculated as a function of the water depth where the rotor diameter was assumed to be 0.7 times the water depth. The total tidal energy resource was then calculated by multiplying these values by a factor of 0.59, since the maximum power which can be extracted from a flow is 59% according to the Betz criterion, as described in Section 2.6.

It was also necessary to define the landward and seaward boundary limits, between which the energy resource would be calculated. The landward boundary was taken as the 10m depth contour and the seaward boundary was taken as the 12 nautical mile territorial limit. The total resource between these limits can be seen in **Figure 2.6**. The theoretical energy resource was calculated for 10m depth intervals from 10m-50m water depth, **Figure 2.7**, and for water depths in excess of 50m, **Figure 2.8**. This equates to a total of 230TWh/yr for the island of Ireland. This is a significant figure but it should be noted that this is a theoretical value. It will not be practical to extract all of this energy due to technology limitations, and physical and environmental constraints.

2.9 Summary

1. Computational models have been used to model current flows around Ireland. These models have been validated using current meter data recorded at four locations around the Irish coast.

2. The theoretical energy resource has been calculated as being 230TWh/Yr, taking the landward boundary as the 10m depth contour and the seaward boundary as the 12 nautical mile territorial limit. This is 5-6 times the predicted electricity consumption for Ireland in 2010. It will not however be possible to extract all of the theoretical energy resource.

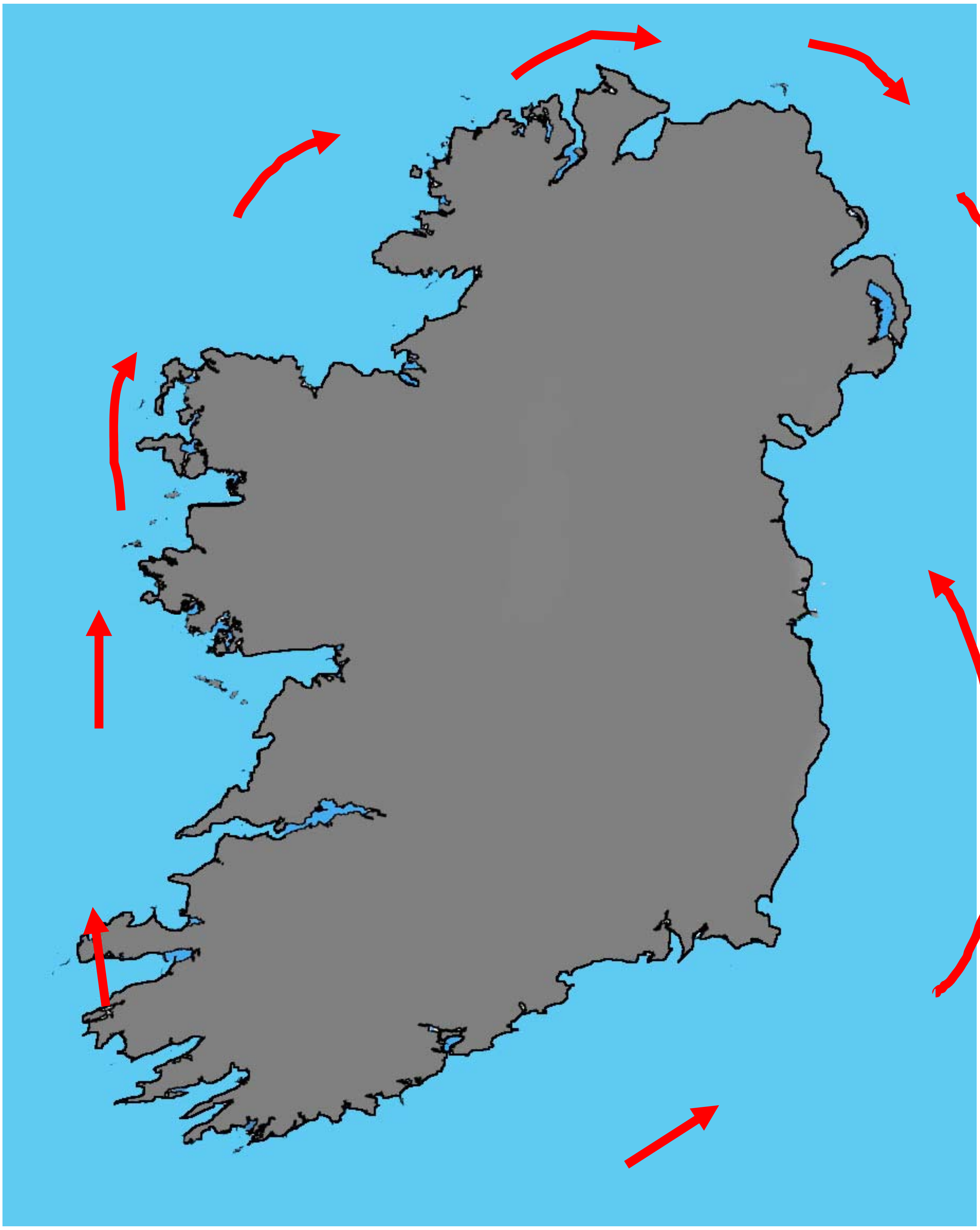


Figure 2.1 **Direction of the Flood Tide around Ireland**

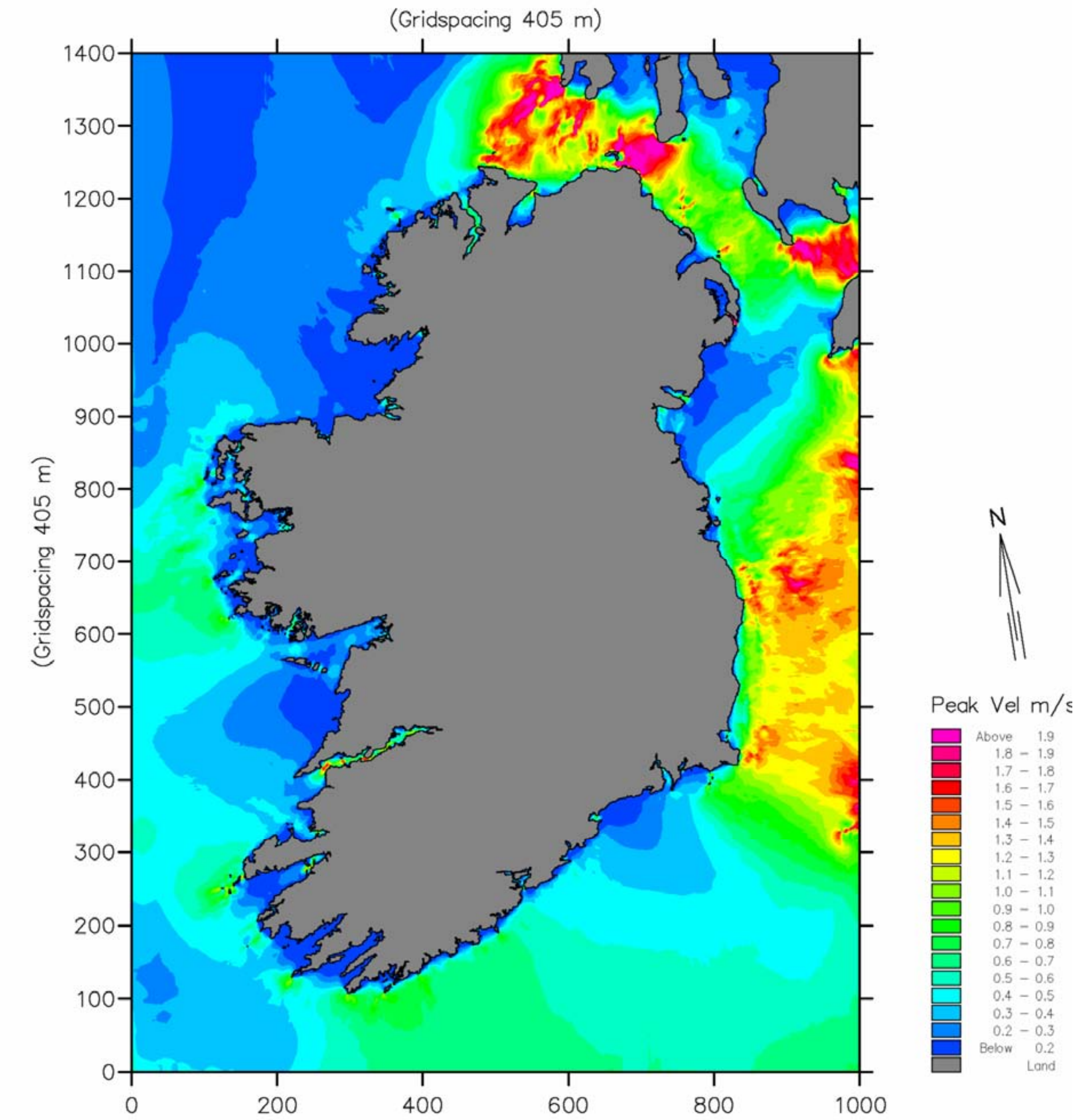


Figure 2.2 **Depth Averaged Peak Spring Tidal Currents**

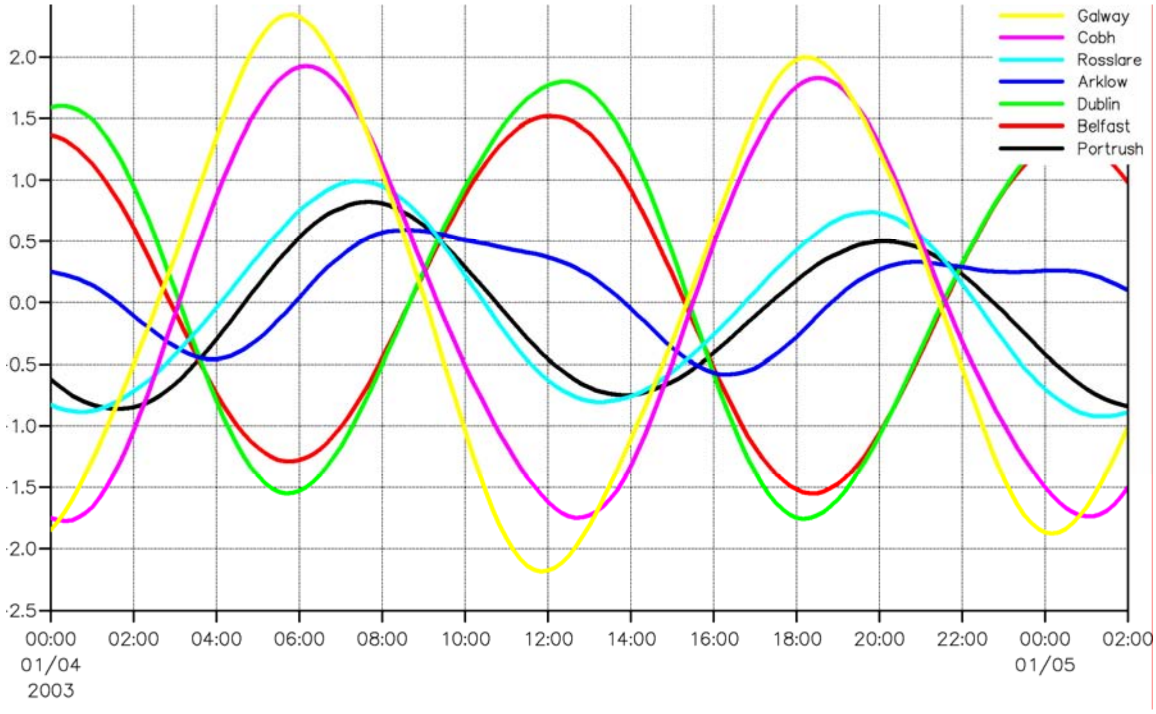


Figure 2.3 Difference in Phasing of the Tide around the Coast of Ireland

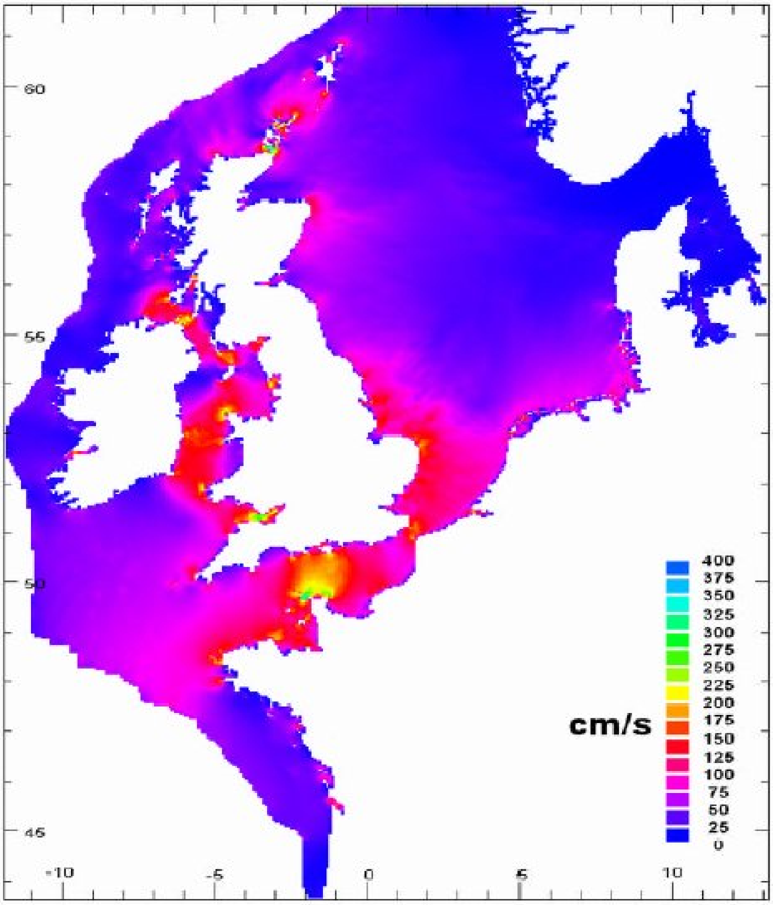
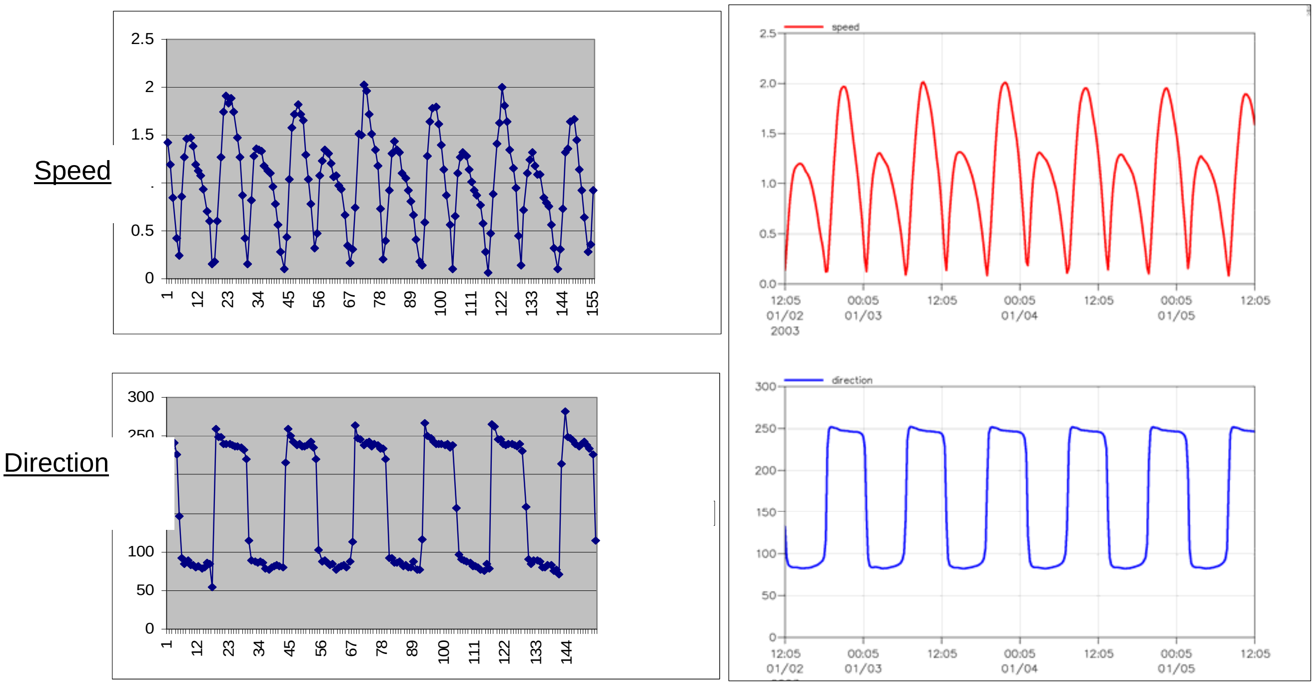


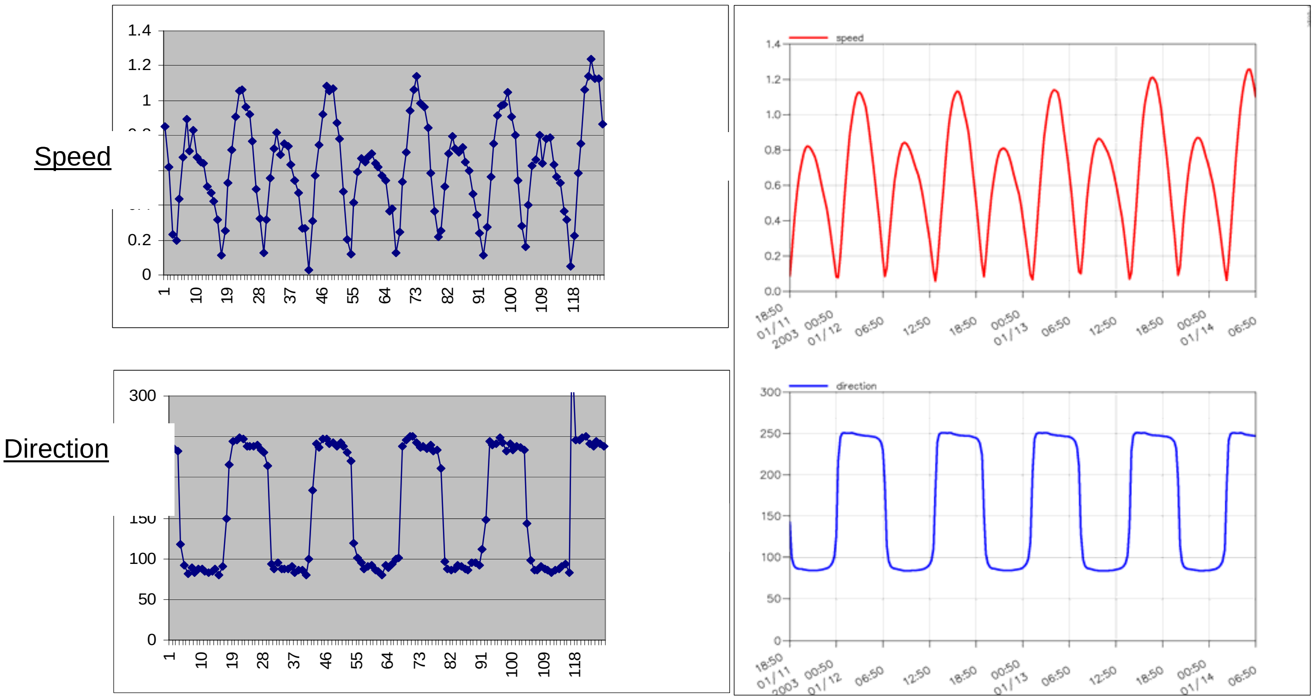
Figure 2.4 Veloc



ADCP – Mid Depth

Depth Averaged Tidal Model

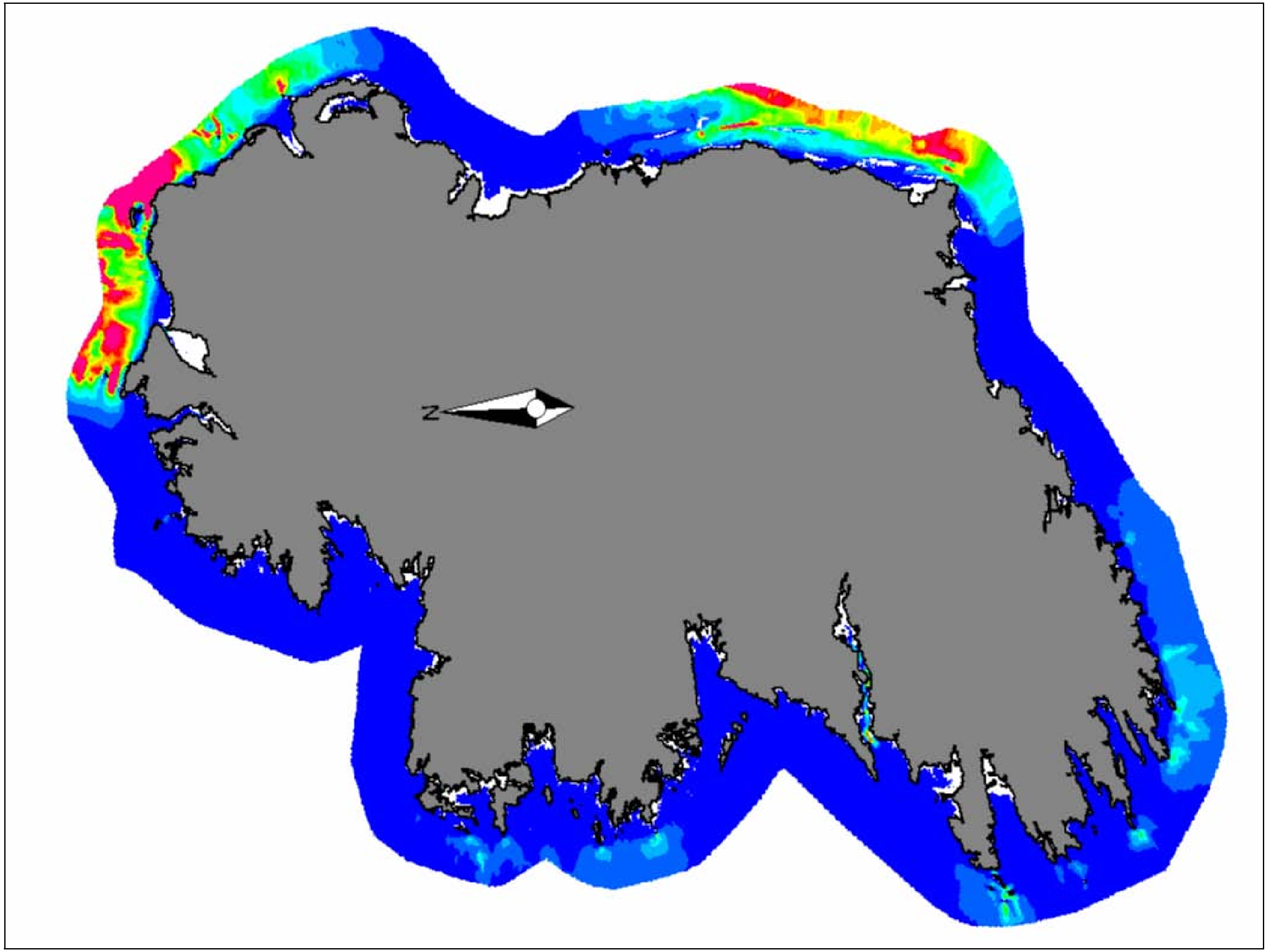
Figure 2.5(a)- Shannon Tidal Model Verification: Spring Tide–Speed & Direction



ADCP – Mid Depth

Depth Averaged Tidal Model

Figure 2.5(b)- Shannon Tidal Model Verification: Neap Tide–Speed & Direction



Z

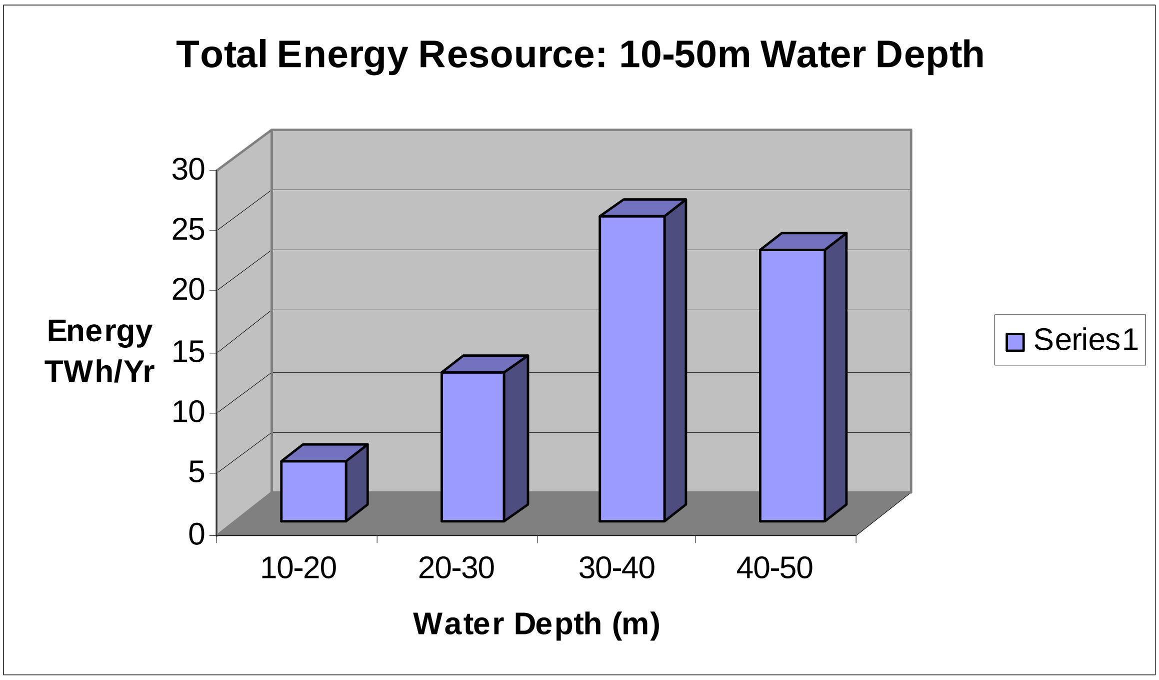


Figure 2.7 – Total Energy Resource 10-50m Water Depth

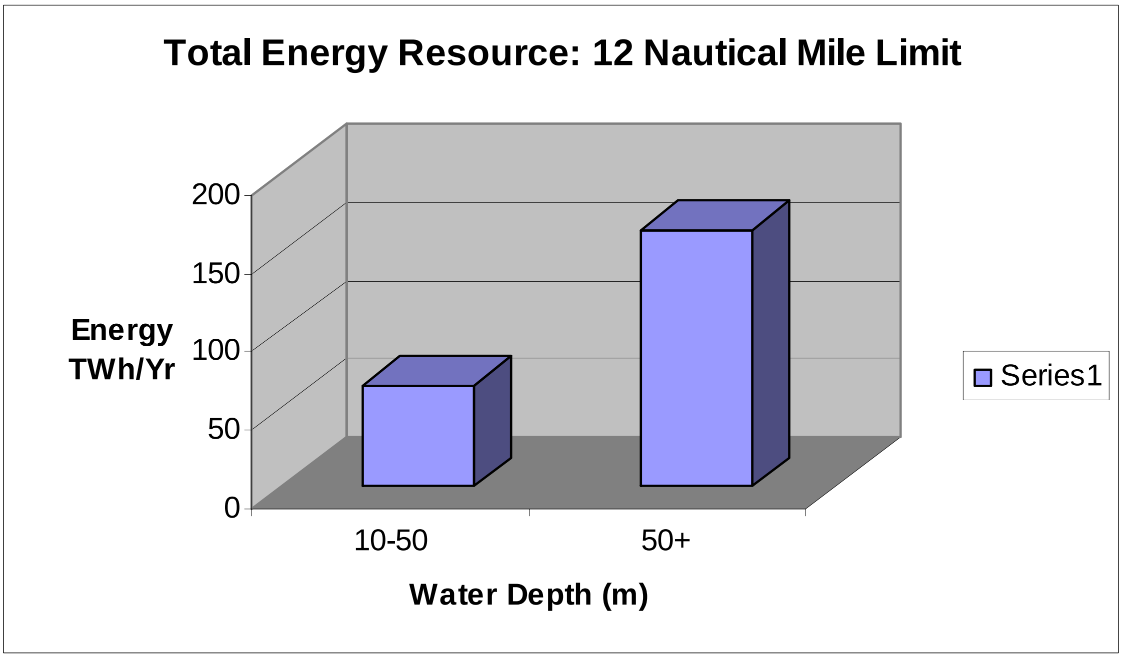


Figure 2.8 – Total Energy Resource: 12 Nautical Mile Limit

3.0 TECHNICAL RESOURCE

The "technical resource" is the theoretical resource constrained by the efficiency of currently available and predicted future technology.

The technology associated with tidal energy devices, offshore foundations and electrical systems is discussed in this chapter, and includes existing technologies and a discussion on expected future development. Tidal energy technology is in its early stages of development with a wide range of different technologies currently being researched. To date only a small number of successful prototypes have been demonstrated.

3.1 Summary of Existing Technology

There are many similarities between wind and tidal current generating systems both in terms of devices and the nature of the driving force. Compared to wind technology, tidal systems are in their infancy and there have been only a small number of prototype scale demonstrations of plant with an installed capacity of over 100kW. It is expected to take several years before items of equipment are produced for purchase and installation. Three of the most significant technology demonstrations have taken place during the past two years and two of these are ongoing. None of the demonstration units is a pre-production prototype and all research teams plan to build and test larger systems before going into production. There is very little published data on the performance of tidal current systems either at model or prototype scale. Consequently most of the available information is sourced from company literature and the world wide web. Generally, this information has not been reviewed in the technical literature

In the past, systems have been developed for river current energy. For example floating water wheels have been used in Europe since the 12th century on rivers such as the Danube. This system was reportedly used on the Thames in the late 16th century to pump water. In recent years some small scale systems suitable for tidal currents have been developed and tested on rivers.

Tidal mills have been used for centuries and there have been a number of tidal barrages constructed in the past forty years but these have been excluded from this study as they involve the impoundment of water in either man made or natural catchments.

Consequently tidal current generators are not yet developed at the size necessary for large scale exploitation of the resource. Companies with small scale demonstration prototypes are expected to develop these to sufficient size to generate from the resource by 2010. In addition there is also a range of design concepts which are being developed at model scale prior to small scale prototype development. However, these are mostly variations in engineering detail of equipment currently being demonstrated or to be demonstrated in the near future. They are not expected to make significant changes in either performance or cost. The most important developments are expected to be in the design of cost effective plant which can exploit more of the resource which exists in water depths of 50m and more.

Classification

Tidal current generators are classified in terms of the form of motion of the primary interface with the water and are either rotational or oscillatory. Using linear momentum theory, systems using hydrodynamic lift are shown to be three times more efficient than drag machines. Consequently, drag machines have not been considered in this study. The rotational devices with lifting, aerofoil section blades can be supported on either horizontal or vertical axes. Similarly the hydrofoil devices can oscillate either vertically or laterally. Consequently there are four basic configurations for tidal current systems and the range of devices described in the following sections are variations in terms of support structure or mooring system, detailed engineering design and method of secondary power conversion.

The classification is therefore summarised as follows;

- primary motion – rotational or oscillatory,
- orientation of the prime mover – horizontal or vertical,
- sea bed connection – moored or fixed structure,
- type of secondary converter – mechanical, hydraulic, electrical.

3.1.1 Rotational machines – horizontal axis turbines – 'free stream'

- Hammerfest Strøm AS[4]
- Marine Current Turbines Ltd.[5]
- J.A. Consult Tidemill, UK[6]
- Soil Machine Dynamics SMD[7]
- Tidal Hydraulic Generators Ltd. [8]

This group of machines has turbines mounted on horizontal drive shafts which are coupled to electrical generators through large reduction ratio gearboxes. Mostly the rotor blades are variable pitch so that the optimum angle of attack of the flow over the blades is maintained to ensure maximum hydraulic conversion efficiency as the stream velocity varies over the tidal cycle. Blade pitching is used to limit the peak power so that the installed capacity of the generator is not exceeded. In these devices torque and power train rating is limited on economic grounds.

In this group Hammerfest Stom AS and Marine Current Turbines Ltd. have working prototypes with an installed capacity in excess of 300kW. The other companies have either small scale working models or conceptual designs.

Marine Current Turbines Ltd. are currently demonstrating a 12m diameter two bladed horizontal axis machine off the north Devon coast known as the Seaflow project. It has a rated power of 300kW in a current of 2.7m/s. A schematic of the device is shown in **Figure 3.1** .The system is mounted on a 2m diameter monopile driven into the sea bed. The entire installation process was carried out from a jack-up platform. The nacelle houses the bearing assembly, water seals, the blade pitching mechanism, a two stage epicyclic gearbox and the generator. The nacelle can be jacked clear of the water for maintenance and inspection and so avoids the use of divers.

The mechanism used is similar to that on the legs of a jack-up barge. A twin blade rotor is used so that the entire turbine is clear of the water when the nacelle is raised. The generator is not grid connected and the electrical output is dumped into a resistor bank housed in the control room at the pile head clear of the water. The plant has been running frequently for research purposes during the past year and a considerable amount of data has been collected. However, the information has yet to be released. Following discussions with the development team it is reported that performance has exceeded expectations. Early indications suggest that the hydrodynamic conversion efficiency is greater than 40% and is comparable to a modern wind turbine.

The team has also developed a mathematical model for optimising the system in terms of size, capacity and cost. It takes into account loading on the various components to predict their size and weight and applies parametric costing information to assess the capital outlay and running costs of the plant. The component costs from the Seaflow project form part of this data base.

The tidal current power input is estimated from a knowledge of the current velocities throughout the tidal cycle at the site superimposed on the daily variations calculated for a complete year from published harmonic constants and the Admiralty tidal prediction equations. Variations in the current velocity over the vertical water column are included. The mathematical model and its predictions have been independently checked as reported in reference 9 and 10. The independent reviews are in close agreement with the overall projected costs and productivity claimed by the development team.

The next stage in the development process will be to build a unit with two rotors located on one pile. This is to make better use of the relatively expensive monopole and economise on the next most expensive element, the electrical connection. The machine will incorporate the main features of the ‘Seaflow’ project but in addition it will be grid connected. As shown in **Figure 3.2** it will comprise a pair of 14m diameter twin bladed rotors connected to epicyclic gearboxes and 600kW generators. It will be located in a water depth of approximately 22m.

In phase three of the development programme once the twin rotor device has been fully tested an array of pre-production machines will be installed and tested to determine interference effects between units. This will lead to the development of fully commercial projects.

Hammerfest Strøm AS have recently installed a 300kW horizontal axis turbine at Kvalsund in northern Norway. The general arrangement of the machine is shown in **Figure 3.3**. The 20m diameter 3 blade rotor is connected to the generator via a gearbox housed in a 10m long 2m diameter nacelle weighing 54 tons. This is located on top of a tubular steel tripod structure weighing 120 tons and held to the sea bed by three 200 ton anchor weights. The water depth is 50m and the nacelle height is 20m below the surface. The structure is completely submerged and maintenance is carried out by divers. The test site has a mean current of 1.8m/s. The blades pitch to optimise performance in the varying tidal flows and pitch is reversed for flow in the opposite direction. The estimated energy output is 0.7 GWh equivalent to an average power production of

80kW. Unfortunately no information is available on the current status of this project and in particular to its costs and performance.

This system can and has been deployed in deeper water than the Marine Current machine, which in its present configuration is limited to 30m depth. This is the operational depth limit for the currently available jack up barges with necessary facilities to drill the pile socket in the sea bed. The Hammerfest Strom unit has certain disadvantages such as difficult access and deep working conditions for divers. In addition there will be more blockage from the tripod structure compared to the monopole with a probable reduction in turbine efficiency due to the increased turbulence when the rotor is downstream from the support structure. When the rotors are up stream from the support structure both machines should have similar hydrodynamic efficiencies.

J.A. Consult Tidemill, UK, has a comprehensive web site describing a range of novel tidal current machines. This group tested a 1kW 1.5m diameter horizontal axis turbine in the river Thames under a floating jetty in 2001. The model and an artists impression of the full scale system shown in **Figure 3.4**, has an inclined tension leg connected to a sea bed universal joint to hold the partially buoyant vertical tube which supports the turbine. The turbine operates down stream from the support tube and orientates with the tide. The turbine can be brought to the surface for maintenance by pumping water out of the support tube. Fixed pitch stall regulated blades are proposed. There are also multiple rotor configurations of the system.

The system is suitable for deeper water up to 60m. However, the proposals appear to be in the conceptual stages of development and will require detailed engineering design. The concepts may be developed for the next generation of systems for the future. At present there is no detailed information on performance and cost solutions to the engineering challenges posed by the universal joint and its fastening to the sea bed.

Soil Machine Dynamics SMD, have tested a 1/10th scale model of a moored twin rotor system with a tension mooring system known as the TidEL system. The twin rotors and nacelles housing the gearboxes and generators are mounted on opposite ends of a buoyant cross beam. This is held down by four mooring cables connected to the sea bed, as shown in **Figure 3.5**. The mooring cables are aligned with the principal current directions and the cross beams and nacelles and rotors flip over when the tidal stream reverses.

The team intends building a much larger scale prototype for deployment in the next year. In order to service the unit the mooring cables can be winched out to allow the cross beam and nacelles to float on the surface. The system has several novel features and should be suitable for deep water applications.

However, there are also some significant engineering challenges such as how to design epicyclic gearboxes to operate upside down, how to maintain stability of the power modules when operating and how to accommodate the very considerable mooring loads which result from the shallow angles in combination with the upward buoyancy force and the horizontal reaction force. This system or elements from it may form part of the next generation of systems. There is no detailed cost and performance data available at this time.

Tidal Hydraulic Generators Ltd. in collaboration with the Babtie Group. In principle a number of small diameter horizontal axis turbines are mounted on columns connected to a sea bed space frame. This frame is ballasted on to the sea bed. In this system power is taken from the turbine shafts hydraulically and fed into a centralised accumulator. Biodegradable oils will make the system environmentally acceptable in the event of leakage from the large number of connections to the multiple generating heads. The turbine nacelles rotate through 360° to accommodate changes in tidal current direction.

A single turbine module mounted on a flat bottomed barge has been tested in Milford Haven. The consortium currently plans to build and deploy a five turbine unit in 2004. The hydraulic system and space frame connection to the sea bed is novel and still in the early stages of development. This system or its novel components may form part of the next generation of systems. At present no information is available on system performance, the effect of rotor spacing or costing for production systems.

3.1.2 Rotational machines – horizontal axis turbines – shrouded

- Hydrohelix Energies (France)[11]
- Lunar Energy,

Both **Hydrohelix Energies** and **Lunar Energy** have conceptual designs for shrouded horizontal axis turbines to be placed in caissons on the sea bed either across an estuary to form a sub sea tidal fence or in line clusters in open water. The shroud is claimed to concentrate the velocity of flow through the turbine rotors thus enabling them to have a smaller diameter and run faster than open machines. However, as previously stated, the Betz criteria still holds relative to the frontal area of the venturi caisson. There is also a severe limitation on the compactness and rotational speed of the turbine rotors in order to avoid cavitation and an accompanying significant loss of efficiency. **Figure 3.6** shows an artists impression of the Hydrohelix Energies system. Full details of these systems and potential development plans are not available at this time.

3.1.3 Rotational machines – vertical axis– 'free stream'

- Darrieus, fixed pitch - Cross flow turbines
- Gorlov Helical Turbine[12]
- Voith type, cyclic pitch - Cross flow turbines
- 'Polo' device, Professor Stephen Salter[13]

The **Darrieus**, fixed pitch cross flow turbine was patented in 1932. This turbine comprises a number of vertical aerofoil section blades mounted vertically between top and bottom support frames which constrain the blades to rotate about the vertical axis. The blades are driven by hydrodynamic lift. The concept has been used in wind turbines with machines up to 4MW having been built.

In air power coefficients of around 35% have been achieved at tip speed ratios of 6. Water versions of this system have been tested in the laboratory and at sea by Nihon University in Japan. Shiono et al[14&15], have published data on both Darrieus straight blade rotors and helical versions. **Figure 3.7**.

The best hydraulic conversion has been 24% at a tip speed ratio of 1.75. In the 2002 paper an efficiency of 33% was claimed but a private communication with the lead author revealed this to be in error and the figure of 24%, reported in the earlier paper, was correct. The relatively low efficiency of the Darrieus turbine results from the fact that each blade is lifting and producing a driving torque for approximately 10% to 15% of its circular excursion. For the remaining time the blade is being dragged through the water.

In water the tip speed ratio is relatively low compared to the air equivalent. In spite of its low potential efficiency it has several advantages over horizontal axis machines. It can accept flow from any horizontal direction, the swept area can be wider than its depth so for a given generating capacity the system can be located in shallower water and the generator and gearbox can be mounted above the water surface where it is accessible.

Gorlov Helical turbine: One of the problems with the Darrieus rotor is the very low starting torque. This can be overcome by powering the rotor up to operational speed or by configuring the blades in a helical manner, as in the Gorlov rotor. This is shown in **Figure 3.7**. Experimental work reported by Shiono et al[14&15] shows that the helical bladed machine has a lower efficiency than the straight bladed version. They report a peak efficiency of 17% at a tip seed ratio of 1.75.

Voith and Polo: Both of these machines are variable pitch ‘Darrieus type machines. The Voith type is similar to the propulsors used in some tugs while Polo is shown in **Figure 3.8**.

If an extraction system could be developed to operate in lower velocity currents, the overall national figure would be much greater than the numbers mentioned so far in this report.

A Dublin based group has developed a horizontal rotating turbine – the CAL turbine – which received some Enterprise Ireland support to test a 2.4 metre diameter unit in the Wicklow estuary. The promoters of the CAL system are concerned about the IPR rights of their design, and consequently only a limited amount of information has been made public by the group. The DCMNR, the SEI, and the Marine Institute have been kept informed.

The CAL systems turbines combine lift with kinetic deflection. The basic concept is not new, what is new is its application in sea currents coupled with a number of enhancing features.

The most significant aspect is it's suitability for harnessing the energy in low velocity currents.

3.1.4 Rotational machines – vertical axis– shrouded

- Blue Energy Canada Inc., Davis Hydro Turbine[16]
- Tide Waterpower Turbine TWT,

Blue Energy Canada Inc. (known as Nova Energy Ltd. Prior to 1997) has based their technology on the Davis turbine named after its inventor Barry Davis. Work commenced in 1978 and prototypes rated at up to 20kW have been tested in free streams (turbine B1 1983) and up to 100kW in a duct where all flow passed through the turbine, (turbine B2 1984). Much of the development has concentrated on river flow situations. In 1985 VEGA 1, a 4kW unit was lowered from a boat to a depth of 60m in the Gulf Steam off the Florida coast and an electrical output was produced from a deep tidal current for the first time.

The general arrangements of the Blue Energy systems are shown in **Figure 3.9**. They comprise a vertical axis Darrieus type four bladed rotor mounted in a caisson which directs the flow. There is an inlet taper to accelerate the flow towards the rotating hydrofoil blades; top, bottom and side walls to trap the flow and shroud the turbine and an exit taper to recover some of the exiting kinetic energy.

Theoretically it should be possible to exceed the Betz criterion for maximum power extraction efficiency of 59% from an extended fluid stream as a consequence of the shrouding. However, the fluid is still unbounded beyond the surrounding caisson and the limiting theoretical efficiency will be relative to the total frontal area of the duct which is greater than that of the rotor.

It is stated that 'turbine B1 had a measured hydraulic conversion efficiency of 45% but it is not stated which cross sectional area was used in the calculation. It is probable that this was relative to the maximum duct area at the mouth of the venturi. A detailed analysis of the theoretical and experimental data has not been published in the technical literature.

The company is proposing two tidal current systems aimed at different scales of generation. It has not been publicised if full scale prototypes of either system have been built and tested. The first system known as 'Midrange 250' is a floating free stream unit comprising a pair of 125kW Davis Hydro Turbines housed in a modular caisson. It is claimed that the technology is viable in water depths down to 10m and currents in excess of 1.75m/s. and the full rated power is achieved in 3.5m/s flows.

The second scheme is for multi MW units in a tidal fence across an estuary. Consequently it is a barrage scheme and outside the scope of this study. The Dalupiri project being considered in the Philippines would comprise 274*14MW Davis Hydro Turbines in a barrage 4km long and on average over 40m deep.

Tide Waterpower Turbine TWT, A small version of this type is available to charge batteries on boats moving through the water or moored in currents. There are plans for larger generating systems comprising , bulb turbines in shrouds mounted on the sea bed. Full details of the system are not currently available.

3.1.5 Reciprocating Machines

- The Engineering Business Ltd. Stingray[17]

The Engineering Business Ltd. The stingray project is being developed and funded commercially by the Engineering Business Limited and through the Department of Trade and Industry, under the UK Governments Sustainable Energy Program. A full description of the project is given in references 18 and 19.

Stingray, shown in **Figure 3.10a**, uses one or more hydrofoils with adjustable angles of incidence mounted across the flow so that they are forced up or down by the water current passing over them. The oscillatory motion drives hydraulic rams pressurizing an accumulator. This can be used to power an hydraulic motor connected to a generator to provide an electrical output.

During 2002 and 2003 a 150kW demonstration system was tested for limited periods of a few weeks at a time in Yell Sound, Shetland. The Yell test site has a mean current of 1.5 m/s which yielded an average of 90KW. The demonstration project experienced some problems including an underestimation of the hydraulic oil reservoir and a power supply failure. The Engineering Business believes the project to be successful and to have demonstrated the accuracy of their technical and financial models.

The next stage of development for the stingray project, described by Trapp, is a 5MW farm. However, in scaling up the system the design has been altered from that of an undulating arm to a concertina arrangement as shown in **Figure 3.10b**. The new design also utilizes multiple blades, which are capable of rotating to unitize the current in both directions. The Engineering Business has given the provisional cost of electricity production for such non-commercial farm between 5p/KWh and 19p/KWh.

One of the main problems with this system is its overall efficiency. Although it is possible to achieve very high efficiencies when the foil is moving at optimum pitch for the available flow, the lift force on the surfaces is slow to re establish after the system stops at the top and bottom of the stroke. Cyclic efficiencies of around 9% were measured in the initial experiments and although there is scope for improvement it is unlikely to match that of a horizontal axis machine.

3.1.6 Future Research

Tidal energy devices are still in their early stages of development and many aspects of the technology require further research including;

- Full scale monitoring of the flow regime, turbulence, vertical velocity field distribution and resulting device performance to verify and further develop 3D numerical models of the system.
- Wave current interaction, its effect on the tidal stream resource and how machines perform in pulsating or even reversing flows.
- Measurement of the upstream and downstream wakes of machines and the longitudinal spacing of lines of devices with different blockage coefficients.

Several existing tidal energy devices are reported to be only economic when operating at velocities greater than 2.0m/s. It is imperative that future development concentrates on reducing this minimum operating velocity if the resource is to be competitive with other forms of renewable energy.

3.2 Foundations

Support structures for tidal energy devices are a vital component in the development of tidal energy. Similar to other offshore structures, the devices will be subject to loadings mainly due to selfweight, wave and current loading. In removing energy from tidal currents, the devices have to withstand horizontal forces which depending on the local maximum current velocity and rotor size[24] may be in the order of 1,000 kN to 3,000 kN.

The review of existing technologies in Section 3.1 has highlighted the main foundation types as being the mono-pile as used with the MCT device and a combination of tripod and gravity structure which has been used by Hammerfest Strøm AS. Moored structures have also been proposed by Soil Machine Dynamics, however this device is in the early stages of development and it is thought that this system will form part of the next generation of systems.

A prototype support structure, called the ‘Sea Snail’ has been developed by the Robert Gordon University/Ian Bryden[20], which operates by using a number of hydrofoils mounted on a frame in such a way as to induce a downforce from the current flow. As the current increases, so does the overturning moment on the turbine and the down force on the foils. Provided that the ratio of surface areas is such that the down force generated exceeds the overturning moment, then the Sea Snail will remain in position. A full size model of the Sea Snail is currently in Orkney awaiting favourable weather conditions before being launched.

Monopile Foundation Structure

Monopile foundation structures have been used by MCT for their Seaflow project off Lynmouth, Devon.

The monopile foundation consists of large diameter steel cylinders, typically 2m diameter, of wall thickness between 40mm and 60mm, driven typically 20-30 meters into the seabed. In some circumstances the monopiles may be drilled and grouted into position depending upon ground conditions at the site.

One of the advantages of this type of foundation type is that no preparation of the seabed is necessary.

Tripod Foundation Structure

The tripod foundation draws on the experience with light weight and cost efficient three legged steel jackets for marginal offshore fields in the oil industry.

The tripod foundation is anchored into the seabed using three relatively small steel piles at each corner. Typically the three piles are driven 10m-20m into the seabed, depending on specific ground conditions, and connected to the central column via a steel frame.

Advantages of this type of structure include:-

- Corrosion allowance may be reduced as the leg diameter is reduced
- Cheaper, more readily available plant than is required for monopile installation
- The punching shear capacity of the connections between the upper braces and the centre column is increased
- The hydrodynamic load is reduced

Gravity Foundation Structure

Gravity foundation structures have been used extensively in offshore wind projects, with the main elements of the foundation consisting of a steel bottom plate with a hollow concrete cylindrical upstand and a central concrete cylinder into which the tower is bolted.

A variation of this type of structure is the ballasted steel gravity structure which consisits of a steel upstand and base, which is ballasted with a high density material. The advantages of this type of gravity structure are its ease of production, transportation and installation. However, these structures can be sensitive to scouring in sandy locations or where sand mobility is high. Extensive bed preparation may be required for both types of gravity foundation.

Moored Floating Structure

This type of foundation structure has yet to be fully developed, but works on the principle of mounting the tidal energy device under a floating vessel which is then moored to a structure attached to the seabed. The floating vessel may be either on the surface or held by tension moorings below the surface. The installation to which it is held may be piled into the seabed or be held in place as a gravity structure.

3.3 Tidal Stream Farm Electrical Systems

Introduction

Many of the electrical issues relating to offshore energy sources are similar to those for on-land alternative energy sources. For example, voltage stability losses and reactive power compensation. Other issues are significantly different. For example, cable installation methods. This section describes the design of offshore tidal stream farm sites and cable installation.

First generation tidal stream farms around Ireland are likely to be in the range from 1MW to 25MW, featuring turbines of 0.25MW to 1MW capacity.

Site Design

It is expected that the voltage will be generated at 0.6 kV to 1.1 kV and transformed to 20 kV to 38 kV by standard unit transformers located in each group of three units. These units will be interconnected at 1.1 kV. Some typical arrangements are shown in **Appendix B**.

The interconnectors of the turbines within the farm will largely depend on local circumstances. The site developer should provide redundancy in the event of a cable failure which could otherwise result in a reduction of generated power. The balance between redundancy and increased costs will depend on the likelihood of failure, the time to repair a cable and whether or not the cables are buried in the seabed.

Cable Installation

Submarine cable installation techniques have been used extensively in the oil, gas and telecommunications industries and should be applicable to the installation of cables at offshore tidal current farms. However the installation of short lengths of cable and their burial could present problems not encountered in the longer cable runs found in cross channel connections. The major issue with cable installation is whether the cables should be buried or laid on the seabed. It is most likely that the cables to shore, which carry the entire wind farm output, will be buried for maximum protection. This will increase the tidal current farm cost, but will significantly reduce the risk of cable failure and loss of revenue. Cables within the farm are not likely to suffer in this manner but will be subject to high current flows.

The method of cable burial will depend upon the character of the sea bed. Sand can be fluidised to form a trough in the seabed. Once the cable has been laid in the trough the sand will back-fill naturally. If the seabed is a harder material, such as clay, a plough may be required. If the seabed is rock a cutter will be required.

Electrical Issues

Electrical losses within a tidal current farm are of concern as they will affect its profitability. On-land losses in wind farms are generally low (2% at rated output) as wind farms are normally located close to the grid. These losses can be expected to be greater (around 5% at rated output) for tidal current farms because of the distance from the shore. Losses can be reduced by increasing the voltage at which power is transmitted or by increasing the number of cables.

Electrical equipment has effectively two loss components, one which is proportional to load (resistance losses in the copper) and one that is related to voltage (magnetic field losses). The latter component is effectively constant since the voltage does not vary significantly with load. If equipment is operated at less than full load then it is possible to allow the equipment to operate normally at reduced voltage. This has the effect of reducing the magnetic losses and increasing the efficiency at part load.

For tidal stream equipment, operation at part load will occur on a cyclic basis and if tap-changing transformers are used increased efficiency will be achieved resulting in increased output. A further benefit will be a reduction in the reactive current taken by induction generators. Clearly, a detailed study will be required to assess the economic gain against the additional transformer costs.

Because of the cyclic nature of the loading the temperature of electrical equipment will fluctuate with load. Thus after the minimum flow periods the equipment will be cooler and be able to sustain an overload for a short period, say 5% for 20 minutes. If this period occurs at maximum demand the extra supply could prove valuable and would be relatively easy to implement with the use of normal protective relays.

Load Management

An electrical grid system is composed of interconnected links where, if a fault occurs on one link, the grid can still supply power at an acceptable voltage. To enable this to be achieved it is necessary to control the power injected at different points. Although referred to as load management it is in fact the management of generation.

Load management is therefore an important issue in controlling the power flow in the grid in order to maintain acceptable security and voltage profile throughout the system. Supply authorities are legally obliged to maintain voltage on the system within specified limits. There are two aspects to this. Firstly, the overloading of lines may give rise to cascade tripping and secondly, the control of reactive power which is an important aspect of voltage control.

Investigation of the potential contribution of renewable sources to the supply and the effect of the cyclic nature of tidal energy must be considered. For small sources, (<25 MW), the intermittent effects on load management are minor. Practical figures for tidal current energy indicate that the first generation of tidal farms is likely to be in the sub 25 MW range and that links to the grid at 33kV or 38kV are considered to be acceptable.

Future Developments

Future development of tidal current farms is expected to concentrate on the exploitation of resources in deep water and with increased wave action. These sites will be further from shore but otherwise are unlikely to present any additional electrical problems.

3.4 Technical Resource Evaluation

Tidal energy technology is at an early stage of development and much research is still required. It has been noted that existing tidal energy devices are only economic when operating in waters with peak tidal velocities greater than 2.0m/s. However it is expected that this operating velocity will reduce as tidal energy devices improve. It is understood that several developers are working on devices that will operate economically in peak tidal velocities of approximately 1.5m/s.

It is expected that machines will be sufficiently advanced by 2010 to extract power from tidal streams with peak velocities greater than 2.0m/s. It is perhaps more likely that it will be 2015 before economic extraction becomes possible for peak tidal velocities of 1.5m/s. However, attaining economic generation at peak tidal velocities of 1.5m/s will depend upon the level of research carried out and on any technological breakthroughs which may occur.

The technical resource was calculated in a similar way to the theoretical resource, but only areas where the peak tidal velocities are greater than 1.5m/s have been included. Based on existing technology the device efficiency has been limited to 39% and the resource has been calculated between the 10m water depth contour and the 12 nautical mile territorial limit.

The technical resource has been calculated as being 10.46TWh/yr as shown in **Figure 3.11**. The technical resource represents approximately 25% of Irelands predicted electricity consumption for the year 2010.

3.5 Summary

1. The technical resource has been calculated for areas where the peak tidal velocity is greater than 1.5m/s and is equal to 10.46TWh/yr which represents approximately 25% of the predicted electrical consumption for the year 2010.

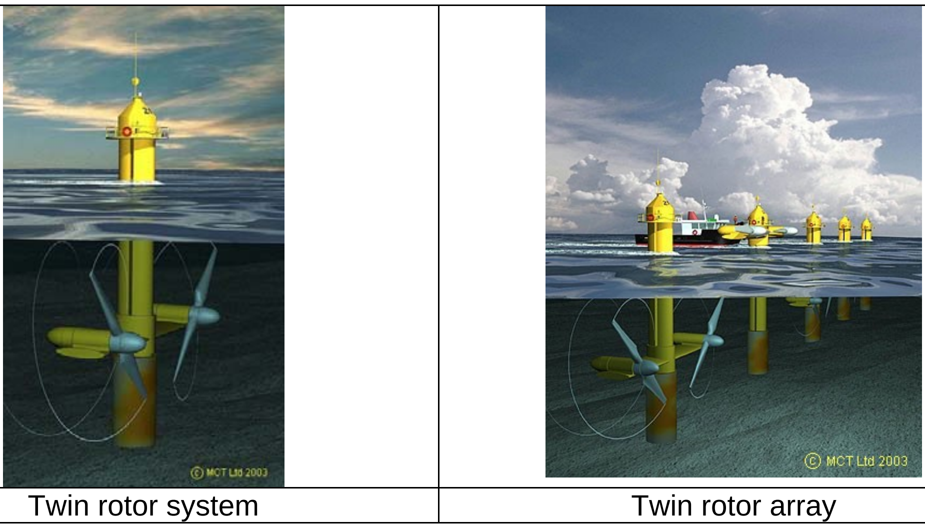
2. Tidal current machines are in the early stages of development with only a few examples at reasonable size having been demonstrated to date.

3. Existing electrical and subsea cabling technology as used in offshore wind power developments is sufficiently advanced and should be directly applicable to tidal current farms without major modification.

4. Extensive research into tidal energy technology is still required if economic electricity generation is to be achieved with peak tidal velocities of 1.5m/s.

Schematic | Operational mode | Rotor raised for servicing

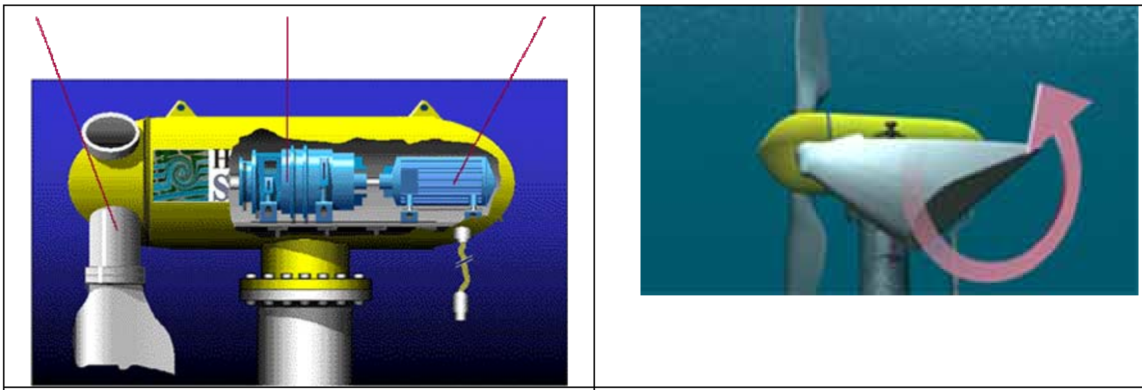
Figure 3.1 Seaflow Project



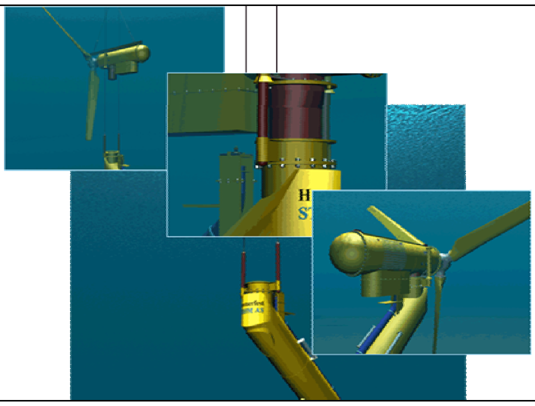
Twin rotor system | Twin rotor array

Figure 3. 2 Schematic of twin rotor 1.2MW production units
(*source – www.marineturbines.com)*

Turbine array | Support structure

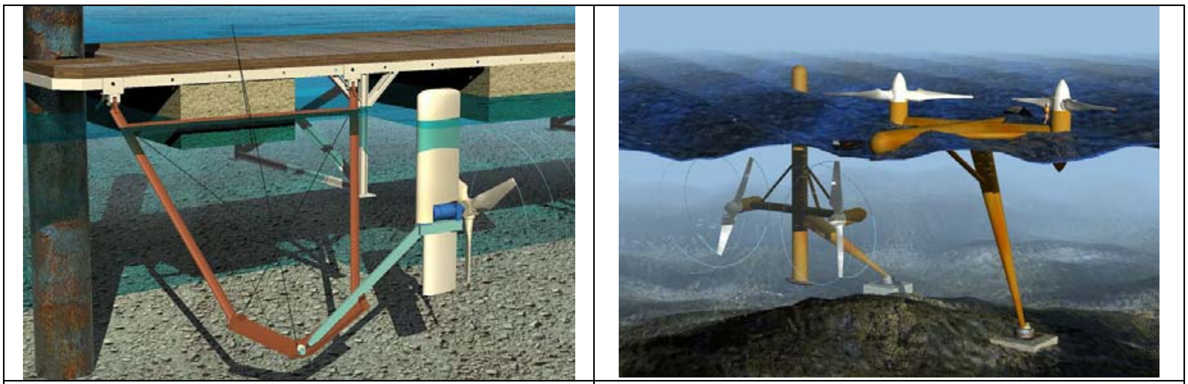


Nacelle - hub, bearings gearbox, generator | Pitching turbine blades



Nacelle – sub structure connection

Figure 3.3 Hammerfest Strøm AS *(source - www.tidevannsenergi.com)*

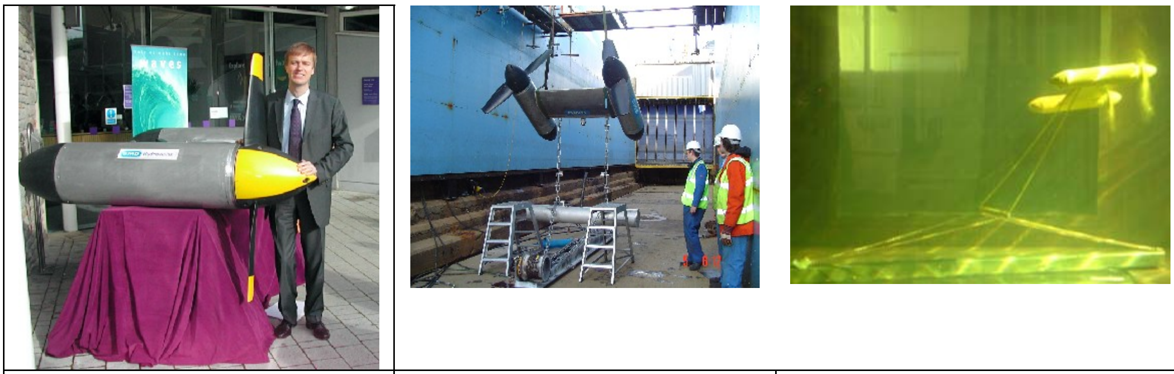


1.5kW model – Thames - 2001

Schematic of prototype system

Figure 3.4 J.A.Consult Tidal Steam Generating Systems

(source www.tidalstream.co.uk)



Rotor and nacelle

Mooring arrangement

Test flume

Figure 3.5 Soil Machine Dynamics – 10kW test model

(source www.smdhydrovision.com)

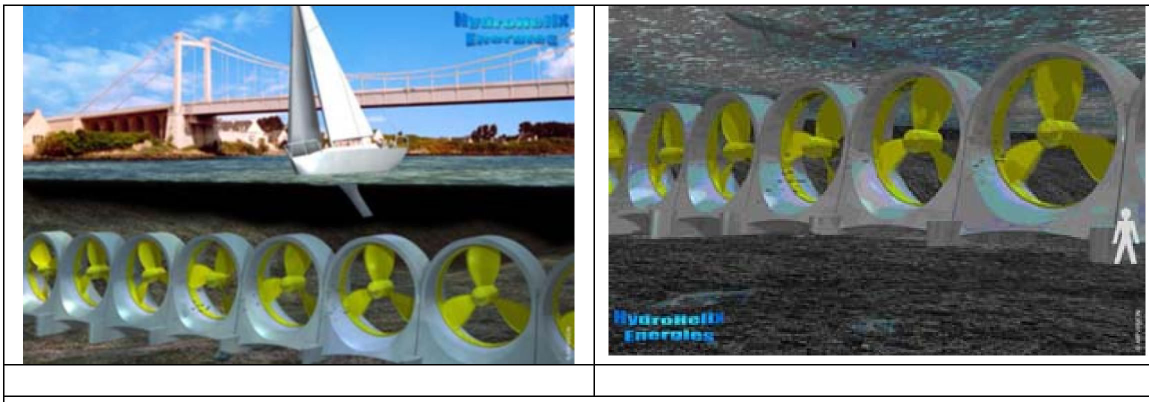


Figure 3.6 Hydrohelix Energies Tidal Fence with Rim Generator Turbines

(source ccientreprises,icomme.fr)

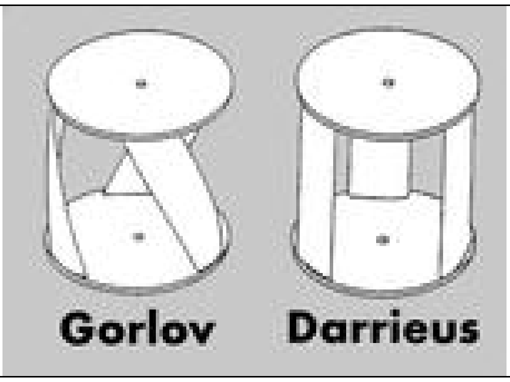


Figure 3. 7 Gorlov Helical and Darrieus Straight Blade Cross Flow Turbines
(source www.mos.org)

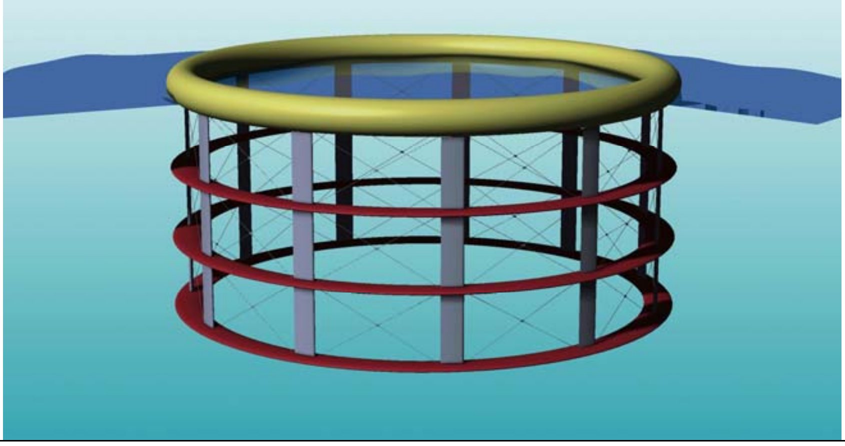
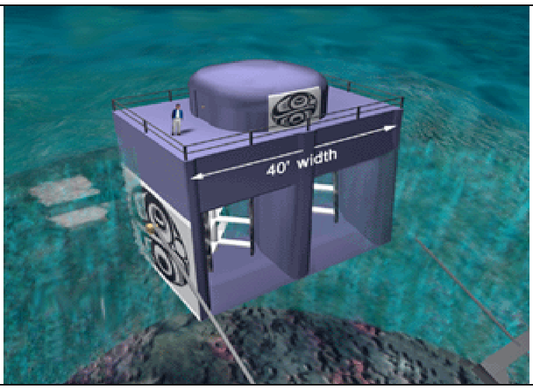


Figure 3.8 Polo Device – Professor S.Salter Edinburgh University
(source www.mech.ed.ac.uk)

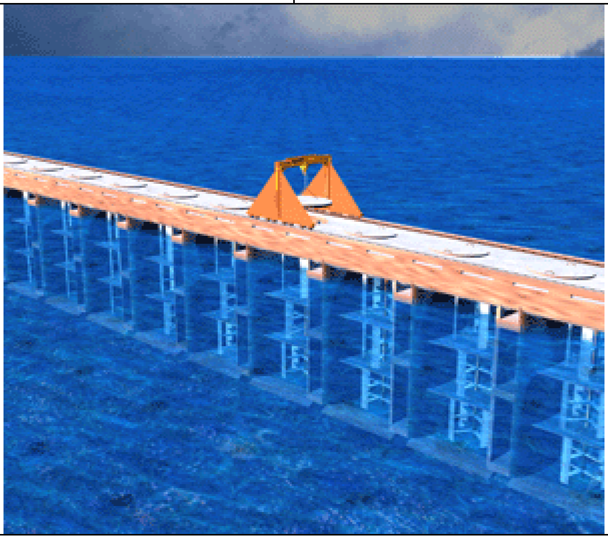
Davis hydro turbine test model mounted in venturi

VEGA 1 – 4kW unit 1985

100 kW duct mounted Davis turbine B2 1984



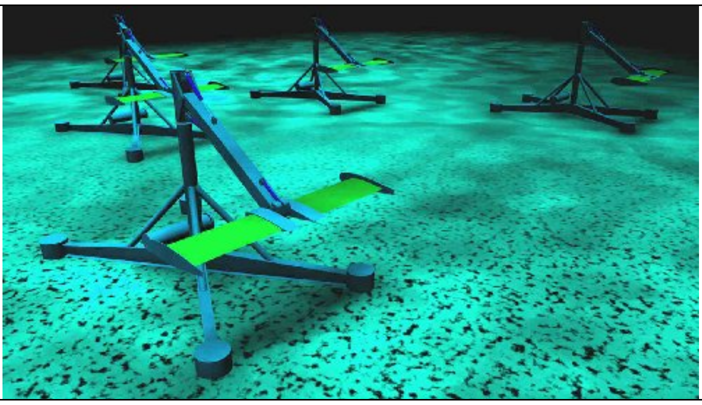
Schematic floating twin rotor unit



Schematic of tidal fence

Figure 3.9 Blue Energy Canada Inc. Schemes Tested and Proposed

(source www.bluenergy.com)



Schematic of Stingray

Stingray being launched 2002 Yell Sound

<u>Figure 3.10 a Engineering Business ‘Stingray’</u> *(source www.engb.com)*

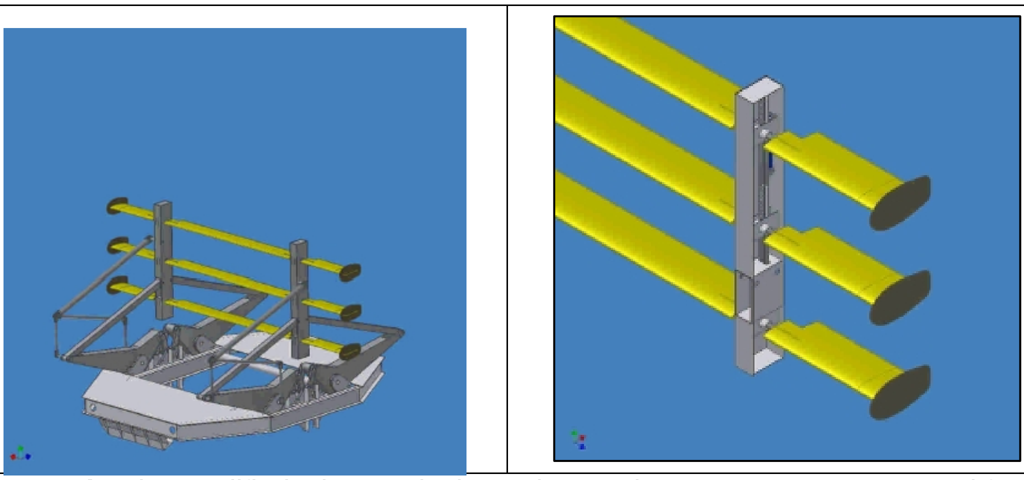


Figure 3.10b. The modified stingray design to be used on larger systems planed for use in the 5MW farm (Trapp, 2004).

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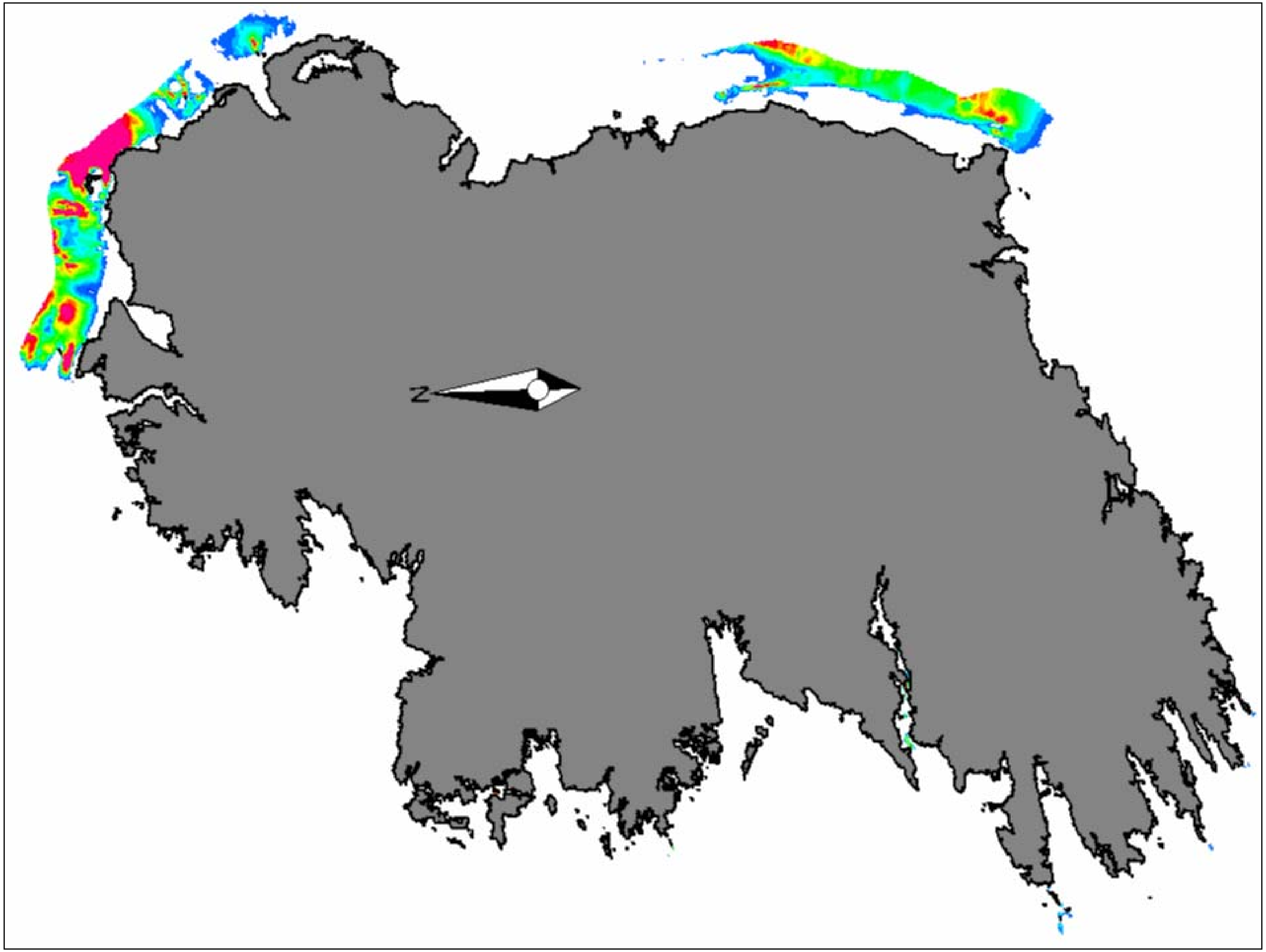


4.0 PRACTICAL RESOURCE

The “practicable resource” is the technical resource constrained by practical, physical or other interference.

The theoretical and technical energy resource around the coast of Ireland has been discussed in previous chapters. However, tidal energy may only be extracted at a limited number of sites due to the many constraints including physical and construction constraints and defined area restrictions.

4.1 Construction and Physical Constraints

4.1.1 Water Depth

It is expected that first generation devices (before 2010) will not be capable of operating in water depths greater than 50m and therefore the scope of this section has been limited to this depth. This restriction has significantly reduced the available resource. From a practical aspect it is more probable that first generation devices will be limited to a maximum water depth of 40m as this is the maximum water depth in which jack-up barges, required to install the devices, currently operate. However it is expected that second generation devices will be capable of operating in water depths greater than 50m and will therefore be capable of capturing a much greater percentage of the technical energy resource.

A minimum water depth of 20m has been selected as this provides adequate clearance for a 15m diameter turbine to operate. It is not practicable at this time to use turbine diameters less than 15m for tidal energy generation

4.1.2 Wave Climate of Offshore Site

In cases where the structure extends above mean sea level, it will be exposed to breaking waves in shallow water and must be capable of withstanding shock pressures. Wave and current forces will also act on the submerged structure from the existing seabed level to the maximum wave crest level.

Figure 4.1 shows the wave height and direction roses for five locations around the coast of Ireland. The roses for the swell wave component of the wave climate are also shown.

On the west coast waves of over 12 metres occur in the offshore area, with wave directions mainly in the south west and north west sector. There is a high proportion of swell wave activity in this area with swell waves greater than 1 metre for more than 50% of the time. Swell wave periods can exceed 21 seconds with 12-15 second periods occurring quite frequently.

In contrast to the west coast, the wave climate in the Irish Sea is much less intense with wave heights typically less than 6 m and wave periods less than 9 seconds. Atlantic swell waves do not penetrate significantly into the main body of the Irish Sea so that the swell wave activity at the Codling and Arklow Banks is relatively benign. The full effects of wave action on turbine efficiency should be the subject of further research by developers.

4.1.3 Geotechnical Suitability for Sub-Base Structures

Seabed conditions vary significantly around the coast of Ireland. The west coast is characterised by deep water relatively close to the shore with the presence of large bays and estuaries. These estuaries, including the Shannon Estuary, generally consist of soft muds, sands and gravels, underlain by rock at shallow depths.

The south coast is characterised by deep water close to the shore, with the seabed generally consisting of rock. The east and south east coasts are characterised by shallow water nearshore and the presence of sand banks and beaches.

The design of offshore foundations is influenced by the geotechnical stability of the bearing strata and sub-sea strata and the type of foundation being considered. For example, sandbanks provide suitable conditions for a range of foundation types whereas an undulating rock surface makes bed preparation very difficult for gravity structures and is more suited to piled foundations. For gravity structures located on sandbanks, they must be protected against deep scour and potential mobility of the seabed. Piled foundations may have to contend with variable pile driving conditions.

Notwithstanding the above comments, potential sites will require a detailed site investigation which will include bathymetric and geophysical surveys, boring, drilling, sampling, soil testing and interpretation of the results for each strata encountered, before any detailed design can be carried out.

4.1.4 Defined Area Restrictions

The Department of Communications, Marine and Natural Resources document – ‘Offshore Electricity Generating Stations – Note for Intending Developers’ provides details of area restrictions as follows:

(i) Shipping Lanes

Traffic separation zones are in operation around the coast of Ireland in areas where shipping congested or where vessels are manoeuvring in confined spaces. These zones are located off Tuskar Rock, Mizen Head and Fair head.

Principle shipping routes are shown in **Figure 4.2**, however detailed information on routes and destinations is not available. Commercial shipping on the west coast of Ireland using the ports of Galway, Foynes, Killybegs and Sligo needs to be considered.

Although the Shannon sites lie on or near shipping zones the resource has not been restricted because it is expected that the required number of turbines can be installed. When further research on wake effects has been carried out the spacing of turbines can be more accurately defined.

(ii) Military Zones

The largest military areas around the coast of Ireland include the naval base in Cork Harbour, County Donegal and County Meath. The main army training centre is located on the south coast of Ireland at Bere Island.

Air and naval firing ranges are located in the sea area off County Meath, County Cork and Cork Harbour.

Fishery Protection Patrols carried out by the Irish Naval Service Ships and Department of Agriculture and Rural Development occur daily within the fishery limits.

The Admiralty charts indicate the locations of sub-marine exercise areas including an area off the east coast of Ireland, outside the area of Irish territorial waters. For development in these areas it will be necessary to consult with the Ministry of Defence for further site specific information.

(iii) Sub-Marine Pipelines and Cables

The majority of cables and pipelines extend from the east coast of Ireland with the exception of two which extend from the south coast, as shown in **Figure 4.2**. A 500m exclusion zone has been shown on either side of the pipes and cables but this zone may increase to 1000m depending upon the requirements of the individual operators.

(iv) Others

Other restrictions include areas which are used for aggregate extraction and licensed dump sites.

4.2 Practical Resource Evaluation

The energy resource will therefore be limited by the following constraints:-

- Water depth between 20m and 40m
- Sites outside major shipping lanes
- Sites outside military zones and restricted areas
- Sites which do not interfere with existing pipelines and cables
- 12 nautical mile limit
- Peak tidal velocity greater than 1.5m/s

It is expected that first generation devices will be limited primarily by water depth. Taking this into consideration and other factors previously listed a total of 11nr sites around the coast of Ireland were identified as having potential for the practical extraction of tidal energy. These eleven sites are shown in **Figure 4.3**.

Sites which were particularly exposed, subject to swell wave activity, or considered to have particularly turbulent flows were not considered as having potential for the practical extraction of tidal energy.

Of the eleven sites chosen detailed modelling of seven sites was carried out to determine the practical resource. An estimation of the resource at the remaining four sites was prepared.

Detailed Modelling

Inishtrahull Sound
Codling Bank & Arklow Banks
Tuskar Rock & Carnsore Point
Shannon Estuary
Ram Race – Copeland Islands
North East Coast
Strangford Lough

Resource Estimation

Gascanane Sound
Lough Foyle
Dursey Sound
Bull’s Mouth

For the purpose of the detailed modelling, Codling and Arklow Banks have been considered as two individual sites. Three locations in the Shannon Estuary have been modelled but the results have been combined to give a single figure for these sites.

The model which was used to determine the practical resource has a twin rotor system as the basis for its calculation of available resource. This technology and hence the model itself is restricted by certain basic conditions.

Taking depth and current velocity criteria into account, each site was assessed for the most suitable number of turbines which could be accommodated.

In general turbines are packed closely together across the flow, with no more than 5m clear distance between rotors. In the longitudinal direction the turbines are spaced at approximately 20 rotor diameters apart to allow sufficient distance for mixing of the flow between rotors to eliminate the energy deficit in the wake of the first row of turbines.

As previously discussed it is expected that it will be 2015 before tidal energy devices will have reached the stage of development where they can operate in peak tidal velocities of 1.5m/s, and this will only be achieved if intense research into the technology is carried out in the coming years.

In order to estimate the practical energy resource the rotor diameter and number of devices per site were chosen for each site after examination of water depth and physical constraints. The practical resource for each of the eleven sites is shown in **Figure 4.4**, and totals 2.633TWh/y.

This represents 6.27% of the predicted electricity consumption for Ireland in 2010.

A previous study was carried out for the Bulls Mouth site by *MarCon Computations International Ltd.* in 2002, for Mayo Energy Agency. This study considered two cross-sections, one across Bulls Mouth, which yielded a resource of 1.52GWh/y, and the other through Bulls Mouth which yielded a resource of 21.22GWh/y. In our calculation of the practical resource we have considered the entire area and our calculations have estimated the resource to be 6 GWh/y.

4.3 Summary

1. Constraints on site suitability include water depth, seabed conditions and defined area restrictions such as shipping lanes and military zones. Each site requires individual assessment in relation to these parameters.

2. Following evaluation of these parameters, seven sites around the coast of Ireland were selected for detailed analysis.

3. The practical resource was calculated for sites with water depth between 20m and 40m and with a peak tidal velocity greater than 1.5m/s. The calculated resource was 2.633 TWh/year and represents approximately 6.27% of the predicted electrical consumption for the year 2010. However, depending on the rate of technological development this level of energy extraction is not expected to be available before 2010 and possibly not before 2015.

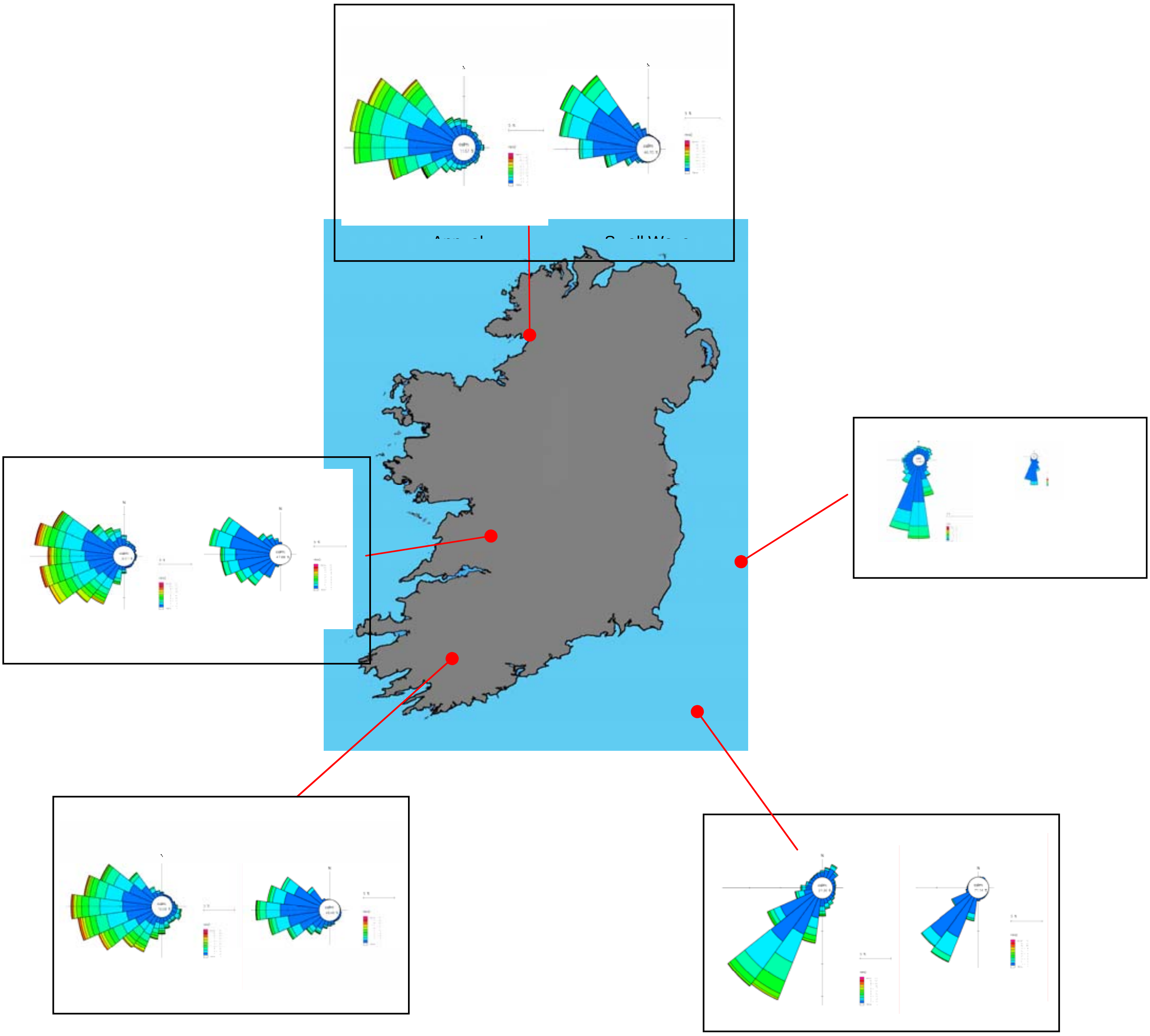


Figure 4.1 Wave Climate Around Ireland

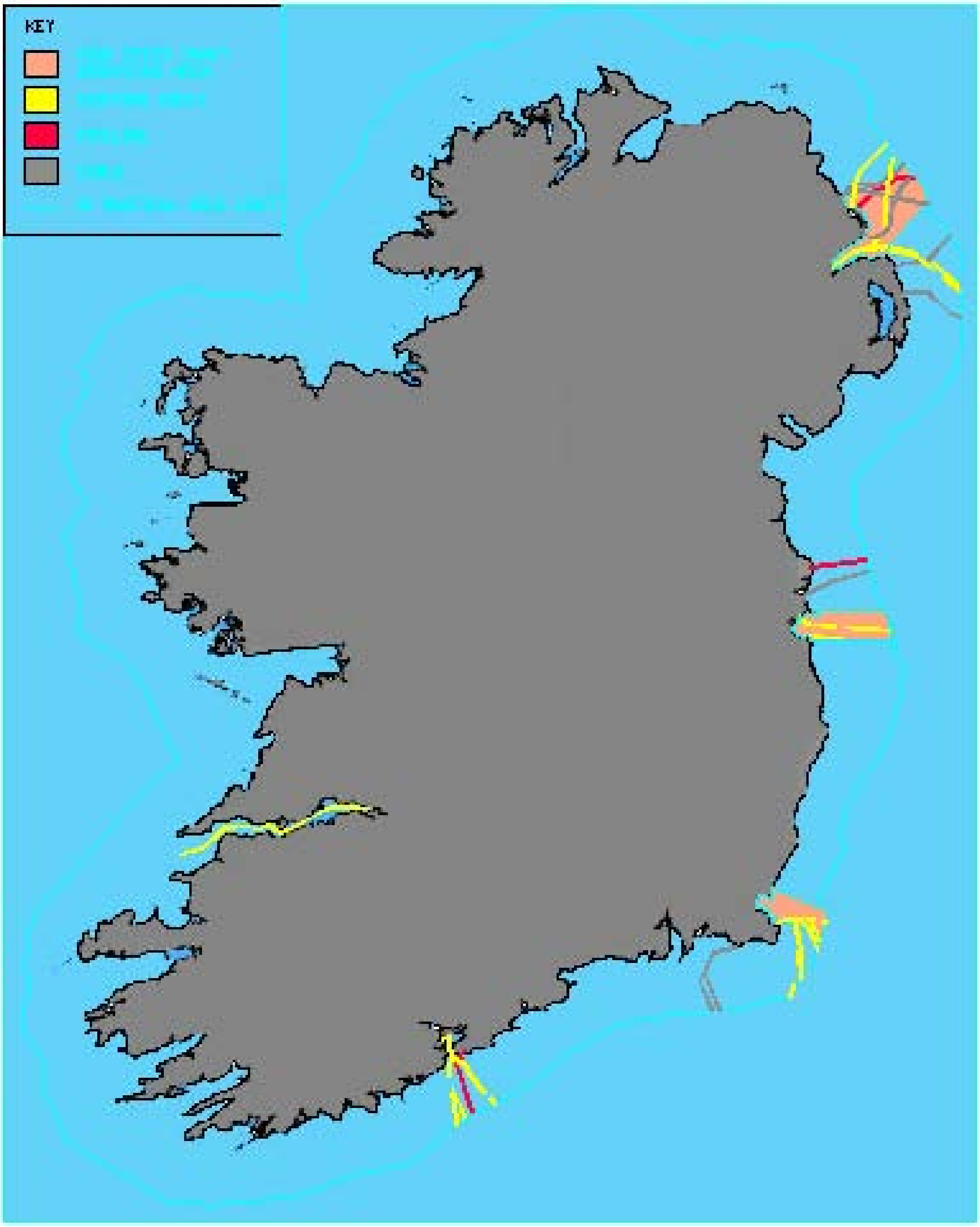


Figure 4.2 Pipelines, cables and Shipping Routes

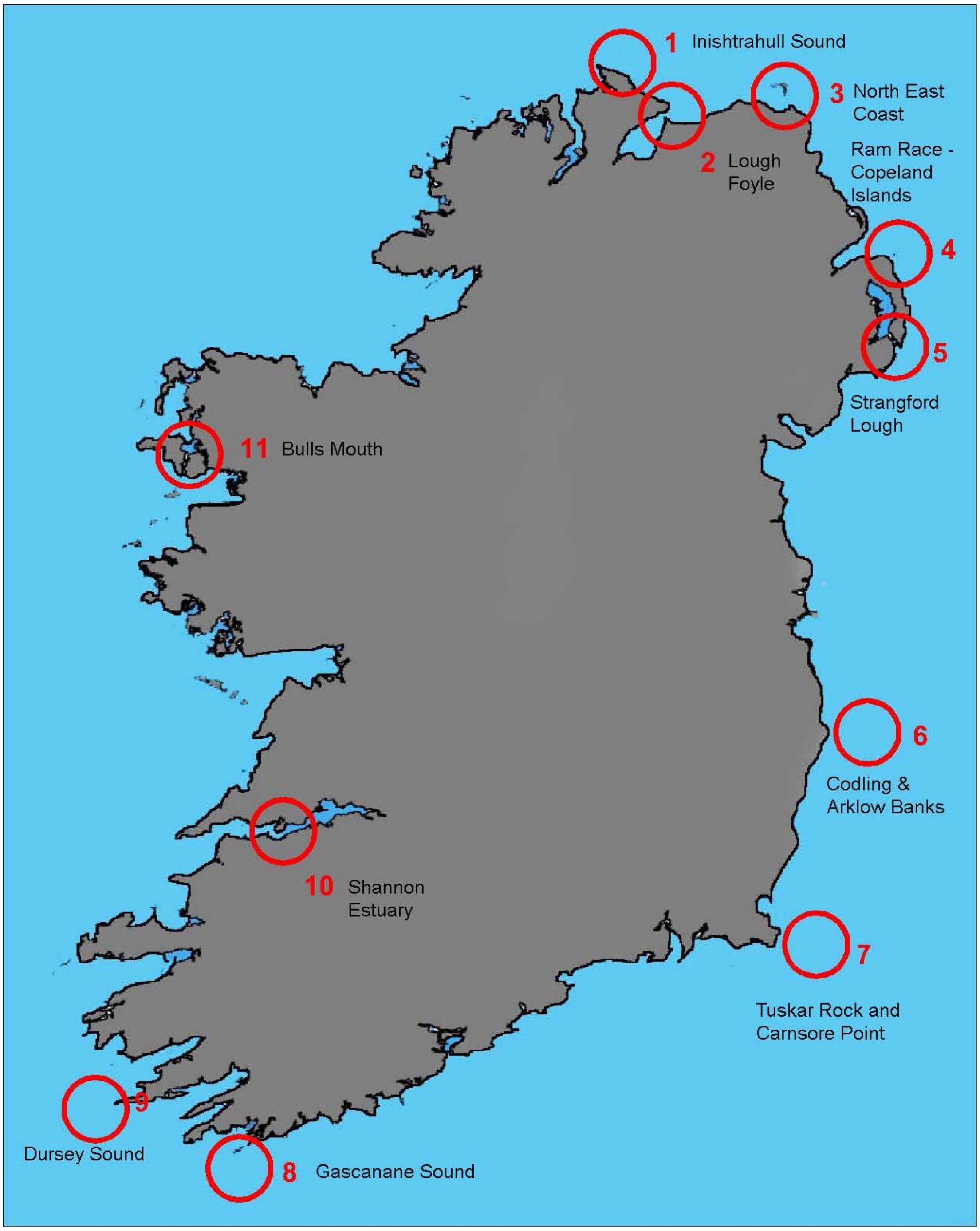


Fig 4.3 Practicable Resource Sites

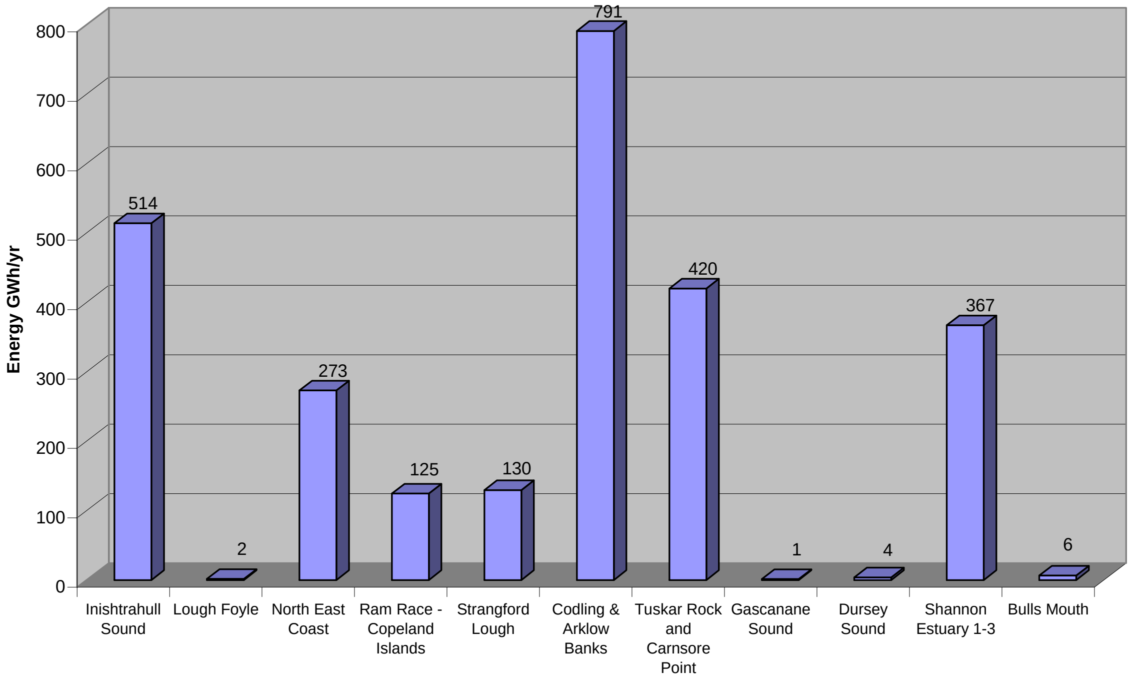


Figure 4.4 Practicable Energy Resource

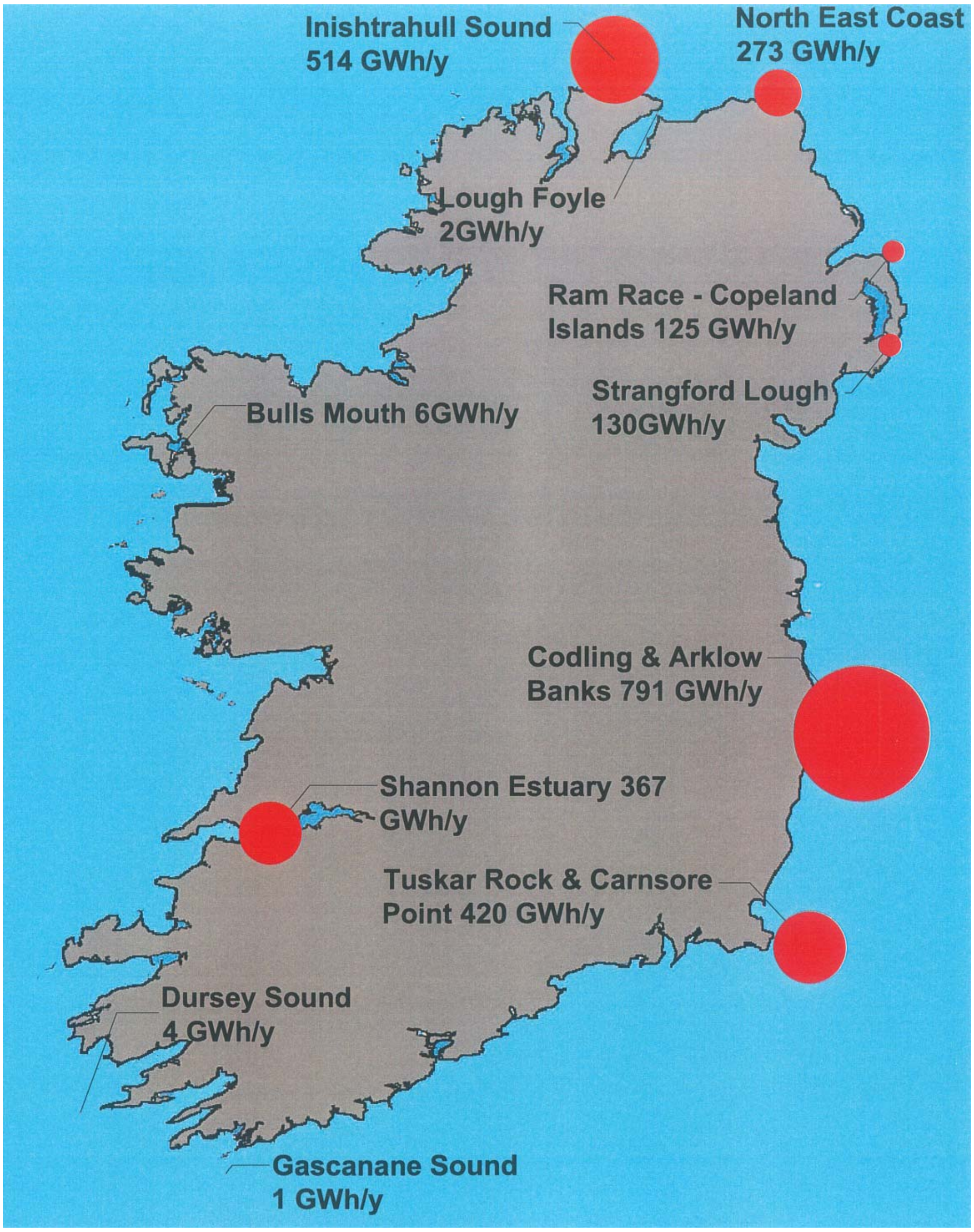


Figure 4.5 Practical Energy Resource

5.0 ACCESSIBLE RESOURCE

The "accessible resource" is the practical resource constrained by man-made, institutional and regulatory deletions which limit energy extraction. These may include environmental, health and safety and planning zonation. In this section the effect of these factors on the energy resource has been assessed.

5.1 Environmental Issues

The assessment of the tidal and marine current energy resource in Ireland needs to be viewed in the context of the impact of human induced climate change and global warming. While differing opinions may develop over the scale of impact there is now a broad scientific consensus on the threat from climate change and the need to reduce greenhouse gas emissions, particularly carbon dioxide, from fossil fuel consumption.

However, action to address these global environmental issues may result in negative environmental impact at a local level and it is important that full consideration be given to this local impact in assessing the costs and benefits of current tidal development and other renewable sources of energy.

As a first step to ensuring that the full environmental impact associated with the development of tidal energy in Ireland was considered, a desk study was carried out with various statutory bodies to determine the potential issues which could arise from the development of tidal power.

5.1.1 Characteristics of Tidal Energy Devices

A detailed description of tidal energy devices and associated technology is provided elsewhere in the report. However, the following points are relevant to the impact which these devices may have on the marine and coastal environment:-

- Technical assessments indicate that initially turbines will be constructed with foundations on the seabed thus limiting the location to a maximum water depth of 40 metres. The number of turbines per site could be in the 5nr to 50nr range.
- For safety reasons it is expected that the area within a tidal farm will not be navigable. Given the potential number of turbines in an array and the distance required between turbines (300-500 metres), ships, fishing boats, and recreational boats may be excluded from the farm area.
- Each array of turbines will be linked with an underwater network of cables. Power from the farm will be taken ashore and from that point will be conveyed to the national grid by overhead or underground cables. The provision of overhead power lines may give rise to particular concerns in sensitive coastal landscapes.

5.1.2 Scoping of Environmental Issues

The first stage of the investigation was to generate a range of preliminary environmental impacts associated with the issues outlined above.

The preliminary considerations have included the following:-

- Benthic ecology
- Fisheries and spawning grounds
- Marine Mammals
- Recreational users
- Migrating and other sea birds
- The visual character of the coast
- Underwater archaeology
- The effects of cable connections on and close to the coast

Each of the preliminary issues are dealt with below in the context of potential environmental impact and recommendations are made on action that can be taken to ensure that these issues are addressed in any future development of tidal energy.

Benthic Ecology

The benthic ecology in the vicinity of the marine current turbine may be affected by the foundations and seabed disturbance associated with installation of devices.

An application for a tidal energy facility should be supported by a detailed ecological assessment of the site and its environs.

Fisheries and spawning grounds

Three types of stock should be considered:-

- Highly mobile stocks including cod and whiting
- Inshore stocks including whelk and razor shell
- Migratory stocks including sea trout and salmon.

The impact of tidal energy devices should be considered under the following:-

- The affect of the structures and related cabling on existing stocks or their food sources.
- The physical disruption or reduction in available fishing grounds.
- The impact of structures and cabling on habitats such as spawning gravel for herring.

Impact on the fishery in Irish waters may affect not only fishermen from Ireland and the UK but also significant numbers from Belgium, France, and the Netherlands

Marine Mammals

There are significant numbers of cetaceans and seals in Irish coastal waters. For example in the Shannon Estuary there is a colony of Bottlenose Dolphins. Vertical and horizontal axis turbine devices could cause problems for marine mammals in terms of collisions and impact on their echo-sounding ability. The impact of turbines on marine mammals during construction and operation will need to be fully investigated as part of any application.

Recreational users

Recreational activities which take place on the coast include:-

- Walking
- Swimming
- Watersports
- Sailing (all types)
- Canoeing
- Offshore angling
- Sea angling
- Diving.

All of the activities listed above are dependant to a greater or lesser extent on the quality of the surrounding environment for the pleasure they give to the participants. The value of the recreational resource is based strongly on their location in an attractive environment. They may be affected in some way by any visual and audible impact of the turbine. The water based activities may also be adversely affected if access to areas of open water previously available to them is restricted for safety reasons.

There may also be a real or perceived effect which could impact on the use of adjoining waters for sailing. Recent research carried out by the ISA (Irish Sailing Association) has identified the scale of involvement in sailing in Ireland and the potential for sailing based tourism development.

Sea angling has been developing in recent years and is now a part of the tourism product sold at home and overseas. Restrictions in access to areas of relatively shallow water should be assessed to establish if there could be a negative impact on this developing activity.

Migrating and other sea birds

A possible concern is the affect on migratory seabirds and/or coastal colonies. Whilst the above water structures may not interfere greatly with seabirds in flight, the below water structures could prove to be a hazard to diving birds.

There is also concern that lighting of the structures at night could affect migrating birds. This may be mitigated against by using suitable lighting.

The visual character of the coast

As the greater part of the marine current turbine is underwater, the visual impact should be negligible. However, there may be landside developments associated with the marine current turbine which will be situated on the coast, and the visual impact of these buildings will need to be assessed.

Underwater archaeology

There are numerous sites of shipwrecks both recent and ancient in the shallow underwater banks and shoals around the coast. Some of these sites are under the protection of the Heritage Service of the Department of Environment, Heritage and Local Government and the National Museum of Ireland.

Government departments will require a full assessment of any marine current turbine site to determine if any listed shipwrecks would be affected and may refuse permission for such development if a particular site was considered to be in danger.

It is noted that shipwrecks are generally compact sites and if a turbine base does not directly affect a site there should be few concerns in this regard. The matter would be assessed within an EIS which should accompany any application. A distribution density map for offshore archaeological sites is currently being prepared.

The effects of cable connections on and close to the coast

The cabling associated with the structures may have environmental impact in the following areas:-

- affects on shore and seabed ecology and habitat
- potential reduction in available fishing grounds
- potential disruption of recreational activities

These are matters which will require site specific investigation.

Safety and navigation

In the Republic of Ireland, safety and navigation are the responsibility of the Marine Safety Office of the Department of Communications, Marine and Natural Resources. Safety and navigation issues will need to be fully addressed.

5.2 Statutory Permissions and Planning Legislation

5.2.1 Republic of Ireland Legislation

A distinct land / marine divide is evident in the legislative framework with separate legislation governing land and marine based activities and environmental protection. The legislation which will be relevant to a proposal for a tidal energy device includes:-

- Planning and Development Act 2000
- The Foreshore Acts 1933-1992
- EC Environmental Impact Directives 1985 and 1997
- National Monuments Act 1930-94
- Conservation Designations (SAC, SPA, NHA)

5.2.2 Coastal Developments

The land beyond the high water mark is normally outside the jurisdiction of the planning authority. The Foreshore Acts (1933-92) were specifically enacted ‘for the protection and preservation of the foreshore and of coastal areas.’

The term foreshore refers to the seabed and the shore below the line of high water, of the sea and of every tidal river and tidal estuary and of every channel, creek, and bay of the sea or of any such river or estuary. The seaward limit of the foreshore extends 12 nautical miles from the coast, but may be increased to 200 miles in line with the UN Law of the Sea. The state currently owns most of the foreshore.

The seashore means the foreshore and every beach, bank and cliff contiguous thereto and includes all sands and rocks contiguous to the foreshore.

The Minister for the Department of Communications, Marine and Natural resources may grant a lease of the State foreshore if it is in the public interest to do so. The lease can refer to the foreshore itself or any buildings/structures thereon. A foreshore lease confers property title for a specified period and allows exclusive use of the foreshore and the right to undertake certain works.

Development of the foreshore is regulated under section 12 of the Foreshore Act and provides for the erection of any building, piers, walls or other structure on state foreshore. It is unusual to obtain authorisation from the Minister for the Department of Communications Marine and Natural Resources for any development on state foreshore until planning permission and various matters which may be required under other legislation for the same development has been obtained. Both a foreshore license/lease and planning permission may be required for development that adjoins, abuts or is adjacent to the functional area of the planning authority.

The Department of Communications, Marine and Natural Resources has issued the document; ‘Offshore Generating Stations – Note for Intending Developers’, detailing all consultations and permissions required for such a development and identifies restricted and prohibited areas around the coast. A full list of restrictions and permissions is given in **Appendix C**.

5.2.3 Environmental Impact Assessment

EU Directive 97/11/EC, amending Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment requires that:

“*Member States shall adopt all measures necessary to ensure that, before consent is given, projects likely to have significant effects of the environment by virtue, inter alia, of their nature, size or location are made subject to a requirement for development consent and assessment with regard to their effects (Article 2).”*

The European Communities (Environmental Impact Assessment) (Amendment) Regulations, 1999 (S.I. No. 93 of 1999) transposed EU Directive 97/11/EC into Irish law. Under these regulations the preparation of an Environmental Impact Statement (EIS) is mandatory for installations for the harnessing of wind or wave power for energy production with more than 5 turbines or having a total output greater than 5 MW. It is expected that an EIS will be required to accompany the foreshore license application for a tidal energy device.

Prior to the preparation of an EIS the applicant should consult with all relevant parties, particularly those likely to be affected by the project. These consultations should be carried out at an early stage in the project planning so that potential conflicts can be identified and where possible the project can be modified to overcome them.

5.2.4 National Monuments Act 1930-94

The National Monuments Acts (1930-94) makes extensive provision for the protection and preservation of national monuments, historic monuments and archaeological areas. These Acts operate in addition to the planning controls and are relevant to this study as they apply to the seabed, which is outside the jurisdiction of the planning authority. The Acts can impose tighter restrictions than would be expected under planning legislation on developers whose development affects a listed site.

5.2.5 Special Protection Areas (SPA)

Special Protection Areas (SPAs) are designated because they are important habitats for birds. The legal basis for the SPA is the European Birds Directive (79/409/EEC). The Birds Directive is incorporated into Irish law mainly by the Wildlife Act, 1976 and the European Communities (Conservation of Wild Birds) Regulations, 1985. Under the Birds Directive, Ireland is required to conserve the habitats of:

- Listed rare and vulnerable species of birds; and
- Regularly occurring migratory species of birds.

Those areas that warrant protection are categorized as Special Protection Areas (SPA) within which steps must be taken to avoid any pollution, deterioration and excessive disturbance affecting the wild birds. Only activities which do not have significant effects on birds are permitted in SPAs.

5.2.6 Special Areas of Conservation (SAC)

Special Areas of Conservation (SAC) are among the most important areas of wildlife in Ireland and throughout the European Union. The legal basis for the SACs is Council Directive 92/43/EEC of 21 May 1992, commonly known as the Habitats Directive. The aim of the Directive is to ensure the protection of biodiversity through the conservation of natural habitats of wild flora and fauna. The Directive is binding on the Member States and its agencies. The Department of Environment, Heritage and Local Government is the statutory agency responsible for the selection and designation of SACs.

5.2.7 Natural Heritage Areas (NHA)

The NHA designation is the basis for the protection of Irish natural habitats and is a National designation. NHAs include the best of Ireland’s remaining natural habitats and emcompass 1,246 sites. The NHA designation evolved from the Area of Scientific Interest (ASI) designation. NHAs have statutory protection under a recent amendment to the 1976 wildlife Act. The statutory body with responsibility for NHAs is the Department of Environment, Heritage and Local Government.

The Natural Heritage Areas, the Special Areas of Conversation, and Special Protection Areas for the 11 potential sites previously identified have been shown in **Appendix D**. A brief description of each of the designations is also provided.

5.3 Summary

1. An environmental impact statement will be required for each site and therefore the accessible resource has not been adjusted for the environmental constraints discussed in this chapter. The accessible resource is therefore the same as the practical resource, i.e. 2.633 TWh/y representing 6.27% of Irelands' predicted electricity consumption in 2010.

2. For each site a foreshore lease/licence and planning permission will be required from the relevant statutory authorities.

3. The scope of the Environmental Impact Statements will include, but may not be limited to the following:

   Benthic Ecology
   Fisheries and spawning grounds
   Marine mammals
   Recreational issues
   Migrating and other sea birds
   The visual character of the coast
   Underwater archaeology
   The effects of cable connections

6.0 VIABLE RESOURCE

The “viable resource” is the practicable resource constrained by matters of commercial viability. These may include development cost, scale, resource distribution, market reward, timing and other risk which will be variable over time.

In order to calculate the viable resource, detailed computational hydraulic models have been produced and suitable turbine arrays selected for the 7 sites for which detailed modelling was carried out in determining the practical resource. This data formed part of the input to the techno-economic model and an iterative process of optimisation of these and other parameters was carried out in order to determine the viable resource.

Each site was examined individually in order to determine the most suitable turbine array. In general the turbines have been positioned in rows across the current leaving adequate space for shipping to bypass the array, generally in slower moving water. The turbine array for Codling and Arklow Banks is given in **Figures 6.1 & 6.2.** Turbine arrays for all other sites are given in **Appendix E.** These are only approximate as more detailed site analysis would be needed to establish precise locations for each turbine.

6.1 Techno-Economic Model

In order to determine the viable tidal energy resource and provide costings for particular sites the techno-economic model developed by Marine Current Turbines Ltd (MCT) was used. This model is based on the MCT Seaflow device and an earlier version of this model was independently evaluated for the UK government Department of Trade and Industry in 2001[10]. A techno-economic analysis has previously been carried out for sites in Northern Ireland as part of the Northern Ireland study[21].

The model has a double sinusoid algorithm which provides an acceptable representation of the variation of current velocity over a complete cycle. The model can also indicate the size of a turbine for a specific location once key parameters including water depth, wave height, rotor size and maximum velocities are known. In addition to this the analysis will also yield the size and hence cost of key components including system structure, gearboxes and generators.

The model has been validated against known industrial costs and contains cost-functions for a range of bought-in components. All anticipated costs in addition to the turbines and support structures themselves, such as site preparation overheads (site surveys/mobilisation etc.) and fixed site overheads (grid connection/pile installation) are costed. Hence the model can calculate the total capital cost of a project with a specified number of turbines in a given location.

6.1.1 Physical Constraints/Assumptions

Generating efficiency increases with higher velocities and in depths which permit the largest rotor sizes that can be economically installed with existing technology. The following constraints were applied.

- Minimum water depth of approximately 20m so that a minimum rotor diameter of 15m can be accommodated. This constraint applies to all tidal energy devices and is not confined to the MCT model.

- Maximum water depth in the short to medium term of approximately 40m due to the depth limitations of jack-up barges and other marine plant.

- Mean maximum spring tide current velocity preferably exceeding 2.5m/s but always exceeding 2.0m/s. This is purely for economic reasons as energy availability is proportional to velocity cubed. Velocities significantly slower than 2.5m/s have insufficient energy for cost-effective generation.

- For sites where the distance to the national grid was indeterminate a value of 133% of the distance to shore was used. The grid connection costs are most significant for small projects where they can represent a large investment.

- For each site a turbine rotor size was chosen to suit the average depth of water. A minimum of 2m water above the rotor and 3m between rotor and the seabed was chosen. Taking LAT into account, rotor sizes of approximately 7m less than average water depth were chosen.

6.1.2 Financial and Operational Assumptions

The model calculates lifecycle costs based on a Discounted Cash Flow (DCF) analysis to discount the capital cost (an 8% discount rate over 20 years was used in this case). Using a discount rate of 10% would have the effect of increasing the unit cost of electricity by a factor of 1.095 on average, i.e. a 9.5% increase in lifecycle unit costs). The model has data on O&M costs (taken to be 3% of the gross capital baseline cost), anticipated insurance premiums and sea bed rental fees based on UK experience. Recent increases in the cost of steel have also been applied

For the purpose of estimating revenue, the machine availability is taken to be 90%, allowing for a downtime of one month in twelve. It is expected that downtime in exposed locations would be greater than this but would be less in more sheltered locations. No allowance has been made in this analysis for the significant difference in exposure between sites on the Shannon and those offshore.

6.1.3 Model Input

Input data required for the techno-economic model includes details of the computational models, turbine layouts and rotor sizes, the neap/spring tidal velocity ratio, the ebb to flood tide ratio, water depths, wave heights and typical costs for foundations, grid, operation and maintenance.

Foundation Costs

Large variations in foundation costs depending on seabed conditions, water depth and site location are to be expected.

The foundation costs are normally dependent on the following matters:

- Site Investigation
- Licences
- Environmental Assessments
- Detailed Design
- Material procurement and fabrication
- Documentation
- Insurance
- Port Dues
- On/off loading
- Onshore/Offshore transport
- Seabed preparations
- Positioning
- Offshore craneage
- Installation
- Cable laying and hookup
- Commissioning

Tidal energy devices are to be located in water depths greater than 20m, and foundation costs will increase significantly with increased water depth. As water depth increases there is a potential increase in hydrodynamic forces on the structure and hence an increase in the structural bracing requirements.

Steel foundation costs are more difficult to predict for water depths greater than 30m, with environmental loads becoming more variable with depth and the whole concept of the foundation changes in respect of bracing elements, configuration and installation methods. Typical foundation and structure costs are expected to be in the order of €300,000 – €500,000 per system.

Grid Costs

Offshore sites require an undersea link and a connection to a suitable grid point. Indicative costs for a site located 10km from the shore are provided in **Figure 6.3**.

It has been assumed that:-

- The distance from shore relates to the stream location for that area.
- The turbine units each consisting of two turbines are spaced 65 m apart.
- The cabling will support the resource from that area.
- The land connections can be made by a 20 kV to 38 kV line and that no underground cabling is required apart from 1 km from the sea to a connection point on land.
- The on shore distance is selected to suit the nearest grid point that could support the available power level
- The turbine farm to land undersea cable will be rated at 11 kV to 38 kV and will be buried.
- The interconnection between turbines and associated node will be at 1.1kV and will be buried.
- Generation will generally be at 1.1 kV and will be grouped around nodes where transformation to a suitable higher voltage will take place.
- No consideration has been given to the costs of obtaining permission for new power lines.

Whilst costing has been indicative only it does illustrate the variation between sites. It is evident that a detailed study will be required for each site before more accurate costs for the electrical connection can be established. The turbine units are assumed to be in electrical groups of three and a high-voltage cable connection is made to a node in each group. The group is then interconnected at 1.1 kV. A high-voltage cable interconnects the nodes in a ring. The ring is assumed to be sectionalised by operation with an open breaker at the mid point.

Operation and Maintenance Costs

The costs associated with operation & maintenance (O&M) of tidal energy devices are expected to be in the order of 2%-5% of the total energy costs and will depend on the number of devices in the tidal farm. Reasons for such high O&M costs include:

- Access to the turbines will be restricted to calm periods only. It is unlikely that transfers from access craft to structures will be carried out in conditions exceeding 1.5m significant wave height.

- Replacement of damaged or failed components will necessitate the use of a floating or integral crane or jack-up platform. This will be an operation which may also be prone to weather delays.

- O&M costs will be associated primarily with the turbines but some of these costs will be associated with the foundations and cabling which require inspection at regular intervals.

6.1.4 Model Optimisation and Output

The model was optimised for each site by selecting a rated velocity for the turbines which minimises the cost of generating electricity. A compromise is always needed between a system that is oversized and hence too costly and a system that is undersized and incapable of delivering sufficient energy hence the model can find the rated velocity and power which results in the most cost-effective solution.

The energy capture is then calculated and reduced to allow for 90% machine availability to arrive at the actual energy capture per unit, and hence per site.

Finally the capital cost of each project is given together with the average cost of generation. Capital investment varies from €1700/kW installed in the Shannon estuary to €3700/kW at the Codling Bank. Unit generating costs corresponding with these figures are in the 10 cent/kWh to 20 cent/kWh range.

Although these costs are high compared to conventional power generation, they should be considered in the context of the following:-

- This is a new technology at an early stage of development. Wind turbine generated electricity today costs approximately 25% in real terms of its cost when first generated some 20 years ago. It is expected that costs will reduce to somewhere in the region of 50% to 75% of today's costs as technology improves and the benefits from increased scale of manufacture are realised.

- Most of the proposed projects are quite small, less than 10MW, and all energy technologies cost more when deployed on a small scale. This is particularly true for marine technologies where relatively large overhead costs apply.

- The projected costs are all inclusive. They cover the anticipated infrastructure costs and overheads as well as the pure technology costs. Many energy technologies are promoted on the basis of the system costs but without overheads such as connection costs.

- The technology considered here is "first generation" and is constrained by as yet undeveloped installation systems. It is expected that if this technology proves to be effective, then more cost-effective "second generation" technology will evolve which may be suitable for use in deeper water and on a larger scale. This could provide access to resources which are not available at this time.

- The unit energy costs apply for the period of 20 years over which the capital cost is amortised. An installation, especially in a sheltered location such as the Shannon Estuary, has the capability of being operated for much longer (albeit with replacement of major drive train components every ten years). Once the capital cost is written off, the generating costs will fall to a much lower level. In this respect the technology is analogous to hydro power where initial generating costs tend to be relatively high, but the long life of these systems permits attractively low cost operation in later years.

6.2 Viable Resource Evaluation

From the techno-economic model the viable tidal energy resource for Ireland has been estimated as 0.915 TWh/yr and represents 2.18% of Irelands predicted electricity consumption for 2010. This is based on a peak tidal velocity of 2.0m/s and water depths between 20m and 40m.The viable resource for each of the eleven sites is given in **Figure 6.4 and 6.5.**

A large proportion of this resource is found along the east coast of Ireland with three of the main sites along the coast of Northern Ireland. The only sizable resource on the west coast of Ireland is located in the Shannon Estuary.

6.3 Levelised Cost

Levelised cost comparisons are widely used to compare power plants, however they are also useful for comparing different forms of renewable energy. The method utilises the capital, operating and maintenance, and fuel prices together with the annual electrical output to produce a levelised electricity cost in terms of c/kWh. It is the present value of all costs divided by the present value of outputs.

A levelised cost graph, **Figure 6.6,** has been developed for the tidal energy resource in the Republic of Ireland and Northern Ireland, using the output from the corresponding techno-economic models. It can be seen that there are large variations between the costs for Northern Ireland and the Republic of Ireland which illustrates how relatively small differences in peak velocity and water depth have a significant effect on the levelised costs at this stage of development. It is anticipated that with further development of tidal energy devices the costs for the Republic of Ireland will align themselves more closely with those costs for Northern Ireland.

6.4 Summary

1. The viable resource for all sites identified for further study in Section 4.0 was calculated as being the practicable resource at 2.0m/s, since energy extraction at lower velocities is not considered to be economical with first generation devices.

2. The techno-economic model developed by Marine Current Turbines Ltd (MCT) has been used to determine the viable resource at the sites which were selected for detailed modelling. For each site the number of turbines, rotor diameter and rated turbine velocity were specifically chosen to optimise power generation at that site. Output from the model included the energy capture per project and the unit capital cost for each site.

3. The viable tidal energy resource for Ireland has been estimated as 0.915 TWh/yr and represents 2.18% of Irelands predicted electricity consumption for 2010.

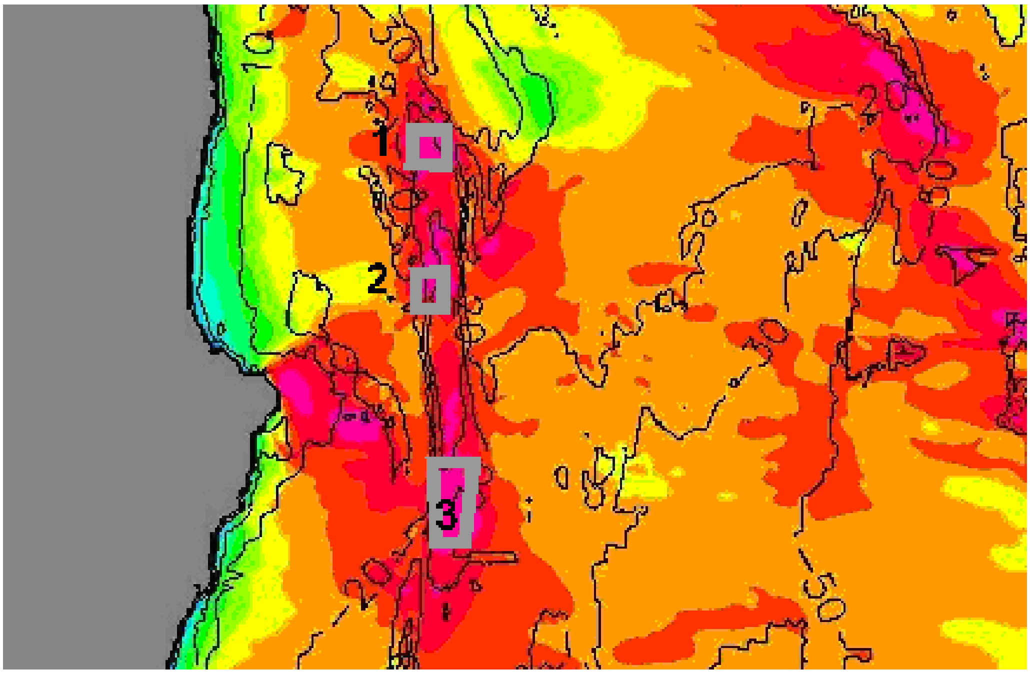
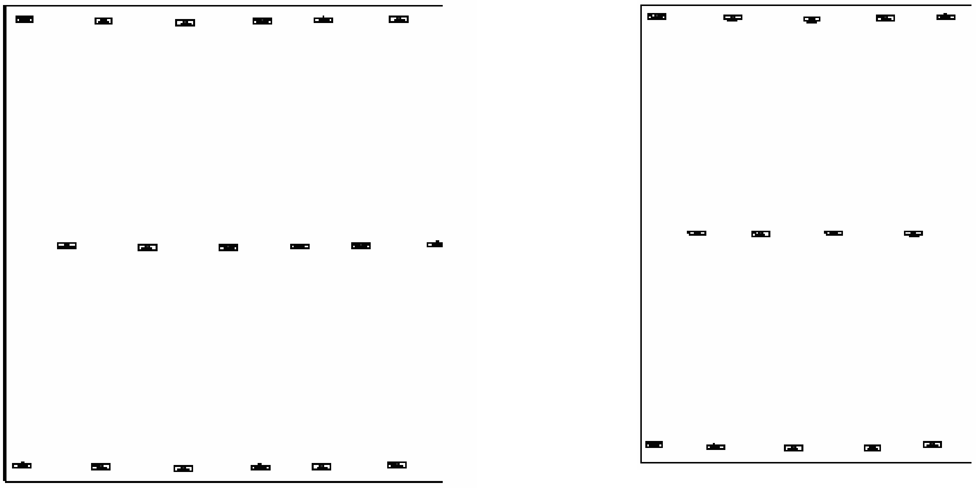


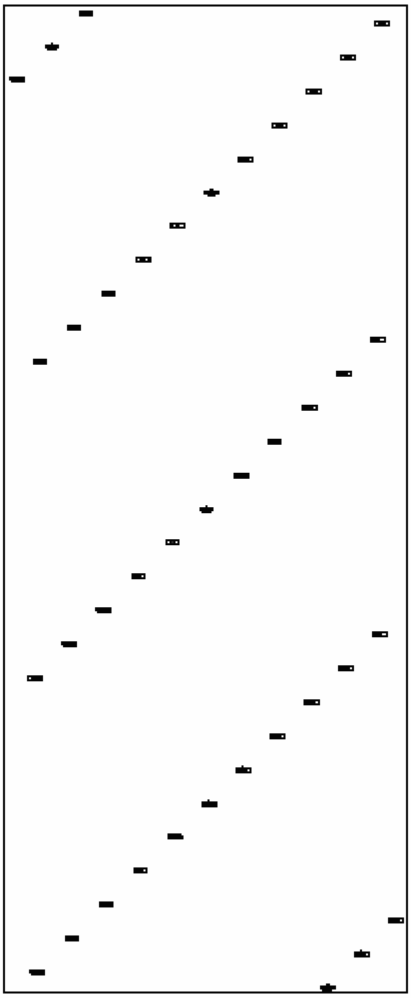
Figure 6.1 Turbine Array Locations at Codling & Arklow Banks



Site No. 1 – 1.5x1.5km

Site No. 2 – 1.2x1.5km

Figure 6.2a Turbine layout



Site No. 3 – 1.5kmx3.5km

Figure 6.2b Turbine Layout

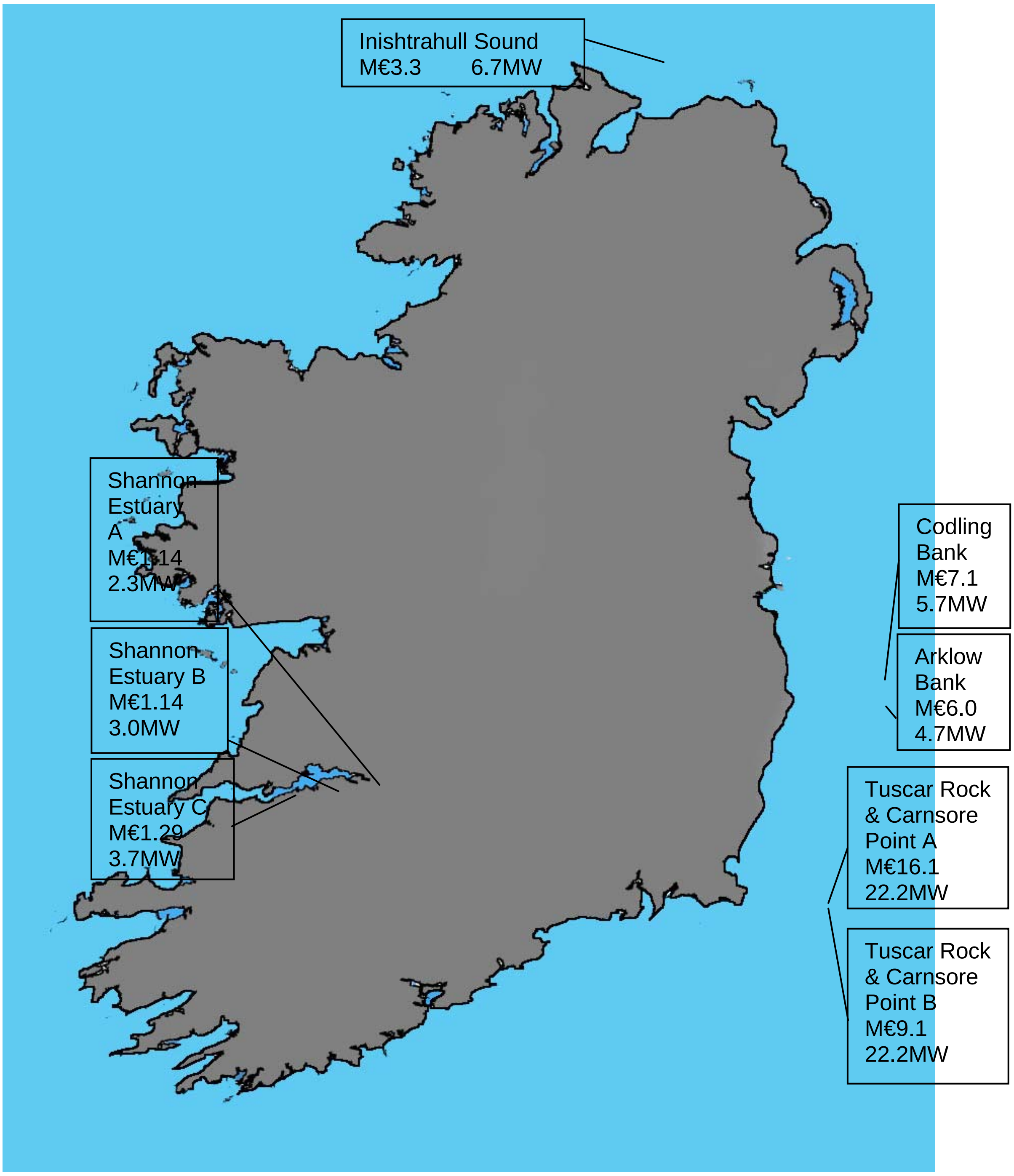


Figure 6.3 Connection Costs in Millions of €

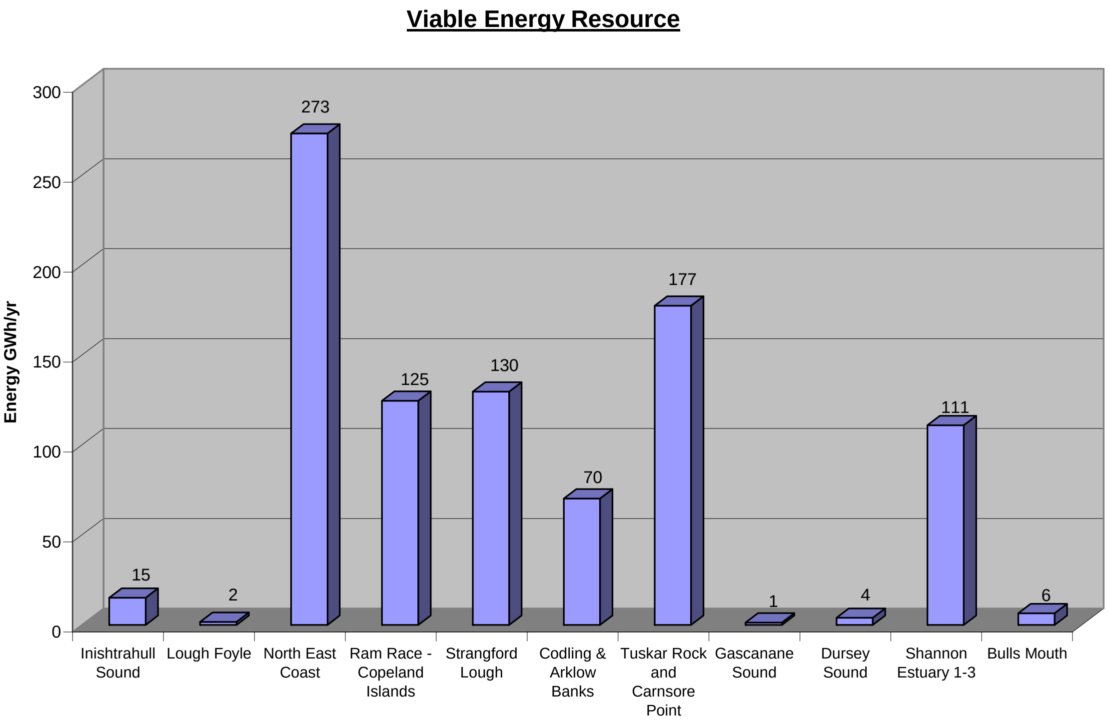


Figure 6.4 Viable Energy Resource

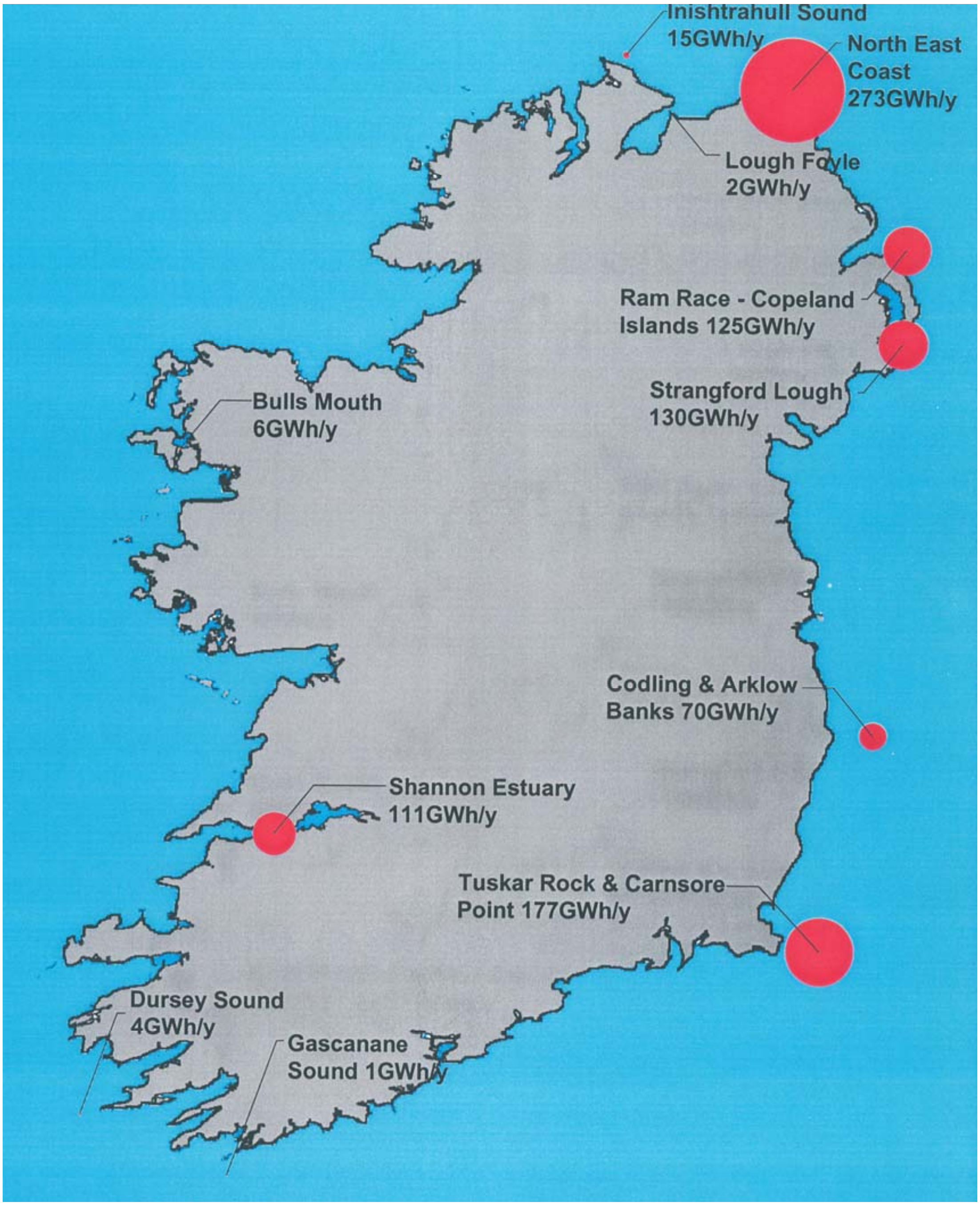


Figure 6.5 Viable Energy Resource

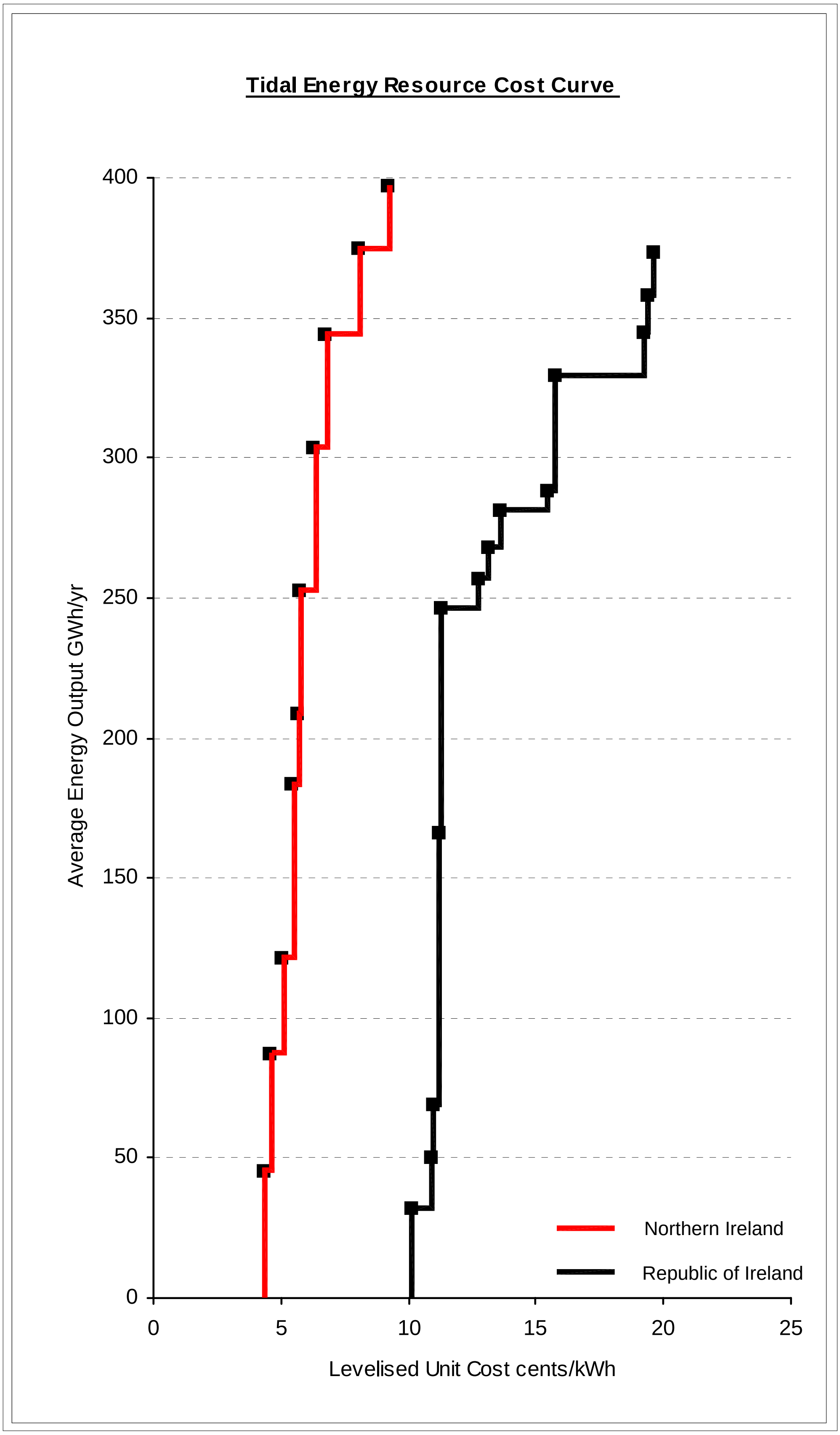


Figure 6.6 Tidal Energy Resource Cost Curve for Northern Ireland and Republic of Ireland

7.0 CONCLUSIONS

7.1 A significant proportion of the tidal and marine current energy resource is to be found on the east coast of Ireland. The resource on the west coast is concentrated in the Shannon Estuary.

7.2 Tidal energy technology is in the early stages of development and stream velocities of at least 2.0m/sec are required for efficient generation. With further technological development, efficient generation from stream velocities of 1.5m/sec should be practicable by the year 2015.

7.3 When technical, physical, institutional and commercial viability constraints are applied the resultant energy resource, referred to as the Viable Resource, reduces to approximately 0.915 TWh/year and this represents 2.18% of the predicted electricity consumption for the year 2010. This figure could rise to 6.27% of the predicted electricity consumption between 2010 and 2015.

7.4 Environmental constraints, specific to each site, may also apply and in such cases exploitation of the viable resource may be affected.

7.5 Many devices are in their infancy as development remains at an early stage. Largely due to commercial confidentiality, detailed information on test results is not widely available.

7.6 A re-assessment of generating viability after a period when further test data should be available is recommended.

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