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Using GIS to evaluate the impact of exclusion zones on the connection cost of wave energy to the electricity grid

Robert Prest[a], Trevor Daniell[a], Bertram Ostendorf[b,*]

[a]School of Civil and Environmental Engineering, University of Adelaide, SA 5005, Australia
[b]School of Earth and Environmental Sciences, University of Adelaide, SA 5005, Australia

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Abstract

An increase in the planning and environmental restrictions associated with wind energy has led to a growth in interest towards wave energy. However, as the connection cost of a wave energy development is a driving factor in the development's feasibility, existing wind farm cable-routing techniques used by renewable energy developers may not be satisfactory. A Geographical Information System (GIS) method is presented which optimises the cable route between a wave farm and the electricity network, while taking a range of exclusion zones, such as native vegetation, into account. The optimisation is presented for a South Australian study area, which subsequently showed that exclusion zones reduce the number of suitable locations for wave energy by almost 40%. The method presented also assesses the effect that each exclusion zone applied has upon the number of suitable locations within the study area. The analysis undertaken showed that National Parks and cliffs pose a significant limitation to the potential of a wave energy industry within South Australia. Allowing the transmission route to travel through a National Park, or traverse a cliff, resulted in an increase in the number of locations from which a connection could be made to the electricity grid for less than \$10 million of 33% and 50%, respectively. Conservation Parks, Wilderness Areas and native vegetation also have an effect upon the number of suitable locations for wave energy within South Australia. The GIS methods developed may be of assistance to governments in setting appropriate marine renewable energy policy, and also in identifying existing policy which may require amending if the government wishes to pursue and support the development of wave energy.

Keywords: Environmental policy; Spatial analysis; Cable route

1. Introduction

The implications of anthropogenic climate change and global warming are a serious threat to the world's ecosystems and the prosperity of human civilisations. Climate scientists argue that in order to stabilise the earth's climate and prevent further global warming, the earth requires a 70% cut in present carbon dioxide emissions by 2050 (Flannery, 2005). This urgent need for a reduction in greenhouse gas emissions has forced policy and decision makers to take a more sustainable approach to development.

As traditional forms of power generation such as coal and gas emit large quantities of greenhouse gases, governments worldwide are currently implementing policies, which aim to increase the development of renewable energy. In 2001, 'new renewables,' which include modern biomass, wind, solar, small-scale hydropower, marine and geothermal energy, comprised 2.3% of the world's primary energy consumption. However, by 2020, Goldemberg (2006) estimates that new renewables will contribute between 6.7% and 12.9% of the world's total energy consumption. Over the past decade, wind power has been the fastest growing renewable energy technology in the world with an average growth rate of 39% per annum (Caglar et al., 2006). However, the growth of wind energy in many countries has been accompanied by an increase in planning and environmental restrictions, predominantly in

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*Corresponding author. Tel.: +61 8 8303 7317; fax: +61 8 8303 6717.
E-mail address: Bertram.Ostendorf@adelaide.edu.au (B. Ostendorf).

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space-limited countries such as the UK (Baban and Parry, 2001). This has led to the development of offshore wind farms, and greater research and development towards marine renewable energy. Jones and Rowley (2002) report that although offshore wind energy is the fastest growing ocean-based renewable energy, growth in the wave energy industry is expected to reach US$100 million per annum by 2010. The UK Government is currently in the process of introducing marine renewable energy legislation, with the objective of speeding up the deployment of wave and tidal renewable energy technologies.

The British Wind Energy Association (BWEA) claims that the worldwide potential extractable wave resource has been estimated to be between 1 and 10 Terawatts (TWs) (BWEA, 2006). Considering worldwide electricity demand is just over 1 TW (IEA, 2004), wave power has significant potential to contribute to global energy demand. Bauen et al. (2003) state that wave energy devices are able to convert between up to 80% of the available resource to useful energy, which is a significant advantage over the 50% conversion rate attained by modern wind turbines (Davies, 2005). Further to this, Agren et al. (2003) specify that the capacity factor, which is the actual amount of power a renewable energy device produces per year divided by the amount of energy that the device could produce per year according to its rated capacity, is critical to the economic feasibility of a renewable energy development. Wave energy devices can generally produce significantly higher capacity factors than offshore or onshore wind energy devices. An additional advantage of wave energy is the ability to predict energy output in advance with more confidence than wind energy (Bauen et al., 2003), which is essential to the successful integration of intermittent renewable energy supply into national electricity grids.

Baban and Parry (2001) suggest that one of the biggest issues facing the exploitation of renewable energy is the selection of suitable sites. Geographical Information Systems (GIS) can be of assistance in this task. Multi-criteria decision analysis (MCDA), within the framework of GIS allows multiple competing site selection objectives to be taken into account at once by renewable energy developers. GIS and MCDA techniques are ideally suited to the spatial nature of site selection decision-making problems (Jankowski, 1995). The use of MCDA within GIS analysis has grown significantly in recent times; Malczewski (2006) reports that over 300 GIS-MCDA articles have appeared in refereed journals since 1990. GIS have previously been used in the siting of wind and wave farms in the UK. Baban and Parry (2001) took a range of factors into account in order to evaluate possible wind farm locations in Lancashire, England. Graham et al. (2003) completed a similar study, which evaluated potential wave farm locations off the Scottish coast. Meentemeyer and Rodman (2006) recently completed a study that used GIS to evaluate the site suitability for wind turbines in Northern California, which took a range of physical, environmental and human impact factors into account. In addition to evaluating potential sites for a certain technology, Yue and Wang (2006) have shown that GIS can also be used to evaluate between the suitability of a range of renewable energy technologies, such as wind, solar and biomass, over a specified study area. The use of GIS to assist decision-making in this field is clearly rapidly expanding.

Cavallaro and Ciraolo (2005) evaluated four different wind turbine configurations on an Italian Island using non-spatial MCDA techniques. As four locations were evaluated by Cavallaro and Ciraolo (2005) rather than a study area, the use of GIS was not necessary. However, many of the wide range of environmental, economic, social and technical factors, which Cavallaro and Ciraolo (2005) incorporated into the MCDA process, are transferable to the development of spatial site selection tools. One of the most important factors that needs to be taken into consideration within the MCDA process is the connection of the renewable energy farm to the electricity grid. This paper focuses on the development of an electricity cost GIS layer as it is a critical component of a GIS-MCDA site selection tool. The cost involved in transmitting power to the electricity network from an offshore location is much more expensive than from an onshore location, due to the cost of underwater electricity cable infrastructure. Consequently, the significant amount of capital required for a wave energy farm is hindering the development of the wave energy industry (Jones and Rowley, 2002). As the connecting transmission route constitutes a major proportion on the development cost, optimising the cost of the route will be imperative to the feasibility of wave farm developments.

Several factors need to be taken into consideration in the planning of a power transmission route between a renewable energy development and the electricity network. The cost obviously needs to be kept to a minimum, which would be achieved by following a direct route between the renewable energy farm and the network. However, Dey and Gupta (2000) discuss that optimal pipeline routing in the oil and gas industry requires the consideration of not only the shortest total distance, but also a range of accessibility and government stipulations. In the case of an electricity cable between a wave farm and the network, taking the shortest path will generally not be possible due to areas such as National Parks, in which development approval for a transmission line would be unlikely to be obtained from government authorities, and accessibility considerations such as cliffs. There are also many other environmental, social and cultural ‘exclusion zones’ which need to be taken into account. A review of the method used to plan the transmission route by an Australian-based wind energy developer revealed that possible exclusion zones are taken into account individually, in order to visually devise a route between the wind farm and the network, which avoids exclusion zones. Whilst this method may be satisfactory in the case of a wind energy development, it is unlikely to be sufficient for a wave energy development, as the transmission route between a wave farm and the network will involve much greater infrastructure costs per metre for the submarine cable than the onshore power lines. The different land and sea transmission infrastructure costs make evaluating a 'lowest cost path' around exclusion zones a much more difficult task, which ideally needs to be undertaken by a more complex cost-weighted optimisation method.

Genetic algorithms have been effectively used to optimise water distribution network planning (Dandy and Hassanli, 2005), and their use has also extended to many more applications. However, such optimisation techniques deal with a number of possible routes, and a number of possible options for each route. If an analysis can be conducted where there is only one possible option for each alternative route, GIS has the capability to take the spatial nature of the problem into account. Clark and Luettinger (2005) discuss the use of a GIS-based pipeline selection process to select an optimal pipeline route from many alternative routes. The analysis undertaken by Clark and Luettinger (2005) took not only construction cost into account, but also a range of exclusion zones that the pipeline could not travel through. This method would be transferable to the optimisation of a wave farm transmission cable route.

Renewable energy MCDA site selection methods were reviewed earlier in the paper. Baban and Parry (2001) included the electricity network as one of the factors in the MCDA method developed for selecting wind farm locations, however the constraints criteria used specified that for a location to be suitable, the electricity network had to be within 10 kms. This method did not take exclusion zones into account, by assuming that the transmission route could follow a direct path between the wind farm and the network. Graham et al. (2003) incorporated the connection cost into a wave farm site selection GIS-MCDA technique. A cost surface map was developed, in which each cell contained the cost per metre of travel through the cell. Once exclusion zone GIS layers have been developed, they could be included in the cost surface map by placing an excessive cost on travel through the cell, which will force the transmission route to traverse around the cell. The lowest cost between each cell in the designated study area and the network could then be evaluated. This method improved upon the proximity criteria used by Baban and Parry (2001), and the current research used a similar method to Graham et al. (2003) to develop a connection cost suitability layer covering the specified study area.

In addition to optimising the transmission route, this research has built upon the connection cost technique developed by Graham et al. (2003), by using GIS to evaluate the effect which each exclusion zone layer has upon the connection cost of cells in the study area. This is an important consideration for policy makers. If legislation is introduced which sets a mandatory marine renewable energy target, policy makers need to be sure that there are enough feasible wave farm locations within the legislation's jurisdiction to enable the target to be met. This first requires an estimation of the amount of marine energy that could be developed within the legislation's jurisdiction. Faber Maunsell (2006) conducted a study for the Scottish Government, which predicted that up to 1300 MW of marine energy capacity could be installed within Scottish waters. However, although there may be enough suitable marine energy resource locations to enable this, each location must also be economically feasible to connect to the network. If the transmission route must traverse around, for example, a Marine Protected Area (MPA), the connection cost may render the location unsuitable.

Using the cost surface method introduced previously, GIS can be used to define a study area from which a marine energy farm could be connected to the network for less than a pre-determined amount. If the government plans to introduce legislation which sets marine energy targets to make full use of the study area, it is possible using GIS to evaluate which exclusion zones are likely to significantly impede the development of a marine energy within the study area, and the government may choose to amend policy regarding the exclusion zones. For example, if an evaluation is made that 500 MW of marine energy capacity could be installed within a government's jurisdiction, but unless the transmission route traverses through native vegetation this amount is reduced to 100 MW, the government may choose to amend legislation to allow such transmission infrastructure development within areas of native vegetation.

A GIS method is presented which optimises the connection of potential locations for wave energy development within South Australia to the electricity grid. This allows an evaluation of the effect that a range of environmental, social and cultural exclusion zones have upon the connection cost and overall area of potential locations. A main focus of this research is to assess, in which exclusion zones a relaxation of government development restrictions would be most beneficial for enabling more wave energy development at a lower cost.

2. Methodology

Defining a study area for the research was predominantly data driven. The majority of spatial data for each state of Australia is held by the state government. Therefore, a South Australian study area was used as data could be obtained relatively easily from various government departments. South Australia also has potential for the development of wave energy, as much of the coastline has significant wave resource, and the electricity network covers a large extent of the coastline. The data used for the creation of the study area and the exclusion zones is shown in Table 1. ArcGIS software was used for the analysis.

The study area was developed from a polygon outline of Australia, and is shown in Fig. 1. All feasible locations for a wave energy development within South Australia were

Table 1
Study area and exclusion zone data

Data use	Data description	Data source
Create study area raster	Australian political	Geoscience Australia (GA)
Define analysis area	Wave resource	Bureau of Meteorology (BOM)
Define analysis area, connection cost evaluation	Bathymetry	Department of Primary Industries and Resources of South Australia (PIRSA)
Define analysis area, connection cost evaluation	Elevation	GA
Define analysis area, connection cost evaluation	Electricity network	ETSA Utilities (ETSA)
Define analysis area, connection cost evaluation	Electricity transmission costs	ETSA
Exclusion zone layer	Petroleum tenement boundaries	PIRSA
Exclusion zone layer	Mining tenement boundaries	PIRSA
Exclusion zone layer	Native vegetation boundaries	SA Department of Water, Land and Biodiversity Conservation (DWLBC)
Exclusion zone layer	Wilderness areas	SA Department for Environment and Heritage (DEH SA)
Exclusion zone layer	National parks	DEH SA
Exclusion zone layer	Conservation reserves	DEH SA
Exclusion zone layer	Regional parks	DEH SA
Exclusion zone layer	Conservation parks	DEH SA
Exclusion zone layer	Game reserves	DEH SA
Exclusion zone layer	Regional reserves	DEH SA
Exclusion zone layer	Lobster sanctuary locations	DEH SA
Exclusion zone layer	Aquaculture area boundaries	PIRSA
Exclusion zone layer	Shipwreck locations	DEH SA
Exclusion zone layer	SA marine park boundaries	DEH SA
Exclusion zone layer	Cth marine park boundaries	Federal Department of the Environment and Heritage (DEH) Federal)
Exclusion zone layer	Aquatic reserve boundaries	PIRSA
Exclusion zone layer	Submarine cables	National Oceans Office (NOO)
Exclusion zone layer	Shoreline classification	DEH SA

covered, and the study area was extended onto land far enough to ensure that the cable route to the electricity network and all impeding exclusion zones could be represented. The study area consisted of a raster, which consisted of 500 m cells. The resolution used was chosen due to the resolution of the bathymetry and elevation data obtained, which was 500 and 250 m, respectively.

Simple wave energy criteria were applied to restrict the size of the study area, as many of the cells in the blue study area shown in Fig. 1 were clearly unfeasible for a wave energy development. The wave energy criteria applied were:

- A minimal water depth of 50 m. Waves begin to lose a significant amount of energy due to friction with the seabed once they travel into water shallower than this depth (Walker, 2006). In addition to this, the majority of the world's leading wave energy technologies specify that they are designed to operate in water depths greater than 50 m (Wave Hub, 2006);
- A wave resource of greater then 15 kW/m of wave front. This final constraint was required because the bathymetry constraint did not exclude areas, which were in deep water, but were effectively 'sheltered' behind islands and headlands. Ideally a wave resource constraint should be used rather than a bathymetry constraint in the first place, but due to the cost of fine resolution wave data, this was not appropriate for the current research. The wave data obtained from the Bureau of Meteorology (BOM) were mean annual significant wave height and period rasters, which were sourced from the BOMs numerical Wave Model (WAM). The rasters were at 0.25° resolution, which is approximately 12 kms. Although this data would not be suitable for delineating the study area, it was suitable for the purpose of eliminating swell blocked areas from the analysis; and
- An unrestricted connection cost to the electricity grid of less than \$30 million. An unrestricted connection refers to the supply and installation of an electricity cable and associated infrastructure, which follows the optimal route between the cell and the electricity grid without considering the need to travel around exclusion zones. The method used to apply this criterion will be discussed in greater detail below. Although the use of \$30 million was an arbitrary threshold, current wave energy development plans suggest that a distance of 16–25 kms offshore places a project at the upper limit of economic

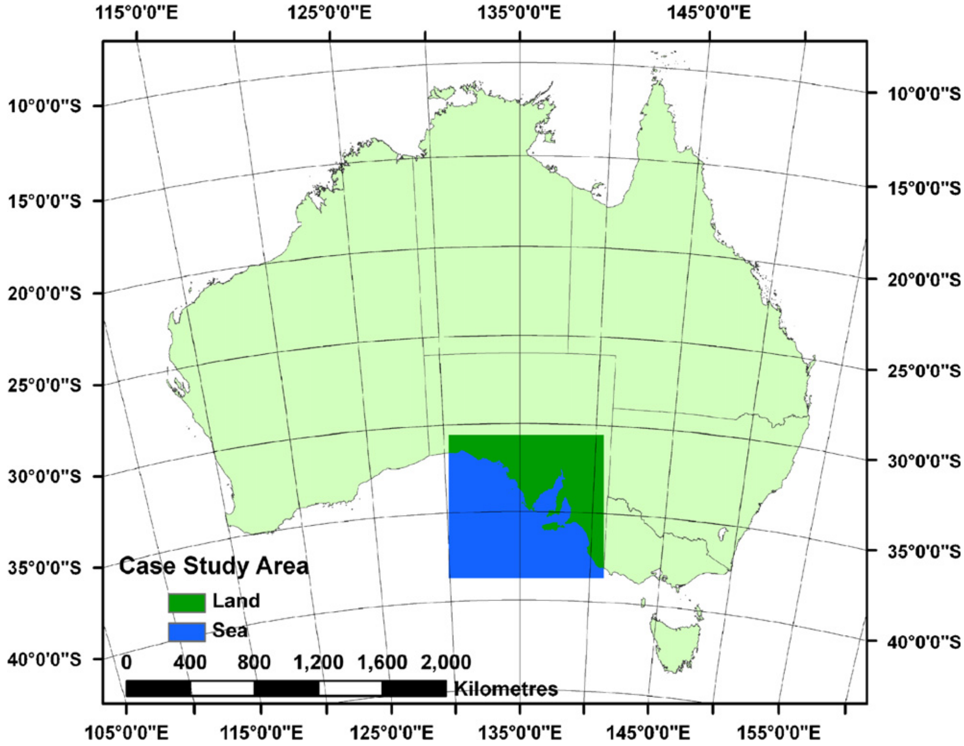

Fig. 1. South Australian study area used in analysis.

feasibility (SWDRA, 2006). This distance equates to a cost of approximately $30 million within this study. This will also be discussed further below.

The three constraints applied to the sea study area in Fig. 1 reduced the size of the study area to a more appropriate analysis area. The analysis area will be shown within the figures in Section 3.

The unrestricted connection cost discussed in the above paragraph was evaluated using the Path Distance tool in ArcMap. The inputs required for this tool included:

- The electricity network: Data was obtained from ETSA utilities, who maintain the low-voltage distribution network in South Australia. Electricity generated from a wave farm can be connected into the network through either a 33 or 66 kV substation, or through a t-switch into 33 or 66 kV transmission line. Electricity will be transmitted via an 11 kV submarine cable from the wave farm to the shoreline. A substation will then need to be installed to step the voltage up to either 33 or 66 kV, depending upon the voltage of the substation or transmission line, which the wave energy will be fed into. From the purpose built substation, a 33 or 66 kV transmission line will be required to connect the wave farm to the matching voltage existing network.
- An elevation/bathymetry raster: This ensures that the vertical distance travelled by the connecting transmission line is taken into account in the evaluation of the lowest cost route for each cell in the analysis area.
- A horizontal cost surface: This consists of a raster of the study area shown in Fig. 1, in which each cell contains the cost per metre for the transmission route to travel through the cell. The costs used were obtained from ETSA utilities, and are shown in Table 2. The substation cost was not included in the use of the Path Distance tool, but was added onto the connection cost for each cell once an evaluation had been made upon the optimal transmission route for each cell in the analysis area. Horizontal cost rasters needed to be developed for connection into the network at 33 and 66 kV. During the analysis, the cost of connection at both voltages into either a substation or a transmission line was evaluated for each cell, and the lowest cost of the four options used.

Table 2
ETSA supply and installation price estimations (Driver, 2006, pers. comm.)

Voltage (kV)	Underwater cable ($/m)	Power line ($/m)	Substation ($)
11	1200	—	—
33	—	100	1,500,000 (11→33 kV)
66	—	150	1,800,000 (11→66 kV)

Once the unrestricted connection cost for each cell in the study area had been calculated using the Path Distance tool, the cells that could be connected to the electricity grid for less than $30 million could be evaluated, and the analysis area was defined. It should also be noted that the GIS software ArcMap enables the evaluation of a 'back-link' raster in conjunction with the Path Distance analysis, which illustrates the actual lowest cost path from each cell in the study area to the electricity grid.

2.1. Baseline analyses

The analysis area represented the cells in the study area, which met the three criteria presented above. However, the delineation of the analysis area did not take into account the effect of exclusion zones on the transmission route. To evaluate an initial comparison between the number of cells in the analysis area, and the number of cells in the analysis area which could still be connected to the electricity network for less than $30 million once a range of exclusion zones had been taken into account, exclusion horizontal cost surfaces were developed. An exclusion horizontal cost surface was needed for each of the 33 and 66 kV connection cases.

The exclusion zones taken into account were detailed in Table 1. Data for 15 of the 18 exclusion zones included in the analysis were obtained in GIS polygon format. Each of 15 polygon zones is protected under relevant South Australian legislation. A raster exclusion layer was developed for each exclusion zone from the polygon data by assuming that a cell in the study area, which included any part of the exclusion layer was an exclusion cell. A greater resolution than 500 m cells within the study area would enable the raster exclusion zones to more accurately depict the polygon data they represent. The three exclusion zones which were not represented by polygon data were:

- *Shipwrecks*. The shipwreck data was point data, and in accordance with South Australian legislation regulations, a buffer of 500 m was developed around protected shipwrecks, and 100 m around unprotected shipwrecks. An exclusion zone raster was then developed in the manner outlined above.
- *Submarine cables*. The data obtained was in polyline format. In accordance with Commonwealth legislation, a 500 m buffer was developed around any existing submarine cables, and then a raster exclusion zone layer was developed. New submarine cables may cross an existing submarine cable at an angle of 90°, however as there were no submarine cables within the study area in which a transmission line would cross between any analysis area and the electricity network, the existing submarine cables were included as an exclusion zone.
- *Shoreline classification*. Data was obtained which showed the shoreline type for the South Australian coastline in polyline format. Graham et al. (2003) state that the landing point of a submarine cable is a very important consideration in the delineation of a transmission route. For this reason, cliffs, which were greater then 50 m high were extracted from the shoreline data, and an exclusion zone raster developed which included any cell in which an extracted cliff was present.

Once GIS layers had been developed for each exclusion zone, they were combined together, and then incorporated into the existing unrestricted horizontal cost surface rasters. To force the transmission route to travel around exclusion zones, an excessively high cost was attributed to cells in the horizontal cost surface rasters in which an exclusion zone was present. The method used in the unrestricted case was then employed to calculate the lowest restricted connection cost for each cell in the analysis area. This enabled a comparison to be made between the amount of cells in which the connection cost was less than $30

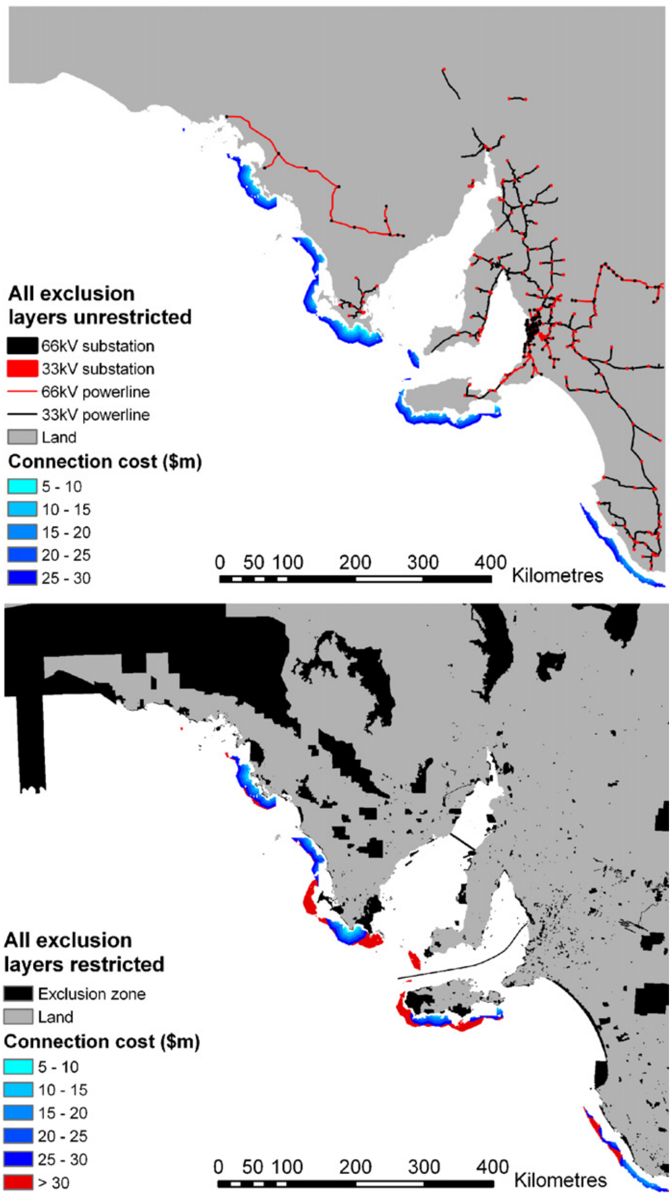

Fig. 2. Comparison between all exclusion zones unrestricted and all exclusion zones restricted cases for study area.

million in the unrestricted case and in the restricted case. A similar comparison could also be made for cells in which the connection cost was less than \$10 million, \$15 million, \$20 million and \$25 million. This gave an indication of the effect, which the exclusion zones had upon the potential of wave energy development within South Australia.

To assess the effect which individual exclusion zones had upon the connection cost within the analysis area, two different methods could be used. The methods are discussed below.

2.2. Unrestricted analyses

Each exclusion zone layer was individually incorporated into the unrestricted horizontal surface cost rasters, and given an excessively high travel cost value so that all transmission routes were forced to travel around the exclusion zone. The Path Distance tool was then used to calculate the cost of connecting each cell in the analysis area to the electricity grid while taking the exclusion zone into account. A comparison was then made between the completely unrestricted analysis, and the single exclusion zone analysis. This provided an indication of the effect, which the exclusion zone itself has upon the analysis area.

Table 3
Total number of cells which can be connected for less than \$30 m in both baseline cases

Connection cost (\$million)	Number of cells in analysis area		Reduction (%)
	No exclusion zones	All exclusion zones	
5–10	794	309	61.08
10–15	3434	1762	48.69
15–20	7430	4310	41.99
20–25	9699	5966	38.49
25–30	11,235	7405	34.09
> 30	0	12,840	(Increase)
Total	32,592	19,752	39.40

2.3. Restricted analyses

Although the exclusion zone analysis method presented in Section 2.2 provided an indication of the effect of each exclusion zone, it is more realistic that a single exclusion zone may be taken off the completely restricted case. As a development application would be unlikely to be approved in any of the exclusion zones, taking one exclusion zone at a time off the completely restricted case would simulate the effect of the government relaxing development restrictions within that exclusion zone. To develop a horizontal cost surface raster for each exclusion zone, the other 17 exclusion zones actually needed to be incorporated into the unrestricted horizontal cost surface raster, as taking the exclusion zone from the fully restricted horizontal cost surface raster resulted in any other exclusion zones which are present in the same cells also being taken away.

3. Results

3.1. Baseline analyses

A visual comparison between the completely unrestricted and completely restricted connection cost cases is shown in Fig. 2.

The analysis area which was developed within the study area by use of the three criteria outlined in Section 2 can be seen in Fig. 2. It is evident that the exclusion zones had a very significant effect upon the connection cost within the analysis area. Table 3 examines the effect upon the connection cost for a range of bins within the analysis area.

On average, approximately 40% of the cells which can be connected for less than \$30 million in the unrestricted case cannot be connected for less than \$30 million once exclusion zones are taken into account. Upon closer examination, Table 3 shows that the exclusion zones have the greatest impact upon the number of cells which can be connected to the electricity grid for less than \$10 million, as over 60% of the potential wave energy development areas are pushed beyond \$10 million.

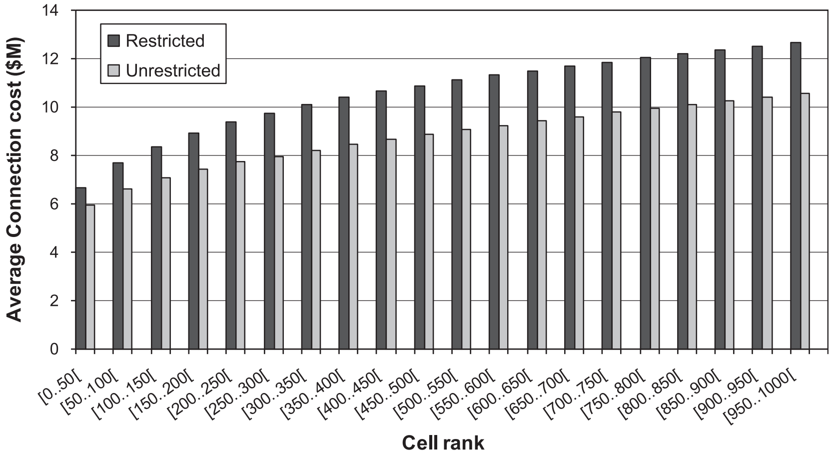

Fig. 3. Resource cost curve for lower cost connection cells.

An alternative method of analysing the results discussed above is through the use of resource cost curves. Resource cost curves allow an investigation of the financial effects that the restricted cells have upon the connection cost. Fig. 3 concentrates on the effect which the restrictions have upon cells that, in the unrestricted case, could be connected to the electricity network for less than $10 million. Cells were sorted according to their connection cost into groups of 50 cells, and the average cost of each cell group for the lowest cost 1000 cells, or 250 km^2, is shown in the figure. It is evident that the restrictions in place in South Australia preventing transmission infrastructure development will significantly reduce the number of locations where renewable energy developers will be able to prospect for potential wave farms that require a certain connection cost in order to be feasible.

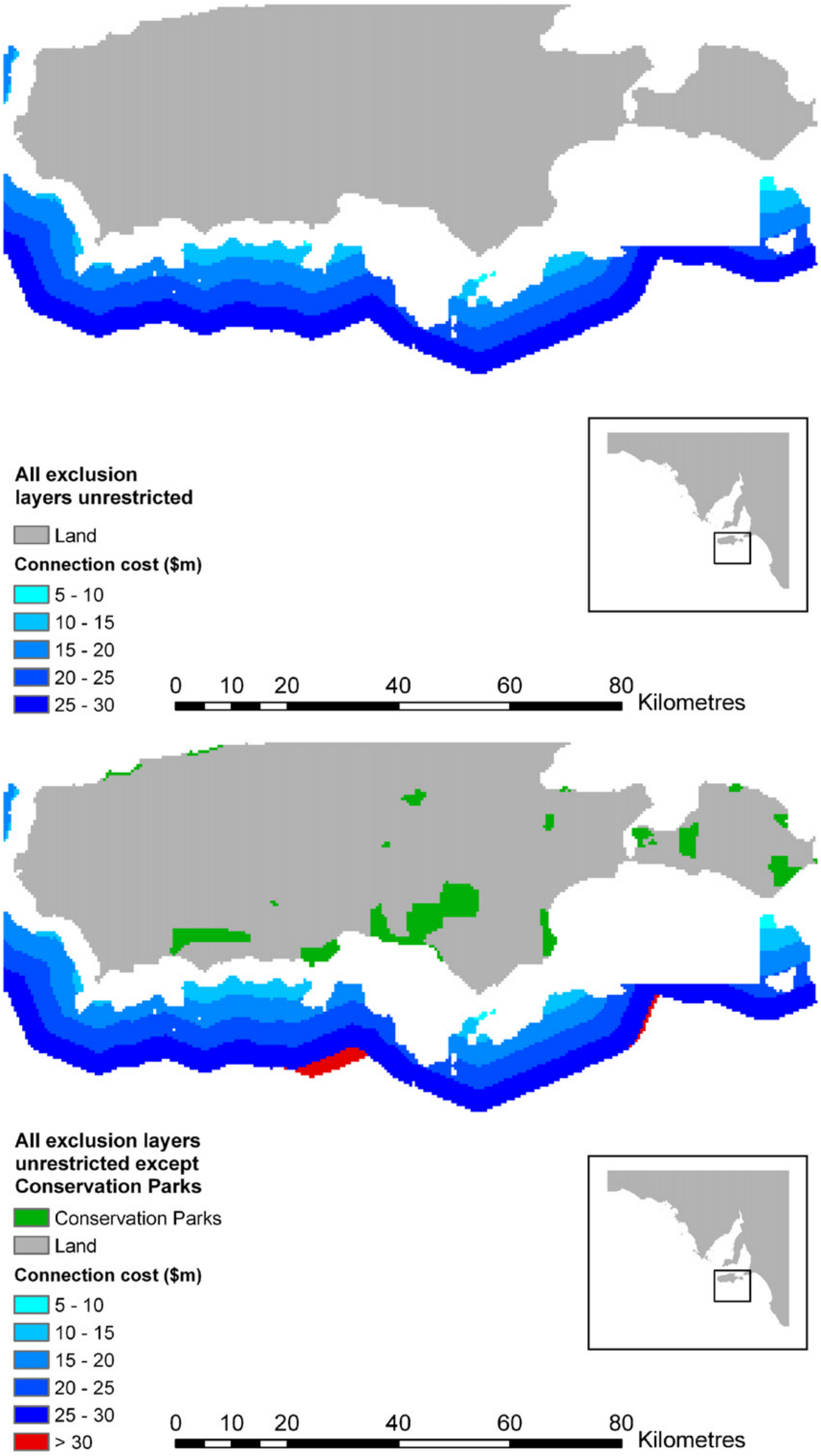

Fig. 4. Effect of Conservation Parks being an exclusion zone upon the all unrestricted case on Kangaroo Island.

Table 4
Effect of each individual exclusion zone upon the all unrestricted case

Restricted exclusion zone	Reduction in total number of cells <$30 m	% reduction in cells <$30 m	% reduction in $5–10 m cells	% reduction in $10–15 m cells	% reduction in $15–20 m cells	% reduction in $20–25 m cells	% reduction in $25–30 m cells
National Parks	7408	22.73	35.64	20.50	24.67	25.55	18.78
Cliffs	1818	5.58	36.78	13.98	8.26	2.78	1.44
Wilderness Areas	1743	5.35	17.00	12.78	9.95	2.44	1.72
Native Vegetation	440	1.35	2.64	3.09	1.36	1.33	0.74
Conservation Parks	309	0.95	0.50	2.91	1.21	0.49	0.60
Conservation Reserves	42	0.13	0.50	0.06	0.01	−0.03	0.34
Mining Tenements	32	0.10	1.76	0.55	0.01	0.01	−0.03
Aquatic Reserves	10	0.03	0.00	0.29	−0.04	0.00	0.03
Shipwrecks	4	0.01	0.00	0.23	0.03	−0.06	0.00
Game Reserves	1	0.00	0.00	0.00	0.00	0.01	0.00
Petroleum Tenements	0	0.00	0.00	0.00	0.00	0.00	0.00
Regional Parks	0	0.00	0.00	0.00	0.00	0.00	0.00
Regional Reserves	0	0.00	0.00	0.00	0.00	0.00	0.00
Lobster Sanctuaries	0	0.00	0.00	0.00	0.00	0.00	0.00
Aquaculture	0	0.00	0.00	0.00	0.00	0.00	0.00
SA Marine Protected Areas	0	0.00	0.00	0.00	0.00	0.00	0.00
Cth Marine Protected Areas	0	0.00	0.00	0.00	0.00	0.00	0.00
Submarine Cables	0	0.00	0.00	0.00	0.00	0.00	0.00

An immediate conclusion from this analysis is that the development of wave energy within South Australia is likely to be significantly constrained, as highly attractive wave energy sites are often jeopardised by the presence of exclusion zones. It must be kept in mind that this analysis only takes the connection cost into account, and the wave resource available would alter the economic favourability of cells within the analysis area.

3.2. Unrestricted analyses

The unrestricted analyses evaluated the effect, which each exclusion zone had individually upon the analysis area. A visual example using the Conservation Parks as an example is shown in Fig. 4.

Conservation Parks appear to have minimal impact upon the connection cost of the analysis area south of Kangaroo Island, although there is a small area which can no longer be connected for between $10 million and $15 million. An analysis of the effect of adding each exclusion zone to the unrestricted baseline case is presented in Table 4.

Table 4 shows that National Parks clearly have the most significant impact on the connection cost when treated as an exclusion zone within the completely unrestricted case. The effect of the National Parks is also biased towards the most attractive cells for a wave energy development in terms of connection cost. The cliffs and Wilderness Areas also have a large impact upon the connection cost within the analysis area. The impact from these two exclusion zones is heavily biased towards the cells which can be connected for less than $10 million. This is not surprising in the case of the cliffs, as the most attractive areas in terms of connection cost are generally where the water depth is 50 m within a few kilometres from land, and this steep descent is likely to relate to a steep ascent on land. Native vegetation and Conservation Parks also have a small impact upon the connection cost within the analysis area. The other 13 exclusion zones have very minimal impact. A negative percentage reduction in cells in Table 4 can be attributed to certain cells from a cost bin being moved to a higher cost bin due to the presence of the exclusion zone, with a greater amount of cells moving into the cost bin from a lower cost bin.

3.3. Restricted analyses

The effect of removing the Conservation Parks exclusion zone from the completely restricted case has upon the connection cost is shown for the area south of Kangaroo Island in Fig. 5.

A visual comparison between Figs. 4 and 5 revealed that removing the Conservation Parks restriction from the restricted baseline case had a far greater impact than adding the Conservation Parks restriction to the unrestricted baseline case. This is due to the spatial interaction, which the Conservation Parks exclusion zone layer had with other exclusion zone layers. Fig. 5 shows a small Conservation Park within the dashed box. Although Fig. 4 showed that the small Conservation Park had minimal impact as a sole exclusion zone, Fig. 5 shows that because it is adjacent to other exclusion zones, when it is removed

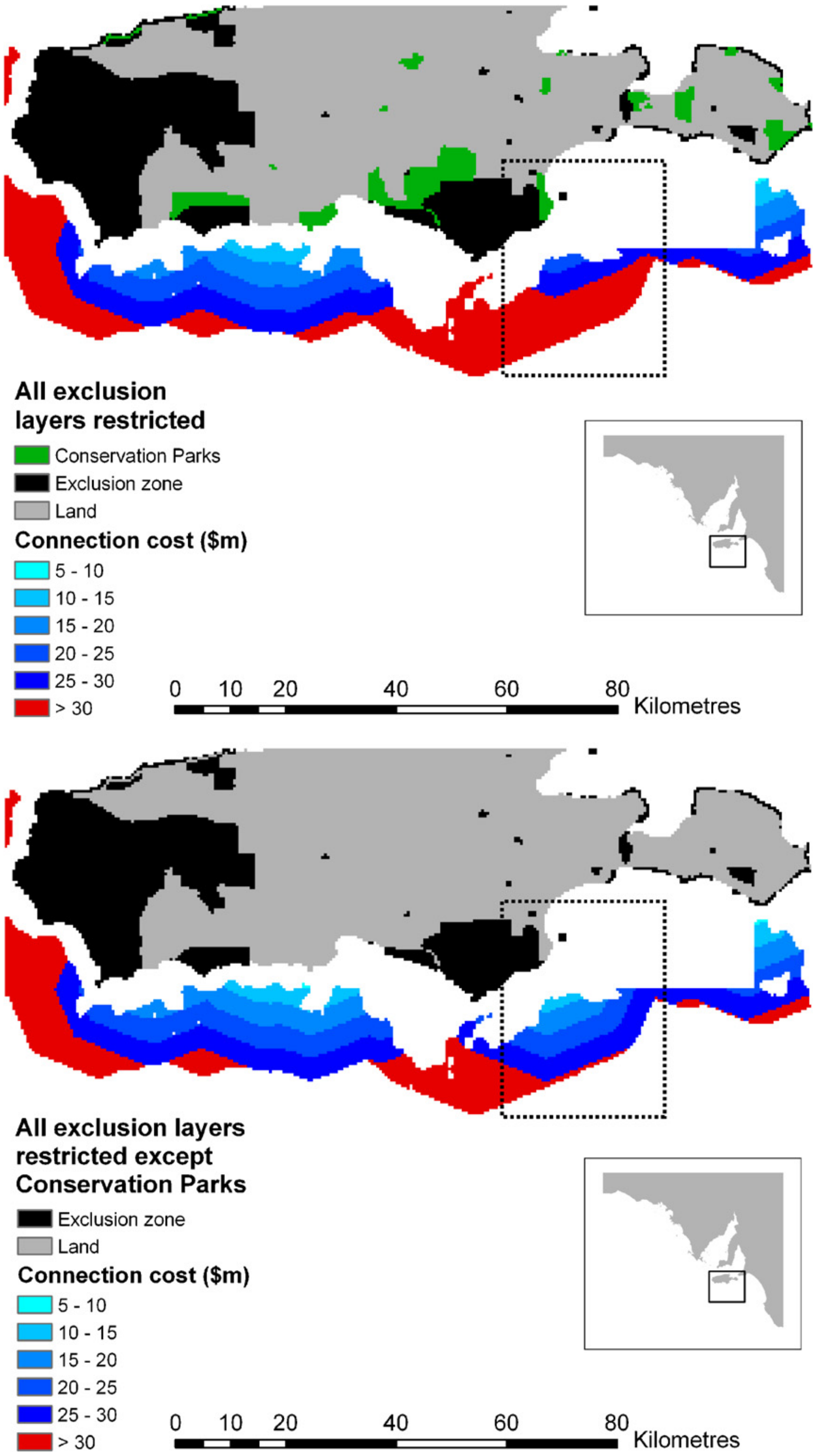

Fig. 5. Effect of Conservation Parks being a non-exclusion zone upon the all restricted case on Kangaroo Island.

from the restricted baseline case there is a large increase in the number of cells which can be connected for less than $30 million. This is an important consideration when there is a number of adjacent exclusion zones along the coast, as relaxing development restrictions upon one type of exclusion zone may significantly increase the potential of the development of wave energy in South Australia. An analysis of the effect of removing each exclusion zone from the restricted baseline case is shown in Table 5.

Table 5 shows that the same five exclusion zones as the unrestricted case had an impact upon the connection cost when removed from the restricted case. National Parks clearly had the greatest impact, and if the development of a transmission line was approved through National Parks for

Table 5
Effect of each individual non-exclusion zone upon the all restricted case

Non-restricted exclusion zone	Increase in total number of cells $<$\$30 m	% increase in cells $<$\$30 m	% increase in \$5–10 m cells	% increase in \$10–15 m cells	% increase in \$15–20 m cells	% increase in \$20–25 m cells	% increase in \$25–30 m cells
National Parks	6563	33.23	40.78	23.33	32.30	37.88	32.06
Conservation Parks	1890	9.57	1.62	8.00	7.12	10.96	10.57
Native Vegetation	1292	6.54	0.32	6.02	6.80	6.05	7.17
Wilderness Areas	1254	6.35	0.00	8.29	4.34	6.17	7.47
Cliffs	972	4.92	48.54	26.84	6.38	−2.00	2.51
Mining Tenements	59	0.30	4.53	1.02	0.90	−0.15	−0.04
Conservation Reserves	51	0.26	0.00	0.06	0.05	−0.03	0.68
Shipwrecks	2	0.01	0.00	0.17	0.02	−0.07	0.03
Game Reserves	0	0.00	0.00	1.14	0.02	−0.35	0.00
Aquatic Reserves	0	0.00	0.00	0.00	0.32	−0.23	0.00
Petroleum Tenements	0	0.00	0.00	0.00	0.00	0.00	0.00
Regional Parks	0	0.00	0.00	0.00	0.00	0.00	0.00
Regional Reserves	0	0.00	0.00	0.00	0.00	0.00	0.00
Lobster Sanctuaries	0	0.00	0.00	0.00	0.00	0.00	0.00
Aquaculture	0	0.00	0.00	0.57	0.02	−0.18	0.00
SA Marine Protected Areas	0	0.00	0.00	0.00	0.00	0.00	0.00
Cth Marine Protected Areas	0	0.00	0.00	0.00	0.00	0.00	0.00
Submarine Cables	0	0.00	0.00	0.00	0.00	0.00	0.00

the purpose of a wave energy development, the amount of potential locations for such a development could increase by 40%. The Conservation Parks and native vegetation exclusion zones had a far larger impact when removed from the restricted case compared with being added to the unrestricted case. This was due to spatial interaction with other exclusion zones, such as the example shown of the Conservation Park on Kangaroo Island. A close inspection of the maps revealed that adjacent Conservation Parks and native vegetation in the South-East of South Australia also had a large impact upon the connection cost of the nearby analysis area. The Wilderness Areas had a greatly reduced impact on the cells which could be connected for less than \$10 million. This was due to a large Wilderness Area located on an Eyre Peninsula headland, which although it had a large impact as a sole exclusion layer, it had no impact in this case because a National Park adjacent to the Wilderness Area completely blocked off connection to the electricity network. As a percentage change in the total number of cells which could be connected for less than \$30 million in the analysis area, the cliffs had much less of an impact when removed from the restricted baseline case. This was because a large proportion of the cliffs are located within protected areas such as National Parks, which prevent a connection. However, Table 5 shows that when the cliff exclusion layer is removed from the restricted baseline case, there is an increase of nearly 50% in the number of cells within the analysis area which can be connected for less than \$10 million. As cliffs were only made an exclusion zone for technical reasons, this possibly poses a challenge for the construction industry to assist in the development of wave energy within South Australia.

4. Conclusion

A clear and concise GIS method was presented to assist in the optimisation of a transmission route between a wave farm and the electricity network. The GIS method has considerable advantages over traditional methods such as assessing a range of maps individually and delineating a transmission route by hand, and therefore may be of valuable use to renewable energy developers.

The effect which certain exclusion zones had upon the wave energy potential of South Australia was assessed. The baseline cases showed that exclusion zones will have a significant effect upon the development of wave energy in South Australia. Within the analysis area specified, exclusion zones reduced the number of cells which could be connected to the electricity network for less than \$30 million by 40%. The most attractive locations, in terms of connection cost, were reduced by over 60% by exclusion zones. This suggests that the rather large impact of the exclusion zones may reduce the potential of a wave energy industry in South Australia.

An analysis was undertaken which simulated the effect of the government relaxing development restrictions on each exclusion zone would have upon possible locations for a wave energy farm in South Australia. The analysis showed that restricting the construction of a transmission route through National Parks, and the construction issues involved in the transmission route traversing a large cliff, pose the most significant limitations to the potential of a wave energy industry within South Australia. Enabling construction of a transmission route through National Parks increased the number of cells which could be connected for less than \$30 million by 33%, and when considering the most attractive locations in which a connection could be made for less than \$10 million, this figure increased to over 40%. Allowing the cable to traverse either a Conservation Park, Wilderness Area or native vegetation increased the number of potential locations for wave energy in South Australia by between 6% and 9%. Quite significantly, if the transmission cable can be constructed to negotiate a 50 m cliff, the number of locations which could be connected for less than \$10 million increased by nearly 50%.

A wave energy industry is unlikely to develop within South Australia in the short term. This is predominantly due to the Australian Federal Government's continual lack of support for renewable energy, including failing to extend the Mandatory Renewable Energy Target (MRET) beyond 2% (Kent and Mercer, 2006). However, the method presented to assess the effect which certain exclusion zones have upon the wave energy potential of a specified area, may be of use to governments worldwide who are keen to implement policies which aim to increase the development of marine energy. The method has the capacity to evaluate suitable areas for the development of wave energy, which may be of assistance in setting appropriate marine renewable energy policy. The method also enabled an assessment to be made on the effect which different exclusion zones have upon the amount of suitable locations for wave energy, which could assist governments in identifying existing policy that they may wish to amend in order to pursue the growth of wave energy within their jurisdiction. This infers a possible trade off between environmental designations such as biodiversity consideration and greenhouse gas reduction, in which a decision needs to be made by policy makers on which is more important.

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