Optimising network integration of wave energy using Geographical Information Systems (GIS) and power flow techniques

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SYNOPSIS

The UK government is promoting marine energy as means to help meet its renewable energy targets. A variety of wave energy and tidal current devices are being developed and within the next decade the first devices will become commercially available. The UK has a vast wave energy resource, with the most favourable sites located off the west coast of Scotland. However, this is the region of the UK with the weakest electricity network infrastructure as customers are generally supplied via long 11 kV and 33 kV radial circuits. This presents the challenge of how to deliver the energy produced from the remote offshore, resource-rich locations, to the onshore consumer base. A novel integrated geographical information system/power flow model is described that is used to identify areas of suitable wave energy resource iri closest proximity to available network capacity to accommodate the new generation. This will allow sites that have the optimal recoverable energy to be identified allowing developers and network planners to identify sites that have greatest economic viability.

INTRODUCTION

The UK government has a target of producing 10% of its electricity needs from renewable sources by 2010, to aid achievement of the Kyoto target of reducing carbon dioxide emissions by 12.5% by the same date. The renewable energy target within Scotland is 18% by 2010, and the Scottish Executive has also set the further aspirational target of 40% by 2020. These targets, which are promoted through the use of Renewables Obligation Certificates that give renewable generators a preferential selling price, have stimulated the market for wind energy within the UK. It is becoming increasingly difficult for developers to obtain planning permission for onshore wind farms so a number of offshore farms are now being planned. However the government realises that it cannot rely solely on wind energy, therefore it is determined that wave and tidal technologies should play a part in the expansion of renewable energy generation [1]. The UK, and in particular Scotland, has a vast marine resource, which could greatly contribute towards the targets, if it can be successfully harnessed. There are a number of wave energy converters (WECs) under development, some of which have reached the stage of full-scale testing, and it is likely that they will be commercially available within the next decade. The WECs are unlikely to contribute greatly to the 2010 target, but there should be the opportunity for them to assist in meeting the 2020 target, providing that weak barriers can be overcome.

Authors' Biographies
Sarah Graham is currently in her third year of a PhD at the Research Institute for Energy Systems, University of Edinburgh. Prior to this she achieved a first class honours BEng in Electronics and Electrical Engineering in 1997, also from the University of Edinburgh.
Dr Robin Wallace is Head of the Research Institute for Energy Systems at the University of Edinburgh. In addition to his research in network integration of distributed generation, he is Principal Investigator on the Engineering and Physical Sciences Research Council's Supergen Marine Energy Consortium.
Dr Gareth Harrison is a Lecturer in Energy Systems at the University of Edinburgh. His research includes network integration of distributed generation, as well as analyses of the impact of climate change on the electricity industry with emphasis on hydropower, marine energy and electricity demand.

One of the main barriers to the development of wave energy will be integrating the new generation with the onshore electricity network. The difficultes of obtaining network connections of sufficient capacity are one of the limiting factors facing the widespread successful exploitation of wave energy in the UK [2]. Most of the suitable resource is in the north west of Scotland, however, this is the area of the country with the weakest electricity network. The network is very sparse and consists mainly of long 11 kV and 33 kV radial circuits. There is very limited capacity for the integration of any new generation, so if any significant quantity of energy is to be recovered it will be necessary to reinforce and upgrade the existing network.

This paper demonstrates the use of geographical information system (GIS) techniques to identify sites with the most favourable resource and environment for WECs. The GIS is also used to calculate the optimal route for a submarine cable to connect the new generation to the onshore electricity network. Power flow analysis techniques are used to analyse the network to determine if it can accept the new generation. These techniques can be used to optimise the integration of WECs into the existing electricity network.

WAVE ENERGY

Scotland has a very favourable wave energy resource as it is at the end of a long fetch, the Atlantic Ocean, and the predominant wind direction is towards the Scottish coast. The annual average wave power available off the west coast of Scotland is 50. kW per metre of wave front [3]. Previous studies have estimated the size of the resource available to be 300 MW providing 691 GWh/y at the shoreline [4] and 14 GW providing 45,700 GWh/y offshore [5]. The offshore resource is significantly greater than the shoreline resource because waves expend much of their energy as friction on the shallowing seabed. Waves approaching the west coast of Scotland tend to start losing energy when the water depth becomes less than 40 m. Therefore offshore WECs are able to capture more energy from the waves, and are the focus of this paper.

A number of different designs of offshore WECs are under construction and testing, but none have yet entered full-scale production. The only WEC that has operated connected to the UK electricity network is the shoreline Limpet oscillating water column by'Wavegen on the island oflslay. The first and only offshore WEC in the world that has operated while connected to an electricity network is the Wave Dragon by Wave Dragon ApS. A prototype of the Wave Dragon successfully generated electricity into the Danish network [6]. The company are now planning to site a full-scale device off the coast of Wales and to connect to the UK network by 2006.

The farthest developed offshore WEC in the UK is the Pelarnis by Ocean Power Delivery (OPD). A full-scale prototype of the Pelarnis successfully completed sea trials in April 2004 and generated its first electricity [7]. Now further testing is going to take place during the summer of 2004 at the European Marine Energy Centre in Orkney, UK where the Pelarnis will generate electricity into the island network [8]. OPD are planning to have the Pelarnis fully competitive with wind energy and other renewable energy technologies by 2010 [7].

SITE SELECTION

A GIS is a software tool used to solve problems or optimise situations where data is dependent on a geographical position. It provides the functions and tools needed to store, analyse and display information referenced geographically. A GIS commonly manages data by dividing the information into thematic layers. For example, one layer may contain the rivers in a geographical area, another layer the hills and another layer the roads. The use of layers therefore simplifies data manipulation and display. A GIS model has been created that encapsulates a wide variety of extensive data for the marine environment off the west coast of Scotland, including:

- Wave power per metre of wave front
- Bathymetry and slope of seabed
- Admiralty charts
- Coastline
- Environmental designations
- Seabed sediment
- Navigation
- Fishing areas
- Submarine cables and pipelines
- Electricity network connection points.

Spatial analysis techniques are used on the data in the GIS to find sites for WECs that fulfil the prescribed resource, bathymetric and environmental criteria. The data is analysed using Boolean and relational operators creating a Boolean true or false map of sites that do or do not meet the criteria. Firstly, areas of the sea that are not suitable for development are excluded from the analysis, for example, those with marine traffic schemes, shipwrecks and explosives dumping areas. Areas of sea within 5 km of the coastline are excluded, as WECs will be placed at least 5 km from the shore to reduce the visual impact. Water depths of less than 40 m are excluded to prevent any loss of energy from the waves by friction on the seabed. These parameters define the area that can be used as a starting point to find sites for specific WECs.

Previous GIS studies of the available wave energy resource use general parameters, which are not specific to any WEC, to identify potential sites. This GIS model enables potential sites to be identified using general or specific parameters of any WEC, or any other values that the user may wish to use. As an example, the following values for a selected WEC are used to define suitable sites:

- Wave power > 40 kW/m to ensure a sufficient amount of electricity generated
- Distance from coast < 30 km to reduce the distance the electricity has to be transmitted
- Water depth < 80 m to reduce the length of moorings and flexible cables
- Low shipping density to avoid conflict of interest
- Avoid strong tidal streams to reduce stress on the WEC.

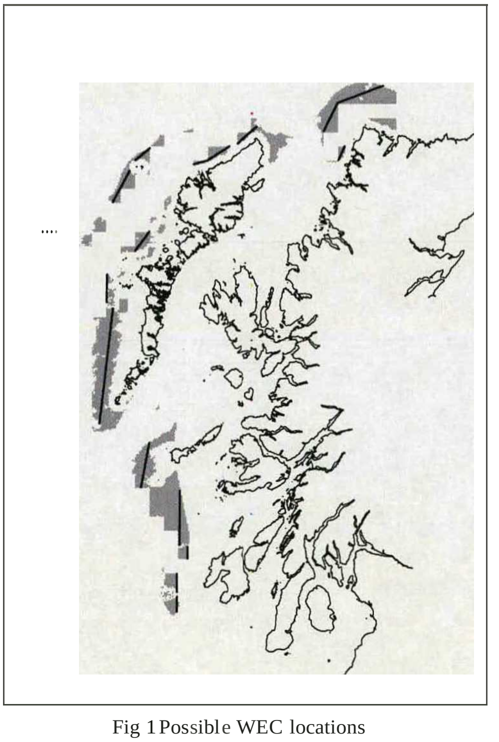

Fig 1 Possible WEC locations

The map in Figure 1 shows the sites identified from the analysis. It is clear that there is a large resource available that fulfils the specifications. The area identified covers 5018 km^2. It is likely that WECs will be placed in lines perpendicular to the predominant wave direction (see Figure 1), although this may vary depending on the WEC design. Most WECs wish to face the oncoming wave so that they can capture the maximum possible amount of energy from the waves. The WECs will be placed in lines because they will extract energy from the waves therefore the sea will be calmer behind them, reducing the amount of energy available to other WECs. The total length of the lines in Figure 1 is 368 km. If the WEC was a terminating device then the lineal extraction would be 14.7 GW. If the WEC was an attenuating device, the capacity extracted would be a proportion of this, depending on the amount of energy the WEC can capture.

Figure 1 highlights the large amount of wave energy resource that is available. However other factors must also be taken into account when choosing the most economically viable site. It must be possible to deliver the electricity generated to the consumer,. so the submarine cable route to shore and the availability of a suitable network connection point will reduce the number of available sites.

OPTIMAL CABLE ROUTE

WECs will be connected to the onshore electricity network via submarine cables. The first farms to be developed will be small and will be connected to the network using alternating current (AC) connections. However, as wave farm sizes increase and the farms are situated further from the shore (greater than 50km [9]), it is probable that high voltage direct current (HVDC) connections will be required. Whatever the method of transmission, the cable route, and hence cable length, is an important factor in the costing of a project. The shortest possible cable route may not be the easiest or cheapest option as it may require traversing areas of the seabed that make cable laying technically difficult, and hence costly, such as over rock or very steep gradients. Furthermore, the onshore electrical connection may be a fixed cost for the project, whereas the cable cost varies with the lengths of different routes, so it is important to find the optimal route. Previous studies of offshore wave energy using a GIS dealt with cable routing in an approximate manner, such as using the line-of-sight route multiplied by a deviation factor [5]. A more comprehensive method has been developed to determine the engineering and economic risks of the development. The optimal route for the cable can be found through using spatial analysis techniques within the GIS taking a lge number of parameters into account.

The optimal route for the cable is found by analysing the extent that the various factors in cable routing contribute towards its cost. With GIS analysis non-financial overall cost is the common denomination that is aggregated for reduction by optimisation. The data layers use different measurement systems so in order to compare them relative to one another they must be represented on a common scale. For example, the seabed layer is reclassified so that rock has the highest cost, sand and mud have the lowest, and the scale between them represents varying extents of gravel. This is because trenches would have to be cut in the rock to bury the cable or rock anchors would have to be used, which is more costly than using a high-pressure water jet to bury the cable in sand or mud. All of the data layers are reclassified to this scale to reflect how they affect cable routing. The scale was developed from relevant literature and discussions with submarine cable experts. The individual data layers are then combined to create one cost surface where each cell has a value indicating how suitable it is for a submarine cable. To do this each layer is given a weighting according to its percentage influence on cable routing, for example the type of seabed sediment is more important than the water depth so it would have a higher rating, and the layers are summed. The process is illustrated in Figure 2.

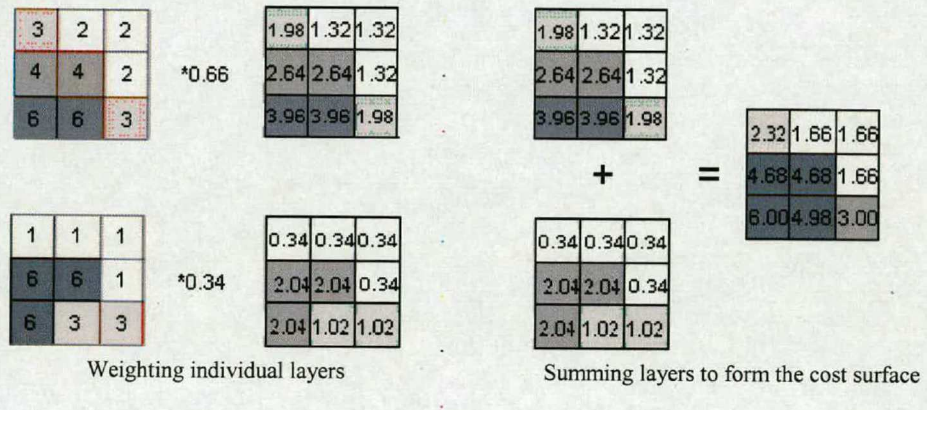

Fig 2 Creating a cost surface in the GIS (10]

The cost surface is used to calculate the cost weighted distance. Cost weighted distance mapping finds the least accumulative cost, which can be money, .time or preference, from each cell to the nearest, cheapest source [10]. The cost is based on the cell's distance from each source and the cost to travel through it. For the cable routing the source is a data layer containing electricity network connection points on the coast. This allows a cost weighted distance map to be calculated that assigns a value to each cell of sea area equal to the least accumulative cost of travelling from that cell to the network connection point.

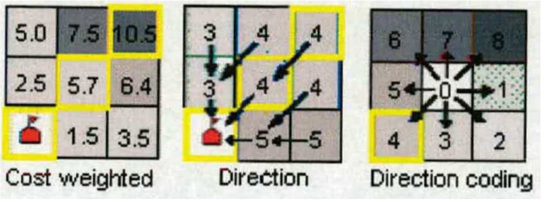

Fig 3 Cost weighted distance and direction [IO]

The cost weighted direction is calculated in conjunction with the cost weighted distance, as this indicates the direction to travel in from each cell along the least cost path to the nearest source, as demonstrated in Figure 3. In Figure 3 the accumulated least costly way of getting from the top right hand comer cell back to the source (bottom left hand comer) is 10.5 and the least cost path is diagonally, as indicated in the direction raster.

In order to calculate the least cost path through the cost weighted distance, a destination layer is required. In this case the destination layer contains the potential WEC sites, so that by carrying out the least cost path analysis the optimal cable route between the WEC and network connection point is found.

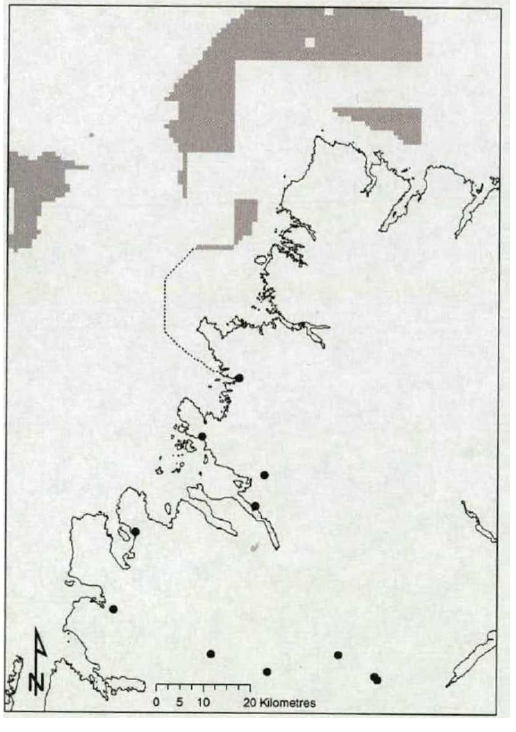

Fig 4 Optimal cable route to Lochinver

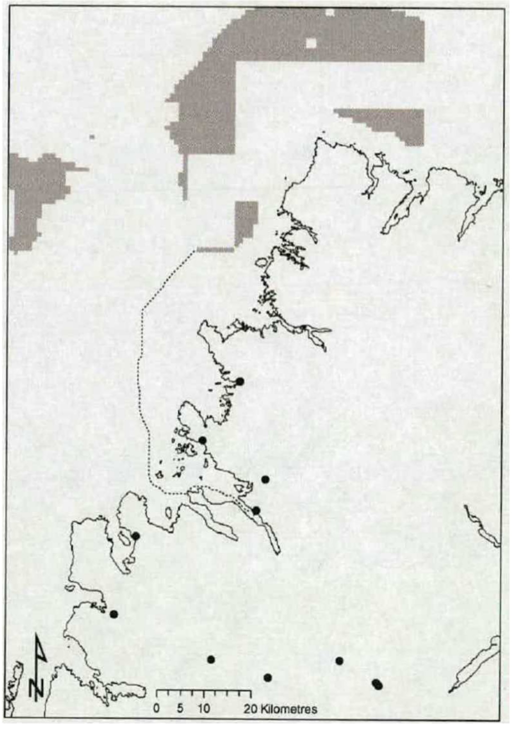

Fig 5 Optimal cable route to Ullapool

The map in Figure 4 shows the possible WEC locations identified in Figure 1, and the electricity network connection points for the area around Ullapool, Scotland. The electricity connection points are 33 kV substations that are within 3 km of the coast. The least cost path analysis identified the optimal cable route to be that in Figure 4 connecting a potential WEC site to the substation at Lochinver. The length of this route is 41.2 km. If the scale given to the environmental designations in the cost surface is altered so that it becomes forbidden to traverse a designated area, rather than being very costly, the only available connection points are at Ullapool and Loch Dubh. All of the other network connection points lie within environmentally designated areas. The new cable route is to Ullapool as shown in Figure 5 and its length is 81.9 km. An AC cable of 81.9 km is at the upper limits of economical operation; therefore a connection of this length is likely to be HVDC.

Through using the GIS it is possible to calculate the optimal route for a submarine cable from a WEC to shore, hence identifying a landfall site for bringing the new generation to shore and a potential network connection point.

NETWORK ANALYSIS

The optimal cable route identifies a substation to connect to that minimises the cable cost, however depending on the operation of the network at that point; there may not be any capacity available for a new WEC generator. Therefore, it is necessary to carry out network analysis to determine if the chosen substation is suitable as a point of connection.

The Scottish electricity network consists of a transmission network operating at 132 kV and above and a distribution network operating at voltages below. The transmission network is concentrated in the south and the east therefore most of the north west is supplied by a distribution network. The electricity network was originally designed so that the transmission network collected electricity from large generators and distributed it around the country to bulk supply points. From these the bulk supply points the distribution network supplies electricity to the consumers. The north west of Scotland is sparsely populated, resulting in a distribution network that consists of a number of long 11 kV and 33 kV radial circuits. The normal direction of power flow is from high voltage, down through the transmission and distribution networks, to the consumer. However, if generation is added as embedded generation within the distribution network, this can reverse power flows. This can effect the operation of the network, having an impact on voltage levels, thermal limits, fault levels, operation of protection devices and network stability. Network analysis is carried out before any new generation is connected to the network to determine the effects, either detrimental or beneficial, that it may have.

Power system analysis software enables electricity networks to be modelled and the effects of varying generation and load to be determined. PSS/E from Power Technologies Inc was used to model an example distribution network. Network data was extracted from the Seven Year Statement (11] and Long Term Development Statement (12] of Scottish and Southern Energy (SSE) to create an example network in the area around Ullapool. The locations of the 33 kV substations are shown in Figures 3 and 4. This area is fed from a radial circuit extending out of Beauly. An interface has been created linking the GIS model and PSS/E so that once a substation is identified as a potential connection point from the optimal cable route, network analysis can be carried out. Optimal power flow (OPF) techniques (13] are used within PSS/E to determine the capacity of the generation that can be connected at that point. In order to do this a negative load is added to the chosen busbar to represent the new generator. The power factor of the generator is specified to indicate whether it is importing or exporting reactive power. The OPF carries out a procedure termed 'reverse load-ability' (13] to determine the maximum capacity that can be connected to the busbar before a voltage or thermal violation occurs. The statutory limits for voltage within the distribution network are +/-6% of nominal voltage. However planning limits are generally lower and on networks such as this where consumers are fed directly from the 33 kV circuit, voltage limits as low as +/-1.2% will be enforced. Carrying out this analysis indicates the maximum capacity that can be connected to this busbar without causing the network to operate outwith its specified limits, and from this the amount of new wave generation that could be connected to the network can be determined.

Table I Capacity available at Lochinver

Power tactor	-0.9	-0.95	*1*	0.95	*0.9*
Available capacity (MW)	1.36	1.16	0.82	0.64	0.59
Violation	Voltage	Voltage	Voltage	Voltage	Voltage

Table II Capacity available at Ullapool

Power tactor	-0.9	-0.95		0.95	*0.9*
Available capacity (MW)	5.07	4.88	4.33	3.78	3.59
Violation	Voltage	Voltage	Voltage	Voltage	Voltage

Running the OPF on the network produces the results in Table I for connecting to the 33 kV busbar at Lochinver and in Table II for the 33 kV busbar at Ullapool[1]. The results suggest that there is a range of capacity available that varies depending on the import or export of reactive power from the generator

1 Additional features, that for reasons of confidentiality have not been included in this assessment, influence ultimate electrical capability. The capacities shown are therefore only indicative, to illustrate the GIS optimisation techniques. Only SSE has final authority to advise actual capacities on their network.

on the WEC and its connection system. It is the voltage on the network reaching its 1.2% planning limit that limits the capacity available at both Lochinver and Ullapool. Tables I and II show the standard result that importing reactive power tends to mitigate voltage rise, therefore a larger capacity of generator that imports reactive power can be added to the network than a generator that exports reactive power. There is more capacity available at Ullapool than Lochinver because Ullapool is closer to the grid supply point, whereas Lochinver is at the end of a radial circuit. The OPF only determines whether the network is in voltage or thermal violation. Other factors that can affect the amount of capacity available, such as fault levels or voltage stability, have not been assessed in this analysis.

The results show that the capacity available is very limited. The small capacities shown are indicative of room to accommodate early prototype WECs however, major development is currently limited by a network wide constraint imposed by the transmission system. Therefore, if the wave energy resource is going to be harnessed on a large scale it will be necessary to reinforce and upgrade the distribution and transmission networks. SSE recently announced plans to extend the transmission network from Beauly to Ullapool with a new 400 kV line [14]. The main reason for this is the proposed wind farms for the Western Isles that would connect to the mainland via a submarine cable. If the line is constructed it will create connection opportunities for generators in the north west of Scotland.

A recent report published by the Carbon Trust [15] said that reinforcement of the transmission and distribution networks is a significant barrier to meeting the 2010 target. In order to overcome this barrier they say that action must be taken to speed up the consents procedure for new overhead lines and incentives must be given to transmission system operators and distribution network operators to carry out the reinforcement work involved. Without reinforcement the amount of new wave generation that can be fed into the Scottish network will be very limited.

CONCLUSION

The techniques described in this paper demonstrate the use of GIS and power flow analysis as a wave energy development tool. Combining the results from the GIS and power flow analysis identifies the location and extent of the most favourable wave energy resource that can be delivered to the consumer via a submarine cable and a network connection point. There is clearly a large wave energy resource off the west coast of Scotland, but the challenge is to deliver the electricity generated to the consumer. A suitable route for a submarine cable has to be found and it must connect to the network at a point where there is sufficient capacity to accept the new generation. The early developers of wave energy wish to identify sites with the optimal recoverable energy to maximise the income from the amount of electricity generated. The cable route and network connection are optimised to reduce the capital expenditure required and to minimise the need for network reinforcement. The GIS/power flow model can identify suitable wave energy resource in closest proximity to available network capacity to accommodate the new generation, hence identifying sites that have the greatest economic viability.

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