



Project Report

Offshore wind energy in the context of multiple ocean uses on the Bermuda platform

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A group project submitted in partial satisfaction of the degree requirements for the Master of Environmental Science & Management


March 2014





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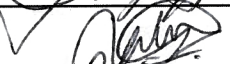
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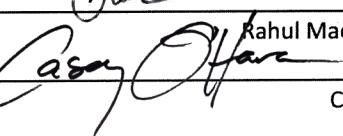
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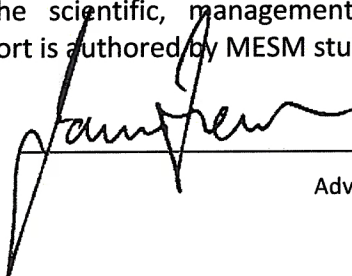

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. The report is authored by MESM students and has been reviewed and approved by:


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Executive Summary

The British island territory of Bermuda currently generates most of its electricity from imported fossil fuels. Bermuda has identified the importance of increasing its use of renewable energy sources to reduce its dependency on fossil fuels and decrease greenhouse gas emissions to address concerns about energy security, increasing energy prices, and climate change-induced sea level rise. To achieve these goals, Bermuda is considering offshore wind energy development on the Bermuda Platform. In its 2011 Energy White Paper, Bermuda stated a goal of generating 30% of its energy demands from renewable sources by 2020. Bermuda anticipates that offshore wind energy will generate over 90% of its stated renewable energy goals. It is estimated that a wind farm with an installed capacity of 35MW will be needed to achieve its 2020 renewable energy goals.

Multiple activities occur in the limited space of the Bermuda platform, and the addition of a wind farm could lead to tradeoffs with other ocean users. Furthermore, the development of offshore wind energy will need to consider potential impacts to Bermuda's marine ecosystem, which provides important services to its community. In order for Bermuda to make an informed decision on the siting of offshore wind energy, marine spatial planning methods would be required to identify regions of the Bermuda Platform that minimize impacts to existing uses and ecological features on the platform while simultaneously achieving energy goals.

To examine the economic viability of offshore wind development in Bermuda, we developed a wind energy cost model that incorporated estimates from a number of existing offshore wind energy developments. Our analysis shows that offshore wind energy on the Bermuda Platform is an economically viable option: the calculated LCOE of \$0.261/kWh is significantly lower than the price of electricity paid by consumers. Even with a substantial markup on a project's LCOE in a negotiated power purchase agreement, it is very likely that the actual cost of energy from offshore wind power will be less than the prevailing prices.

To investigate the interactions between offshore wind energy development and economic and conservation interests on the Bermuda Platform, we developed a spatial analysis models based upon negotiable thresholds of suitability. While Bermuda's stated short-term goal is 35 MW of wind power capacity by 2020, we used our model to analyze development of a 100 MW capacity farm to simulate further growth in wind energy development in pursuit of Bermuda's longer-term emissions reduction goals. A demonstration of our spatial analysis model shows that, for our chosen set of parameters, it is possible to site a 100 MW wind farm on the Bermuda platform with minimal risk of impact to marine habitat and fisheries.

Our investigation revealed that all regions on the Bermuda platform have associated ecological, economic or social values that could be impacted by offshore wind development. This necessitates a negotiated solution among various stakeholders and the decision maker of an acceptable amount of risk of impact. The need for marine spatial planning is addressed by our spatial threshold analysis model, which can identify suitable locations for turbine placement, through a transparent, iterative process.

We recommend consideration of the following actions should Bermuda pursue offshore wind energy:

- Study viewshed zone of influence and impacts
- Involve stakeholders early in the planning process
- Research implications to avian migratory patterns
- Study impacts during construction phase
- Emphasize inter-departmental information sharing

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1. Project significance

The British island territory of Bermuda currently generates most of its electricity from fossil fuels, which must be imported, and energy prices in Bermuda are among the highest in the world. Because of increasing concern about rising fuel prices and sea level rise resulting from climate change, the Government of Bermuda has identified the importance of increasing its use of renewable energy sources to increase energy security and decrease greenhouse gas (GHG) emissions.

Bermuda's consistent winds and sizeable shallow seabed, commonly known as the Bermuda Platform, make offshore wind energy an attractive option to achieve Bermuda's renewable energy goals. The deployment of offshore wind turbines on the Bermuda Platform would contribute towards achieving Bermuda's stated goals of reducing its dependency on fossil fuels and decreasing GHG emissions. The Bermuda Wind project will assist the Government of Bermuda in identifying potential wind farm locations that minimize socioeconomic and ecological impacts while achieving stated wind energy goals.

2. Project objectives

- Determine economic viability of offshore wind energy with respect to Bermuda's current energy context
- Identify and characterize potential conflicts with ocean uses and ecological features
- Develop a spatial analysis model to identify potential locations for offshore wind farms with acceptable risk of impacts

3. Background and literature review

3.1 Bermuda's energy situation

Bermuda is heavily dependent on imported fossil fuels for its energy production, and as such is vulnerable to short-term supply disruptions due to unpredictable fuel prices, transportation issues such as weather delays, and limited fuel storage facilities (Dept. of Energy, Government of Bermuda 2011 : 1.3.1). While mitigation strategies have been established to reduce short-term supply risks (Dept. of Energy, Government of Bermuda 2011 : 1.3.1), the Bermuda government is concerned about long-term energy security. Peak oil theory suggests future declines in oil availability, leading to increasing costs (Dept. of Energy, Government of Bermuda 2011: 1.3.2).

Because Bermuda relies on imported fossil fuels to meet its energy demands, its consumers pay some of the highest electricity rates in the world. Table 1 shows the breakdown of 2012 energy prices in Bermuda for residential and commercial consumers. The price of energy includes an energy production charge ("Energy") and a fuel adjustment rate ("Fuel"). The fuel adjustment rate accounts for both the cost of the fuel and the cost of importation (Ascendant Group, 2012).

Table 1. 2012 Energy Prices

Residential	\$ 0.4625/kWh
Energy	\$ 0.2620/kWh
Fuel	\$ 0.2005/kWh
Commercial	\$ 0.4508/kWh
Energy	\$ 0.2554/kWh
Fuel	\$ 0.1954/kWh

In 2011, the Bermuda Department of Energy (DOE) released an Energy White Paper describing the long-term energy strategy for the island. The Energy White Paper outlines policies and strategies that will allow Bermuda to reduce its fossil fuel dependence, increase energy security, and reduce per-capita GHG emissions below 10 metric tons of CO₂ equivalent per person (CO₂eq/person) by 2020, with a long-term emissions goal of 1 metric ton CO₂eq/person by 2050.

Bermuda's 2008 per capita GHG emissions of 14.4 metric tons CO₂eq/person were more than twice the global average (Dept. of Energy, Government of Bermuda 2011: 1.4.2), and much higher than a sustainable GHG emissions rate of less than 1 metric ton CO₂eq/person by 2050 (Allison et al., 2009). While Bermuda's total GHG emissions are an insignificant fraction of total global emissions, the Bermuda government understands that its carbon mitigation strategies will be closely scrutinized by the international community, and would like to establish itself as a responsible leader in reducing GHG emissions (Dept. of Energy, Government of Bermuda 2011: 1.4.3).

The DOE has established a goal to reduce per capita GHG emissions to less than 10 metric tons CO₂eq/person by 2020. To meet this goal, the DOE has determined that it will be necessary for 30% of total electrical energy capacity to be generated from renewable energy resources (Dept. of Energy, Government of Bermuda 2011: 4.0). Bermuda anticipates that offshore wind energy will generate over 90% of its stated renewable energy goals (Dept. of Energy, Government of Bermuda 2011: 4.3.1). Bermuda estimates that a wind farm with an installed capacity of 35MW will be needed to achieve its 2020 renewable energy goals. Considering the DOE's 2050 goal of reducing emissions to 1 metric ton CO₂eq/person, it is likely that the proportion of wind power would need to increase.

3.2 Costs involved in wind energy development

Numerous studies have been conducted over the past decade on the costs and trends of offshore wind energy (Levitt et al., 2011; Kaiser and Snyder, 2012; Krohn et al., 2009; Tegen et al., 2013). Estimates for the price of offshore wind energy typically include capital expenditure costs (CAPEX), sometimes referred to as installed capital costs (ICC), annual operating expenditure (AOE), sometimes referred to as operations and maintenance costs (O&M), expected lifetime of the project and discount rate. CAPEX cost estimates typically include the costs of the wind turbines, foundations, electrical infrastructure, installation, developmental costs, and soft costs that include the cost of construction financing, bonding, and insurance. CAPEX costs account for about 75% of an offshore wind project, while AOE, which include costs for management, operation, maintenance, and area leasing, constitute the remainder of a project's costs.

A review of cost estimate studies indicates that there is no clear trend in the cost of offshore wind development. However, cost reduction estimates for future offshore wind development have been identified and range from 12% to 25% (BVG Associates, 2012; Maples et al., 2013). The specific institutional setting in combination with the highly variable nature of commodity prices, fuel prices,

subsidies and incentives, and an emerging carbon market make prediction of future prices difficult (Krohn et al., 2009).

Estimates for the cost factors previously identified are used to calculate a levelized cost of energy (LCOE), which represents the cost per unit of energy (\$/kWh) from an energy project. However, the LCOE is not the energy price paid by energy consumers. The price paid by energy consumers will be the LCOE plus additional add-ons to account for regulations, measures to mitigate power generation intermittency and contractual obligations, such as a power purchase agreement (PPA).

The cost of offshore wind energy development in Bermuda will depend on numerous variables such as wind conditions, water depth, foundation type, seafloor geology, oceanographic conditions, commodity prices, transmission costs, distance to port, distance to a grid connection point, and policy factors (Kaiser and Snyder, 2012; NREL, 2013; Levitt et al., 2011).

Wind conditions at an offshore wind turbine site will have a significant effect on overall energy production potential and hence the price of energy generated. Higher wind speeds will generate more energy on an annual basis, which would reduce the LCOE.

In addition to selecting a site with higher wind speeds, it is equally important that the correct wind turbine be chosen. Offshore wind turbines are available in a range of power ratings. Yet, wind turbines with higher power ratings do not necessarily generate more energy in a given set of wind conditions. An important consideration in choosing which wind turbine to install is the capacity factor. The capacity factor of a wind turbine is the average amount of power a wind turbine generates over time for a given set of wind conditions divided by the maximum amount of power that wind turbine is capable of producing. Therefore, the capacity factor of a turbine is an important factor in determining the LCOE for a project.

Other factors may also be important considerations in the selection a specific turbine model for a given project. For example, reducing the number of wind turbines in a given location by selecting a wind turbine with a higher power rating may provide benefits such as reducing viewshed and environmental impacts.

3.3 Wind turbine technology

Technological advances in design, materials, and computerization have made modern wind turbines significantly more efficient at converting wind energy to electricity. Future advances in engineering may soon allow for the placement of wind turbines in deep waters located beyond the platform. Currently, offshore wind turbine capacities range from 2.3-6.0 MW, and new wind turbines are being developed with capacities of up to 8 MW (“Siemens - Wind Turbines”; Kapsali and Kaldellis, 2012).

Wind turbines operate most efficiently and are subject to less fatigue in steady, undisturbed airflow. Modern wind turbines will automatically shut off when local wind speeds get too high (around 90 km/h), and are built to withstand wind gusts of up to 240 km/h (Environmental and Energy Study Institute, 2010). Wind farm installations are typically designed so that as many wind turbines as possible are positioned perpendicular to the prevailing wind direction. A general rule of thumb for turbine installations is to design the wind farm with a lateral separation of 4 to 5 rotor diameters between crosswind turbines and a spacing of 7 to 10 rotor diameters between downwind turbines (Moeller, 2013). Future wind farms may be designed with spacing between crosswind turbines of 10 rotor diameters and 12 rotor diameters of spacing between down wind turbines to reduce wake turbulence and mechanical fatigue (Musial et al., 2013).

The two most common types of foundations used for offshore wind turbine installation are gravity-based structures and piled structures such as monopile or jacket foundations (Figure 3-1) (Veritas, 2010). Gravity-based structures rely on the dead weight of the foundation structure to secure the wind turbine in place and maintain stability. Gravity-based foundations are suitable for water depths up to 25 m. Gravity-based foundations have a relatively large footprint and may impact a larger surface area of the seabed than piled structures. Piled structures secure and stabilize a wind turbine and consist of large piles that are driven into the seabed through the use of hydraulic or steam powered hammers (Veritas, 2010). Piled structures are typically used for water depths up to 45 m. Monopile foundations have been used in water depths of up to 25 m and jacketed foundations have been used in depths greater than 25 m.

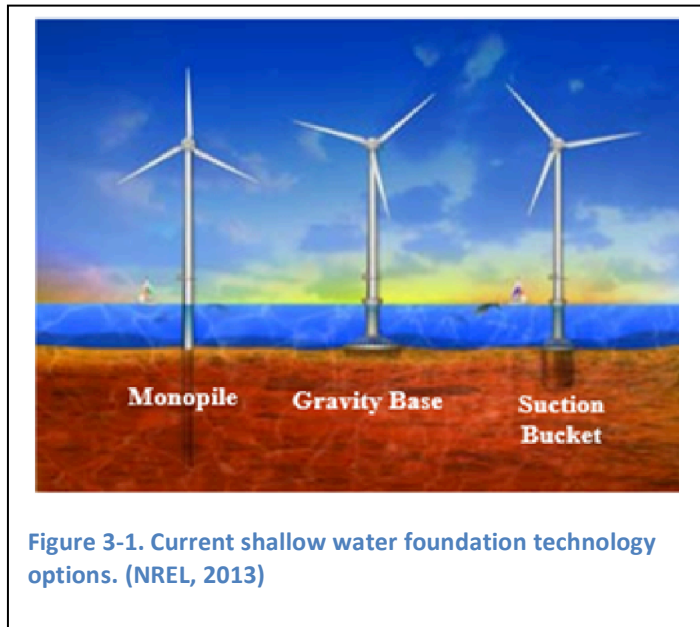


Figure 3-1. Current shallow water foundation technology options. (NREL, 2013)

Research, development, and demonstration of floating offshore wind turbines are ongoing. Should floating offshore wind turbines become a commercially viable option in the future, they would provide Bermuda with more options regarding wind turbine placement. However, since there are currently no commercially deployed floating offshore wind turbines, they will not be considered for purposes of this project.

3.4 Impacts to the marine environment

Bermuda’s marine ecosystem provides important commercial and non-commercial services and goods to its community, and its coral reefs are of global importance, as they are the northernmost coral reef system in the world (Dept. of Conservation Services, Government of Bermuda, 2010). The potential environmental impacts from an offshore wind farm should be assessed in order to minimize the impacts to Bermuda’s marine ecosystem and the community that depends on it.

3.4.1 Bermuda’s marine environment

Bermuda’s coral reefs support a diverse and productive community. The coral reef community includes 38 species of stony coral, 274 species of reef fish, 36 species of cetaceans, and 4 species of marine turtle (Fishbase; Viers, 1993; Wood and Jackson, 2005). The reef’s biodiversity and productivity are highly valuable, as they attract tourists, support recreational and commercial fishing activities, provide coastal protection, and allow for research and education opportunities. The total annual economic value of Bermuda’s coral reefs is estimated to be \$722 million per year (USD) (Dept. of Conservation Services, Government of Bermuda, 2010).

The importance of protecting these coral reefs was recognized with the Coral Reef Preserves Act of 1966, which established two preserves, the North Shore and the South Shore Coral Reef Preserves. Bermuda also has numerous marine protected areas that prohibit fishing year-round or seasonally (Fisheries (Protected Areas) Order 2000, 2005). In addition, Bermuda has regulations that protect

threatened and endangered marine species (Protected Species Order 2012, Protected Species Order 2007, Fisheries Protected Species Order 1978). These include all coral species, marine mammals, turtles, various fishes, and mollusks.

Bermuda's seagrass beds are also an important marine habitat, as they provide nursery grounds for juvenile fish and are a key habitat for sea turtles. The five seagrass species found in Bermuda are protected (Department of Conservation Services).

The coastal area serves as a habitat for seabirds and is in the flyway for migratory birds. Under the Protection of Birds Act (1975), all migratory and native birds are protected. Around 375 bird species have been found on Bermuda, and most of them are migratory. Bermuda has a few wetland areas that are used by migratory birds for resting and feeding and that are protected under the Ramsar Convention.

There is also an Important Bird Area on Bermuda that overlaps with the coastal zone, which was recognized by BirdLife International as being globally important.

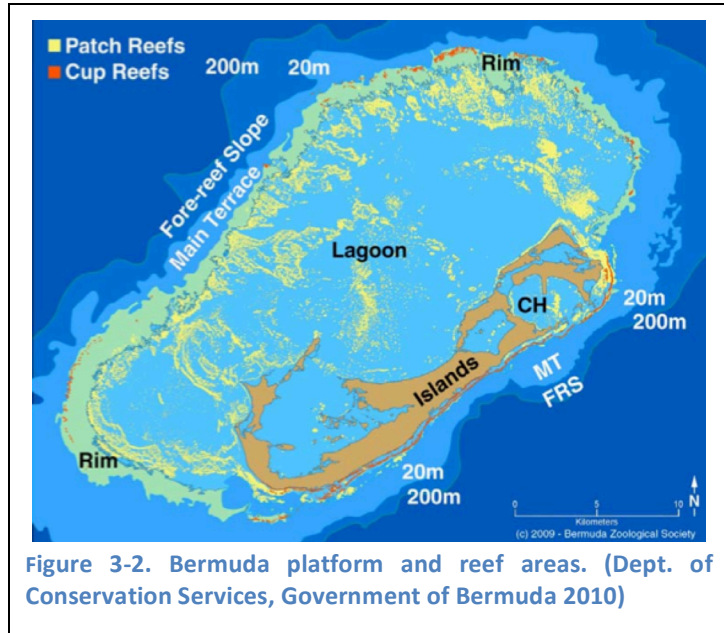


Figure 3-2. Bermuda platform and reef areas. (Dept. of Conservation Services, Government of Bermuda 2010)

3.4.2 Ecological impacts of offshore wind energy

The ecological impacts of offshore wind energy development differ in type and duration between the construction, operational and decommissioning phases, though it is thought that the impacts of decommissioning are similar to those of the construction phase (Gill, 2005). The extent of the possible ecological impacts will depend on the specific characteristics of the marine environment.

During construction, the seabed that is covered by the turbine foundation, scour protection, substations and power cables is directly impacted. However, the footprint of the area that is directly impacted is less than the entire area of the offshore wind farm, and the strategic placement of turbines and other structures can minimize the impacts to benthic habitats or species (Petersen and Malm, 2006). Foundation construction and cable-laying can cause the disruption of sediments, which may lead to habitat degradation and loss, and increased water turbidity. An altered habitat may cause the displacement of mobile species, while sedentary species, such as corals, may be impacted due to smothering by sediments and reduced light levels (Gill, 2005). In some cases, the changes are short-term and the disturbed habitats are likely to return to their original state (Lindeboom and et al., 2011). In Bermuda, the impacts from sedimentation may be negligible as the natural disturbance of sediments from storms is far greater in magnitude than what would be expected to occur from offshore wind farm construction (Hochberg, 2013).

The noise generated during foundation installation may cause disturbance to marine organisms in multiple ways. It could interfere with communication, finding prey, echolocation, mating, and predator avoidance activities. In particular, pile driving is likely to produce the most noise, which may damage the acoustic systems of certain species and potentially cause behavioral changes, such as avoidance of the area (Gill, 2005). Studies have shown that the risk of damage and mortality is increased for fish located

very near pile driving activities, while fish located further away may be driven away (Snyder and Kaiser, 2009). Pile driving has also been found to directly affect the behavior of cetaceans (Inger et al., 2009). Cetaceans may be particularly sensitive to the noise as they use echolocation to find food and communicate. For example, pile driving of a wind turbine foundation could cause hearing loss in porpoises up to 1.8 km away and would be audible up to 80 km away (Thomsen et al., 2006).

During the operational phase, the noise levels are less intense and are likely to cause less disturbance, but further research is needed to determine its long-term effects (Inger et al., 2009). It has been found that the operational noise of wind turbines could be detected by harbor porpoises around 100 m away and by harbor seals over 1 km away (Thomsen et al., 2006). Fish can react to the noise from wind turbines, and have been found to avoid turbines within 4 m. While these noises may not result in visible physiological damage, they may mask communication and orientation signals. However, it is unknown if noise could cause stress and reduce the survival abilities of fish (Wahlberg and Westerberg, 2005).

Another potential effect during the operational phase is the generation of electromagnetic fields, which could impact electrosensitive and magnetosensitive species. Electric fields may attract or repel electrosensitive species, while magnetic fields emanating from the power cables may affect a species' ability to use magnetic fields for orientation and navigation (Gill, 2005). However, these effects are not well studied or documented, and it is hypothesized that these types of species may adjust to the electric fields (Lozano-Minguez et al., 2011).

Once turbines are in place, the foundation and scour protection can potentially produce positive impacts by creating new habitat and attracting marine organisms. The turbine structures provide additional hard substrate for marine organisms, acting as artificial reefs. They may attract species and become fish-aggregating devices, also known as FADs, causing populations to increase near the foundations (Lozano-Minguez et al., 2011). A study on the Horns Rev 1 Wind Farm in the North Sea found that local fish populations occurred in greater numbers near the farm area after construction than before construction (Stenberg and Støttrup, 2011). This study was the first to use the Before-After-Control-Impact (BACI) design on a long-term study of the effects of offshore wind farms on fish communities. The aim of a BACI design is to examine the *Before* (pre-construction baseline) and *After* (post-construction) condition of the area, as well as to compare a *Control* (reference site outside the wind farm) with the *Impact* site (wind farm site). Higher levels of biodiversity were observed near the turbines, suggesting evidence of the artificial reef effect. Additionally, recruitment of fish near the wind farms increased through time after construction, most likely due to the safety that the farms offer for juvenile fish. The increase in hard substrate can offer refuge for many species that congregate around the base and pole by providing safe environments for fish recruitment. The hard substrate may also benefit species, such as lobsters, which prefer rocky habitat.

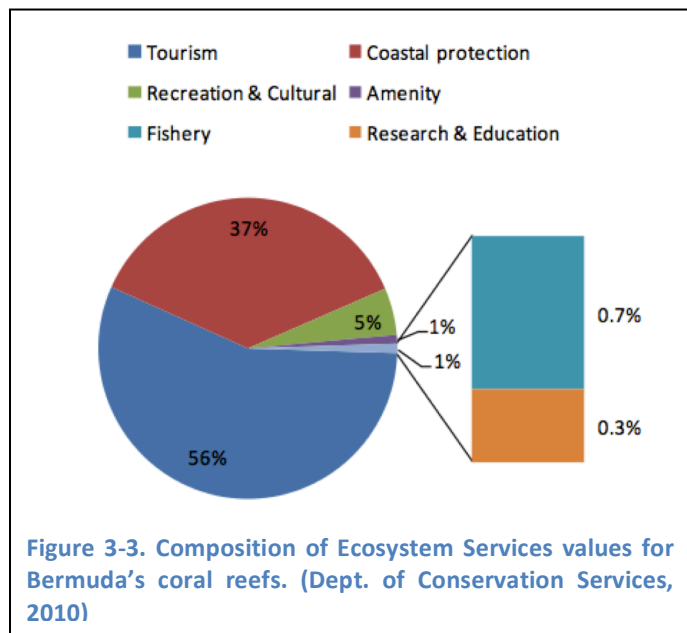
The offshore wind farm area may become a de facto marine protected area. The extent of protection would depend on whether an exclusion zone is adopted or whether certain types of fishing activities will be restricted. Fish populations, especially juveniles, could benefit from this protection. Even if the total wind farm area is not exclusively closed, fishing effort may move to other areas on the platform, creating a safer environment for juvenile fish and spawning activities (Alexander et al., 2013). Fish populations may become more productive, which would benefit fishermen through increased catches via the 'spillover effect' (Alexander et al., 2013).

Above the water, the turbines can potentially negatively impact birds due to collisions, barrier effects, or habitat loss. The moving blades of the turbines can pose a collision risk to birds, but may also present barriers that birds will avoid, disrupting their natural flight patterns. In addition, habitat loss may result from disturbance in the wind farm area during the construction and operational phases (Exo et al., 2003). Many studies have been conducted on the impacts of onshore wind farms on birds, but less is

known about the potential for collision or avoidance for marine species and their interaction with offshore wind farms (Inger et al., 2009). A review of the literature found collision mortality rates between 0.01 and 23 mortalities per turbine per year for onshore wind farms (Drewitt and Langston, 2006). High collision numbers occurred in areas of high bird migration traffic and in farms with large numbers of turbines. Information regarding collision rates for offshore wind farms is limited due to difficulties in detecting the occurrence of collisions offshore (Drewitt and Langston, 2006). Different bird species are likely to have different risks of collision due to the different altitudes at which they fly and their different behaviors (Hüppop et al., 2006). As a result, the collision risks are expected to be site specific. Because Bermuda hosts many migratory birds, which have protected status, a risk assessment would be needed in order to determine the potential impacts.

3.5 Ocean Uses

Multiple activities occur in the limited space of the Bermuda platform, and the addition of a wind farm could lead to tradeoffs with other ocean users. Depending on the location of the wind farm, ocean users could be impacted to varying degrees due to the spatial distribution of their activities. Figure 3-3 shows the economic value that the coral reefs provide to different sectors, and suggests the potential stakeholders that could be affected should the value of the coral reefs be impacted by wind energy development. In this section, we examine the major ocean uses and stakeholders that we identified to be important for the marine spatial planning process for the siting of an offshore wind farm.



3.5.1 Tourism

Bermuda's reefs and waters are a major draw for tourists. However, wind turbines may impact tourist access to recreational areas on the reef, which could also affect Bermuda's tourism industry. A 2010 survey conducted by Bermuda's Department of Conservation Services identified tourists' motivations to visit Bermuda. Of the surveyed tourists, 8.6% came for snorkeling, 8.3% for touring the reef, 6.4% for sailing, 5.7% for diving and 4.9% for fishing (Dept. of Conservation Services, Government of Bermuda, 2010). Around 38% of tourists were motivated to visit Bermuda because of its coral reefs (Dept. of Conservation Services, Government of Bermuda, 2010). The tourism industry represents the largest share of the economic value of the coral reefs, valued at US\$406 million (Figure 3-3). Therefore, the tourism industry is expected to have a large stake in the placement location of wind turbines. Impacts to the viewshed will also likely be an important issue for the tourist industry as wind turbines would be visible on the horizon and affect the coastal scenery. However, examination of the viewshed impact is beyond the scope of our project.

3.5.2 Maritime traffic

The placement of wind turbines must consider the location of existing shipping channels, which are vital to Bermuda and its economy. As an island with limited land resources for manufacturing and agriculture, Bermuda relies on container ships to import most of its food and manufactured goods. Cruise ships are a significant part of Bermuda's tourism industry. In 2007, 53% of Bermuda's visitors arrived by cruise ship (Dept. of Conservation Services, Government of Bermuda, 2010). In 2013, Bermuda was scheduled to have 127 cruise ships visit its ports (Department of Marine and Ports Services, 2013). Bermuda's maritime traffic is expected to continue to increase due to its growing tourism industry and increasing demand for goods. Bermuda also has a ferry system that connects different parts of the island. The specific siting of offshore wind turbines will need to account for potential impacts to Bermuda's maritime traffic.

3.5.3 Radar

Numerous studies have been performed on the impacts of offshore wind turbines on air surveillance radar (ASR), weather radar, and marine radar systems (Office of the Director of Defense Research and Engineering, 2006; Merico Marine, 2007). Wind turbines can adversely impact the ability of a radar system to detect and track a target. Specifically, this occurs when energy from radar transmitters is reflected off of the wind turbine blades and structures back to the radar system creating clutter.

The rotating blades of wind turbines impact ASRs by creating clutter that can result in the loss of primary radar detection and tracking of aircraft and objects vertically located over the wind turbines (Nancy Kalinowski, 2010). Secondary systems such as transponders are not impacted thus allowing for detection and tracking of cooperative targets. There also exists an ability to apply filters to the radar systems to filter out return clutter (Nancy Kalinowski, 2010).

The impacts of offshore wind turbines on marine radar systems appear to be less pronounced. In 2007 British Wind Energy Association (BWEA) published a comprehensive report on the impacts of offshore wind turbines in the Kentish Flats wind farm on marine radar systems. The report concluded that though vessel radar systems were impacted when operating in or near offshore wind turbines the observed impacts could be mitigated through training of radar personnel to recognize the impacts and to adjust radar settings accordingly (Merico Marine, 2007). The ability of stationary marine radars, such as those used by Bermuda Radio, to detect and track vessel activity were also impacted, but with proper training and adjustments the overall impacts could be mitigated (Merico Marine, 2007). The study also concluded that the automatic identification system (AIS) is not impacted by offshore wind turbines. This will allow for the tracking of vessels operating in or near offshore wind turbines.

Ultimately, the impacts of offshore wind turbines on Bermuda's ASR, weather and marine radar systems will have to be evaluated on a case-by-case basis. It is possible that wind turbines could be placed in areas where reduced or degraded detection and tracking capabilities do not significantly impact the ability of the radar systems to perform their intended purpose.

3.5.4 Wrecks and marine heritage sites

Bermuda is known for its large number of shipwrecks, which possess historical and recreational value. All shipwrecks and marine heritage sites are protected under the Historic Wrecks Act of 2001. There are at least 150 known shipwrecks, though it is estimated that there are at least 300 altogether (Department of Conservation Services). Wrecks have a recreational value for SCUBA divers. A survey showed that wrecks rank third in terms importance of underwater sightings, after coral reefs and fish (Dept. of

Conservation Services, Government of Bermuda, 2010). There are 19 wreck dive sites scattered around the platform that are protected areas.

3.5.5 Research and education

The biodiversity of Bermuda's coral reefs provide opportunities for research and education, and its value to this sector was estimated to be US\$2.3 million in 2007. The major governmental departments and NGOs that are involved in coral reef-related research and education are: Department of Conservation Services, Department of Environmental Protection, the Bermuda Zoological Society and the Bermuda Institute for Ocean Sciences (Dept. of Conservation Services, Government of Bermuda, 2010).

3.5.6 Fisheries

The installation of offshore wind turbines on the Bermuda platform may affect access to fishing areas or pose some risk to fishing activity. Economically, local fishermen represent a working minority on the island (National Economic Report of Bermuda, 2013), though they are an important stakeholder group to consider in the development of any type of offshore project.

Bermuda's fisheries are culturally significant to the locals, and fish caught in Bermuda are primarily for local consumption. However, growth in the island's tourism sector in recent years has significantly increased the demand for local fish for consumption (Luckhurst et al., 2003).

Bermuda's fisheries are divided into the reef fishery, which occurs in the shallow waters of the platform, and the pelagic fishery, which occurs in the deep waters beyond the rim reef surrounding the platform. Reef-associated catches make up 42% of total commercial catch, and 79% of total recreational catch value. Though once thought not to be as productive as the reef fishery, Bermuda's pelagic fishery effort has increased significantly in recent years with considerable increases in reported landings (Luckhurst and Trott, 2000). This re-distribution of fishing effort is most likely due to stricter regulations on the reef fishery, as fishing pressure became too great to sustain reef fish populations (Luckhurst and Trott, 2000). For our project, we focused our efforts on analyzing the reef fishery, as any activity outside the platform is outside our area of consideration for wind turbine placement.

The fisheries are further divided into commercial and recreational sectors and are regulated through the use of gear restrictions, size and weight limits, temporal closures, restricted access to spawning sites and implementation of no-take zones (Luckhurst et al., 2003).

Bermuda's commercial fishery requires licenses and utilizes a variety of methods, including hook-and-line, trolling, and traps and/or nooses for lobster fishing. This fishery is limited entry, presently capped at 200 vessels including those used for charter (Robertson, 2013). The commercial lobster fishery targets spiny lobster and guinea chick lobsters, also known as spotted spiny lobsters. The fishery is divided into inshore and offshore areas. The inshore area is defined as within the 10 m depth contour, while offshore is defined as the area beyond the 10 m contour. The inshore area is then further divided into east and west areas. Commercial lobster fishermen are confined to specific areas, which are established during the licensing process.

The recreational fishery is classified as 'open', meaning licenses are not required to fish for personal purposes. However, recreational spearfishing and lobster fishing do require licenses, which limit catch and methods. Recreational fishermen primarily use hook-and-line, rods, and small nets for finfish and nooses for lobster.

Impact to fishing activity from the installation of offshore wind farm

The installation of offshore wind turbines on the Bermuda Platform may affect the fisheries in the surrounding area. Exclusion zones around wind turbines, in which fishermen will not be allowed to enter, are heavily dependent on a variety of factors and are thus considered on a case-by-case basis (Vattenfall, 2011). During the construction phase of the offshore wind farm, the entire area will be deemed an exclusion zone for at least the duration of the construction period (Rodmell and Johnson, 2003). In some cases, exclusion zones may not necessarily span the entire wind farm area; for the Kentish Flats offshore wind farm in Kent, England, the developer set a 500 m safety exclusion zone around the turbines during the construction phase and then set a less conservative buffer zone of 50 m during the operational phase. Rather than create a categorical exclusion zone, it is possible for some wind farms to limit certain kinds of fishing methods, or to set a size limit on vessels that are allowed to navigate through the area (Mangi, 2013; Poseidon (Aquatic Resource Management Ltd), 2002).

The physical presence of offshore wind farms could be incompatible with specific types of fishing techniques. The use of bottom gear, such as trawling, is likely to be the most conflicting type of technique when employed near the structures and/or the submerged cables (Rodmell and Johnson, 2003; Mangi, 2013). Trolling also has the potential for entanglement with the turbine structures, though is considered to be a rare occurrence (Rodmell and Johnson, 2003). Since Bermuda fisheries do not use trawling methods, and trolling is typically limited to outside the platform area, it is likely that their gear and methods will not be in conflict with wind turbines.

Previously conducted surveys have found that fishermen's perceptions of the impacts of offshore wind energy development to the fishing community may not be factually justified (Mackinson et al., 2006); the perceived impacts are likely to be greater than actual impacts. The measurable effects of offshore wind farms on fisheries have not been well studied or documented (Rodmell and Johnson, 2003), thus there is a need to include fishermen interests in the planning process for an offshore wind farm. Fishermen have stated that their largest concern is loss of livelihood as a result of offshore wind farm development (Alexander et al., 2013). Even if fishermen are not excluded from the wind farm area, fishing activity may still be affected. In a 2005 survey, U.K. fishermen expressed that even if a comprehensive exclusion zone was not implemented, they would still likely avoid the area and not enter due to safety concerns (Poseidon (Aquatic Resource Management Ltd), 2002).

The offshore wind farm could also bring benefits to the fishermen in the form of increased stocks (Fayram and de Risi, 2007). As discussed earlier, turbine structures could act as fish-aggregating-devices (FADs) and/or as artificial reefs, prompting an increase in species diversity, size of individuals, and population productivity (Rodmell and Johnson, 2003).

Though fishing activity is likely to be minimally impacted from offshore wind development we anticipate significant political resistance from the local fishing community. As such, fishermen interests, representing a significant stakeholder, will need to be incorporated into the planning process.

3.6 Social impacts

The role of the public as a key stakeholder is important to consider in decisions regarding offshore wind farm locations. Studies of public reactions to wind energy projects are useful in providing a broad understanding of general attitudes and identifying significant areas of concern. Wind turbines may be clearly visible from land due to the size of the turbines, their color, movement, and the openness of their locations in the ocean, thus impacting the scenic or other landscape values attached to many parts of the coastline (Haggett, 2011).

Research regarding wind farm developments in Scotland and Ireland supports the view that aesthetic perceptions, both positive and negative, are the strongest single influence on individuals' attitudes toward wind power projects (Haggett, 2011). This study identified four main factors that underlie support for or opposition to offshore wind turbines: aesthetics, community harmony, local fishing industry, and recreational boating (Haggett, 2011).

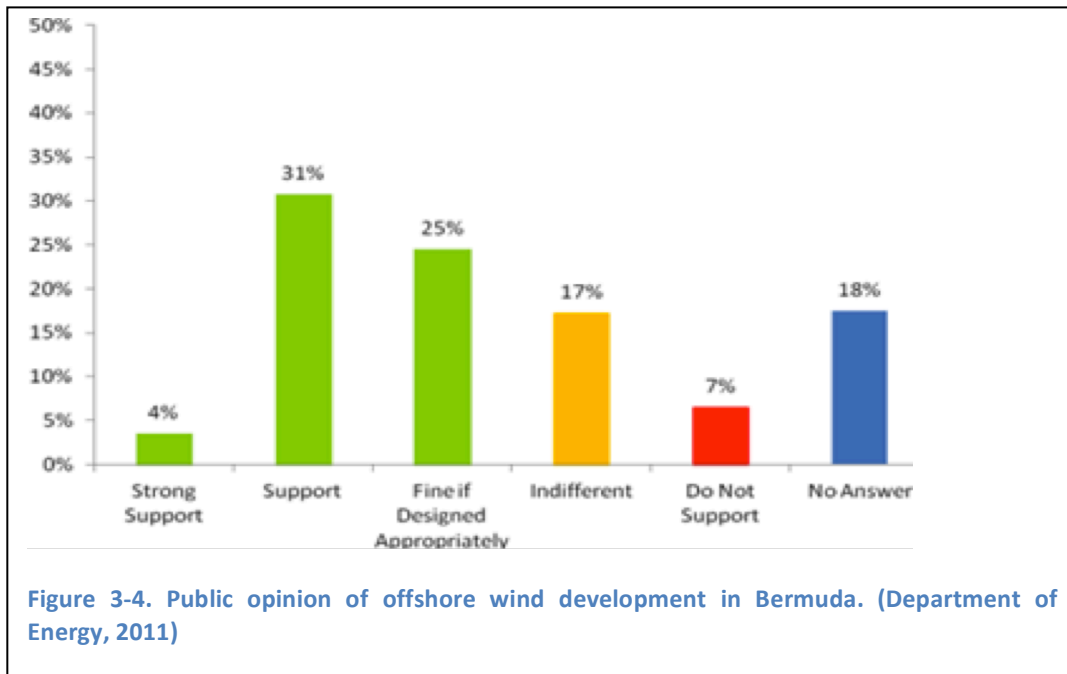
Studies suggest that opposition to wind power is due to more complex reasons than just the NIMBY (Not In My Backyard) idea that is often suggested (Devine-Wright and Howes, 2010). NIMBY is the concept that a person or community is opposed to a project that is perceived as harmful or undesirable in their own neighborhood, but recognizes the need and is not opposed to a similar development elsewhere. Instead, public opposition can be attributed to the overall aesthetic value associated with a particular landscape, as opposed to the proximity of wind turbines to the individual forming the opinion (Devine-Wright and Howes, 2010).

A study based on neighboring Welsh towns highlights the relation between public perception and equity. Less affluent neighborhoods accepted wind turbines positively and framed it in terms of jobs and prosperity while more affluent neighborhoods saw wind turbines as a significant threat to an area of aesthetic value (Devine-Wright and Howes, 2010).

Viewshed perceptions change with distance. A large survey study indicated a rapid drop in negative feelings about turbines in the landscape with distance. At a distance of 4 km from shore, the rate of negative responses was 70%, dropping to 36% at 12 km. Of the respondents who already live near wind farms, the respondents at 8 km and 12 km were only marginally more negative than those living in proposed or approved areas, where farms were yet to be built, but respondents at 4 km were substantially more negative. This effect suggests that living within 4 km of a wind farm is even worse than the already negative expectation they had prior to construction (Bishop and Miller, 2007).

Several studies have concluded that people tend to prefer fewer taller turbines to a larger number of shorter turbines (Thayer and Freeman, 1987). Lower capacity turbines tend to be shorter but require larger numbers to meet the needed capacity. This suggests a tradeoff between the height of the structures and the quantity required to meet the required nameplate capacity.

According to a survey by the DOE in 2010 (Figure 3-4), "76% of residents either support or are indifferent about the use of offshore wind turbines in Bermuda" (Dept. of Energy, Government of Bermuda, 2011). The assumption in the survey was that the developments would be several miles offshore. While the responses to the survey are generally positive, the preceding sections underline the importance of public perception.



3.7 Marine Spatial Planning

Marine spatial planning (MSP) is a process used to identify stakeholders, activities, and resources of the marine environment, analyze their temporal and spatial interactions, and propose a comprehensive plan for where different uses and activities should occur. Governments and management agencies increasingly use MSP to balance a diversity of uses of and benefits from the marine environment, including food and energy production, resource extraction, recreation, and the cultural needs of a growing global population.

In order to assist decision makers and stakeholders in the decision-making process, numerous decision support tools are available (Center for Ocean Solutions, 2011). These tools provide a framework for more comprehensive, flexible, science-based planning processes and are used to promote a more efficient use of the marine environment that reduces conflicts among competing ocean users. The common function of these tools involves using spatially explicit data to map, visualize and/or analyze planning scenarios, which can be evaluated by decision makers and stakeholders.

Tradeoff analysis is a useful tool that can help support the MSP process (White et al., 2012; Lester et al., 2013). This quantitative method is used to assess the tradeoffs between competing values in different decision scenarios, and to identify decisions that can increase efficiency. This type of analysis has traditionally been a concept in economic theory, but is being used increasingly for comprehensive environmental planning. Decision makers, managers, stakeholders, and the general public can use the resulting information to decide how best to combine various economic, social, and ecological objectives into the planning process.

A challenge of the MSP process is overcoming the suspicion of stakeholders concerning the true impacts of management decisions. Tradeoff analysis provides a transparent method for quantifying and communicating potential management outcomes (White et al., 2012). For example, White et al. (2012) used tradeoff analysis to model scenarios for the contentious Cape Wind Project, an offshore wind farm planned for the Nantucket Sound in Massachusetts, USA. The authors assessed the potential spatial

conflicts among offshore wind energy, commercial fishing and whale watching sectors and identified wind farm locations that maximized the combined value of the multiple sectors. Using this analysis, they were able to show that MSP could prevent more than \$1 million in losses to the fishery and whale-watching sectors, and generate more than \$10 billion to the wind energy sector. This study demonstrates the value of tradeoff analysis to MSP, by helping to inform the stakeholder discussion and to identify efficient solutions.

4. Wind energy model

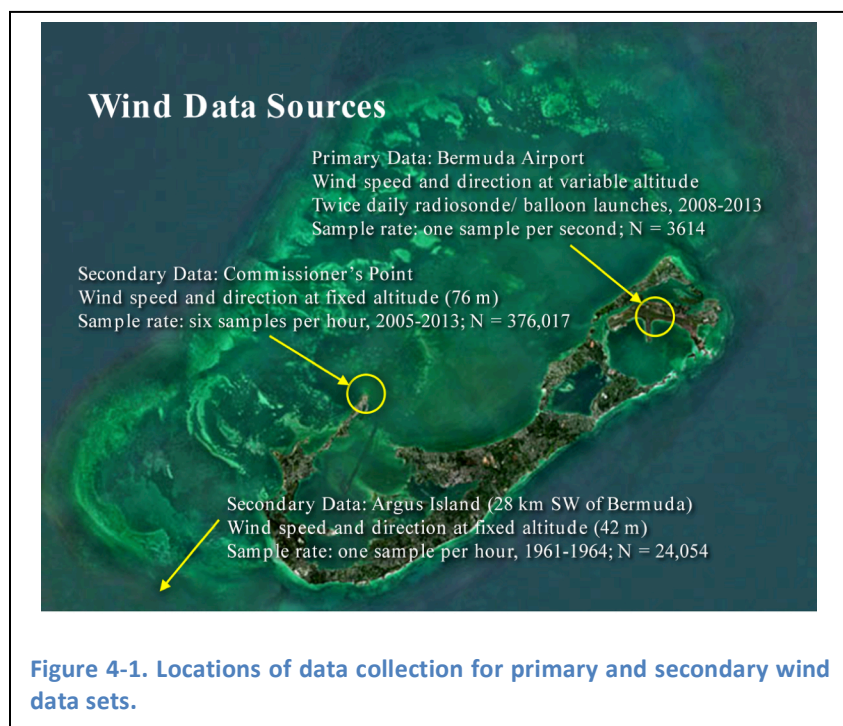
4.1 Methods

In order to determine if wind energy is economically viable for Bermuda, we looked at the quality of wind energy available over the platform and used this to calculate a levelized cost of energy. In its 2011 Energy White Paper, the Bermuda DOE stated a nameplate wind capacity goal of 35 MW by 2020. Our analysis targeted a much more ambitious nameplate capacity of 100 MW to simulate further growth in wind energy development, as well as to have a conservative look at associated spatial interactions.

4.1.1 Wind resource estimation

In order to estimate the wind resources available on the Bermuda Platform, we analyzed a number of data sets to characterize the parameters of the probability density function of wind speed as a function of altitude. Assuming that the results are representative of spatial and temporal wind patterns over the platform, we could then use the wind speed probability distribution function and published power curves for representative wind turbine models to estimate the expected capacity factor of a given turbine at a given altitude.

The primary data set used for this analysis was collected using a radiosonde device attached to a weather balloon, sampling wind speed, direction, and altitude at one-second intervals as the balloon/radiosonde apparatus was spooled out and allowed to rise in a controlled fashion. Radiosonde data trials were collected twice daily from 2008 to 2013, from a location at the Bermuda airport.



To verify the assumption that the primary data set accurately represents the wind speed regime over the entire Bermuda Platform, we analyzed two secondary data sets to determine wind probability density functions at exposed locations around the platform.

A land-based secondary data set was taken from the weather station atop Commissioner's Point, an exposed point 76 m above sea level on the tip of the "hook" on the southwest end of the island, extending out into the platform. Wind speed and direction data were taken at ten-minute intervals from 2005 to 2013. No data points were available from this location for 2007.

A wind study performed at the Argus Island observatory, a laboratory platform in the open ocean 28 km southwest of Bermuda, provides a probability density distribution of wind speed and direction based on data collected hourly between May 1961 and April 1964, with a sample size of approximately $n = 24,000$. The laboratory no longer exists, but based on digital image analysis of existing diagrams of the platform, the sensor height is estimated to have been 42 m.

Wind energy resource characterization

We imported wind speed, wind direction, and altitude data from the primary data set measured at the Bermuda airport into a MATLAB data structure. In order to estimate wind speed at a specific target altitude typical of wind turbine installation, we created a MATLAB script to interpolate the speed and direction from each radiosonde launch data trial. We chose a turbine hub height of 100 m for our analysis, based on discussions with wind turbine industry representatives (Moeller, 2013; Mayba, 2013).

The MATLAB script identified data points immediately below and immediately above the target altitude as upper and lower bounds. For both bounds, the wind speed was broken into x and y components (latitude and longitude components) based on the wind direction. The vector components of speed at target altitude were interpolated separately from the vector components of speed at the upper and lower bound, and then recombined.

The resultant vector from this linear interpolation provided an approximation of wind speed magnitude and direction at the target altitude.

Once resultant wind speed and direction were determined for all individual radiosonde launch data sets, the data were combined into a single time series spanning the years 2007 through 2013. We applied a Weibull fit, commonly used to model wind speed distributions, to approximate the probability density function for annual wind speed at the target altitude.

Validation of wind energy resource assumptions

Our analysis of available wind power depends on understanding prevailing wind patterns at locations suitable for offshore turbines on the Bermuda Platform. Our primary data source is confined to a single spatial point on the mainland, and no detailed spatial study of wind was available for our analysis. Therefore, we must make the assumption that our primary data is reasonably representative of wind patterns over the entire platform. Representatives from the Bermuda Weather Service stated that they felt this assumption was reasonable (Currie, 2013). In addition, they provided additional data to us from several other sites to further test our assumption.

We compared the results of the analysis of the radiosonde data with analyses of data taken from two spatially distinct secondary locations (Commissioner's Point and Argus Island), each collected from wind speed and direction sensors at a fixed altitude. Based on input from representatives of the Bermuda Weather Service, exposure of these sites suggests that we could expect the wind patterns to be similar to the conditions on the open platform (Currie, 2013).

Data from each of the secondary sites were analyzed to determine a probability distribution of wind speed. In order to provide a similar reference altitude for comparison, we interpolated wind speed from our primary data set to meet the same altitudes as our secondary data collection sites. To provide a comparison to the Argus Island data, we interpolated the radiosonde data at an altitude of 42 m above sea level. For the Commissioner's Point data, we interpolated the radiosonde data to determine wind speeds at 76 m above sea level.

In order to compare the secondary data to the interpolated primary data, we used the Welch two-sample t-test. Visual inspection of the wind-speed distribution suggests a non-normal distribution of the population, but because the sample sizes are very large ($n \gg 350$), we can assume that based on the central limit theorem, the means of samples from the population would be normally distributed.

Capacity factor

The capacity factor of a wind turbine is the ratio of the actual power generated versus the maximum power a wind turbine is capable of generating. For our analysis, we focused on a typical 5.0 MW turbine, approximating the power curve based on published power curves from Siemens. We determined the expected average power generated by integrating the product of probability of a particular wind speed and the power generated at that wind speed as determined by the power curve.

4.1.2 Levelized cost of energy from wind development

In order to determine the economic viability of offshore wind energy in Bermuda, we need to be able to compare the cost of electricity generated from offshore wind turbines to the current cost of electricity to Bermuda energy consumers. A commonly used metric to calculate and compare the cost of electricity generated from different energy generation technologies is the levelized cost of energy (LCOE) (Salvat et al., 2006; Maples et al., 2013; Levitt et al., 2011). The LCOE represents the cost per unit of energy (\$/kWh) from an energy project, which is determined by dividing the sum of present value (PV) of costs by the present value of total energy production. The LCOE we calculate represents the minimum price of energy (\$/kWh) needed by a wind developer to cover its cost to include return on investments.

The costs are comprised of capital expenditure costs (CAPEX), annual operating expenditures (AOE), and an appropriate rate of return on investments referred to as the discount rate. The CAPEX estimate encompasses the cost of the wind turbine assemblies, foundations, transportation, cabling between the turbines (inner-array cabling), cabling connecting the wind farm to an onshore grid connection point (export cabling), installation costs (including the cost of installation vessels, labor, and material), and decommissioning costs. The AOE estimate encompasses levelized replacement costs, labor equipment and facilities costs, management costs and platform area leases (Maples et al., 2013).

We calculated the LCOE using the following variables and equations given in Table 2 (Salvat et al., 2006; Kaiser and Snyder, 2012; BVG Associates, 2012; Maples et al., 2013).

Table 2. Equation for calculating LCOE

$$PV_{revenues} = \sum_{t=0}^T [(AEP_t \times P_{energy}) \times (1+r)^{-t}]$$

$$PV_{costs} = \sum_{t=0}^T [(CAPEX + AOE_t) \times (1+r)^{-t}]$$

Since $PV_{revenues} = PV_{costs}$

$$P_{energy} = LCOE = \frac{\sum_t [(CAPEX + AOE_t) \times (1+r)^{-t}]}{\sum_t [(AEP_t) \times (1+r)^{-t}]}$$

Annual Energy Produced (AEP_t)	=	total energy produced in year “t” (kWh)
P_{energy}	=	real price of energy (\$/kWh)
r	=	discount rate (%). A weighted average cost of capital is used for the discount rate
$(1+r)^{-t}$	=	discount factor in year “t”
CAPEX	=	total capital expenditures (\$/MW). The CAPEX accounts for the cost of the wind turbine assemblies, foundations, cabling,

In order to calculate the LCOE we used a combination of peer-reviewed literature, energy industry papers, and energy agency reports to obtain estimates for capital expenditure costs (CAPEX), annual operating expenditure costs (AOE), discount rate (r) and expected lifetime (T) of an offshore wind project. Estimates for the CAPEX of a project, normalized by name plate capacity, ranged from \$2.5 to 6.5 million per installed MW (Salvat et al., 2006; Kaiser and Snyder, 2012; BVG Associates, 2012; Moeller, 2013; Maples et al., 2013).

Because Bermuda is geographically close to the U.S., we anticipate the cost of logistics, material and labor for a Bermuda offshore wind project will closely mirror the costs of a U.S. offshore wind project. We used the National Renewable Energy Laboratory (NREL) CAPEX estimate of \$5.6 million/MW and AOE estimate of \$40/MWh (Tegen et al. 2013). These estimates reflect the anticipated costs to offshore wind development in the US and thus serve as a proxy for anticipated cost estimates for offshore wind development in Bermuda.

For the purposes of our calculations the following assumptions have been made:

- The amount of annual energy production (AEP) remains constant over the lifetime of the project. The methodology and calculation for determining the capacity factor of the wind turbine, which was used to calculate the AEP, are discussed in section 4.1.1.
- The calculated LCOE is in real dollars and remains constant over the lifetime of the project. This assumes a fixed price escalator (annual price increase) to the nominal price of energy (\$/kWh) that will equal the annual rate of inflation thus making the real cost of energy constant over time (Levitt et al., 2011).

- A 10% weighted average cost of capital is commonly used in similar studies as the discount rate. We use this for our calculations (Salvat et al., 2006; Levitt et al., 2011; BVG Associates, 2012; Maples et al., 2013; Mayba, 2013). The discount rate used to calculate the PV of discounted revenues is equal to the discount rate used to calculate the PV of discounted costs.
- The lifetime of the project is set at 20 years.
- The CAPEX estimate assumes that wind turbines will be constructed in waters $\leq 25\text{m}$. The CAPEX estimate also assumes that the wind farm will be constructed within 40 km from a port and shore grid connection point (Kaiser and Snyder, 2012; BVG Associates, 2012; Maples et al., 2013).
- The total installed capacity of offshore wind energy, commonly referred to as the Name Plate Capacity, is 100 MW.
- We used a decommissioning cost estimate of \$165/kW and an area leasing cost estimate of \$21/kW/yr (Maples et al., 2013). The costs of a decommission bond are included in the CAPEX cost estimate and the costs of an offshore lease are included in the AOE cost estimate.
- We incorporated factors that would result in losses in the amount of energy produced in order to calculate a net capacity factor. These included turbulence wake losses, line losses and availability, estimated at 12.4%, 3% and 96% respectively (Levitt et al., 2011; Tegen et al. 2013)
- LCOE does not account for administration costs, transmissions costs, taxes, depreciation, incentives, carbon credits, or other mechanisms to account for the benefits of reduced greenhouse gas (GHG) emissions

In order to gain confidence in our LCOE calculations using wind data from Bermuda we also calculated LCOEs using cost estimates from the 2012 BVG Associates report and from the wind model in the Natural Capital Project's InVEST planning software.

Sensitivity Analysis

Although the values of the input parameters were reasonably consistent among the various cost estimate studies, there nevertheless exists a considerable amount of uncertainty in these estimates. In order to quantify the uncertainty in the LCOE calculations, we varied the input estimates for CAPEX, AOE, discount rate, and gross capacity factor across the estimated range of values for each input parameter holding all other inputs equal to the original input values.

4.2 Results

4.2.1 Wind resource estimation

Wind energy resource characterization

Figure 4-2 displays wind speed probability density histogram at 100 m, interpolated from the radiosonde data, plotted against a Weibull distribution fit.

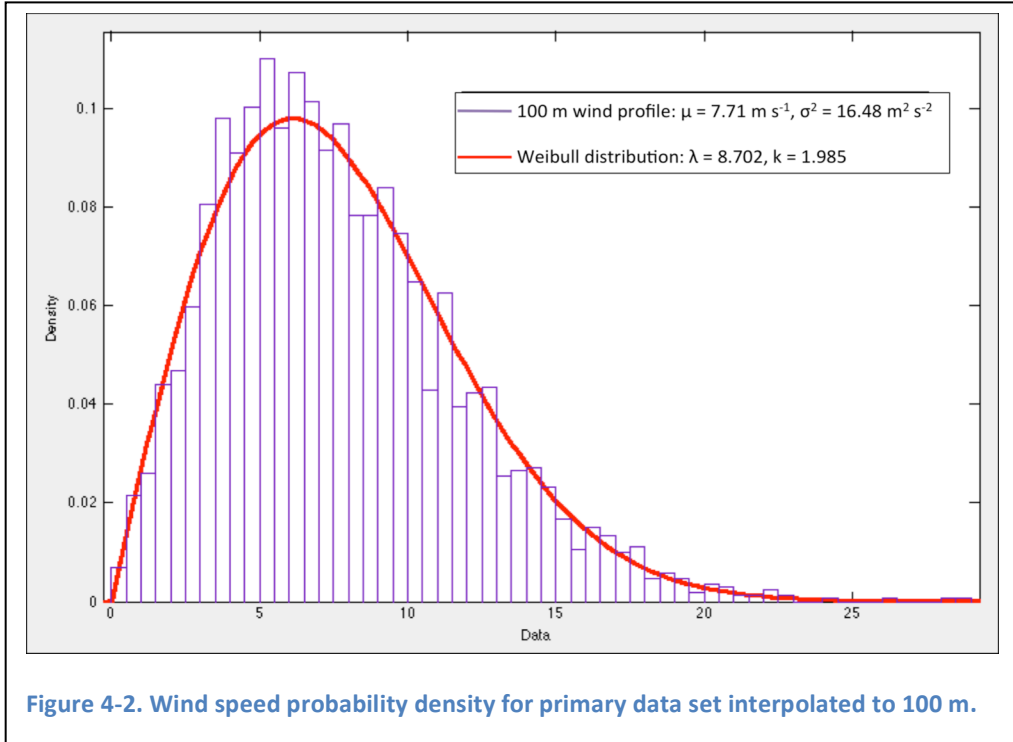
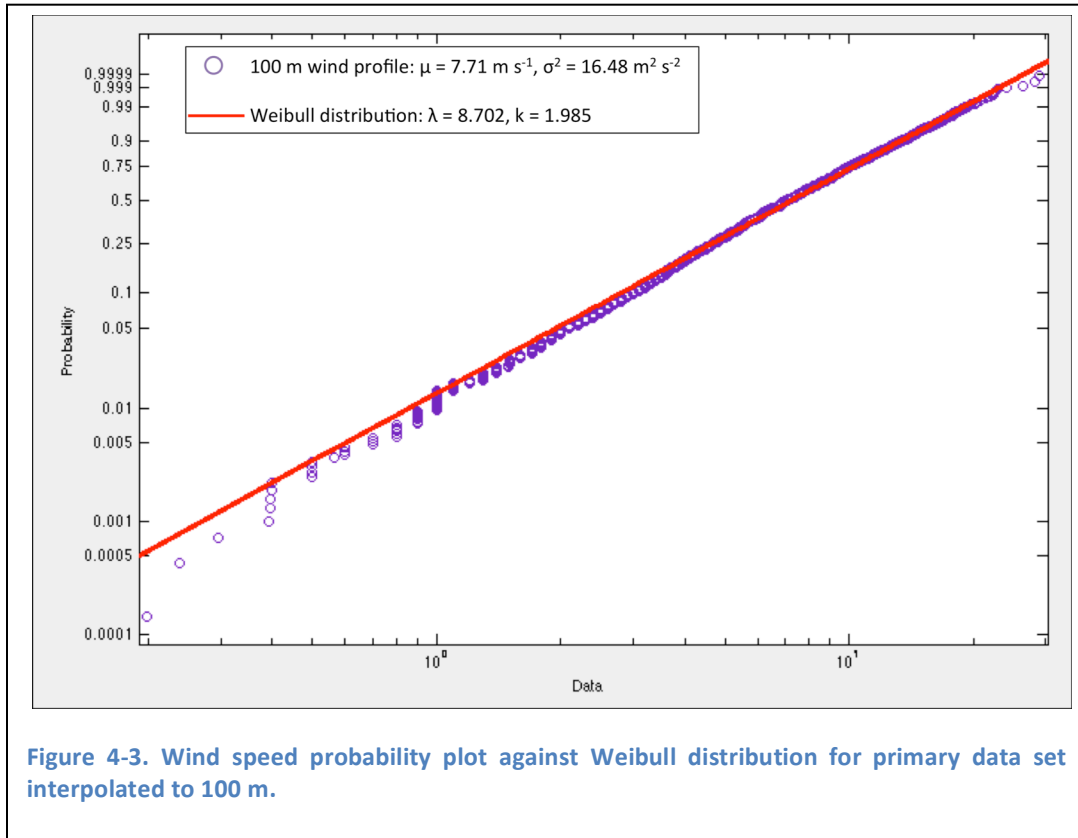


Figure 4-3 plots the wind speed data interpolated to 100 m against a Weibull distribution, demonstrating that a Weibull fit is an appropriate model for our wind speed distribution.



For wind at a 100 m hub height, we determined a distribution with a mean wind speed of 7.71 ms^{-1} , variance of $16.48 \text{ m}^2\text{s}^{-2}$. The probability distribution function for wind speed v can be approximated through a Weibull distribution:

$$f(v, \lambda, k) = \frac{k}{\lambda} \left(\frac{v}{\lambda} \right)^{k-1} \exp\left(- \frac{v^k}{\lambda} \right)$$

For the primary data set interpolated to 100 m, the Weibull scale parameter is $\lambda = 8.702$ and shape parameter $k = 1.985$.

Generalization of wind energy resources over Bermuda Platform

We compared the mean wind speed of the primary data set to the mean wind speeds of each of the secondary data sets using a one-tailed two-sample t-test.

One-tailed t-tests showed that the mean wind speed of the primary data set was less than both the Commissioner’s Point mean wind speed, at an exposed point extending into the Bermuda Platform ($p < 2.2 \times 10^{-16}$), and the Argus Island mean wind speed over the open ocean ($p < 2.2 \times 10^{-16}$).

These results imply that the radiosonde data, taken over the landmass of Bermuda at the airport, may not be an accurate representation of wind patterns over the entire Bermuda Platform. However, as the mean was lower than the mean at the other locations, the primary data set provides a conservative estimate of the wind resources available across the Bermuda Platform. This result is not unexpected, as wind pattern models typically predict that wind speed increases sharply with increased distance from shore (Musial and Butterfield, 2006).

Capacity factor

Based on our primary data set, interpolated to a turbine hub height of 100 m, we determined the following results for a range of turbines from two manufacturers, using published power curves (Table 3). Power curves were not available for a mid-range representative turbine, so based on recommendation from a turbine manufacturer representative, we modeled a 5.0 MW turbine by scaling up the power curve for a Siemens 3.6-120 turbine (Moeller, 2013). This power rating was a compromise between 2.0-6.0 MW turbines commonly seen in older offshore wind farms and the larger turbines, up to 8.0 MW, in development for future wind farms. This turbine had a capacity factor of 38.3%, based on the wind profile at the Bermuda airport. This capacity factor value was used to calculate the LCOE.

Table 3. Capacity factors for a range of turbines.

Make	Model	Power Rating (MW)	Average Power (MW)	Gross Capacity Factor at 100 m
SIEMENS	S2.3-108	2.3	1.15	0.502
VESTAS	V112-3.3	3.3	1.40	0.424
SIEMENS	S3.6-120	3.6	1.38	0.383
VESTAS	V164-8.0	8.0	3.14	0.392

Capacity factor is highly dependent on wind speed, and wind speed typically increases with distance from shore. Because we used conservative data for our wind profile, we would expect to see even higher capacity factors for a wind farm located several kilometers away from Bermuda’s shoreline.

4.2.2 Levelized cost of energy calculation

Based on the NREL estimates, we calculated an LCOE of \$0.261/kWh. The results of our calculations were similar to the LCOE estimates that the DOE independently received from wind project developers (Bermuda DOE, 2013).

The LCOEs calculated using the BVG and InVEST wind model cost estimates, listed in table 4, are within ±9% of the LCOE we calculated using the NREL estimates.

Table 4. BVG and InVEST LCOE calculation

Estimate source	CAPEX	AOE	DECOM	LCOE
BVG	\$4,235k/MW ¹	\$256/MW/yr ¹	\$554/MW ¹	\$0.284/kWh*
InVEST	\$4.8 million/MW ²	3.5% of CAPEX ³	3.5% of CAPEX ³	\$0.254/kWh*

*Cost estimate is in 2011 USD

- (1) Conversion from £GBP to \$USD made with Jan 2011 conversion rate of 1.561£/\$1
- (2) Kaiser and Snyder, 2012
- (3) Bocard, 2010

Figure 4-4 illustrates how the LCOE would vary based on the range of estimated input parameter values. The figure illustrates that the LCOE is most sensitive to changes in the estimated gross capacity factor followed by changes in the CAPEX, discount rate and AOE estimates.

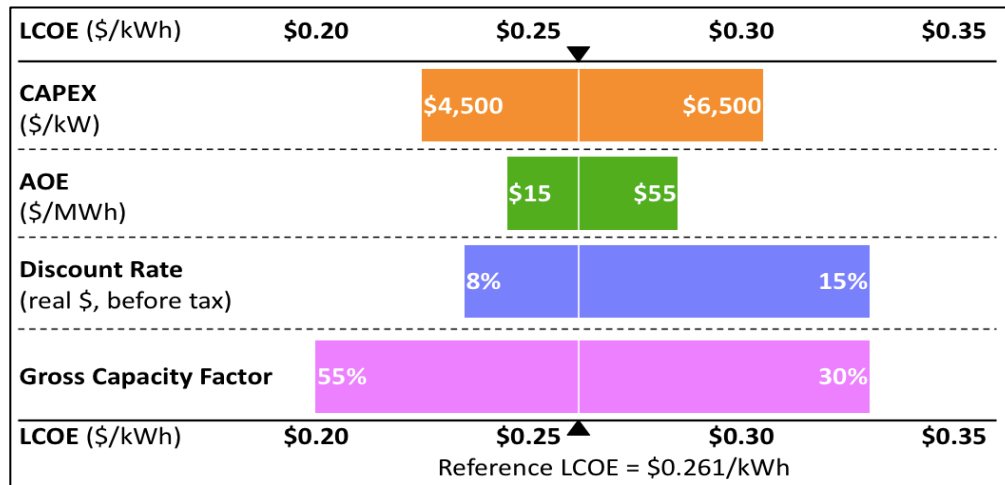


Figure 4-4. Sensitivity analysis of LCOE calculation with variation in CAPEX, AOE, discount rate, and gross capacity factor. The values of the input parameters used to calculate the reference LCOE (\$0.261/kWh) is indicated by a white line running through the colored bars.

5. Spatial analysis model

5.1 Methods

5.1.1 Spatial analysis overview

We created a spatial analysis model that determines areas that are potentially suitable for wind turbines, considering existing ocean uses, ecological features and developer preferences. The model consists of three phases: 1) a suitability analysis, 2) a wind farm optimization analysis and 3) a post-hoc analysis (Figure 5-1). This methodology can identify areas with low risk of impact on the Bermuda platform as part of an iterative multi-stakeholder planning process. In the following sections, we explain this methodology. For the sake of brevity, we will use the term ‘sectors’ to collectively refer to economic ocean uses, recreational ocean uses, and ecological features on the Bermuda Platform.

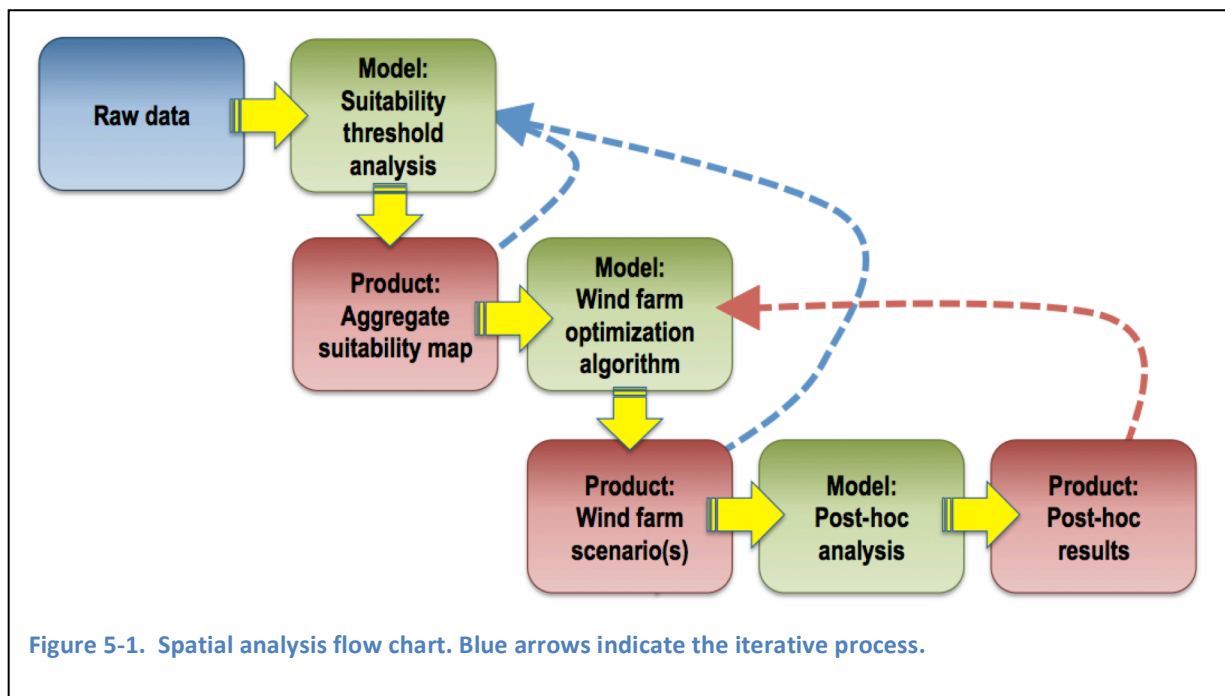


Figure 5-1. Spatial analysis flow chart. Blue arrows indicate the iterative process.

Suitability analysis

The three-phase analysis begins with defining suitability thresholds for all sectors of importance, and devising an overall map of sites that are deemed suitable for turbine placement. Because there is potential conflict between existing sectors and turbine placement everywhere on the platform, an acceptable level of risk of impact needs to be determined. The suitability threshold determines whether an area is considered or excluded from turbine placement based on the value of a sector at that location. This threshold could be set based on a preference to avoid risk of physical or economic impact due to turbine placement. A higher threshold signifies a higher level of risk of impact, but also allows for a greater area of the Bermuda platform to be considered for turbine placement. Determining the balance between risk and reward is an exercise for decision makers. By allowing for thresholds to be set

independently while examining the effect in aggregate, this suitability analysis allows for decision makers and stakeholders to visualize and negotiate thresholds and effects in a transparent way. This analysis is to be used iteratively in the negotiation process, such that output maps can inform changes in suitability thresholds.

Wind farm optimization analysis

The second phase of the model uses the suitability map to generate multiple wind turbine placement scenarios that meet the suitability criteria while minimizing the spread of the turbines. This analysis assumes a preference for a compact wind farm, which could potentially factor into the developer's choice of wind farm site and arrangement. A compact wind farm would minimize costs to the developer due to a decreased amount of cable, cable routing effort, and transit time during construction and maintenance. A large number of other variables may be important to a developer, including spatial variations in wind energy potential, seafloor substrate, distance to shore, and depth. However, due to the lack of this spatial information, we were unable to include these variables in our model. Outputs from this analysis can be used to inform changes in the suitability analysis.

Post-hoc analysis

The final phase of the model analyzes the potential risk of impact to other sectors that are not likely to be driving factors in the siting of turbines. Using wind turbine placement scenarios from the wind farm optimization analysis, this phase of the analysis examines the overlap of the wind farm area with these sectors. Understanding the potential risks to these sectors would be useful for informing management decisions and mitigation strategies.

5.1.2 Identification of potential conflicts with ocean uses and ecological features

With input from the Department of Environmental Protection, we determined the spatial compatibility of each of the identified sectors with wind energy development. The Marine Resources Officer at the Department of Environmental Protection filled out a compatibility table in order to show which sectors were 0% compatible, 100% compatible or partially compatible with wind turbines.

Based on the compatibility of each sector as well as the nature of each associated data layer, we categorized the sectors into three separate categories: 1) Categorical Exclusion, 2) Threshold and 3) Post-hoc (Table 5).

The "Categorical Exclusion" and "Threshold" sectors were included in the suitability analysis, the first of the three analyses. The "Categorical Exclusion" category consists of sectors that were identified as being 0% compatible with wind turbines, and also had clearly defined boundaries in which wind turbines could not be placed. In the suitability analysis, these areas were categorically excluded from consideration of potential wind energy development.

The "Threshold" category consists of sectors that had more complex patterns of spatial distribution and where there may be an acceptable level of risk of impact that could be negotiated with stakeholders. The spatial data for these sectors represents the value of a certain sector in different locations on the platform. These data were used as criteria in defining areas that could be suitable for wind turbines. For each of these data layers, we are able to set a threshold level of each sector to define low conflict areas where turbines could be suitable.

The “Post-hoc” category consists of sectors that are partially compatible with wind turbines and are not crucial for determining turbine suitability. Impacts on these sectors were evaluated after turbine siting decisions were made; i.e., “post-hoc.”

Table 5. Data categories

Categorical Exclusion	Threshold	Post-hoc
Marine Protected Areas	Reef (proxy for stony corals)	Benthic species (Soft coral, sponges, calcareous green algae, other algae)
Avian areas	Seagrass	Humpback whale areas
Shipping Channels	Commercial finfish fisheries (reef)	Air surveillance, weather and marine radar detection areas
Airport Control Area	Commercial lobster fishery	
	Recreational fishery (overall)	
	Recreational spearfishing	
	Recreational lobster fishery	

Spatial data collection and preparation

The Department of Conservation Services provided the raw GIS data for most of the ocean uses and ecological features that were examined in our analysis. We created our own spatial data for the commercial finfish fisheries, which was based on survey results. In addition, we created GIS layers that represent fish aggregation sites within seasonally protected areas, humpback whale areas and radar detection areas.

The region of interest for our analysis was delimited using the 20 m contour line outside the rim reefs. Although monopile foundations can be placed at depths greater than 20 m, we chose the spatial extent of the 20 m contour line as an intermediate distance between the extent of the fisheries data, which extends out to the 200 m contour line, and the extent of the benthic data, which was limited to the 10 m contour line.

The Bermuda platform was divided into planning cells in order to conduct the spatial analysis. Each planning unit was 250 m x 250 m, and all data layers were processed to be analyzed at this resolution. This cell size was chosen based on the minimum spacing distance required between wind turbines. We determined that wind turbines would not be placed any closer than 500 m assuming a rotor diameter of 100 m (Moeller, 2013). Therefore, a resolution of at most 250 m would be needed to prevent aliasing effects. A reference raster was used to align the different layers and was created from the feature layer of the 200 m contour line. All data layers were converted to a raster format to be used for analysis in both ArcMap 10.1 and MATLAB. Maps for these data layers can be found in the Appendix.

Shipping channel

We chose to include a buffer zone measuring 1 nautical mile (1.872 km) around the shipping channel to represent areas where turbines could not be placed. According to a guidance document written by the UK Maritime and Coastguard Agency, a 1 nautical mile buffer distance would reduce risks to shipping to a “medium” level. We created a spatial layer representing this categorical exclusion area. However, a

specific buffer distance would need to be determined by the Department of Marines and Ports and policymakers based on their own requirements (UK Maritime and Coastguard Agency, 2008).

Radar viewshed

In order to determine locations in which air surveillance radar, weather radar or marine vessel tracking radar systems could detect a 160 m tall wind turbine (100 m hub height plus blade length), we used the ArcMap viewshed tool. We used a DEM raster file for the island and a modified point layer that contained the specific locations and antenna heights of the radar systems (Jeppesen, 2007). The air surveillance radar antenna height is 47.54 m above ground level and the weather radar height is 45.25 m above ground level (Jeppesen, 2007). Figure 13 in appendix iv illustrates the areas on the Bermuda platform where a 160 m tall wind turbine would be detected by the different radar systems.

Marine protected areas

The DEP considered the following marine protected areas to be incompatible with wind turbines: dive site protected areas, Blue-striped grunt fish aggregation areas, areas where net fishing is prohibited and fish aggregation sites within the seasonally protected areas. These were categorically excluded from the potential area available for wind energy development. Bermuda's other marine protected areas (Coral Reef Preserves, areas where lobster fishing is prohibited, Spearfishing Exclusion Zone, Spiny Lobster reservoir) were identified as being partially compatible with wind turbines. The concern from the DEP regarding these areas was primarily associated with protection of specific habitats, such as the coral reefs. As the coral reefs are being considered independently, these other marine protected areas were not considered directly in the analysis.

Avian areas

To account for the potential impacts of wind turbines on birds, we considered three distinct zones (Avian Zones 1, 2 and 3) identified by the Department of Conservation Services based on their importance to courtship activity, food foraging, and access to and from nesting concentrations and based on the presence of endangered species and/or species known to be susceptible to noise or to collision with obstructions (Madeiros, 2013). We also considered the "Important Bird Area," an area identified by BirdLife International as being globally important for the conservation of bird populations. The DEP considered Avian Zones 1 and 2 and the Important Bird Area to be incompatible with wind turbines, and Avian Zone 3 to be partially compatible. We decided to consider all four areas as categorical exclusion areas to wind energy development. Although Avian Zone 3 was determined by the DEP to be partially compatible, for our analysis, we chose to exclude this area because this area is also very close to shore (within ~2.5 km) and is likely not an ideal location for a wind farm due to viewshed impacts. However, hundreds of migratory bird species visit Bermuda; our analysis does not account for the migratory paths of these birds beyond the Avian Zones and the Important Bird Area.

Reef data and benthic habitat data

We obtained a reef GIS mosaic layer that is based on aerial photographs taken in 1997 and at a resolution of 0.5 m. Coral reef boundaries had been determined visually based on color differences and the presence of sand halos around reefs (Murdoch et al., 2008). The reef polygon layer was converted to a raster with cell values representing the area (m²) of reef within each 62,500 m² (250 m x 250 m) cell.

We obtained spatial point data representing 533 benthic surveys conducted between 2006 and 2008 (Manuel et al. 2011). Each survey site includes a density measurement for seagrass (*Thalassia testudinum*, *Syringodium filiforme*, *Halodule* spp., *Halophila decipiens*), stony corals (Order *Scleractinia*), octocorals (Subclass *Octocorallia*), sponges (Phylum *Porifera*), calcareous green algae and other types of algae (*Caulerpa* spp., *Dictyota* spp., *Laurencia* spp., *Padina* spp.). The density at each site was calculated using an average of the modified Braun-Blanquet scale that was measured at ten 0.5 m x 0.5 m quadrats that were surveyed at each site (Table 6. Fourqurean, 2001).

Table 6. Modified Braun-Blanquet Scale

Modified Braun-Blanquet scale value	Interpretation
0	No specimens present
0.1	Solitary individual present
0.5	Few individuals with <5% cover
1	Many individuals with <5% cover
2	5-25% cover
3	25-50% cover
4	50-75% cover
5	75-100% cover

Stony corals are protected species and were identified as being incompatible with wind turbines. Because the point data from the benthic habitat surveys were limited in showing the extent of stony coral cover, we used the reef polygon layer as a proxy for stony coral, since stony coral are reef-building corals. Approximately half of the survey sites with stony coral cover coincided spatially with the reef polygon layer. The other survey sites with stony coral cover that did not coincide with the reef polygon had very low density (less than a score of 2.75). Therefore, we decided to not explicitly include the stony coral data set in any further analysis and used the data in the reef layer as representative of stony coral coverage.

Seagrasses are protected by law and were identified by DEP to be incompatible with wind turbines. Due to the importance of avoiding potential seagrass habitat, we interpolated the spatial extent of the seagrass using the 2006-2008 survey data to provide a prediction of where seagrass might occur. Because the Braun-Blanquet density measurement uses an ordinal scale, it was determined that a Thiessen polygon interpolation should be used, as other interpolation methods (e.g. IDW, natural neighbor, kriging) require an interval scale. Furthermore, a Thiessen polygon interpolation was considered a reasonable representation of the spatial behavior of seagrass since seagrasses in Bermuda occur in patchy meadows. This patchiness can be represented by the Thiessen polygon interpolation, which generates a uniform density value within each polygon. In contrast, other interpolation methods generate a gradual change in value between points. We used the sum of the average Braun-Blanquet value for the four seagrass species to do the interpolation. The seagrass polygon was converted to a raster, where the value of each cell represents the summed Braun-Blanquet density value.

This interpolation predicted large areas of seagrass due to the spacing of the survey points. In general, seagrass beds are thought to be found in meadows as large as 100,000 m² (Healey and Hovel, 2004), which is only about the area of two grid cells (125,000 m²). However, based on aerial photographs in Bermuda, seagrasses in Bermuda have been found to grow in meadows as large as 316 hectares (3,160,000 m²), although the certainty of these estimates may be limited by the visual interpretation of the photographs (Murdoch et al., 2008; Shailer, 2013). Nevertheless, the interpolation can provide a conservative estimate that would help to minimize impacts to seagrasses.

Soft corals (octocorals) are protected species and were identified as being incompatible with wind turbines. They are found both on and off of the reef and are not reef-building corals, so we could not use the reef layer as a proxy. We interpolated the distribution of soft corals also using Thiessen

polygons. However, due to our limited understanding of the spatial behavior of soft coral biology and distribution patterns, we decided not to include this interpolation in the suitability analysis, but to instead include it in the post-hoc analysis.

All of the other benthic species were also interpolated using Thiessen polygons and were included in the post-hoc analysis. Since all of the interpolations of benthic habitat were based on the same point data, the extent of each interpolated value was the same for each habitat type. Although it is not realistic for different types of benthic species to show the same spatial behavior, these interpolations nevertheless provide a general depiction of where different habitats occur and their densities.

Humpback whale locations

We obtained information on potential humpback whale locations from Andrew Stevenson, a local Bermudian expert on the North Atlantic Humpback Whale. Whales have been observed in shallow waters in the southwest area of the platform. This area was defined by a boundary line extending from Ely Harbour to Chubb Head and also extending due south from Ely Harbor along the coastline to the 10 m bathymetry contour. The rest of the area is delimited by the 10 m contour as humpback whales are likely to be found in depths greater than 10 m. The humpback whale location data is considered in the post-hoc analysis rather than the suitability analysis because construction of a wind farm can potentially be timed so as not to coincide with the whale season.

Fisheries

Commercial and recreational fisheries were identified by our client as key sectors to include in our analysis due to their economic, social, and cultural significance to Bermuda. For our analysis, we focused on the commercial finfish and lobster fisheries and the recreational fisheries (overall, spearfishing and lobster). Our background research suggests that the impacts to Bermuda fisheries from the development of an offshore wind farm on the platform would likely be minimal after the construction phase is complete. However, commercial and recreational fisheries were identified by our client as key sectors to include in our analysis due to their economic, social, and cultural significance to Bermuda. Therefore, we categorized fishing activity under the “threshold category” to account for input and interests of participants in these sectors in the development of such a project and to address any perceptions of risk within Bermuda’s fishing community.

The data for each fishery came from fishermen or proxies serving for fishermen, who drew on paper maps indicating where a particular fishery’s grounds are located. Each map was digitized using ArcMap, and we adjusted the data to fit our 250 m grid. Further explanation of the data sources is given below.

Recreational fishery

Spatial data for the overall recreational fishery were obtained through a survey administered to recreational fishermen by the DEP in 2011. The fishermen were instructed to indicate on a map the locations where they fish. A total of 222 maps were completed. The GIS layer that we used represented the number of recreational fishermen per 250 m grid cell. The shoreline fishing consisted mostly of hook and line and some cast netting. The offshore fishing consisted mostly of hook and line, some rod and reel fishing and included lobster diving and spearfishing.

More specific spatial data for Bermuda’s recreational lobster divers and spearfishermen were obtained from statistical returns, which record the location of catches using a grid map provided by the Marine Resources and Fisheries Enforcement Section upon landing. The original grid cells measured 2 minutes by 2 minutes. Spatial data on lobster diver landings were available for ten lobster seasons from 2002 through 2013. Spearfishing landings data were from 2011 through 2013. The GIS layers for these

fisheries represent the number of lobsters caught per 250 m grid cell over the period of the collected data.

Commercial fishery

Spatial data on Bermuda’s commercial lobster fishery was obtained from a survey conducted by the DEP, Marine Resources Division in July 2013. This survey, completed by 12 out of the 29 licensed commercial fishermen, indicated spatial locations that the fishermen frequented. The GIS layer for this fishery represents the number of fishermen per 250 m grid cell.

To map areas valued by the commercial finfish fishery, we applied the ‘100 pennies approach’ (Scholz et al., 2006). We elicited the expert opinion of the Fisheries Wardens, employees under the DEP, to serve as proxies for actual commercial fishermen. The Fisheries Wardens’ knowledge of the Bermuda Platform was used to identify and value areas fished by commercial fishermen.

We created a map of the Bermuda Platform extending to the 200 m depth contour, and overlaid a 1 km² grid on top (Appendix iii). The Fisheries Wardens were then instructed to use the maps provided to draw polygons along the grid lines to represent boundaries of reef fishing hot-spots. Each warden was given a budget of 100 pennies per fishery, to be considered as “value points”, to allocate across the grid to their selected cells.

Each hotspot, j , was associated with a distinct number of cells C_j , and a value, P_j , between 1 and 100, such that $\sum P_j = 100$. We advised the wardens that the hotspots were to be valued based on fishermen activity and frequency to the hotspots. A lower value indicates that the spot is not as active or as popular for commercial fishing; a higher value indicates that the spot is popular and is highly frequented. For each cell not marked, we assumed that it is valued at 0, indicating that no significant fishing activity occurs in that area.

For each warden’s completed survey, every cell across the grid then holds a unique value, which is equal to the value of the hotspot to which it belongs, divided by the number of cells for that particular spot (P_j/C_j) (Scholz et al., 2006).

The degree of precision in selecting fishing hotspots varied among the wardens’ completed surveys; some concentrated on very specific locations, while others drew larger shapes, allocating their penny budget more broadly across the grid. In order to account for these differences, we determined the relative importance of the cells for each warden’s selected fishing grounds (G_w) in relation to the composite fishing grounds (G) that was reported from all the wardens.

Each cell for every given shape is now represented by the relative importance value normalized by the total area, or V .

$$V_j = P_j / C_j * G_w / G$$

Where:

P = the stated importance value (number of pennies)

C = the number of cells

j = the hot-spot shape

G = the total number of cells in the entire fishery

G_w = the total number of cells in the fishery defined by the respondent

The result of this analysis is a weighted surface of the extent of the commercial fishing grounds for Bermuda, valued by fishermen frequency to the spots.

For this analysis, we received a total of three maps from DEP, completed by three Fisheries Wardens, and used them for mapping the commercial fishing grounds of Bermuda.

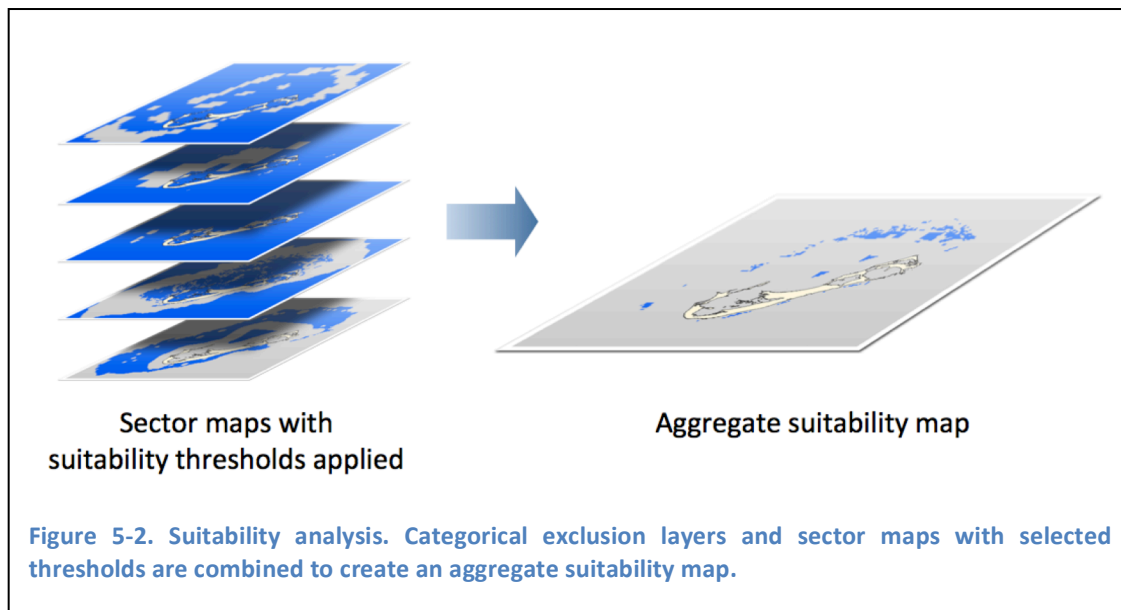
5.1.3 Spatial Model

Suitability Analysis

Spatially explicit values for each threshold sector are mapped across the Bermuda platform region of interest, as described above. For each threshold sector, a threshold value is selected to define the upper limit of “suitability” for that sector, meaning that the potential impact of wind turbine placement is deemed to be acceptable, perhaps because the risk of impact is small, or because the risk of impact has been addressed through mitigation or compensation between negotiating parties.

For each threshold layer, the cell values are compared to the selected threshold to determine whether a particular cell is deemed suitable, and can be considered as a potential site for turbine placement.

An aggregate suitability map is generated by first identifying all areas of categorical exclusion, and then simply stacking the individual sector suitability maps to determine which cells meet suitability criteria across all threshold sectors.



Wind farm optimization analysis

Using the results of the suitability map, the wind farm optimization analysis determines areas on the platform where compact wind farms can be built in order to highlight areas where a developer might choose to build.

We used a MATLAB script to create a number of optimal wind farm scenarios, each designed around a “seed point” cell on the platform, and based upon the aggregate suitability map. For each scenario, we determined a “spread index” based on the spacing of turbines relative to the “seed point.” The process using the following steps:

Identify a spatial cell as the seed point around which to create an optimal turbine placement scenario.

Identify the nearest cell to the seed point that meets suitability criteria.

Place a virtual turbine in this cell, and identify an appropriate buffer around the cell to ensure minimum inter-turbine distance.

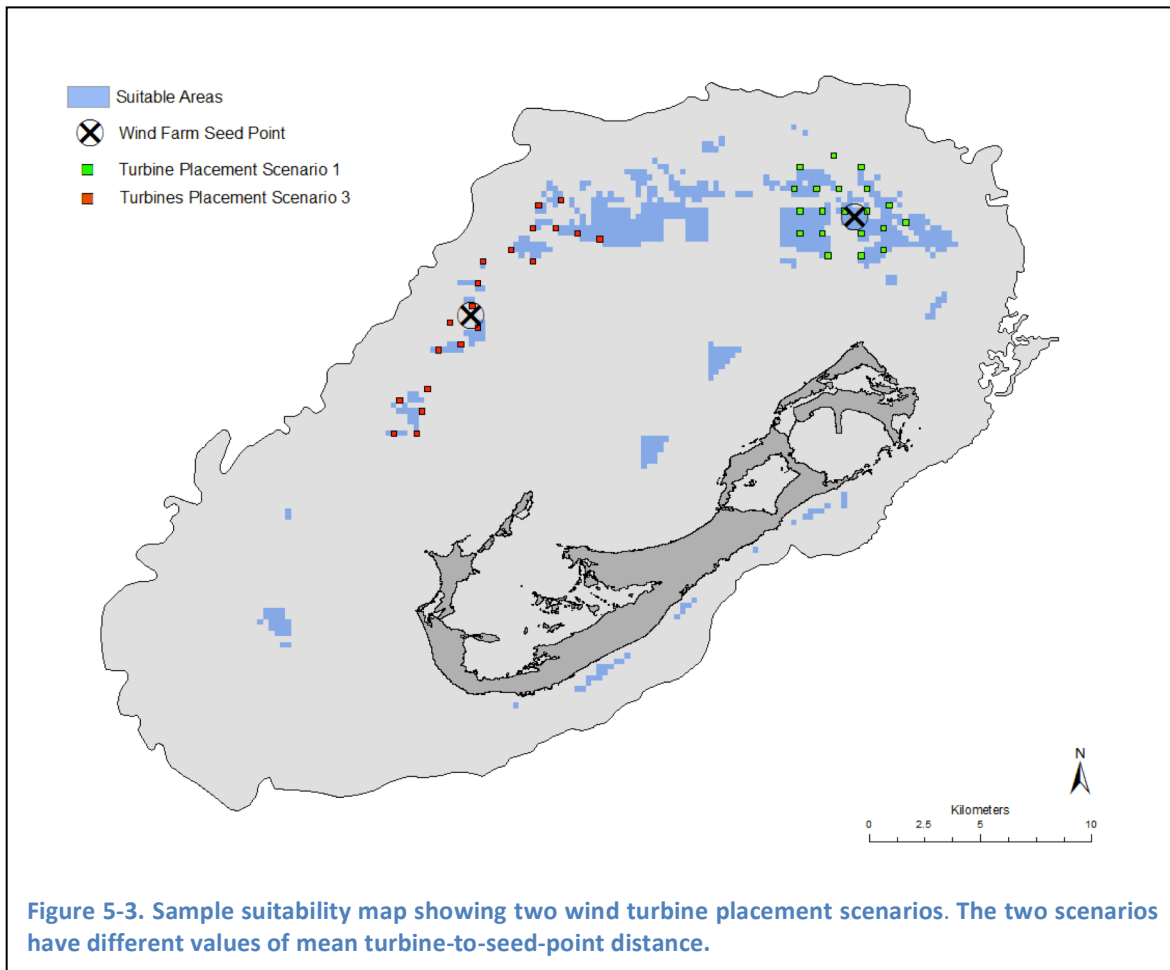
Identify the next nearest cell to the seed point that meets suitability criteria, while not encroaching upon the inter-turbine distance buffer of previously placed turbines. Identify another buffer.

Repeat this last step until the target nameplate capacity has been reached or exceeded.

Determine the mean turbine-to-seed point distance for this optimized scenario centered on this seed point. Mean turbine-to-seed point distance for our model has been defined as the sum of distances from each turbine back to the seed point, divided by the number of turbines. The turbine-to-seed point distance value is recorded as the spread index for this seed point.

A new seed point is selected, a new scenario is created, and the spread index quantified, until each cell on the platform has been considered.

The result of this process is a map of the spread index in each cell across the Bermuda Platform, based on a particular set of threshold values and wind farm parameters. By identifying local minima on this map, an interested party can identify optimal locations for wind energy development, simultaneously minimizing the spread of the farm area and meeting all suitability criteria.



Post-hoc analysis

Based upon the spread index map generated in the wind farm optimization analysis, multiple suitable locations for wind energy development can be identified and wind farm scenarios can be modeled. The post-hoc analysis examines the overlap between the turbine placement scenarios and the spatial distribution of non-threshold sectors, which include various benthic organisms, radar detection areas, and humpback whale areas (Table 5).

For each farm scenario, the boundary of the wind farm is specified by a convex hull polygon connecting the outer corners of the outermost cells containing virtual turbines. By generating maps of the value of each post-hoc sector within this boundary, we can compare the potential impacts to each of these sectors for each scenario. While these maps do not affect the outcome of the spatial analysis, they provide additional information that can help a decision-maker choose between otherwise suitable scenarios or that can be used to inform management strategies and mitigation measures.

Model Parameters and Values

In addition to the spatially explicit maps of threshold sector values, our threshold analysis model requires a number of input parameters, based upon energy targets, turbine specifications, and preferences of the decision-maker. Any of these inputs can be changed easily to explore a range of

options or to conduct a sensitivity analysis. For the purposes of illustrating the output of our model, we have selected initial values for each of the input parameters.

We identified thresholds for each sector that provided a low risk of impact to a given sector, while allowing for large areas to be deemed suitable.

Table 7. Thresholds

Sector/Ecological Feature	Scale	Threshold used in analysis
Coral reef	Percent area of reef coverage in cell	10% reef coverage
Seagrass	Braun-Blanquet scale	1.0 (5% spatial coverage)
Commercial finfish fishery	Percent of value of the most valuable commercial fishery cell based on warden survey.	10% of highest-value cell
Commercial lobster fishery	Number of lobster fishermen (out of 12 respondents) who identified a given cell based on survey.	2 fishermen per cell
Recreational fishery (overall)	Number of recreational fishermen (out of 222 respondents) who identified a given cell based on survey.	5 fishermen per cell
Recreational lobster fishery	Average lobster yield density over 10-season reference period.	2 lobsters per cell
Spearfish fishery	Percent of maximum spearfish yield density over three-year reference period.	50% of maximum spearfish value

Note that these thresholds do not indicate the expected impact upon a sector, but merely indicate that a cell can be considered for turbine placement, nor does placement of a turbine within a cell of a particular value indicate that there is any expected actual impact upon that cell. For example, when considering a cell with 5% coral reef coverage and low fishery value, placement of a turbine is not likely to reduce the reef coverage, nor is the turbine expected to have any significant impact upon the fishermen who rely upon its fish stocks.

We selected a target nameplate capacity of 100 MW and 5.0 MW wind turbines for the wind farm optimization analysis. Under these assumptions, we must place 20 turbines to reach our target nameplate capacity.

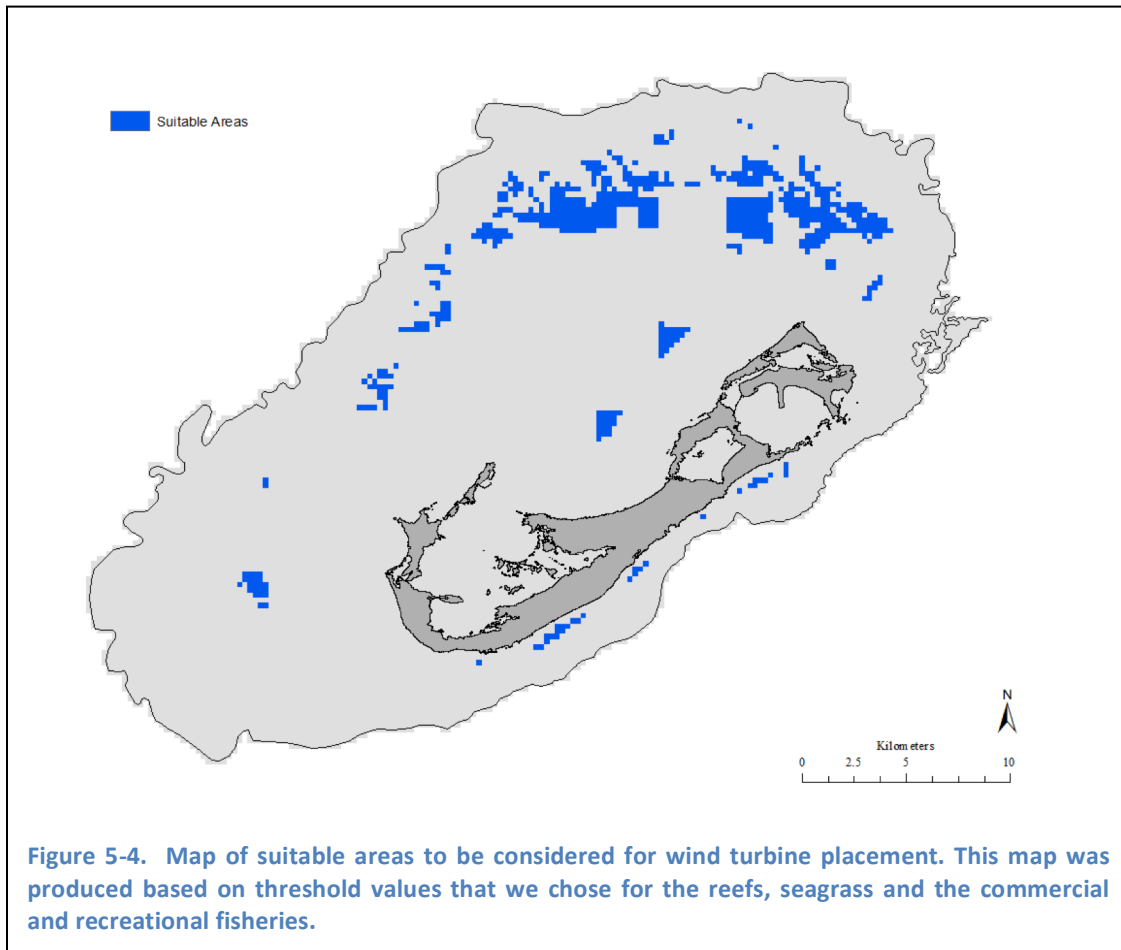
Using these parameter values and suitability thresholds, we demonstrate the choice of three different seed points and the generation of the wind farm around these seed points. Two of these seed points are located in areas that are suitable for compact wind farms while the third seed point is located in an area that is less suitable for a compact farm. We then conducted a post-hoc analysis for each of these farms.

5.2 Results

Suitability analysis

With the parameter values that we selected, we obtained a suitability map showing areas that would be considered suitable for turbine placement (Figure 5-4). The total amount of suitable area on the

platform was 42,250,000 m² (676 cells). Most of the suitable areas, especially large contiguous suitable areas, were located on the northeast of the platform.

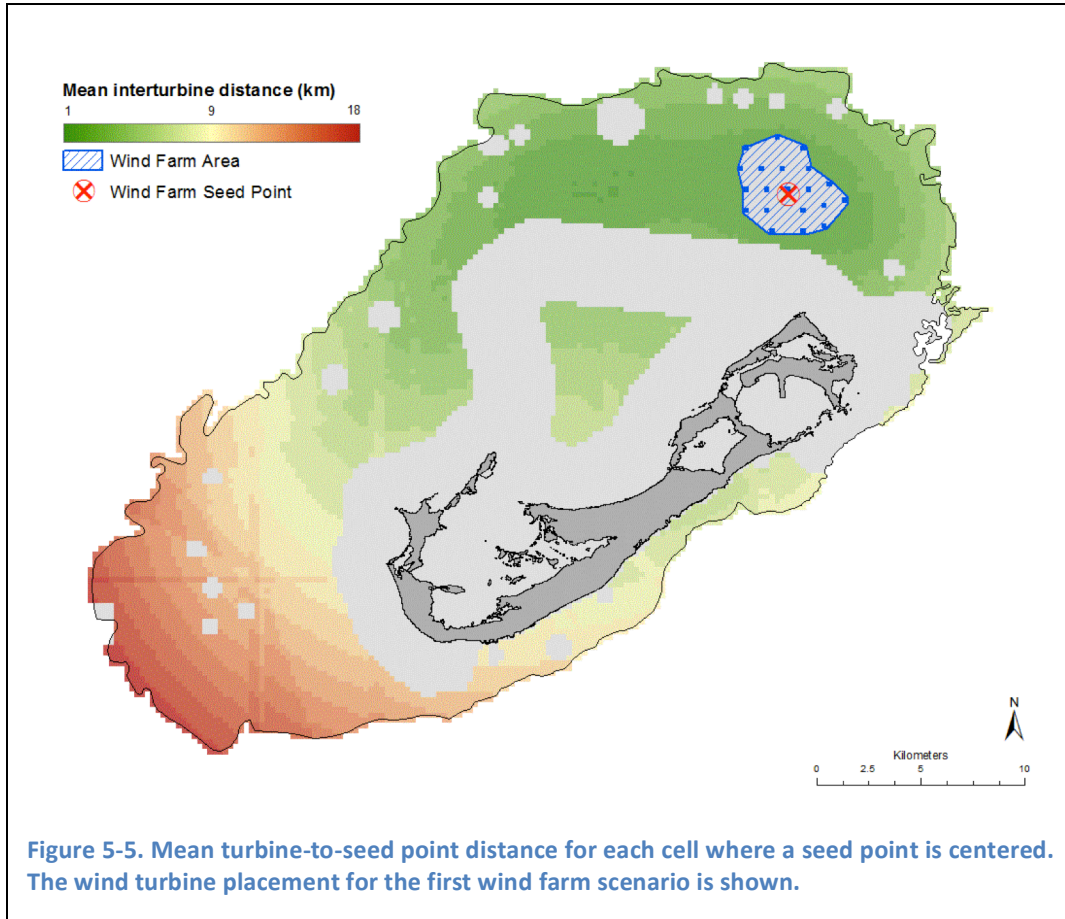


Wind farm optimization analysis

We found that the northeastern area of the platform is the most favorable for building compact wind farms. Figure 5-5 shows the map of mean turbine-to-seed point distance for each cell where a seed point is centered. The mean turbine-to-seed point distance ranged from 1.80 to 18.83 km. Areas of low mean turbine-to-seed point distance coincided with the location of the large suitable areas in the northeast of the platform. At an increasing distance away from those areas, the mean turbine-to-seed point increases, indicating that these areas were less favorable for placing a compact wind farm.

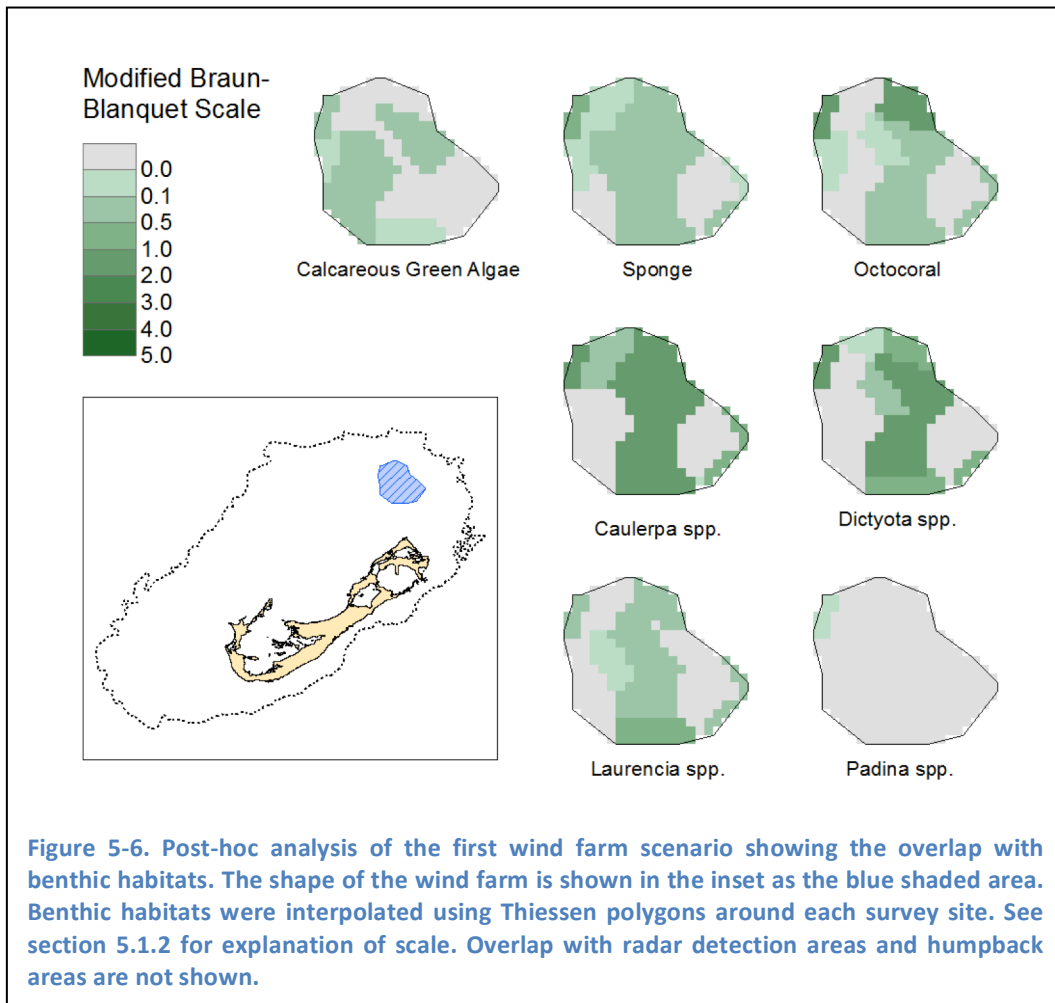
Figure 5-5 also shows the arrangement of turbines around the first of the three seed points that we chose to demonstrate as sample farm scenarios. The maps for the second and third scenarios are found in the Appendix ii. The seed points of the first and second scenarios were located in the northeastern area of the platform. These two scenarios showed tightly packed turbines that form compact farms. The mean turbine-to-seed point distance was 1.82 km for the first scenario, and 1.90 km for the second scenario. The seed point of the third scenario was located farther away from this northeastern area,

where there were fewer suitable areas nearby. In this third scenario, the turbines were dispersed, creating a less favorable wind farm shape. The mean turbine-to-seed point distance was 3.88 km.



Post-hoc analysis

The three wind farm scenarios overlapped with areas with relatively low density of benthic habitat and were not located in potential humpback whale areas. However, they were all within the air surveillance radar and weather radar detection areas (see maps in Appendix iv).



For the first wind farm scenario, the benthic species with the highest densities were the octocoral, *Caulerpa* spp. and *Dictyota* spp. with modified Braun-Blanquet values equal to 1.6, 2, and 1.9, respectively (Figure 5-6). The other species had very low density values within the farm area. The second wind farm scenario mostly overlapped with very low densities of benthic species and very small areas where octocorals, sponges, *Dictyota* spp. and *Laurencia* spp. had modified Braun-Blanquet values close to 1 (Appendix ii). The third wind farm scenario overlapped with small areas of octocoral and calcareous green algae, where the modified Braun-Blanquet values were 2.65 and 2.46, respectively (Appendix ii). The remaining benthic species had low density within this third farm area.

6. Discussion

6.1 Energy Model

Our analysis determined that offshore wind energy is an economically viable option to secure Bermuda's energy independence and reduce per capita emissions of GHGs. In table 1, we outline the prices paid by consumers for energy generation and fuel importation. Our calculated LCOE of \$0.261/kWh estimates the cost of electricity generation to the wind developer, not the customer; therefore we cannot compare the numbers directly. However, the wide margin between our LCOE estimate and current Bermuda energy prices leaves room for a reasonable margin for add-on costs.

The actual price Bermuda consumers would pay for energy generated from offshore wind power will have to be negotiated in a power purchase agreement (PPA) between an energy provider and the wind energy developer. Given that our calculated LCOE is well below the current cost of energy for Bermuda energy consumers, we can conclude that it is very unlikely that the actual cost of energy from offshore wind power will be greater than current energy prices, even with a substantial markup on a project's LCOE in a negotiated PPA. Additionally, because the cost of offshore wind energy would remain constant in real dollars for the life of the project, as stated in our assumptions, the cost savings to consumers would likely increase over the life of the project.

Our study of wind energy potential was limited by the lack of spatially explicit wind data. As seen in the sensitivity analysis seen in figure 4-4, turbine capacity factor is the most significant driver in estimates for the cost of energy generated. In order to maximize the capacity factor, and thus minimize LCOE, the developer must match an appropriate size and design of wind turbine to the expected wind speed profile of the development area. To inform an appropriate turbine choice, the prospective wind developer would be expected to perform an in-depth wind assessment using measurement towers, at a range of heights up to the proposed hub height, to better characterize wind speed profiles across the Bermuda Platform.

6.2 Spatial analysis model

We have demonstrated the functionality of a spatial analysis model that helps to identify potential areas for wind energy development with consideration to existing ocean uses, ecological features and developer preferences. We envision this methodology to be useful in any marine spatial planning process, including but not limited to offshore wind energy development. It is intended to be explicit, based on objective data, and practical for Bermuda's needs, providing a means for stakeholders to visualize and identify areas of potential conflict. It facilitates transparent and iterative negotiation of thresholds to address conflicts and concerns, allowing stakeholders to converge on a consensus.

In practice, this model could be used in the negotiation process in the following way. Initially, thresholds set at zero represent the most conservative starting point for negotiations. The decision maker would then set thresholds with feedback from stakeholders in order to identify low-conflict areas that may meet the developer's needs. To shift thresholds higher, the developer may need to make a negotiated offer that would mitigate impacts to other stakeholders; negotiation would continue until developer and other stakeholders reach consensus. The developer may incur costs, but gains access to more valuable locations, while other stakeholders will have the opportunity to voice concerns, which can then be explicitly addressed.

Tradeoff analysis, which has been shown to be a useful tool in marine spatial planning, relies on quantitative data or models of impacts to determine optimized solutions. Yet, uncertainty in actual or perceived impacts to ecological and economic sectors can complicate a tradeoff analysis. By framing tradeoffs as a consensus negotiated between stakeholders and the decision maker, our threshold analysis model becomes a tool that can accommodate uncertainty and perception of risk.

For example, in our demonstration of our suitability threshold analysis, opening of the northeastern area was possible due to the threshold value of 50% of the maximum cell value for the 2011 - 2013 spearfish catch, since the other sectors did not occur in high levels in this area. Although 50% may seem to be a high threshold value, it was still a very small amount of catch (0.09 fish per cell), and we assumed that it would be less costly to displace the fishing that occurs in these areas.

The suitability threshold analysis is flexible to additional information. As new or higher-quality data or information becomes available, it can easily be incorporated into the threshold analysis model. For example, if it is determined that fishermen will not be excluded from the wind farm area, then the risk of impact to fishery stakeholders drops, and fishing stakeholders may be open to accepting a very high fisheries threshold.

In addition, the threshold analysis avoids subjective weighting of one sector against another, increasing transparency to stakeholders and avoiding the need for subjective judgments on the part of decision makers. Our methodology allows for each sector to be examined independently, so that changes in the suitability thresholds have clear consequences to the output of the analysis.

Fishermen represent a small but vocal stakeholder group that often perceive high risk of financial loss due to external management and development of offshore areas. To counter a potential source of vocal opposition, it is critical to maintain positive relations with fishermen by including them in the decision-making process. Objective fisheries data with good spatial resolution will better inform suitability threshold decisions, and may help to bridge any gap between the actual risk versus perceived risk of impact to fisheries due to wind energy development. Policy decisions that restrict fishery access have the potential to increase conflict and must be carefully considered.

Data pertaining to migratory bird patterns and flight paths were unavailable and thus excluded from our spatial analysis, despite the fact that public perception of negative wind turbine impact on birds is a major concern and driver of potential opposition. As overall scientific literature pertaining to bird impacts from offshore turbines improves with additional research, information of the flight paths and patterns of migratory birds in Bermuda can assist in making siting decisions.

Visual impacts of wind farm development are frequently controversial and contentious, and as such, efforts should be made to account for viewshed considerations in spatial planning. Our demonstration of the suitability threshold analysis model identified areas on the southeast side of the island, in close proximity to the shore. Since the suitability analysis did not include a proxy for viewshed impact, such as distance to shore, areas close to the island were not rejected as unsuitable. In Appendix i, we explored several viewshed valuation methods that may provide a starting point for further investigation.

Due to the lack of spatially explicit understanding of wind energy costs and benefits, our threshold analysis model is not able to account for the preferences of the wind energy developer. Instead, we model the spatial preferences of the developer based on a simple assumption of increased developer cost with increased turbine spacing. However, developer preferences would likely be driven by a complex set of parameters including turbine spacing, seafloor substrate, seafloor depth, and available wind energy. An improved wind energy model that accounts for spatial distribution of wind resource availability, as well as marginal costs due to spatial variations in substrate, depth, inter-turbine distance,

and interconnect distance to shore, would better inform the marine spatial planning process and strengthen the validity of the results.

In its 2011 Energy White Paper, the Bermuda DOE estimated it would need a 35 MW nameplate capacity wind farm to meet its renewable energy goals for offshore wind energy by 2020. Any wind energy development proposal would consider a number of factors when identifying a target capacity, including changes in energy demand, shifts in technology, and availability of other renewable energy sources. Our analysis simulated a more ambitious nameplate capacity of 100 MW to simulate further growth in wind energy development, in pursuit of Bermuda's stated per capita emissions goal of 1 metric ton CO₂eq per year by 2050. However, the flexibility of our spatial analysis model allows for different input parameters to represent other scales of development and other turbine capacities.

Even with an ambitious 100 MW target, our simulated analysis was able to identify several locations that would allow compact wind farm development while minimizing risk of impacts to environmental and economic sectors. A less ambitious nameplate capacity target, requiring fewer turbines, would allow for a greater number of suitable locations in other areas of the platform.

7. Conclusion

With our analysis, we find that there are sufficient wind resources to make offshore wind development an attractive option for the island territory of Bermuda. The LCOE for the power producer that we calculated is well below the current cost of energy paid by the Bermuda energy consumer. Even with a substantial markup on a project's LCOE in a negotiated PPA, it is very likely that the actual cost of energy from offshore wind power will be less than the prevailing prices.

All regions on the Bermuda platform have associated ecological, economic or social values that could be impacted by offshore wind development. This necessitates a negotiated solution among various stakeholders and the decision maker of an acceptable amount of risk. This need for marine spatial planning is addressed by our spatial threshold analysis model which can identify suitable locations for turbine placement, through a transparent, iterative process.

8. Recommendations

Detailed study of Viewshed Zone of Influence and impact

Assessment of viewshed impacts is widely recognized as an important component in the planning process. Wind energy development on the platform would be visible from significant parts of the island, therefore it is necessary to account for impacts to the viewshed before project development.

Early stakeholder involvement

Early stakeholder participation in the planning process is essential in developing stakeholder buy-in. The fishing community is an ideal example. While our research indicates that the actual impact to fish populations may be minimal, the change in the status quo and the associated uncertainty can cause the fishing community to perceive large impacts from offshore energy development. Early active and transparent involvement with stakeholder groups can build trust and improve outcomes of the marine spatial planning process.

Research implications to avian migratory patterns

Our analysis has included the avian zones and important bird areas in Bermuda, but does not account for the movements of migratory birds. Research will be needed to determine the potential impacts to migrating birds to inform bird strike mitigation strategies.

Study impacts during construction phase

The construction phase will have a different impact to the marine habitat, organisms and activities in the region than the operational phase of a wind farm. The impacts from the different phases of the wind farm should be studied to understand the risk. Consideration must be given to the differences in the potential impacts between the construction and operation phases when selecting suitability thresholds.

Sharing of information across departments

A multi-stakeholder project of this nature underlines the importance of streamlining communications and highlights the necessity of information transfer among departments.

References

Alexander K.A., T. Potts, and T.A. Wilding (2013). Marine renewable energy and Scottish west coast fishers: Exploring impacts, opportunities and potential mitigation. *Ocean & Coastal Management* **75**, 1–10.

Allison I., N.. Bindoff, P.. Bindschadler, and N. Cox (2009). The Copenhagen Diagnosis : Updating the World on the latest Climate Science. The University of New South Wales Climate Research Centre (CCRC). Available at: http://www.ccrcc.unsw.edu.au/Copenhagen/Copenhagen_Diagnosis_LOW.pdf.

Andersson M.H., E. Dock-Akerman, R. Ubral-Hedenberg, M.C. Ohman, and P. Sigray (2007). Swimming behavior of roach (*Rutilus rutilus*) and three-spined stickleback (*Gasterosteus aculeatus*) in response to wind power noise and single-tone frequencies. *Ambio* **36**, 636–638.

Ascendant Group (2012). Ascendant Group Limited Annual Report 2012.

Bermuda DOE (2013). Personal Communications.

Bishop I.D., and D.R. Miller (2007). Visual assessment of off-shore wind turbines: The influence of distance, contrast, movement and social variables. *Renewable Energy* **32**, 814–831. (DOI: 10.1016/j.renene.2006.03.009). Available at: <http://www.sciencedirect.com/science/article/pii/S0960148106000838>.

Boccard N. (2010). Economic properties of wind power. *Energy Policy* **38**, 3232–3244. (DOI: 10.1016/j.enpol.2009.07.033). Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0301421509005515>.

BVG Associates (2012). Offshore Wind Reduction Pathways: Technology work stream. BVG Associates.

Center for Ocean Solutions (2011). Decision Guide: Selecting Decision Support Tools for Marine Spatial Planning. The Woods Institute for the Environment, Stanford University, California.

Currie I. (2013). Personal Communication (Bermuda Weather Service).

Department of Conservation Services Bermuda biodiversity project habitat profiles. Available at: <http://www.conservation.bm/publications/bermuda-biodiversity-project-habitat-profiles/>.

Department of Conservation Services Shipwrecks. Available at: <http://www.conservation.bm/shipwrecks/>.

Department of Marine and Ports Services (2013). 2013 Cruise Ship Schedule. Available at: http://www.rccbermuda.bm/Documents/Shipping_schedules/2013%20Cruise%20Ship%20Schedule.pdf.

Dept. of Conservation Services, Government of Bermuda (2010). Coral Reef Economic Valuation Brief.

Dept. of Energy, Government of Bermuda (2011). 2011 Bermuda Energy White Paper: A National Energy Transition. Available at: http://dl.dropboxusercontent.com/u/9805511/MEPIS/bm_energy_whitepaper_doc.pdf.

Devine-Wright P., and Y. Howes (2010). Disruption to place attachment and the protection of restorative environments: A wind energy case study. *Journal of Environmental Psychology* **30**, 271–280. (DOI: 10.1016/j.jenvp.2010.01.008). Available at: <http://www.sciencedirect.com/science/article/pii/S0272494410000174>.

Drewitt A.L., and R.H.W. Langston (2006). Assessing the impacts of wind farms on birds. *Ibis* **148**, 29–42.

Environmental and Energy Study Institute (2010). Offshore Wind Energy. Available at: http://www.eesi.org/files/offshore_wind_101310.pdf.

Exo K.-M., O. Huppopp, and S. Garthe (2003). Birds and offshore wind farms: a hot topic in marine ecology. *Water Study Group Bulletin* **100**, 50–53.

Fayram A.H., and A. de Risi (2007). The potential compatibility of offshore wind power and fisheries: An example using bluefin tuna in the Adriatic Sea. *Ocean & Coastal Management* **50**, 597–605.

Fishbase Reef-associated Fishes Occurring in Bermuda. Available at: http://www.fishbase.us/Country/CountryChecklist.php?what=list&trpp=50&c_code=060&csub_code=&sortby=alpha2&vhabitat=reef.

Fourqurean J.W., A. Willsie, C.D. Rose, and L.M. Rutten (2001). Spatial and temporal pattern in seagrass community composition and productivity in south Florida. *Marine Biology* **138**, 341–354.

Gill A.B. (2005). Offshore renewable energy: ecological implications of generating electricity in the coastal zone. *Journal of Applied Ecology* **42**, 605–615. (DOI: 10.1111/j.1365-2664.2005.01060.x). Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2664.2005.01060.x/abstract>.

Haggett C. (2011). Understanding public responses to offshore wind power. *Energy Policy* **39**, 503–510. (DOI: 10.1016/j.enpol.2010.10.014).

Healey, and Hovel (2004). Seagrass bed patchiness: effects on epifaunal communities in San Diego Bay, USA. Available at: <http://www.sciencedirect.com/science/article/pii/S0022098104004617>.

Hochberg E. (2013). Personal Communication (Bermuda Institute of Ocean Sciences).

Hüppopp O., J. Dierschke, K.-M. Exo, E. Fredrich, and R. Hill (2006). Bird migration studies and potential collision risk with offshore wind turbines. *Ibis* **148**, 90–109. (DOI: 10.1111/j.1474-919X.2006.00536.x). Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1474-919X.2006.00536.x/abstract>.

Inger R., M.J. Attrill, S. Bearhop, A.C. Broderick, W. James Grecian, D.J. Hodgson, C. Mills, E. Sheehan, S.C. Votier, and M.J. Witt (2009). Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology* **46**, 1145–1153. Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2664.2009.01697.x/full>.

Jeppesen (2007). Bermuda International Airport. Swissphoto.

Kaiser M.J., and B.F. Snyder (2012). *Offshore Wind Energy Cost Modeling : Installation and Decommissioning*. Springer, London, (ISBN: 978-1-4471-2488-7).

Kapsali M., and J.K. Kaldellis (2012). 2.14 - Offshore Wind Power Basics. In: *Comprehensive Renewable Energy*. Ali Sayigh, (ed.), Elsevier, Oxford pp.431–468, (ISBN: 978-0-08-087873-7). Available at: <http://www.sciencedirect.com/science/article/pii/B9780080878720002171>.

Krohn S., P.-E. Morthorst, and S. Awerbuch (2009). *The Economics of Wind Energy*. European Wind Energy Association.

Lester S.E., C. Costello, B.S. Halpern, S.D. Gaines, C. White, and J.A. Barth (2013). Evaluating tradeoffs among ecosystem services to inform marine spatial planning. *Marine Policy* **38**, 80–89. (DOI: 10.1016/j.marpol.2012.05.022). Available at: <http://www.sciencedirect.com/science/article/pii/S0308597X12001200>.

Levitt A.C., W. Kempton, A.P. Smith, W. Musial, and J. Firestone (2011). Pricing offshore wind power. *Energy Policy* **39**, 6408–6421. (DOI: 10.1016/j.enpol.2011.07.044). Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0301421511005763>.

Lindeboom H.J., and Et. Al. (2011). Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters* **6**, 1–13.

Lozano-Minguez E., A.J. Kolios, and F.P. Brennan (2011). Multi-criteria assessment of offshore wind turbine support structures. *Renewable Energy* **36**, 2831–2837.

Luckhurst B., S. Booth, and D. Zeller (2003). Brief History of Bermudian Fisheries, and Catch Comparison between National Sources and FAO Records. *Fisheries Centre Research Reports* **11**, 163–169. Available at: http://epub.sub.uni-hamburg.de/epub/volltexte/2011/12206/pdf/11_6.pdf#page=171.

Luckhurst B.E., and T. Trott (2000). Bermuda’s Commercial Line Fishery for Wahoo and Dolphinfish: Landings, Seasonality and Catch Per Unit Effort Trends. *Gulf and Caribbean Fisheries Institute* **51**, 404–413. Available at: http://aquaticcommons.org/13368/1/gcfi_51-31.pdf.

Mackinson S., H. Curtis, R. Brown, K. McTaggart, N. Taylor, S. Neville, and S. Rogers (2006). A report on the perceptions of the fishing industry into the potential socio-economic impacts of offshore wind energy developments on their work patterns and income. Cefas Lowestoft. 99 pp.

Madeiras J. (2013). Personal Communication (Department of Conservation Services, Government of Bermuda).

Mangi S. (2013). The Impact of Offshore Wind Farms on Marine Ecosystems: A Review Taking an Ecosystem Services Perspective. *IEEE* **101**, 999–1009.

Maples B., G. Saur, M. Hand, R. van de Pietermen, and T. Obdam (2013). *Installation, Operation, and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy*. National Renewable Energy Laboratory.

Mayba K. (2013). Personal Communication (AWS True Power).

Merico Marine (2007). Investigation of Technical and Operational Effects on Marine Radar Close to Kentish Flats Offshore Wind Farm. Round 2 offshore wind farm developers.

Moeller K. (2013). Siemens Wind Power - Personal Communication.

Murdoch T.J.T., M.P. Hammond, A.F. Glasspool, M. Outerbridge, J. Clee, M. Shailer, and M. Colella (2008). A multi-scale assessment of the benthic communities of Bermuda's shallow water platform focusing on existing MPA's & control sites to enhance local management practices. Bream Programme, Bermuda Zoological Society.

Musial W., and S. Butterfield (2006). *Energy from Offshore Wind*. National Renewable Energy Laboratory.

Musial W., D. Elliot, J. Fields, Z. Parker, G. Scott, and C. Draxl (2013). *Assessment of Offshore Wind Energy Leasing Areas for the BOEM New Jersey Wind Energy Area*. National Renewable Energy Laboratory.

Nancy Kalinowski (2010). Statement of Nancy Kalinowski, Vice President for System Operations Services.

National Economic Report of Bermuda 2012 (2013). Government of Bermuda, Ministry of Finance.

Office of the Director of Defense Research and Engineering (2006). *The Effect of Windmill Farms on Military Readiness*. Department of Defense.

Petersen J.K., and T. Malm (2006). Offshore Windmill Farms: Threats to or Possibilities for the Marine Environment. *AMBIO: A Journal of the Human Environment* **35**, 75–80. (DOI: 10.1579/0044-7447(2006)35[75:OWFTTO]2.0.CO;2). Available at: <http://www.bioone.org/doi/abs/10.1579/0044-7447%282006%2935%5B75%3AOWFTTO%5D2.0.CO%3B2>.

Poseidon (Aquatic Resource Management Ltd) (2002). *The Burbo Bank Offshore Wind Farm- Impacts on the Human Environment (Main Report on Commercial Fisheries)*. DONG Energy. 1–20 pp. Available at: <http://www.dongenergy.com/SiteCollectionDocuments/New%20Corporate/Burbo/BurboAppVol4DFisheries.pdf>.

Robertson M.E. (2013). Specialised Recreational Fisheries of Bermuda: An analysis of the distribution and impacts of recreational lobster diving and spear fishing activities in Bermuda. Environment Department, University of York, UK.

Rodmell D.P., and M.L. Johnson (2003). The Development of Marine Based Wind Energy Generation and Inshore Fisheries in UK Waters: Are They Compatible? In: Hart P, ed. Scarborough Centre for Coastal Studies, Department of Biology, University of Hull at Scarborough, UK, Tjärnö, Sweden. 2003, 76–114 pp.

Salvat F., J.M. Fernández-Varea, and J. Sempau (2006). PENELOPE-2006: A code system for Monte Carlo simulation of electron and photon transport. In Proceedings: *Workshop Proceedings*. 2006, 7 pp. Available at: <https://www.oecd-neo.org/science/pubs/2009/nea6416-penelope.pdf>.

Scholz A., C. Steinback, and M. Mertens (2006). *Commercial fishing grounds and their relative importance off the Central Coast of California*. ecotrust. Available at: http://www.ecotrust.org/mlpa/downloads/report_review_final.pdf.

Shailer M. (2013). Personal Communication (Department of Conservation Services, Government of Bermuda).

Siemens - Wind Turbines Available at: <http://www.energy.siemens.com/us/en/renewable-energy/wind-power/wind-turbines/>.

Snyder B., and M.J. Kaiser (2009). Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy* **34**, 1567–1578. (DOI: 10.1016/j.renene.2008.11.015). Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0960148108004217>.

Stenberg C., and J. Støttrup (2011). Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities. Follow-up Seven Years after Construction. DTU Aqua, Orbicon, DHI, NaturFocus.

Tegen S., E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe (2013). *2011 Cost of Wind Energy Review.pdf*. National Renewable Energy Laboratory.

Thayer R.L., and C.M. Freeman (1987). Altamont: Public perceptions of a wind energy landscape. *Landscape and Urban Planning* **14**, 379–398. (DOI: 10.1016/0169-2046(87)90051-X). Available at: <http://www.sciencedirect.com/science/article/pii/016920468790051X>.

Thomsen F., K. Lüdemann, R. Kafemann, and W. Piper (2006). *Effects of offshore wind farm noise on marine mammals and fish*. Available at: <http://www.offshorewind.co.uk>.

UK Maritime and Coastguard Agency (2008). MCAshippingbuffer.pdf. Available at: http://www.dft.gov.uk/mca/mcga07-home/shipsandcargoes/mcga-shipsregsandguidance/offshore-renewable_energy_installations/public_web-ore-technical_guidance.htm.

Vattenfall (2011). 6.2 Safety Zone Statement - 6.2 Safety Zone Statement.pdf. Available at: <http://infrastructure.planningportal.gov.uk/wp-content/ipc/uploads/projects/EN010036/2.%20Post-Submission/Application%20Documents/Other%20Documents/6.2%20Safety%20Zone%20Statement.pdf>

Veritas D.N. (2010). Design of Offshore Wind Turbine Structures. *Recommended Practice E 305*.

Vieros M. (1993). Coral Reefs of Bermuda. Bermuda Zoological Society. Available at: http://www.gov.bm/portal/erver.pt/gateway/PTARGS_0_2_11280_207_227543_43/http%3B/ptpublisher.gov.bm%3B7087/publishedcontent/publish/new_min_of_environment/environmental_protection___project_nature_fact_sheets/coral_reefs_of_bermuda_0.pdf.

Wahlberg M., and H. Westerberg (2005). Hearing in fish and their reactions to sounds from offshore wind farms. *Marine Ecology Progress Series* **288**, 295–309.

White C., B.S. Halpern, and C.V. Kappel (2012). Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proceedings of the National Academy of Sciences* **109**, 4696–4701. (DOI: 10.1073/pnas.1114215109). Available at: <http://www.pnas.org/content/109/12/4696>.

Wood J., and K. Jackson (2005). Bermuda's Marine Biodiversity. In: *Caribbean Marine Biodiversity: The Known and the Unknown*. DEStech Publications, Lancaster, PA pp.19–35. Available at: http://cbm.usb.ve/CoMLCaribbean/pdf/I-02_bermuda.pdf.

Appendix

i. Viewshed Studies

Viewshed studies are generally considered necessary for wind energy project development but were beyond the scope of our analysis. However, we have done some basic viewshed analysis and have included these results. The primary aim is to outline the potential for including viewshed constraints as part of a future analysis within our framework and to briefly describe some of the methods that can be applied for such a study.

The following analyses are done with ArcMap using the available digital elevation model for Bermuda. This data was available at a 5 m spatial resolution.

Approach 1: A priori consideration of viewshed

In the following examples we show the results of a viewshed analysis, which takes into consideration some of the locations that are important for tourism, one of the largest economic sectors for Bermuda.

Using travel resources, we compiled a list of popular beaches and hotels in Bermuda. Figure 1 shows the range of heights above which an object placed at that location would be visible from at least one of the hotels being considered. For instance, in figure 1, any structure that is taller than 130 m placed in the yellow shaded regions would be visible from at least one of the locations on land under consideration. This is currently not taking into account the height of the building, but that is another level of complexity that could be added. We are using a conservative height estimate of 160 m for the 5 MW turbines in our analysis.

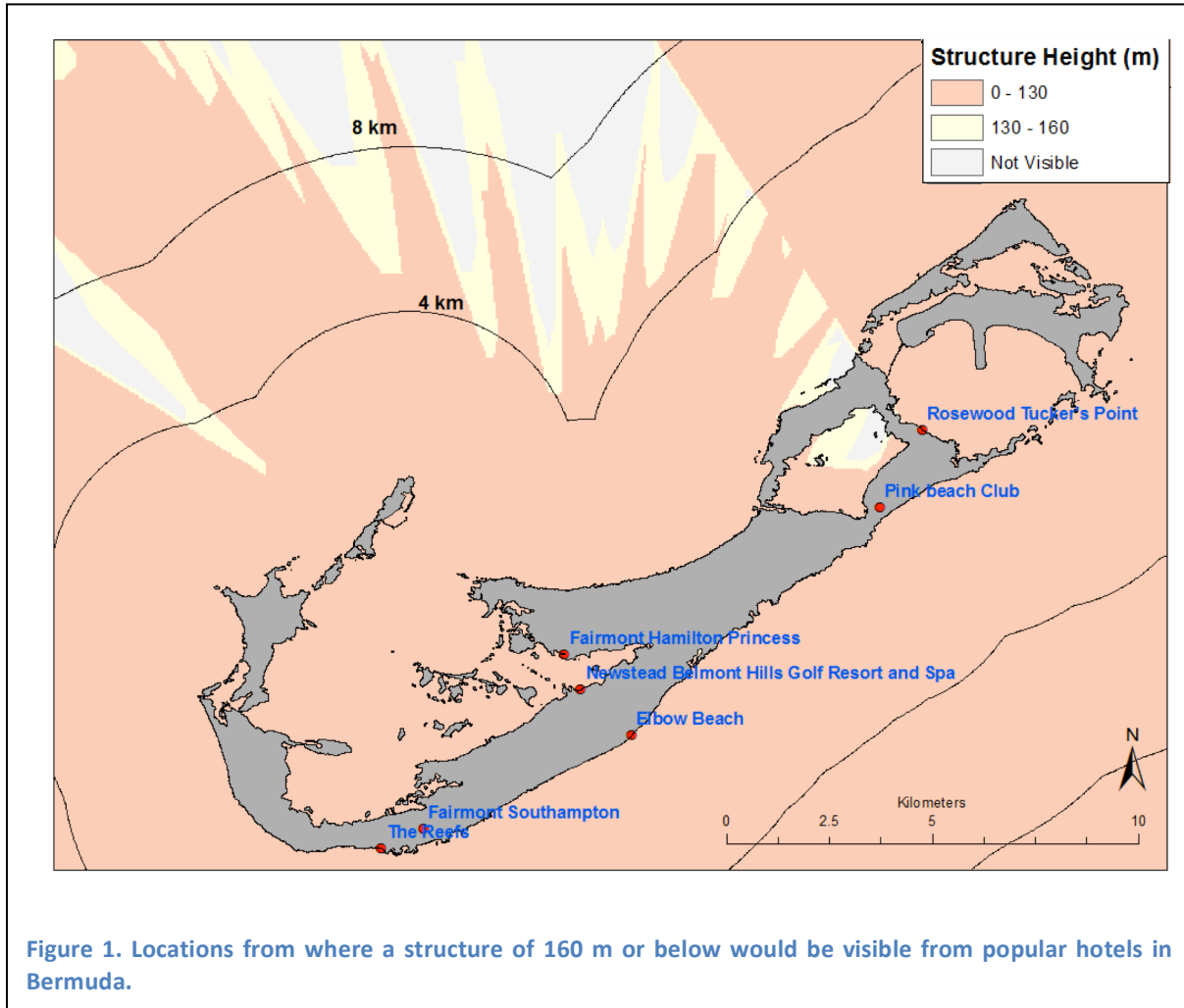
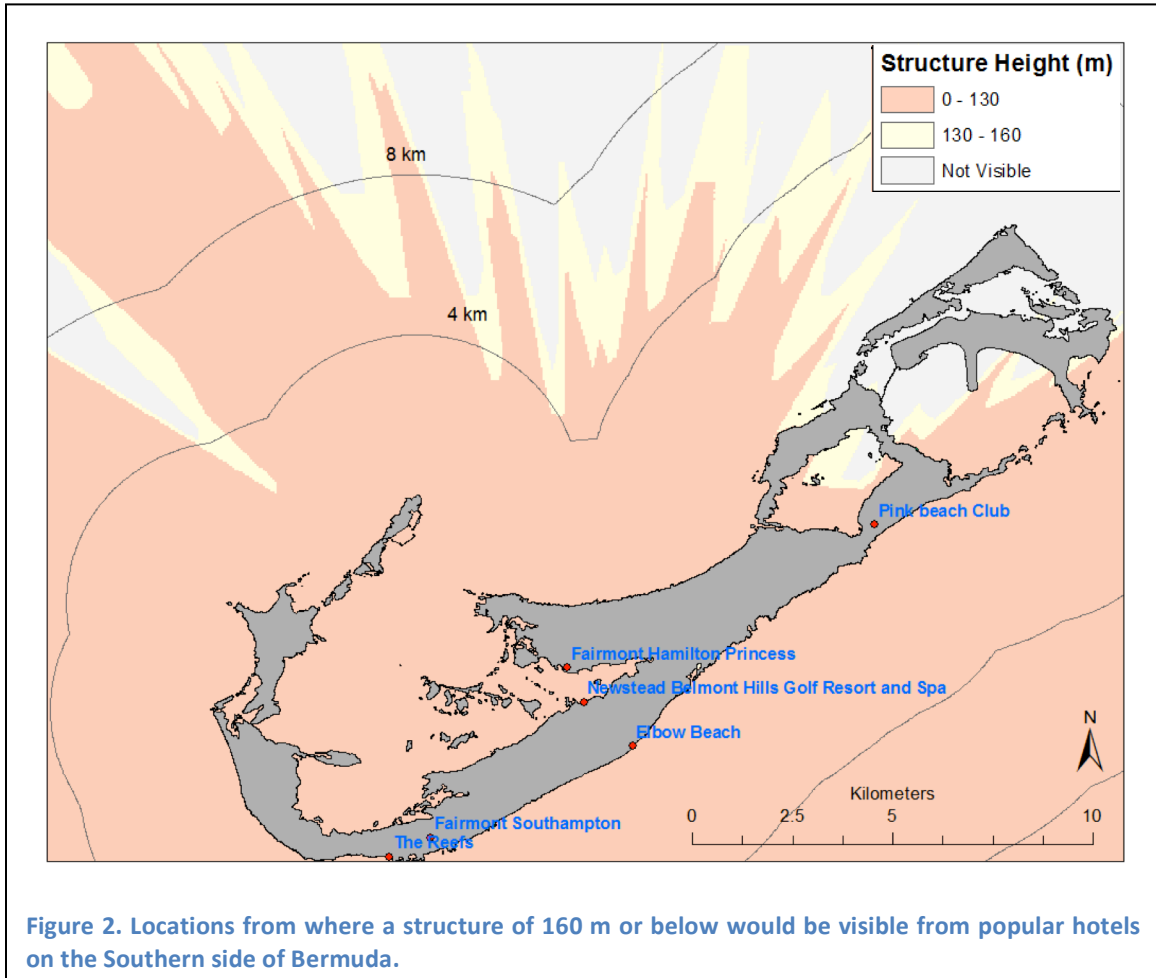
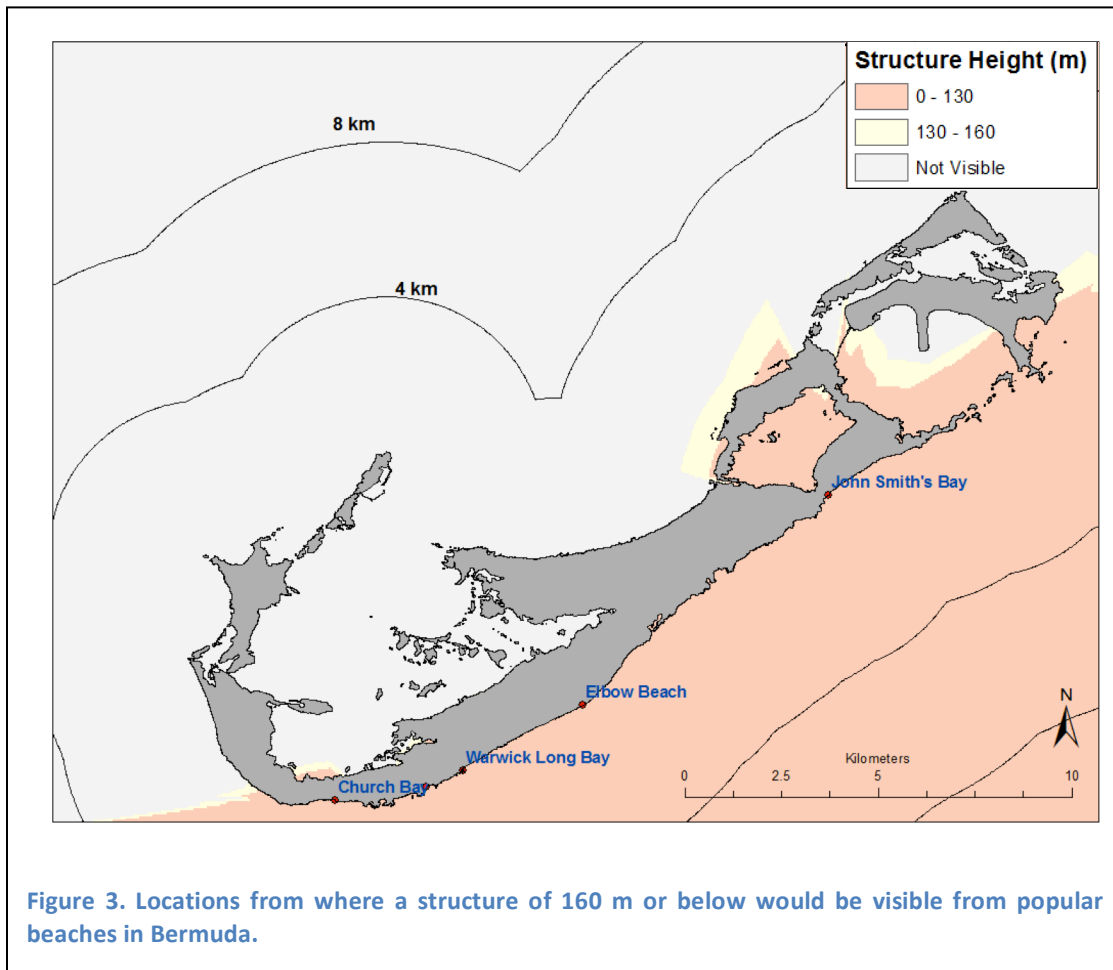


Figure 2, in which one of the hotels has been removed from the viewshed analysis from figure 1, shows the viewshed impacts to the hotels primarily on the south and west of Bermuda in this list. This indicates that the presence of wind turbines located in the north east part of the platform would not be visible from hotels on the list on the southern and central parts of the island. This shows the distributional impacts of wind turbine siting to viewshed. Detailed studies of this nature can be used to prioritize and minimize risks associated to parts of the islands where viewshed impacts might be a larger concern. This also indicates the distributive nature of viewshed impacts and how stakeholders within the same sectors could be affected differently based on site choices.

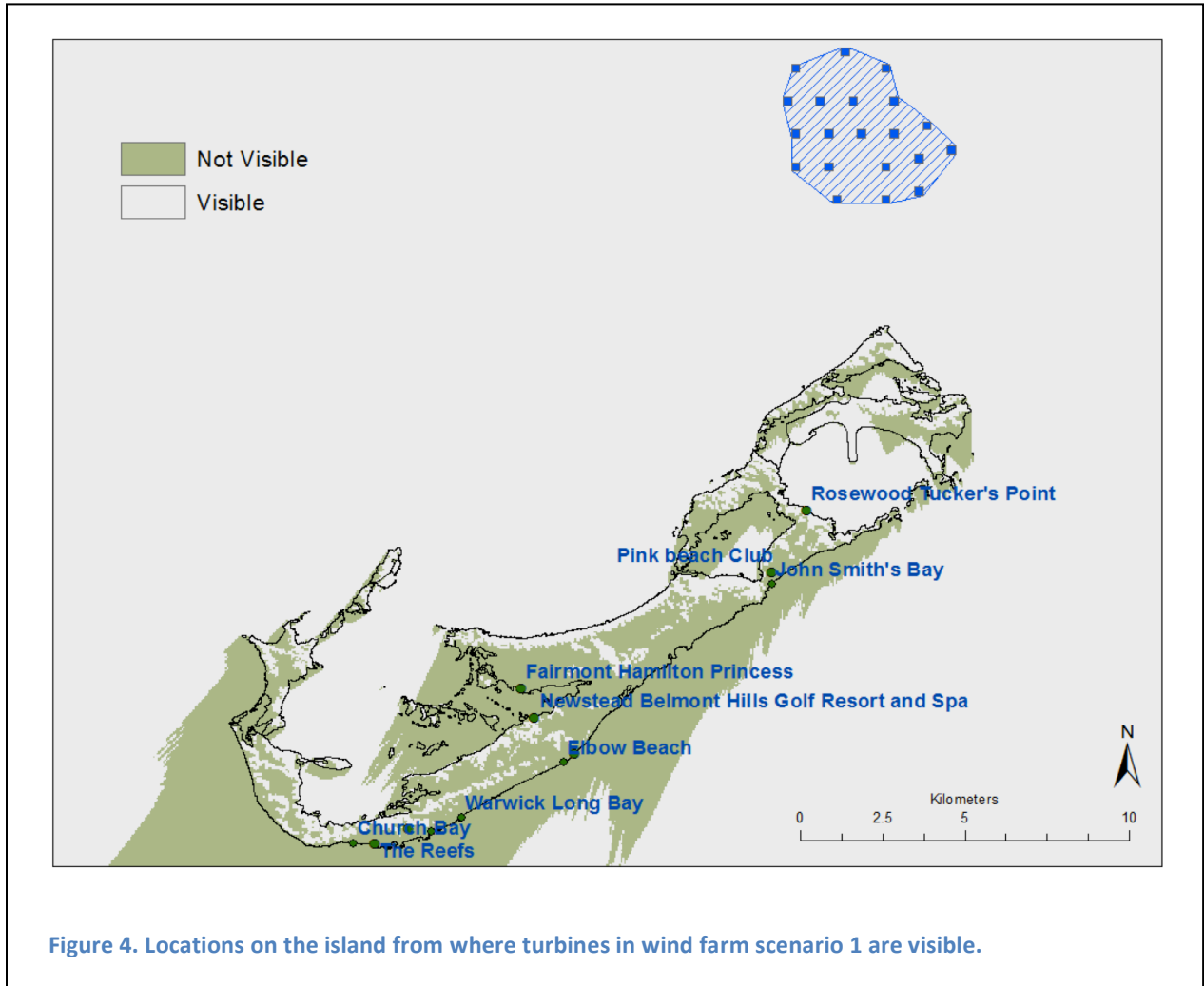


Similarly, figure 3 looks at the viewshed impact of turbines from some of the popular beaches on the island. As shown, the majority of the suitable development sites we have identified are not within view from the popular beaches on the island. A methodology similar to this can be used to inform the model before optimization of any priorities.



Approach 2: Post-hoc consideration of viewshed

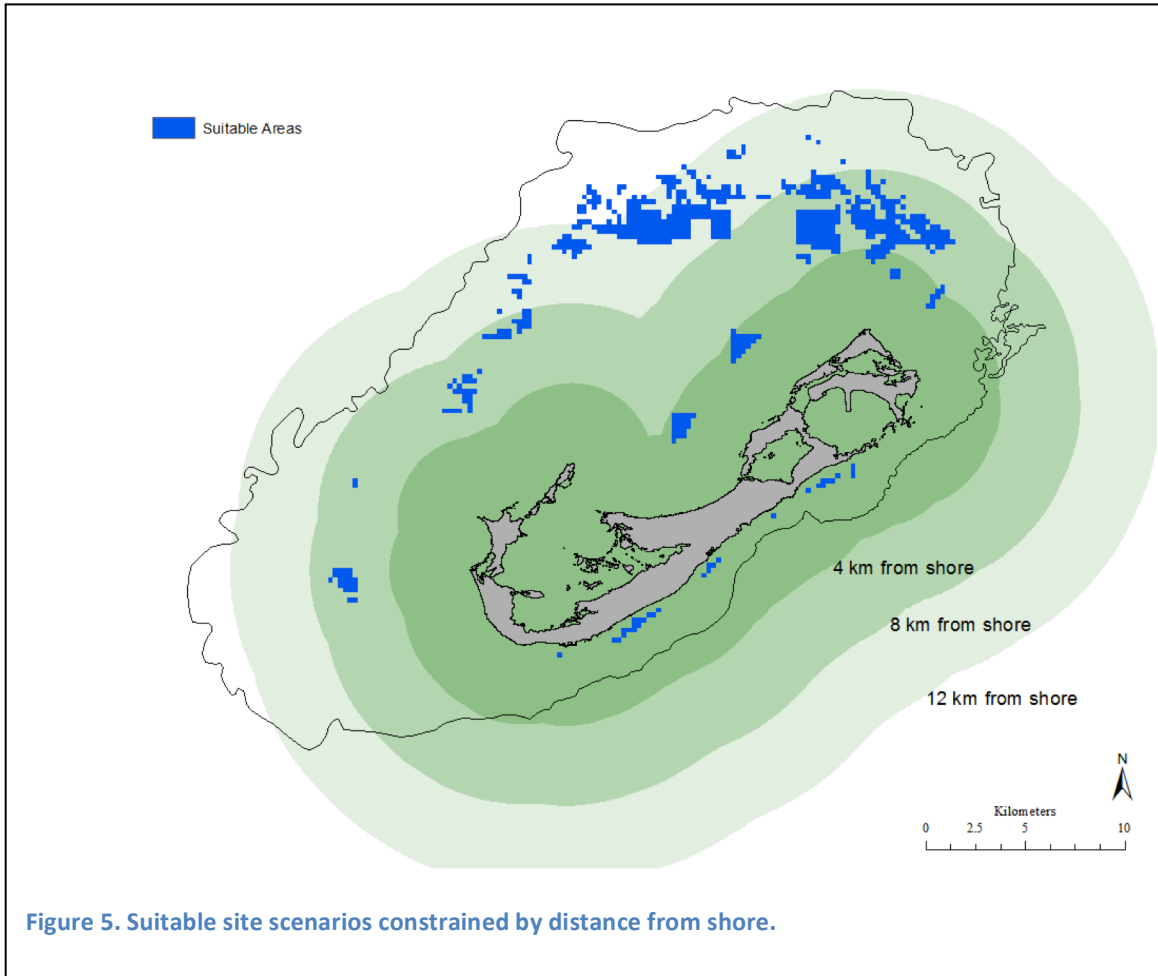
Viewshed can be studied in a reactive or post-hoc manner after suitable sites have been identified. Figure 4 shows the locations on the island from which the wind farm placement scenario 1 can be seen either in part or in its entirety. This study can be used iteratively to further constrain the analysis when necessary.



Approach 3: Hybrid approach

Constraints can be placed on the spatial analysis to account for viewshed by including it as another exclusion layer. This could be due to restrictions on how close to shore the farm can be sited, or on placement on particular parts of the platform etc.

The example scenario we considered limits wind farm development to outside specific distances from shore. We chose 4 km, 8 km and 12 km for our viewshed analysis in line with the study on changes in public perception with distance cited in section 3.6.1 (Bishop and Miller, 2007). Our viewshed analysis shows that there are enough suitable sites to meet the requirements for a wind farm based on the current threshold settings more than 4 km away from shore as well as 8 km away from shore. But, we do not have enough suitable sites to meet the energy requirements given the current threshold assumptions outside a 12 km buffer zone. Placement outside 12 km will necessitate larger tradeoffs and adjustments of thresholds.



Specialized viewshed impact assessment tools

We have detailed some of preliminary analyses that could be done to look at viewshed impacts. If more detailed results are considered useful to assist with decision making, more in depth viewshed studies are recommended. The topic of visual impact has been extensively studied, and methodologies exist for visual impact assessment. A prior assessment of probable visual impacts is widely recognized as an important component in the planning process.

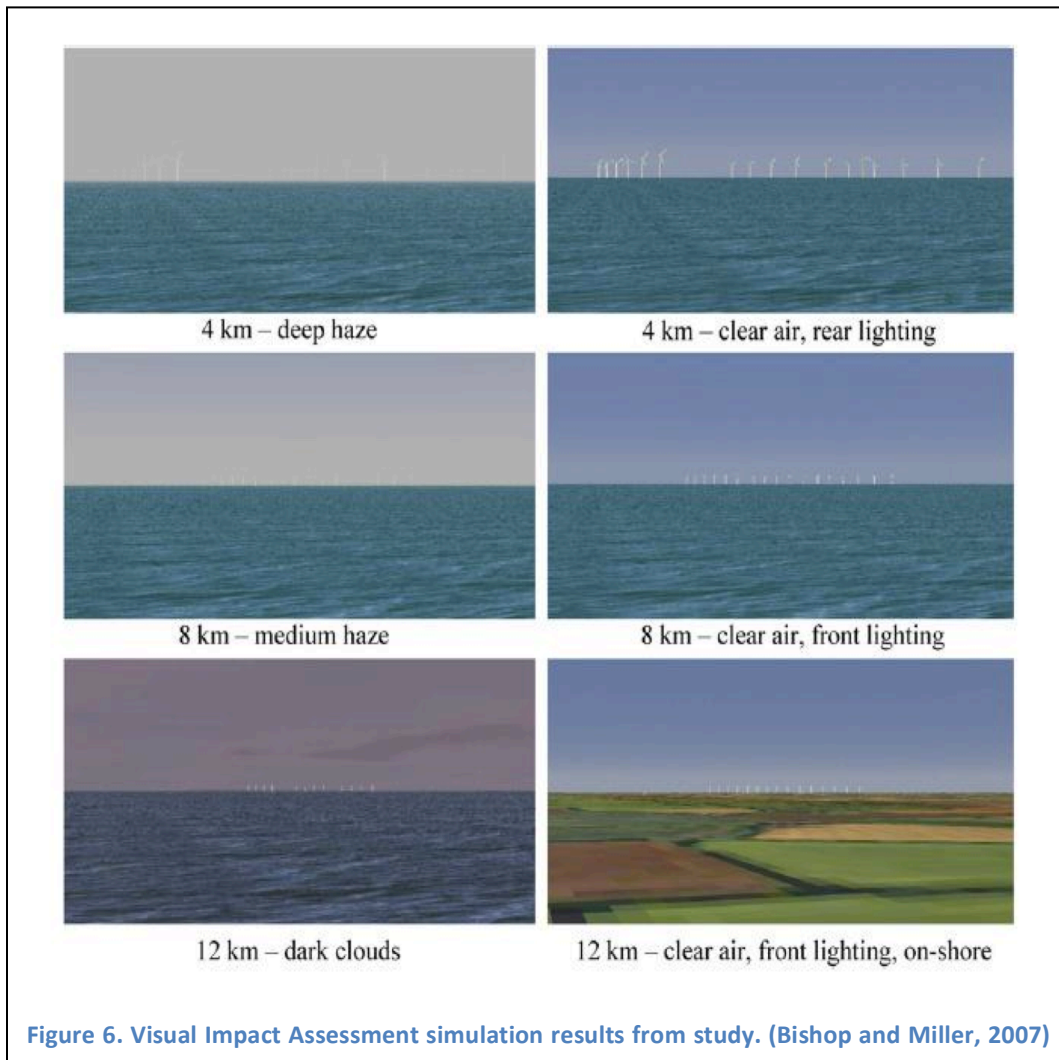
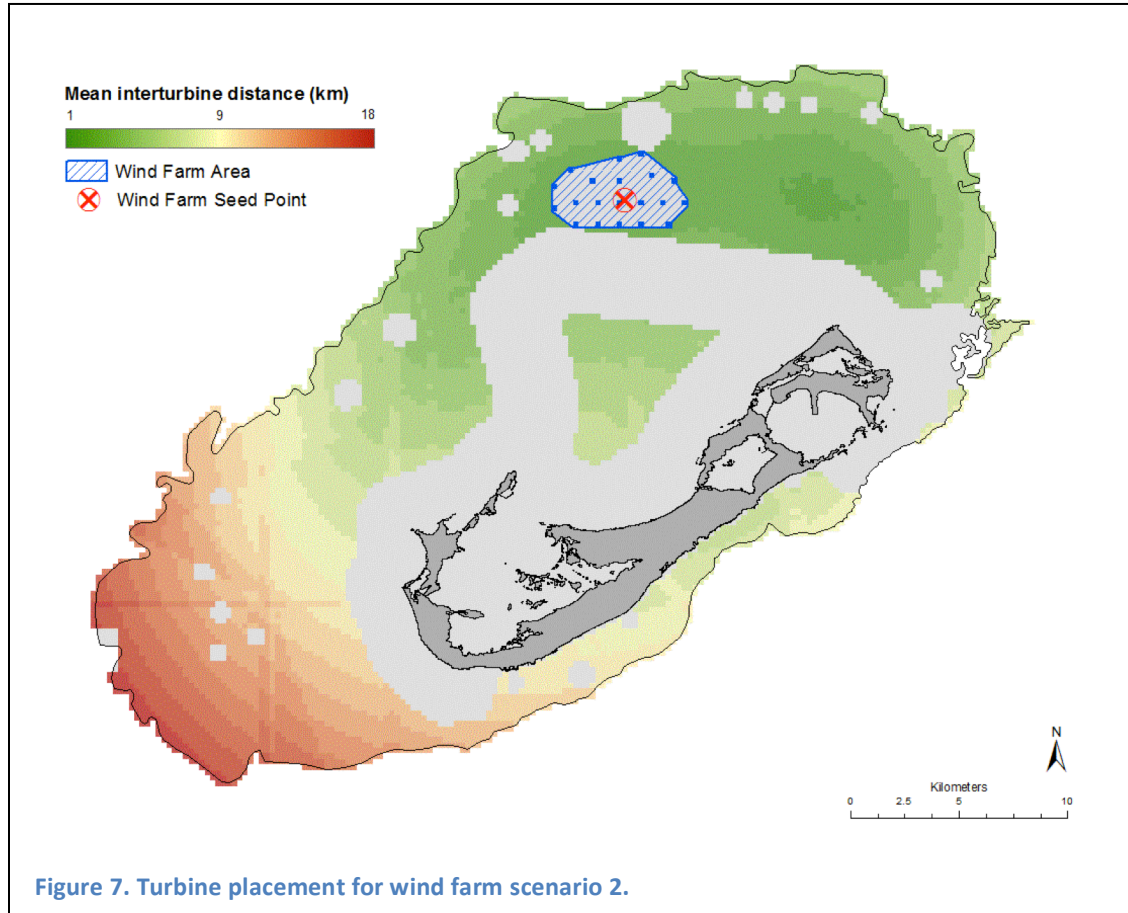


Figure 6 shows some of the results from a study done in Wales which uses a specialized visual impact methodology tool that simulates how turbines would appear on the viewshed based on a range of criteria including lighting conditions, contrast, number and orientations of turbines, difference between moving and stationary blades etc. A methodology of this nature, though approximate, is common in eliciting stakeholder response to a proposed installation (Bishop and Miller, 2007).

ii. Additional Turbine Placement Scenarios and Post-hoc Analysis

Two additional turbine placement scenarios and the associated post-hoc analyses are included below. Scenario 2 shown in Figures 7 and 8 is a more compact placement compared to Scenario 3 shown in Figures 9 and 10.



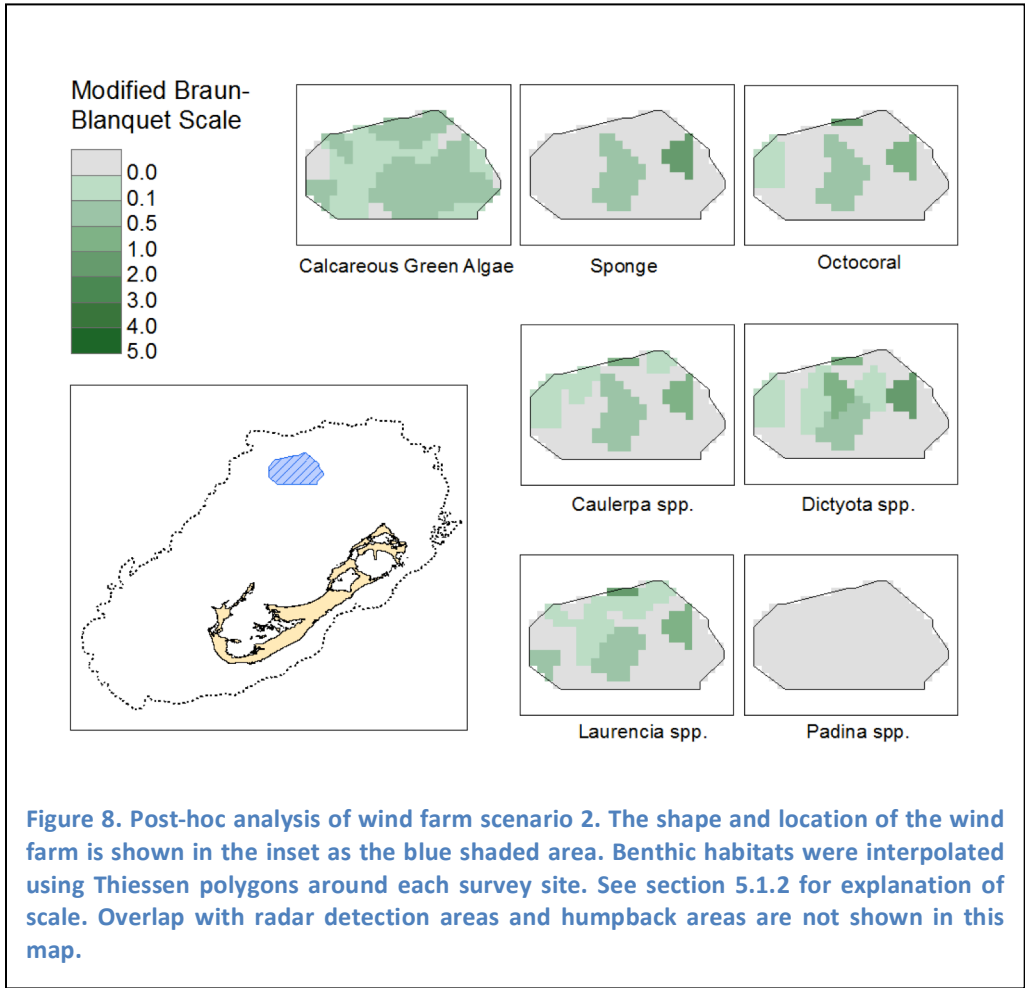
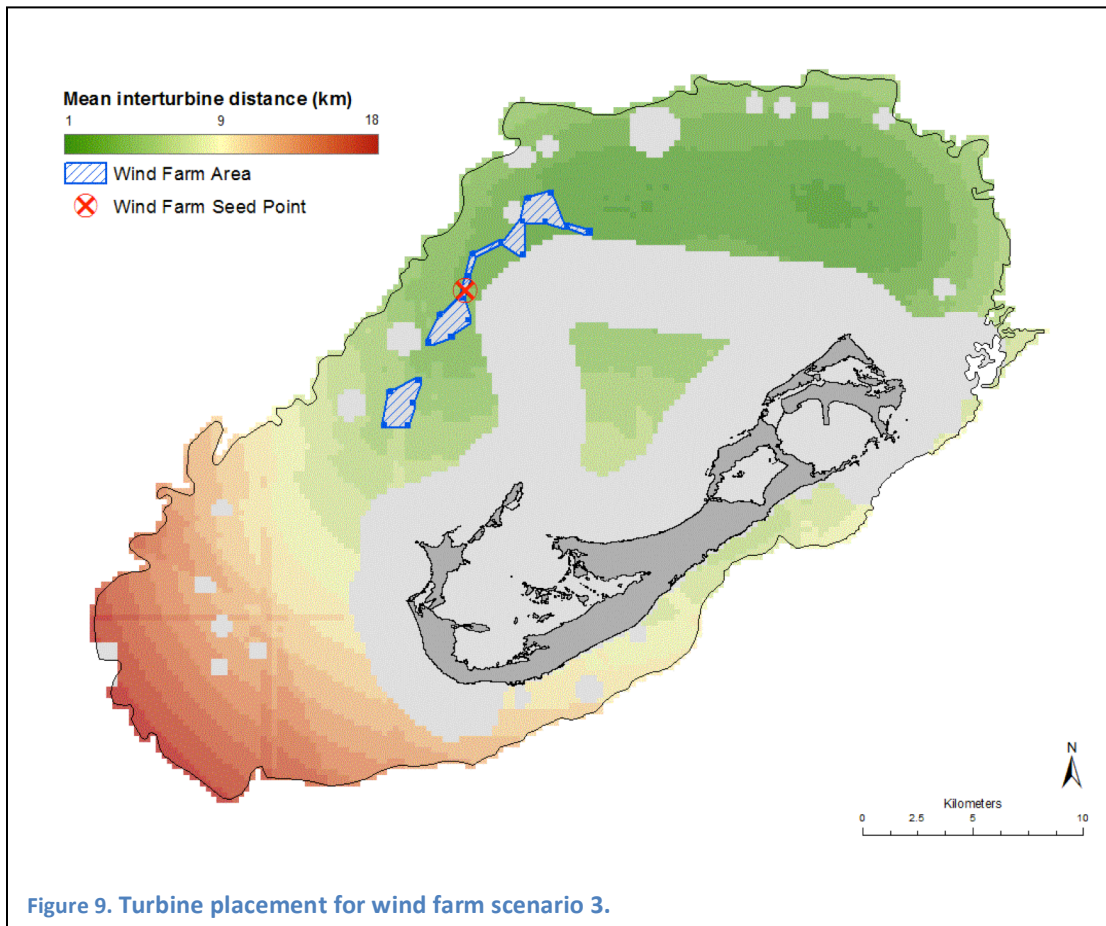
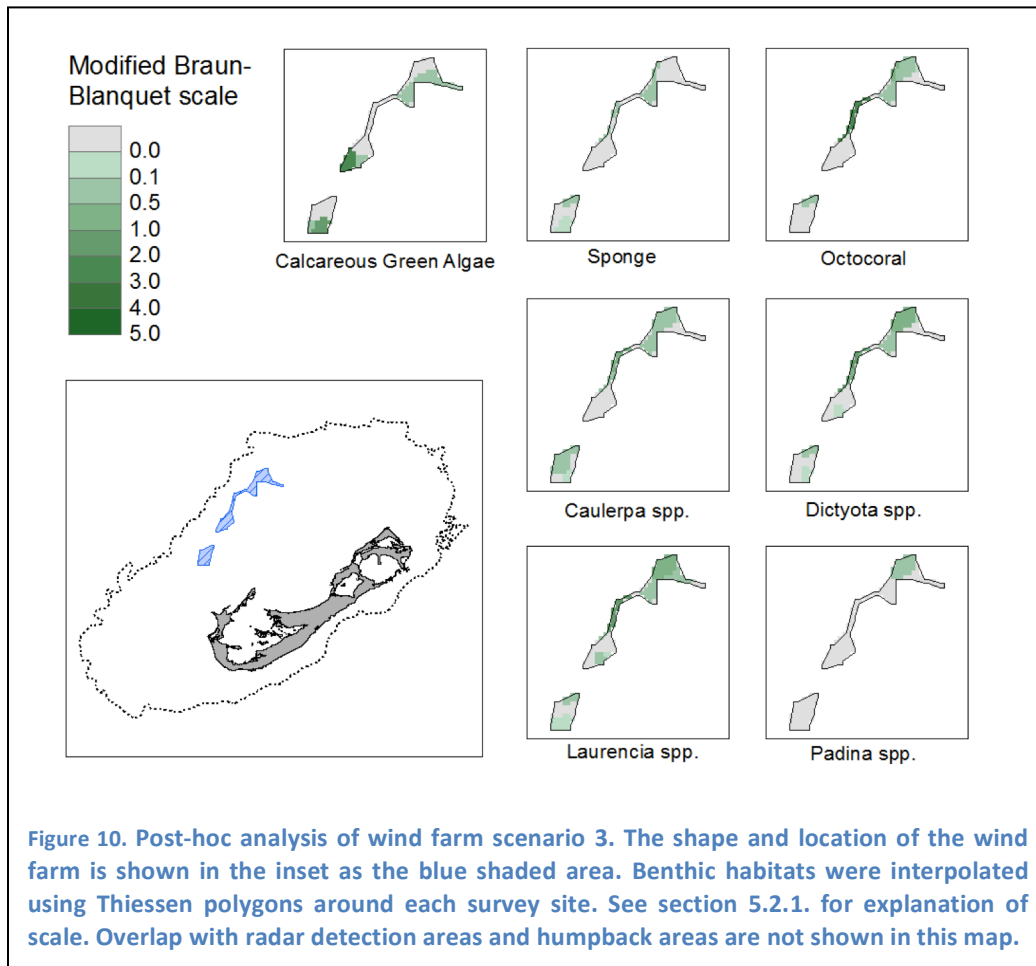


Figure 8. Post-hoc analysis of wind farm scenario 2. The shape and location of the wind farm is shown in the inset as the blue shaded area. Benthic habitats were interpolated using Thiessen polygons around each survey site. See section 5.1.2 for explanation of scale. Overlap with radar detection areas and humpback areas are not shown in this map.





iii. Commercial fishing survey and verification

We sent out a survey to the Fisheries Wardens in Bermuda to obtain the spatial commercial fishing effort. This included the instruction given in the box below as well as the map in Figure 11 where the platform was divided into 1 km x 1 km grids.

Bermuda Wind—Fish Warden Surveys

Re: Important commercial fishing areas on the Bermuda Platform

Purpose: The purpose of this survey is to use the **expert opinion and knowledge** of Bermuda's Fish Wardens as a proxy for the information that would ideally be obtained directly from Bermuda's **commercial** fishermen. The survey will be used to *identify the areas fished* by Bermuda's commercial fishermen and *the relative importance* to Bermuda's commercial fishermen of each area fished. This information will be used to quantify the potential tradeoffs that could result from the closure of those areas due to the installation of offshore wind turbines.

Data format and use: The data will be drawn on a map of the Bermuda Platform. A grid has been placed on the map and is composed of multiple 1000-m² cells. The completed map drawings will then be scanned and e-mailed back to the BermudaWind Team, where we will input the sketches into ArcGIS and create a data layer that shows the relative importance of different grid cells to fisheries (i.e., a heat map of fishing value).

NOTE: The hot-spot cells are to be valued based on **fishermen activity** and **frequency to the sites**. Note that this information is to make a best assumption as to which sites are valuable to Bermuda's commercial fishing industry as a whole.

Directions: We are using the "100 pennies" approach in valuing commercial fishing hot-spots. A penny is thought of as a "value point" to be awarded to high-use or highly frequented areas represented by the grid cells. Each warden allocates a budget of 100 pennies across the Bermuda Platform grid to value the spatial distribution of commercial fishing effort. Using their own knowledge of fishing activity on the Bermuda Platform, the wardens will select cells that are of high use.

*The goal is to produce two separate maps, as **pelagic fishing** and **bottom/reef fishing** are to be valued separately; each will be valued using 100 pennies.*

1. Distribute two maps: one to represent pelagic fishing, and the other for reef fishing.
2. On each map, wardens will mark the appropriate number of grid cells for each hot-spot. The area could span across multiple cells, or just be concentrated on one cell.
3. Assign the cell or group of cells a penny value between 1 and 100. A lower value indicates that the spot is not as active or as popular. A higher value indicates that the spot is popular and is highly frequented.
For each cell not marked, we assume that it is valued at 0, indicating that no or insignificant fishing activity occurs in that area.
4. Any quantity of cells/hot-spot areas can be marked, though the sum of all values from all spots must total 100 pennies, no more and no less.
5. To reiterate, the warden should make the distinction between pelagic and reef fishing, to ensure that he is not comparing both types. These are to be valued separately.

A sample map is included. Please note that the drawn polygons and weighted values have been fabricated and are merely to be used as an example

Commercial Fishing Hotspots Survey- Reef Fishing

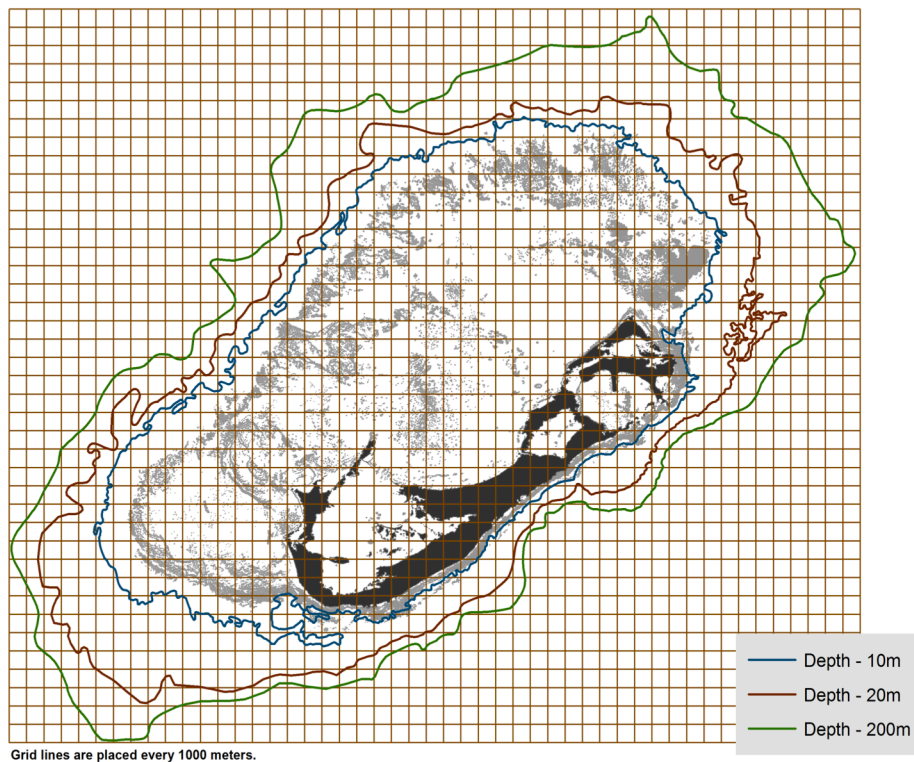
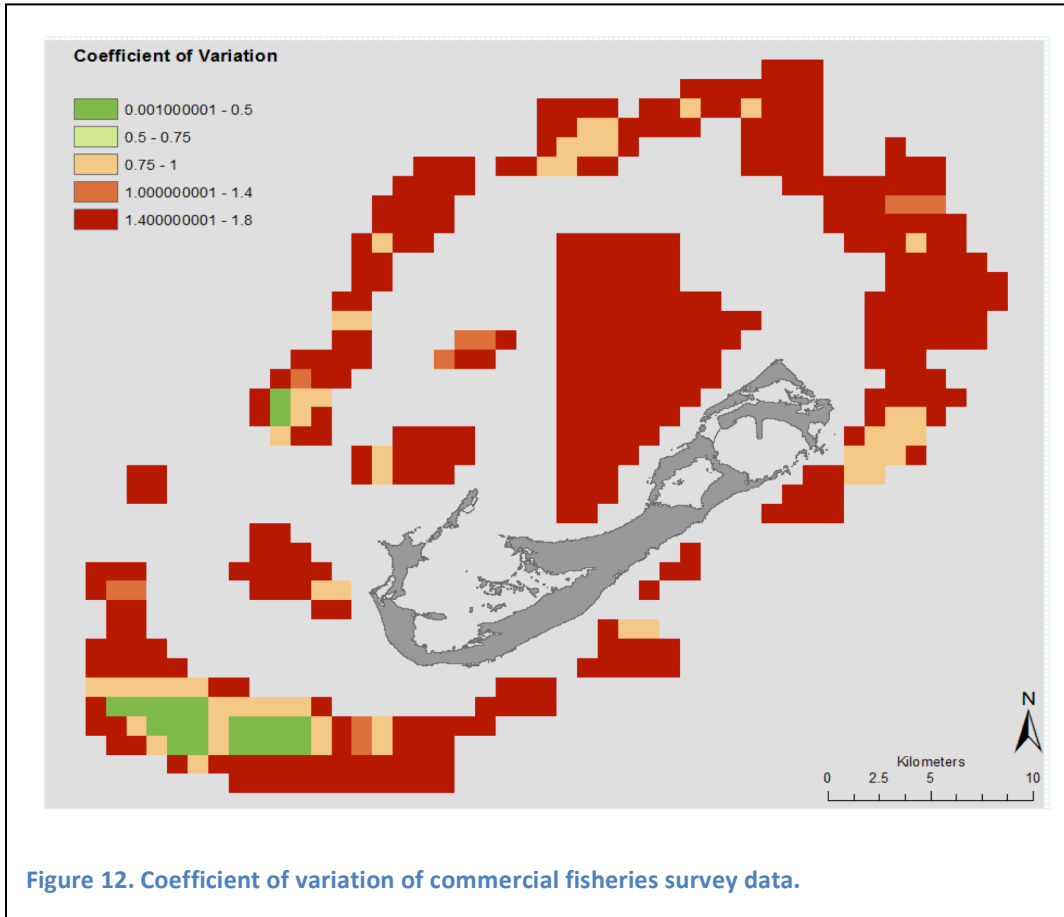


Figure 11. Commercial fishing survey map sent to fisheries wardens in Bermuda.

We performed a data integrity analysis on the survey data received from the three fisheries wardens. The coefficient of variation, which is a normalized measure of deviation, gives an indication of the relative spread in the data and is a useful measure in situations where the means tend to be drastically different as in the case of commercial fishing effort across the platform. This was calculated on the original data in the surveys.



The spatial spread shown in figure 12 reflects the low sample size of the dataset. Since fish resources and associated effort are highly variable, a high coefficient of variation is likely. We adopted a conservative approach for our analysis and included all the sample data points made available to us. The figure 12 also points to the areas of convergence in the sample data. This knowledge can be used to further optimize between spatial locations in the threshold analysis or to prioritize additional data collection efforts.

iv. Air surveillance radar and weather radar detection

Figure 13 shows the regions of the Bermuda Platform where a 160 m tall structure would not be visible by the air Surveillance, weather and vessel traffic surveillance radars.

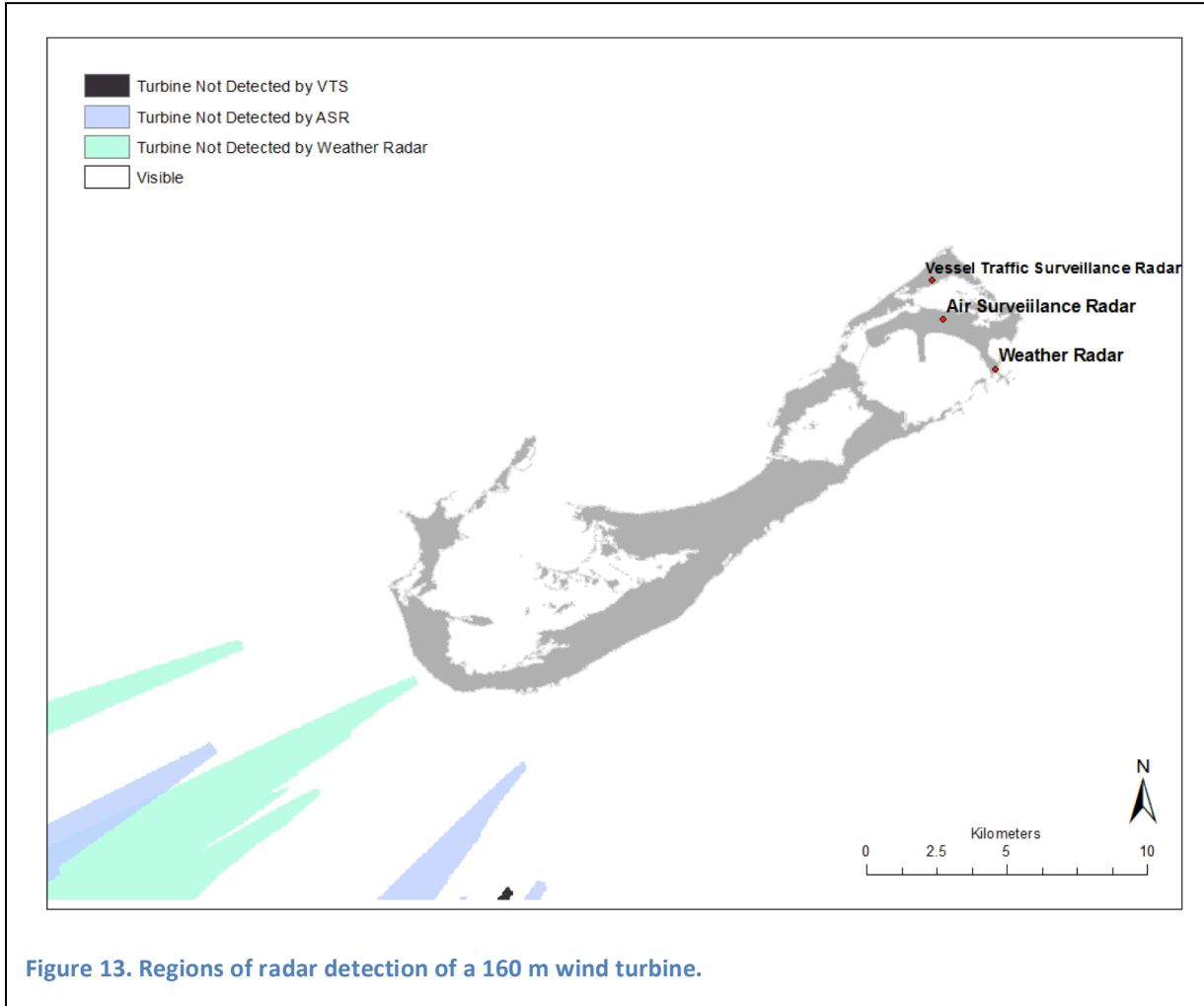
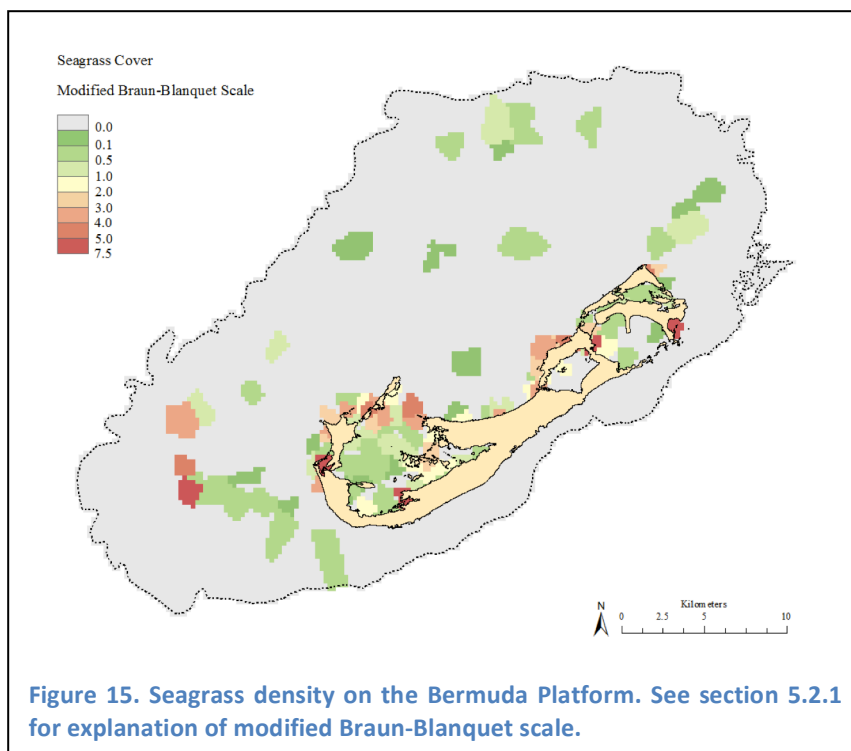
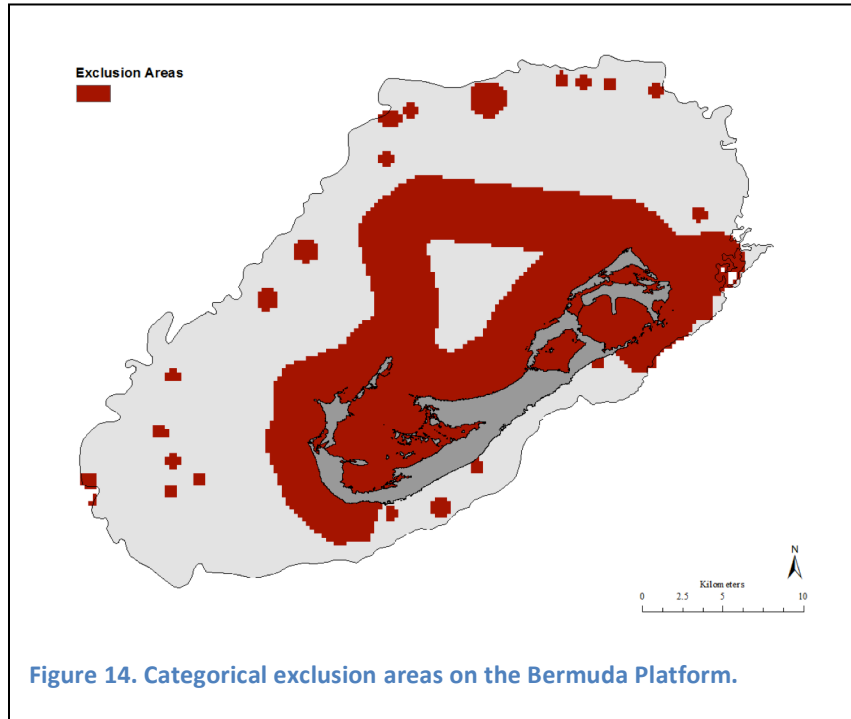
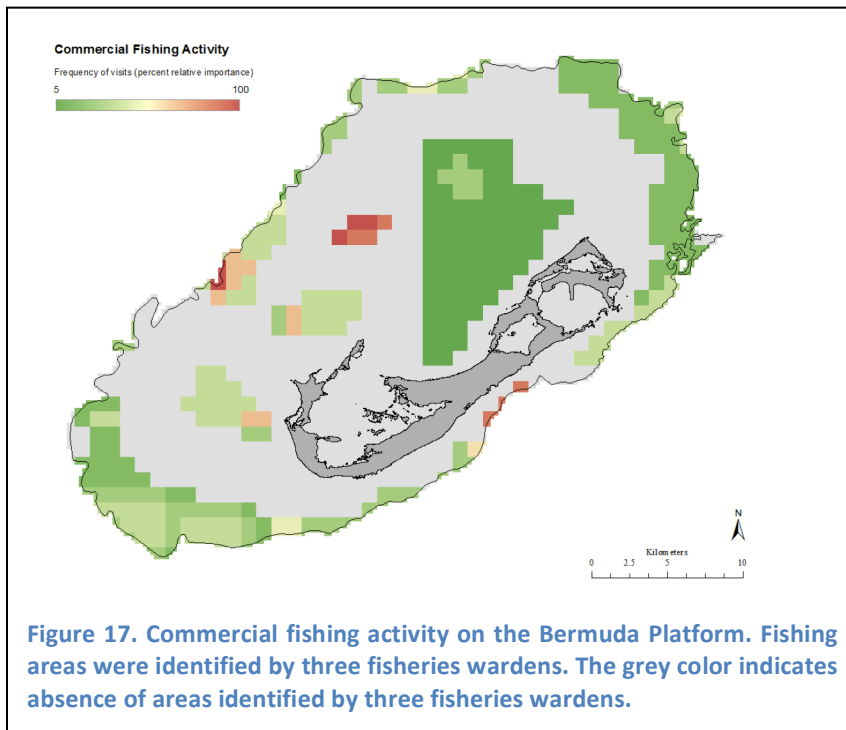
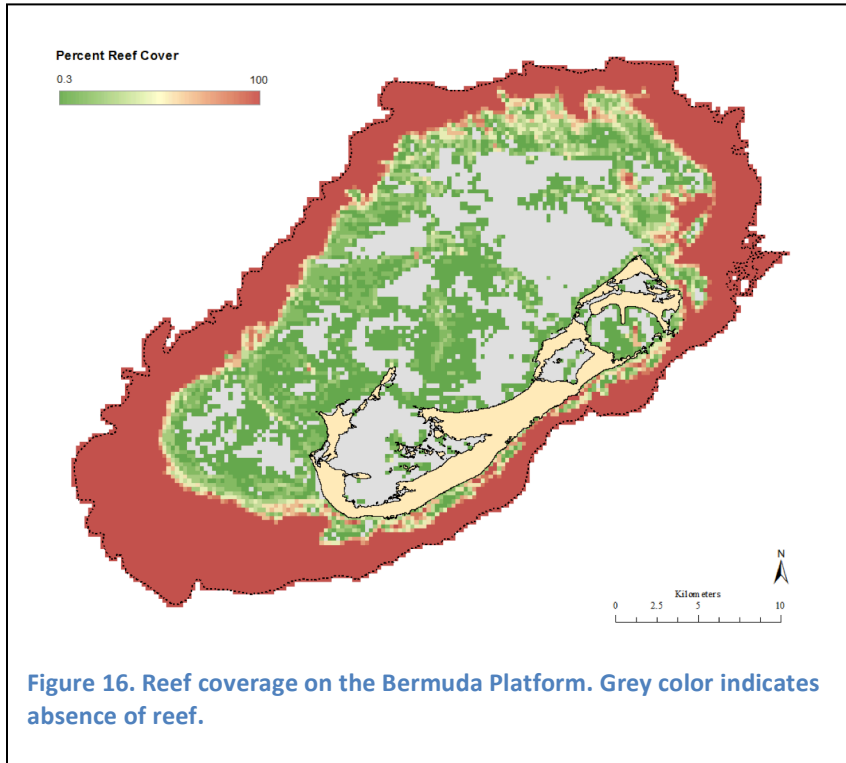


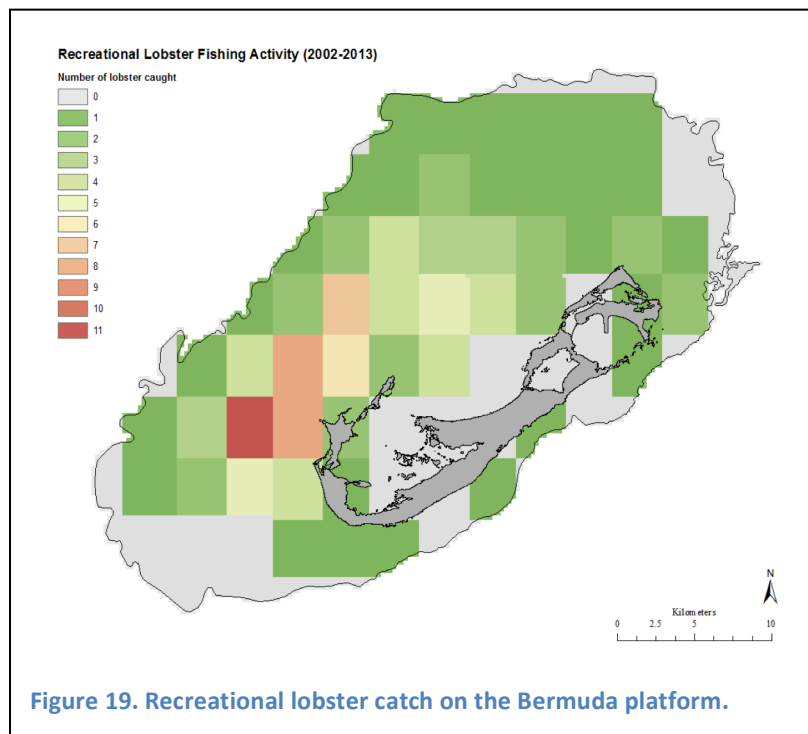
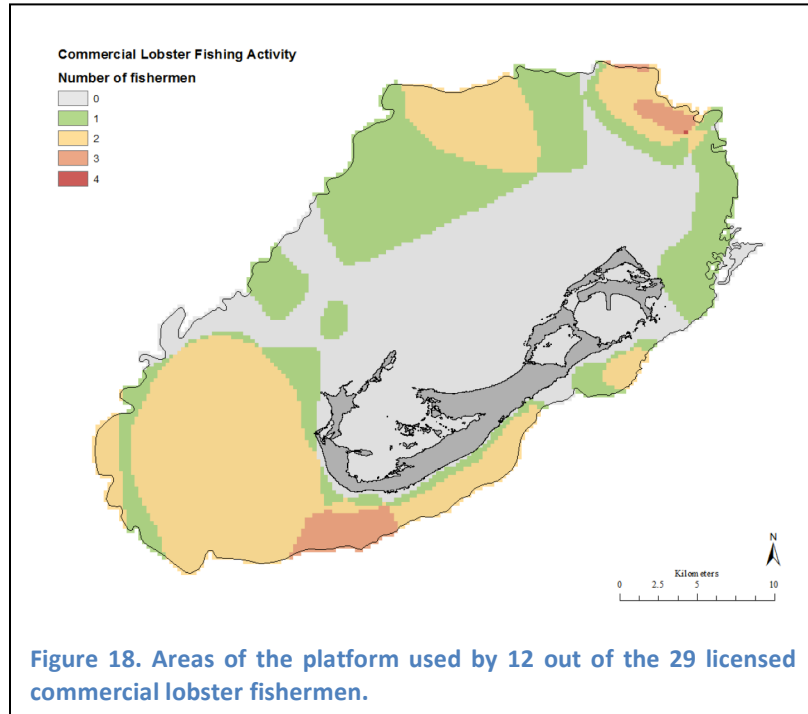
Figure 13. Regions of radar detection of a 160 m wind turbine.

v. Spatial input layers

This section includes all the exclusion and threshold input layers used in the analysis after they have been converted to our common 250m x 250m reference grid.







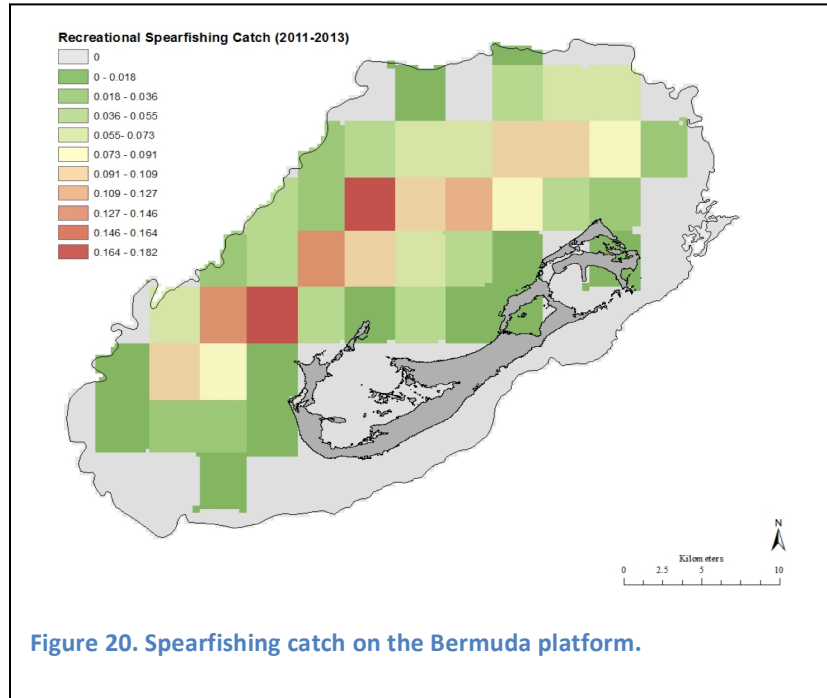


Figure 20. Spearfishing catch on the Bermuda platform.

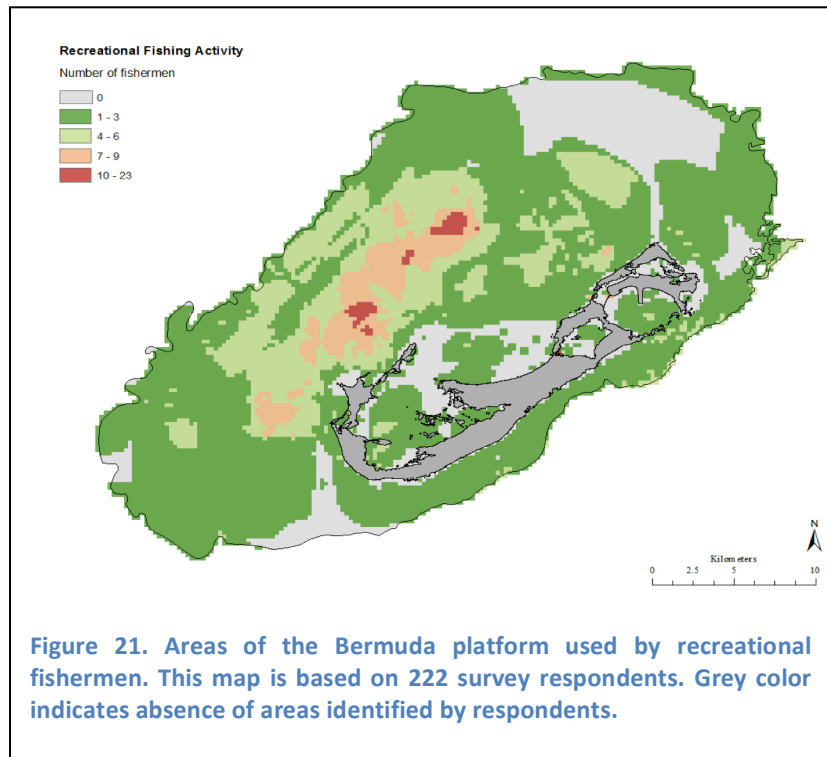


Figure 21. Areas of the Bermuda platform used by recreational fishermen. This map is based on 222 survey respondents. Grey color indicates absence of areas identified by respondents.

vi. Data Table

Description	Data	Original data type	Original data source	Value per 250 grid cell	Analysis category
General	20 m contour line	Line	Dept. of Conservation Services	Presence/absence	Region of interest
	Island contour	Polygon	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	250m x 250 m planning cells	Line and polygon	Current study	N/A	
Benthic habitat and species	Reef	Polygon	Dept. of Conservation Services	Percent reef cover	Threshold
	Seagrass	Point	Dept. of Conservation Services	Braun-Blanquet density	Threshold
	Sponges	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
	Soft corals	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
	Calcareous green algae	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
	Laurencia spp.	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
	Caulerpa spp.	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
	Dictyota spp.	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
	Padina spp.	Point	Dept. of Conservation Services	Braun-Blanquet density	Post-hoc
Fisheries	Commercial finfish fishery (reef associated)	Polygon	Current study	Importance based on frequency of visits	Threshold
	Commercial lobster fishery	Polygon	Dept. of Conservation Services/Current study	Number of lobster fishermen	Threshold
	Recreational fishery (overall)	Polygon	Dept. of Conservation Services	Number of lobster fishermen	Threshold
	Recreational lobster fishery	Polygon	Dept. of Conservation Services	Lobster catch between 2002-2013	Threshold
	Recreational spearfishing fishery	Polygon	Dept. of Conservation Services	Spearfishing catch between 2011-2013	Threshold
Bird and mammal habitats	Avian Zones 1, 2 and 3 and Important Bird Area	Polygon	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	Humpback whale area	Polygon	Current study	Presence/absence	Post-hoc

Infrastructure	Shipping lanes	Line	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	Airport Control Area	Polygon	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	Weather and airport radar viewshed	Polygon	Current study	Presence/absence	Post-hoc
Marine Protected Areas	No net fishing	Polygon	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	Blue-striped grunt fish aggregation areas	Polygon	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	Dive site protected areas	Polygon	Dept. of Conservation Services	Presence/absence	Categorical Exclusion
	Fish aggregation sites within seasonally protected areas	Polygon	Current study	Presence/absence	Categorical Exclusion