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Including Wind Resource Trends in a Micrositing Optimization of the Block Island Wind Farm, RI, USA

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INCLUDING WIND RESOURCE TRENDS IN A MICROSITING OPTIMIZATION OF THE BLOCK ISLAND WIND FARM, RI, USA

BY

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ABSTRACT

The exponential growth of the earth's population has lead to the depletion of natural resources in concert with unrepairable environmental damage. One solution for a more sustainable lifestyle is the supply of electricity by renewable energy technology. Offshore wind energy is expected to play a major role in the extension of this sustainable energy supply. However, several challenges lay ahead due to the high expenses of offshore energy. Consequently, the optimization of a wind farm layout for minimizing costs and maximizing revenue gains high importance.

This study determines the sensitivity of a wind farm layout and its revenue to wind time series length, wind direction and wind velocity trend. The sensitivity analysis is conducted at the Renewable Energy Zone (REZ) and the Rhode Island and Massachusetts Area of Mutual Interest (AMI) in Rhode Island, USA. Optimum layouts are found by minimizing an objective function expressed in terms of the Wind Farm Siting Index (WiFSI) with a Genetic Algorithm. The objective function considers wind resource, technological costs as expenses for tower foundation and cable interconnection as well as ecological and fishery cost. Ecological cost is expressed as abundance and sensitivity of species to wind farms. Fishery cost is implemented proportional to fishing activity intensity. The WiFSI is a dynamic tool adjustable by weighting factors to societal or political choices.

Seven simulations are conducted for the REZ and four simulations are researched for the AMI to complete the sensitivity study. All scenarios exclude ecological and fishery constraints from the objective function to focus on effects of a changing wind resource. Simulation 1 is conducted as a base case for the

REZ with constant wind resource measured over three years. Simulation 2 to 4 apply wind probability distributions of 1992 to 2012, 1980 to 2012 and 2008 to 2012, respectively. Applying the long wind time series leads to several placement solutions in contrast to one optimum layout for simulation 1. Scenario 5 and 6 apply single-year wind roses of the years 1980 and 2012. Resulting layouts differ in orientation to the respective dominant wind direction. Simulation 7 implements a positive, linear trend in usable wind velocity. The same layout as for simulation 1 is found but net revenue increases. One base case simulation with constant wind and one simulation with a positive, linear trend in the usable wind resource are operated for the Northern and the Southern part of the AMI. Optimized layouts of the base case and the trend application simulations vary. The change is due to the high number of possible turbine locations with same WiFSI. The implementation of the trend leads to an increase of net revenue.

Wind turbine layout is highly sensitive to a change in wind time series length and wind direction while net revenue is less influenced. In contrast, the sensitivity of the layout to a trend in usable wind velocity is low while the effect on net revenue is significant. Conclusively, long-term wind predictions over the life time of a farm are necessary to determine the optimum layout as well as produced power of a site.

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PREFACE

This thesis is written in the manuscript format. Manuscript 1 presents the paper *Including wind resource trends in a micrositing optimization of the Block Island Wind Farm, RI, USA*. The paper is in preparation for submission to the Journal of Renewable Energy. The paper explains the implementation of a changing wind resource to the Wind Farm Siting Index (WiFSI) methodology of Grilli et al. (2013). The improved tool is applied to the Renewable Energy Zone (REZ) Southwest of Block Island and the Rhode Island and Massachusetts Area of Mutual Interest (AMI). The paper shows the necessity to consider long-term wind predictions to optimize wind farm sites.

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INCLUDING WIND RESOURCE TRENDS IN A MICROSITING OPTIMIZATION OF THE BLOCK ISLAND WIND FARM, RI, USA

by

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In preparation for submission to the Journal of Renewable Energy

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1.1 Abstract

Due to the depletion of natural energy resources offshore wind energy has become of great interest for sustainable electricity supply. Regarding the high expenses for construction and maintenance of a offshore wind farm, research focuses on finding a turbine layout with minimum cost and maximal power production. This study overcomes the limitation of using a constant wind resource by implementing changing wind time series lengths, varying wind direction and a trend in usable wind velocity. The sensitivity study is applied to the Renewable Energy Area (REZ) with five turbines as well as the Rhode Island and Massachusetts Area of Mutual Interest (AMI) with 100 turbines. The changing wind resource is implemented in the methodology of the Wind Farm Siting Index (WiFSI). This tool combines technological, ecological and fishery constraints in an objective function to find optimum turbine locations. Weighting factors for each constraint are adjustable to societal and political choices. Wind turbine placement is determined to be highly sensitive to a change in wind time series length as well as changing wind direction. In contrast, the impact of a trend in usable wind speed on a layout is low while net revenue is changing significantly. Conclusively, long-term wind predictions over the life time of a farm are necessary to determine the optimum layout as well as produced power of a site.

1.2 Keywords

Offshore renewable energy, Wind farm micrositing, Wind farm siting index, Wind trend, Ecosystem services, Genetic algorithm

1.3 Introduction

The exponential growth of the earth's population has lead to the depletion of natural resources in concert with unrepairable environmental damage. One solution for a more sustainable future is the supply of electricity by renewable energy technology. For several countries, targets range up to 100% of energy supply from renewable sources[1]. As of 2012, 19% of the world-wide energy consumption was produced by renewable energy plants. Offshore wind energy is expected to play a major role in the targeted argumentation of sustainable energy supply. Providing emission-free electricity from a domestic, non-ending source, this technology also strengthens the economy and diversifies the energy supply leading to independence from conventional, environmental unfriendly energy devices[2][3]. However, several challenges lay ahead since offshore energy requires high expenses due to the foundation, installation and maintenance at the open sea[4]. The optimization of a wind farm layout gains high importance in this context[5]. Consequently, recent efforts to site wind farms have resulted in placing a given number of turbines in a predefined area based on a siting optimzation approach which aims on maximizing the revenue[6].

1.3.1 Wind farm siting in Rhode Island

The state of Rhode Island, USA, passed the Rhode Island Energy Standard (RES) in June 2004 in order to tackle the challenges of offshore wind energy. This portfolio demands that by 2019 16% of the total supplied electricity must originate from renewable sources[7]. One contribution to this goal is the first US offshore wind farm Southeast of Block Island which is currently under construction[8]. The location of the Block Island Wind Farm was selected based on an extensive siting optimization research phase performed through the Ocean Special Area Management Plan (Ocean SAMP)[12]. This eco-system based coastal management tool was initiated by the Rhode Island Coastal Resources Management Council (RI CRMC) and developed in close collaboration with the University of Rhode Island. The study area is shown in figure 1. The SAMP area is home to migratory fish, sea

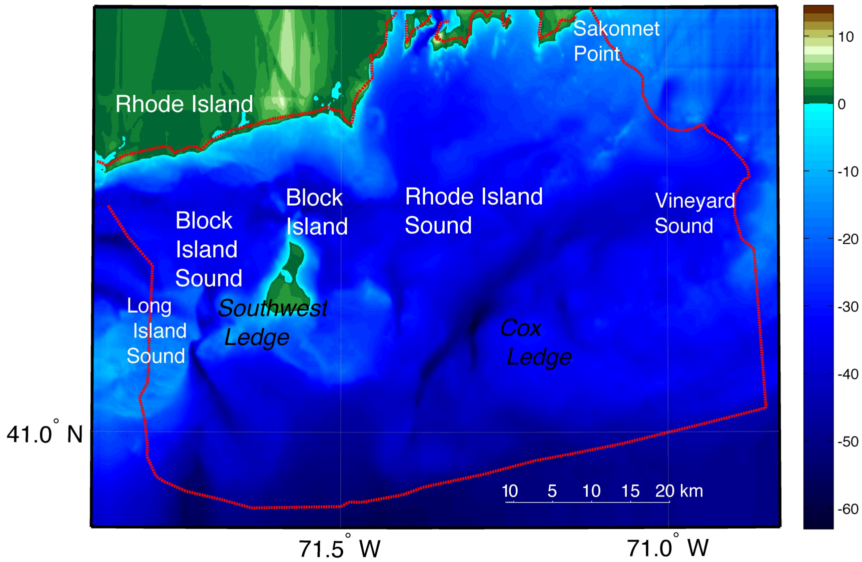

Figure 1. Map of the site of the Special Area Management Plan (SAMP) (outlined in red) with water depth in meter (color shading) from Grilli et al. (2014)[9].

turtles, birds and marine mammals in addition to the presence of several human activities such as ship traffic or recreational and commercial fisheries[10]. These ecological and human activities constitute significant constraints to wind farm development which were tackled in the SAMP project through scientific research and stake-holder meetings. In that context, Grilli et al. (2013)[11] developed a siting optimization protocol including ecosystem service constraints in a wind farm cost model that improved the classic wind farm optimization. Based on the comprehensive Ocean SAMP study[12] and its associated siting optimization tools, a small offshore Renewable Energy Zone (REZ) (Figure 2) was defined in state waters as well as a much larger zone in federal waters. The large zone is called Area of Mutual Interest (AMI) and expands across the offshore area of Rhode Island and Massachusetts (Figure 3)[13][14].

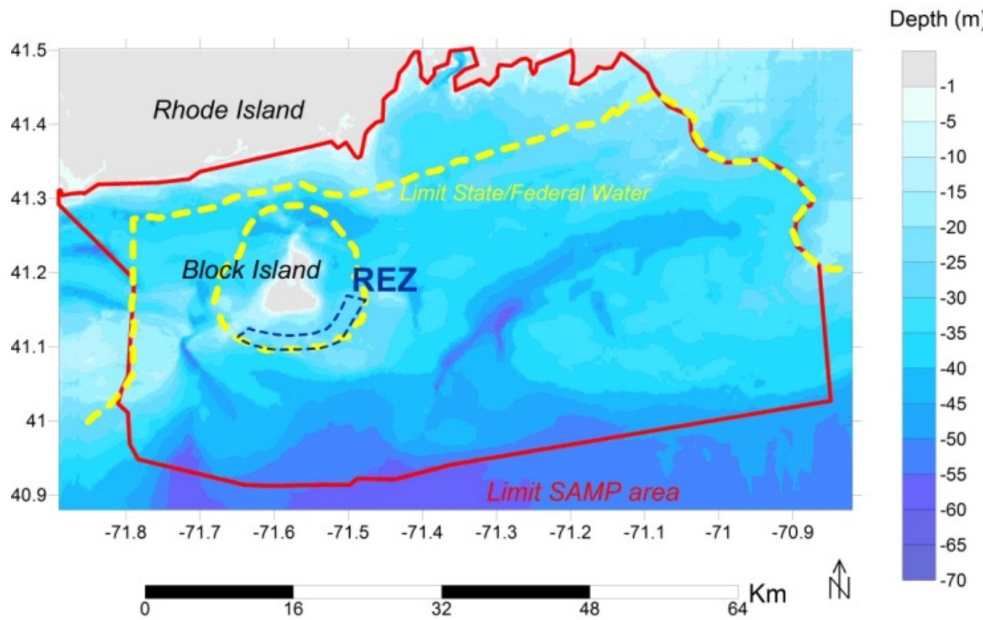

Figure 2. Map of the site of the Renewable Energy Zone (REZ) (dashed blue) in the Special Area Management Plan (SAMP) (solid red) with the limits of state waters (dashed yellow) and water depth in meter (color shading) from Grilli et al. (2013)[11].

1.3.2 Classic wind farm siting optimization

Conventionally, two approaches are followed in research on wind farm siting optimization. The first approach focuses on the development of siting algorithms applied to simple test cases[15][16][17], while the second approach performed in studies such as TopFarm[18] or OWFLO[19] focuses on the refinement of the aerodynamic modelling. These studies validate their model with measurements at existing wind farms. Therefore, the difference in the approaches lies in the complexity of the objective function, the formulation of the constraints to be minimized, and the sophistication of the aerodynamic and economic models. Table 1 gives an overview of previously applied objective functions in both approaches.

Wan et al. (2010)[17] rely on wake effects as single constraint in Annual

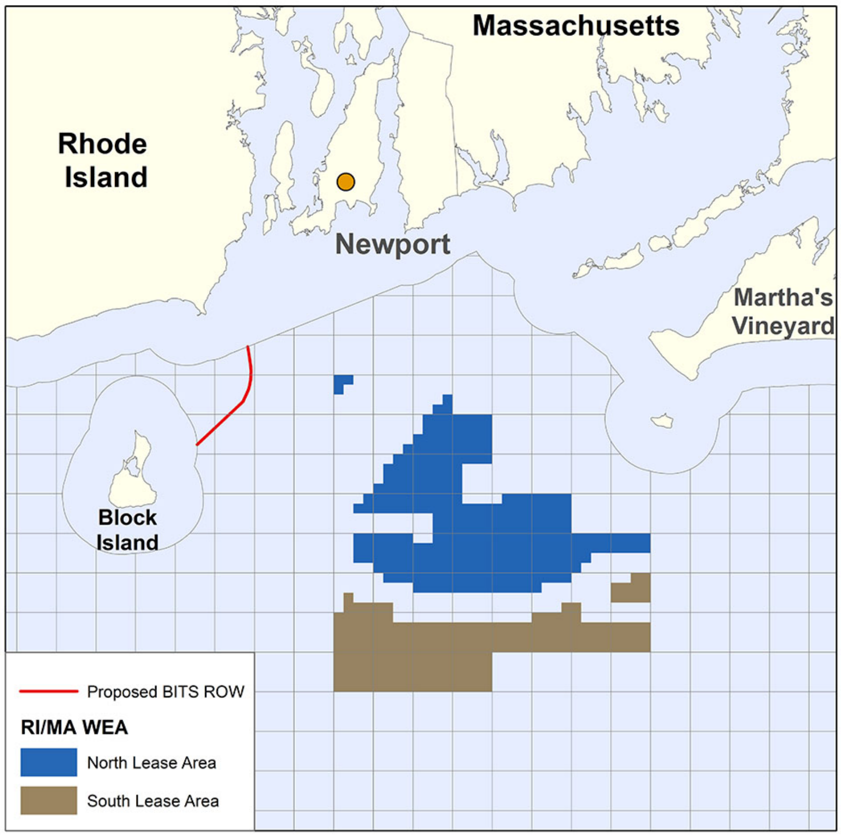

Figure 3. Map of the site of the Rhode Island and Massachusetts Area of Mutual Interest (AMI) divided into North Lease (blue) and South Lease (brown) from the Bureau of Ocean Energy Management (2015)[14].

Table 1. Overview of objective function formulations

Objective function	Short title	Unit	Author & Year
Annual energy production	AEP	KW	Wan et al. (2010)[17] WindFarmer, OpenWind, WindPro
Cost of Energy	COE	$/KWh	Grady et al. (2005)[16] Wan et al. (2009)[24] Wang et al. (2011)[25]
Linear combination		-	Mosetti et al. (1994)[15]
Levelized Production Cost	LPC	$	Elkinton et al. (2006)[19] and (2008)[26] Szafron (2010)[21]
Financial Balance	FB	$	Réthoré et al. (2014)[22]
Net Present Value	NPV	$	Gonzáles et al. (2009) [23]

Energy Production (AEP) when testing a Particle Swarm Algorithm. Many commercial softwares such as WindFarmer, OpenWind or WindPro use energy production alone as single objective. In contrast to that, El-Thalji et al. (2011)[20] and Tesauro et al. (2010)[6] state that maximizing energy production alone is far from sufficient and that all costs of the farm must be included in the cost model to achieve a realistic optimization. Grady et al. (2005)[16] define Cost Of Energy per KWh (COE) as ratio between total investment cost and total extracted power to test a Genetic Algorithm. Mosetti et al. (1994)[15] introduce the rarely used concept at that time of a linear combination of costs where weighting factors can be adjusted to economic choices. Adding expenses for operation and maintenance as further constraints in the model leads to the Levelized Production Cost (LPC) applied by Elkinton et al. (2006)[19] or Szafron (2010)[21]. Réthoré et al. (2014)[22] define a profit function as Financial Balance (FB) including installation cost, cable cost, fatigue degradation cost and discounting rate while Gonzáles et al. (2009)[23] use the concept of Net Present Value (NPV) of an investment for the optimization process.

1.3.3 Current research in wind farm siting

Currently, the classic siting tools' critical components are the wake modelling[21][19][27] and a precise cost representation[6]. Barthelmie et al. (2006b)[28] compare measurements and predictions of the most commonly used wake models. None of these is able to precisely predict wind speed in the nearfield behind a turbine. Gonzáles et al. (2014)[4] therefore suggest a revaluation of the current wake formulations. Elkinton et al. (2006)[19] miss precise cost models for offshore wind farm availability, installation cost as well as expenses for operation and maintenance while Réthoré et al. (2014)[22] demand refinement of the electrical grid models. Improvement of component reliability analysis is requested by Gonzáles et al. (2014)[4].

Restrictions of the conventional models has lead to the development of new approaches to wind farm siting. In particular, the standard computational grid in optimization models has evolved towards a continuous siting approach. Wan et al. (2009)[24] first allowed the devices to be placed freely inside a computational grid cell instead of its center to further reduce the wake. In parallel, a new concept of flexibility in terms of turbine parameters has emerged. Acero et al. (2009)[29] apply variable hub heights for turbines aligned on a straight line while Chen et al. (2013)[30] keep number of turbines and height as free variables when optimizing a simple test site. The Unrestricted Wind Farm Layout Optimization (UWFLO) developed by Chowdhury et al. (2013)[31] as well as Rahbari et al. (2014)[32] combine several of these approaches. The model optimizes under continuous placement conditions with variable rotor diameter, variable hub height and variable power characteristics.

1.3.4 Social and environmental constraints

Studies on the impact of wind farms regarding social and environmental factors have been conducted in the last years followed by the development of models to predict specific impacts of wind farms on the environment. Visual impact increases with number and size of the turbines[33] and decreases with distance to shore[34]. Visual impact is also dependent on arrangement, spacing, color and material[35] as well as on personal attitude towards offshore farms[36]. Shadow impact decreases with distance and flicker frequency while offshore noise level depends on wind direction and distance[37]. A noise emission model for wind turbines was developed by Prospathopoulos (2007)[38]. Bird collision risk at wind farms is lower than with other man-made infrastructures[39]. Nevertheless, even low additional mortality may be significant for slow reproducing species[40]. Band et al. (2007)[41] developed a collision risk model based on flight height, avoidance behaviour and turbine type. Overall, the most effective mitigation technique seems to be shut-down of turbines on demand[42]. Constructional or operational noise is expected to result in displacement or a shift in common migration routes of mammals[43] while fish abundance is larger in the presence of turbines (reef effect)[44][45].

1.3.5 Limitation of current siting tools

Examining the factors taken into consideration in the objective functions of the conventional micrositing tools it becomes obvious that social and environmental factors are missing in most algorithms although several frameworks and models regarding these impacts have been developed in the past years[11]. El-Thalji et al. (2011)[20] introduce the implementation of cold climate as a factor of wind farm siting. Staffel and Green (2014)[46] record turbulent loads and determine output declination. Chowdhury et al. (2013)[31] propose the implementation of land area per kW installed as further decision making tool. Christie and Bradley

(2012)[47] maximize power density as power per unit area of land occupied to overcome limited available sites.

Still, these first approaches to include environmental issues in micrositing tools aim on maximizing energy production. Few studies involve options for minimizing potential environmental impacts of a wind farm. Kwong et al. (2012)[48] run a Genetic Algorithm for optimizing a simple test case while taking in account energy production and noise impact. Overall, there is a lack of research regarding implementation of ecological and social constraints in micrositing tools for the ecological sensitive marine area[49].

Another factor missing in current siting tools is the change in the wind resource over time. Wind speed is the primary factor to a wind farm project[6] since produced power is directly proportional to the cube of wind speed. Satellite altimeter measurements revealed an increase of wind velocity of at least 0.25 to 0.5% over the last 20 years with speeds of extreme events increasing faster than mean conditions[51]. Wind speeds in Spring rise faster than in Fall and meridional wind trends are smaller than zonal trends[52]. Although many studies show a positive trend over the last decades, the magnitudes vary significantly and require further investigation [53].

Conventional siting tools used to apply several wind models to research the effect of wind conditions: unidirectional uniform wind, uniform wind with variable direction and non-uniform wind variable direction[16][17][54]. The complex models either use discrete wind distributions[16][15] or continuous Weibull distributions[31][55][32][56]. To the best knowledge of the authors, no model considers the previous described change in the wind resource over the life time of a wind farm.

1.3.6 Study objective

The current study researches the effects of changes in the wind resource over the life time of a wind farm on micrositing in the Ocean SAMP. Sensitivity of the optimized layout to wind time series length, changing wind direction and a trend in usable wind velocity are tested for the Block Island Wind Farm at the Renewable Energy Zone. The inclusion of a trend in the usable wind resource in a micrositing model is further applied to the Rhode Island and Massachusetts Area of Mutual Interest.

1.4 Materials and Methods

The micrositing optimization model developed by O'Reilly et al. (2013)[63] is expanded to include a usable wind velocity trend in the wind resource. The wind trend is calculated over a usable wind time series of 33 years at the respectively closest Wind Information Study (WIS) Station[57] and projected over the next 20 years. The expanded model also includes a new cable cost algorithm. As in O'Reilly et al. (2013)[63], the optimum location of each turbine is determined using a Genetic Algorithm to optimize an objective function (OF). The objective function is derived from the Wind Farm Siting Index (WiFSI) which was developed as a tool to optimize macrositing of a wind farm by Grilli et al. (2013)[11].

1.4.1 The objective function

The WiFSI describes a non-dimensional balance between technological, social and ecological constraints and the wind resource[11]. The conceptual view of the index is given in figure 4. Each constraint is weighted with a factor w_i which is adjustable according to societal values or political choices[62]. Social

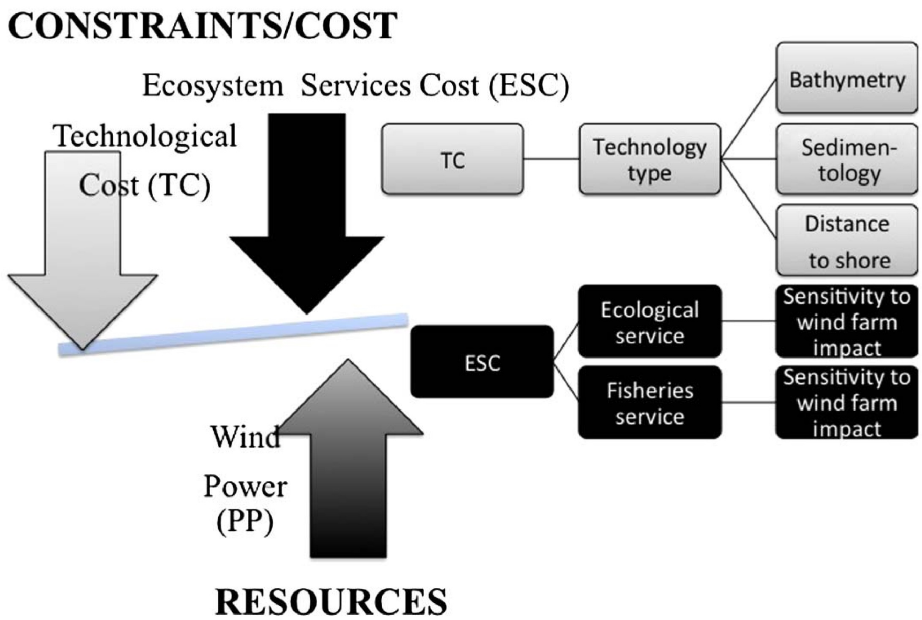

Figure 4. Concept of the Wind Farm Siting Index (WiFSI) as balance between constraints and resources from Grilli et al. (2013)[11]. The constraints are technological cost (TC) as well as ecosystem services cost (ESC) divided into ecological and fisheries service. The resource is wind power (PP).

and environmental value are formulated as the services which the ecosystem provides to human beings[61]. Since these intangible costs[59][60] can not directly be described in monetary terms[58] as the technological costs, all constraints are non-dimensionalized to their maximum value in the research site. Zero then represents the best WiFSI and one the worst WiFSI. The objective function (WiFSOF) derived from this concept and developed in O'Reilly et al. (2013)[63] is expressed as:

$$WiFSOF = \frac{w_1 \cdot SF}{PR} - w_2 \cdot EC - w_3 \cdot FC \tag{1}$$

$$\sum_{i=1}^{3} w_i = 1 \tag{2}$$

where the net revenue (PR) is based on a monetary balance between technological costs and extracted power. The scaling factor (SF) is equal to the worst possible income at that site. This factor non-dimensionalizes the net revenue to be comparable to the non-monetary ecosystem service constraints. EC and FC are mean ecological and fishery costs for the respective turbine locations.

$$PR = \sum_{i=1}^{n} P_{ex} \cdot PL - \sum_{i=1}^{n} TC \tag{3}$$

The net revenue of n-placed turbines is the difference between the produced power in \$/kWh including extractable power (P_{ex}) and power loss due to wake (PL) as well as technological cost (TC)[63]. The extractable power is defined as the usable power density (P_u) in W/m^2 at the rotor level restricted by Betz Law ($P_{ex} = 59.4\% P_u$). In the concept of usable power, wind speeds lower than cut-in as well as higher than cut-out velocity are ignored while velocities higher than rated wind speed are kept constant for the power calculation[64]. The power law is applied to calculate wind speed at rotor elevation[11]. Power loss is calculated with the WAsP Model formulated by Barthelmie et al. (2006)[65]:

$$U_{loss} = U_{freestream}\left[1 - \left(1 - \sqrt{1 - C_T}\right)\left(\frac{D}{D + 2k_{wake}x}\right)^2\right] \tag{4}$$

$$D_w = D + 2k_{wake}x \tag{5}$$

where U_{loss} is the velocity deficit behind the turbine and $U_{freestream}$ the arriving wind velocity. C_T is the thrust coefficient of the turbine. The rotor diameter is expressed by D and the wake diameter D_w describes the lateral extent of the wake in a distance x from the turbine. The model is based on a simple one-dimensional concept where the momentum deficit is expanding linearly behind a turbine with a wake decay coefficient k of 0.05 for offshore sites. Wind speed data is discretized into 1 degree sectors. The data is then expressed in mean wind speed and probability of occurrence for each directional sector[63].

Technological costs represent the technical challenge resulting from the placement of one turbine at a given location. Expenses for foundation and installation as a function of water depth and geological characteristics as well as costs for cable connection depending on distance are considered. Non-relevant costs for micrositing such as expenses for maintenance or device retail price are excluded through the relative cost principle[11][22].

Ecological costs are expressed in non-monetary value based on seasonally averaged abundance of fish species and mammals as well as their intrinsic sensitivity to noise, turbidity and electromagnetic field perceived during the construction and the operation phases. Fishery costs are included as a linear combination of commercial mobile and fixed gear fisheries as well as recreational fishing activities. The costs are assumed proportional to fishing intensity[11].

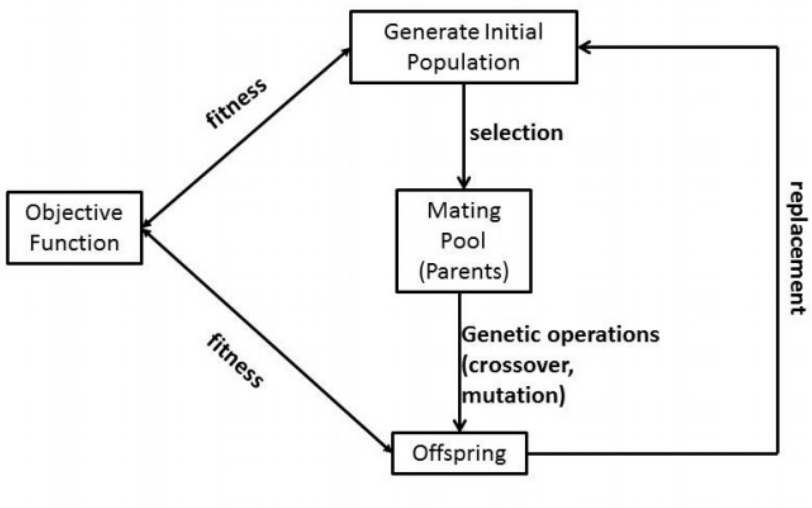

Figure 5. Genetic Algorithm cycle combining natural selection and survival of the fittest to optimize an objective function from O'Reilly et al. (2013)[63].

1.4.2 Genetic Algorithm

A Genetic Algorithm combines natural selection and survival of the fittest philosophy to find the optimum of an objective function (Figure 5). As the initial condition, combinations of turbine locations are randomly selected by the algorithm to create a starting population of solutions. In a breeding process, a new population is developed where 10% of the fittest parents are kept. Fitness of a solution is determined by evaluating the WiFSOF for each combination of turbine locations. A schematic flow chart of the evolution of the model is shown in figure 6. The breeding process is repeated until the predefined number of generations is reached and an optimum layout is found. The optimum layout is defined by a minimal objective function value. To avoid convergence to a local minimum, one single turbine location is randomly changed by a mutation in each generation. Generation size as well as population and sub-population number depend on the chosen number of turbines. The formulas for the number of each parameter

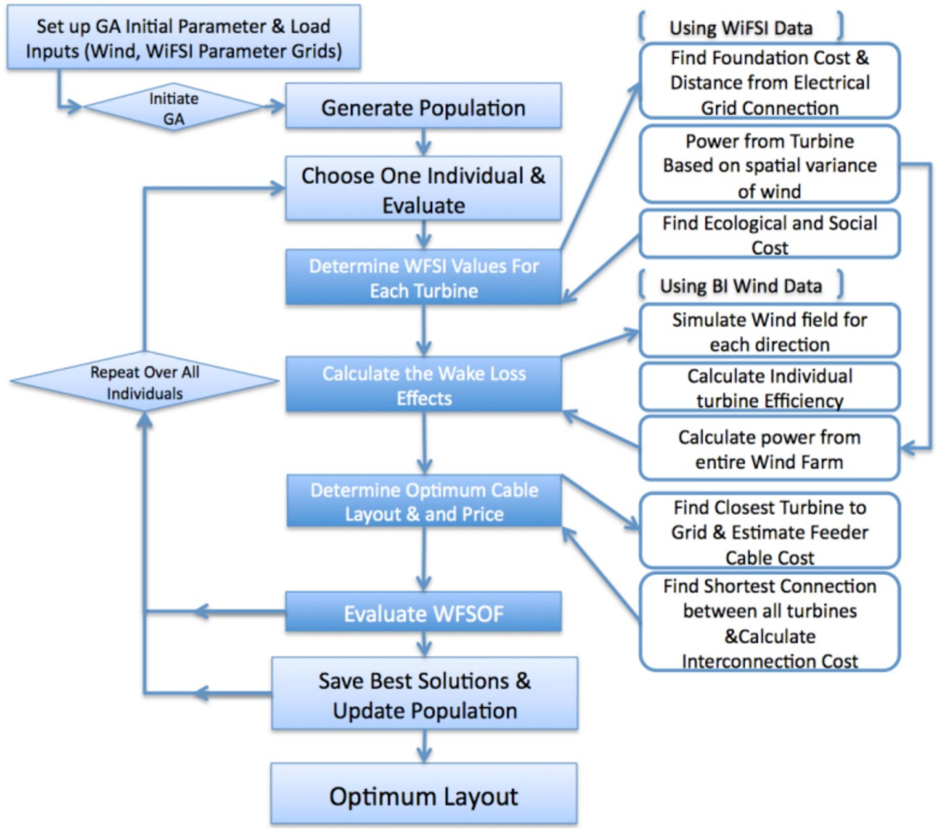

Figure 6. Wind farm siting optimization process in the Wind Farm Siting Index (WiFSI) methodology of Grilli et al. (2013) from O'Reilly et al. (2013)[63].

are[63][66]:

$$Generations = 200 \cdot \lfloor \sqrt{No.ofTurbines} \rfloor \tag{6}$$

$$Populations = 20 + 5 \cdot \lfloor \frac{No.ofTurbines}{10} \rfloor \tag{7}$$

$$Sub - population = 2 \cdot \lfloor \sqrt{No.ofTurbines} \rfloor \tag{8}$$

The model developed in Matlab is amenable to parallel processing and uses the Genetic Algorithm Toolbox[67]. The siting area is gridded with one rotor diameter discretization. Turbine placing is restricted to the center of a grid cell to increase rate of convergence[63]. The distance optimization algorithm for the cable interconnection is a Cluster Algorithm at the REZ. Due to increased turbine number

Table 2. Turbine parameters at the Renewable Energy Zone (REZ) and the Area of Mutual Interest (AMI)[73][74][76][63]

Site	Turbine type	Hub height	Rotor diameter	Cut-in	Cut-out	Rated speed	Efficiency
REZ	Siemens 6MW	110m	154m	3.5m/s	27m/s	15 m/s	0.3034
AMI	Alstom 6MW	100m	150m	3m/s	25m/s	12.5 m/s	0.4786

at the AMI, the distance optimization is updated to a Prim Algorithm[68][69].

1.4.3 Implementation of changing wind resource

The trend in wind velocity is determined by linear regression in a 95% confidence interval over the hourly usable wind speed values. The resulting slope is applied as yearly trend in the calculation of extractable power and power loss due to wake. The sensitivity of a change in wind direction on the optimization layout is tested by implementing different usable wind roses while keeping the power resource constant.

1.4.4 Application to the Ocean SAMP location

Wind farm parameters

The Block Island Wind Farm at the REZ has five Siemens 6MW turbines with an hub height of 110 m and a rotor diameter of 154 m. Cut-in wind speed is 3.5 m/s, cut-out speed is 27 m/s and rated wind speed is 15 m/s. While optimizing the AMI,turbine type Alstom Haliade 6MW[73][74][75] is used with 100 m height and 150 m rotor diameter (Table 2). Cut-in is 3 m/s, cut-out is 25 m/s and rated wind is 12.5 m/s. 60 turbines are distributed over the North Lease while 40 turbines are placed at the South Lease. Project cost of energy is $0.24/kWh over a life time of 20 years for the Block Island Wind Farm (Docket No. 2010-273-M.P. (4185)) and is assumed for the AMI as well. Cost for the feeder cable was determined as $0.6 million/km by the Ocean SAMP study while interconnection cost is set to $860/m[18].

Table 3. Description of the optimization simulations

No.	Site	Turbines	Description
1	REZ	5 Siemens 6MW	Standard with constant wind
2			20 year wind rose
3			33 year wind rose
4			5 year wind rose
5			Wind rose 1980
6			Wind rose 2012
7			Standard wind rose, trend in speed
8	AMI South	40 Alstom 6MW	Standard with constant wind
9			Standard wind rose, trend in speed
10	AMI North	60 Alstom 6MW	Standard with constant wind
11			Standard wind rose, trend in speed

Simulations

Sensitivity of a wind farm layout to wind time series length, wind direction and a trend in usable wind velocity is examined in 11 simulations. A short description of all runs is given in table 3. The changes in the REZ are examined in seven scenarios. The North and South Lease are optimized in two separate simulations each to reduce computational time.

Each first simulation of the three sites constitutes the respective base case of each site, defined by a constant wind probability distribution. For the AMI, the second scenario applies the same usable wind rose but implements a linear trend in usable wind velocity. At the REZ, the standard simulation is followed by a sensitivity study of the layout design and revenue to the length of the wind time series. Simulations are performed for three wind data sets of of 20, 32 and five years respectively (simulation 2, 3 and 4). Simulations 5 and 6 assess the sensitivity of the results to wind direction by applying wind distributions with significantly different dominant wind direction of the year 1980 and 2012. The last simulation (7) applies the usable wind rose used in the base case with a linear trend in usable wind velocity at the REZ. Wind data is discussed in detail in the next section.

Data

The wind resource for the power calculation was estimated from a 2009 to 2012 time series obtained from the Block Island Meteorological Tower at five levels from 10 to 60 m. The shear coefficient r was estimated to a value of 0.11. The tower was established on the Island by AWS Truewind and Deepwater Wind Inc., the current developer of the wind farm[70][71]. Data regarding technological, ecological and fishery cost in the area was collected in the Ocean SAMP project[72][11].

The wind probability distribution used in the wake model is estimated from the closest wind measurement station summarized in table 4. Simulation 1, the standard, and simulation 7 (trend in usable wind speed) use data collected at the Block Island Meteorological Tower. The local usable wind rose at 110 m as hub height of the Siemens turbine is shown in figure 7. Dominant wind direction is Southwest and Northwest while all other directions have a very low occurrence.

The trend in usable wind velocity at the REZ was determined with hindcasted wind data from WIS Station 63101[57]. The available data contains 33 years from 1980 to 2012. The average, linear trend in usable wind speed over this time period is 0.0067 m/s per year. This is 0.13 m/s over 20 years, the life time of a wind farm. The 95% confidence interval is varying between 0.0051 m/s and 0.0083 m/s per year.

In order to create long-term usable wind roses, wind data is taken from the WIS Station 63101 and cut for the usable wind velocity range. For simulation 2

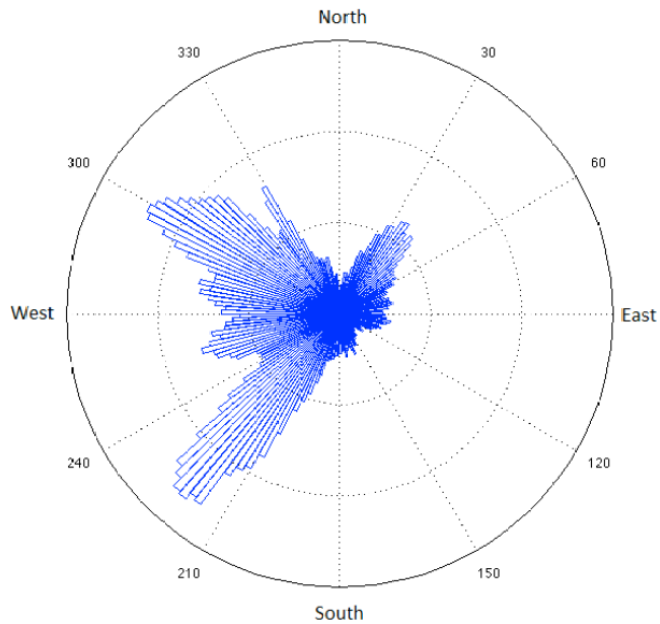

Figure 7. Usable wind rose at the Block Island Meteorological Tower from 2009 to 2012 at hub height 110 m from O'Reilly et al. (2013)[63].

Table 4. Wind data sources for the optimization simulations

No.	Wind data source[57]	Time period wind rose
1	Block Island Meteorological Tower	2009-2012
2	WIS Station 63101	1992-2012
3	WIS Station 63101	1980-2012
4	WIS Station 63101	2008-2012
5	WIS Station 63101	1980
6	WIS Station 63101	2012
7	Block Island Meteorological Tower	2009-2012
8	WIS Station 63095	2008-2012
9	WIS Station 63095	2008-2012
10	WIS Station 63095	2008-2012
11	WIS Station 63095	2008-2012

a wind rose of the youngest 20 years, as the life time of a wind farm, from 1992 to 2012 is used for the optimization. All available wind data is used for case 3 to create a wind probability distribution for 33 years. For simulation 4 only the youngest five years from 2008 to 2012 are included. It was found that reducing the wind data below a minimum time period results in significant changes in the usable wind rose. Changes in the wind farm layout are also expected. For WIS Station 63101 the minimum was determined to be five years which indeed corresponds to the standard length of a representative wind time series[50].

The usable wind rose from 1992 to 2012 can be seen in figure 8. Compared to the usable wind rose calculated from measurements at the Block Island Meteorological Tower, dominant wind directions remain Southwest and Northwest but all previous weak directions gain importance. The years 2009 to 2012 used in the base case optimization seem to be years of an unusual concentration of high velocities in two wind directions (Figure 7).

For simulation 5 and 6 wind probability distributions in 1980 and 2012 are calculated to examine the change in optimized layout for different wind directions. Wind data is taken from WIS Station 63101. The dominant wind direction in the year 1980 is Northwest. Winds between 5 and 10 m/s preliminary occur from Southwest while winds higher than 15 m/s blow from Northwest (Figure 9). Winds in the year 2012 are predominantly blowing from North to South directions while probability of winds higher than 15 m/s is less than the winds in 1980 (Figure 10).

Wind data for the AMI was collected from WIS Station 63095. The applied wind probability distribution covers data from the youngest five years from 2008

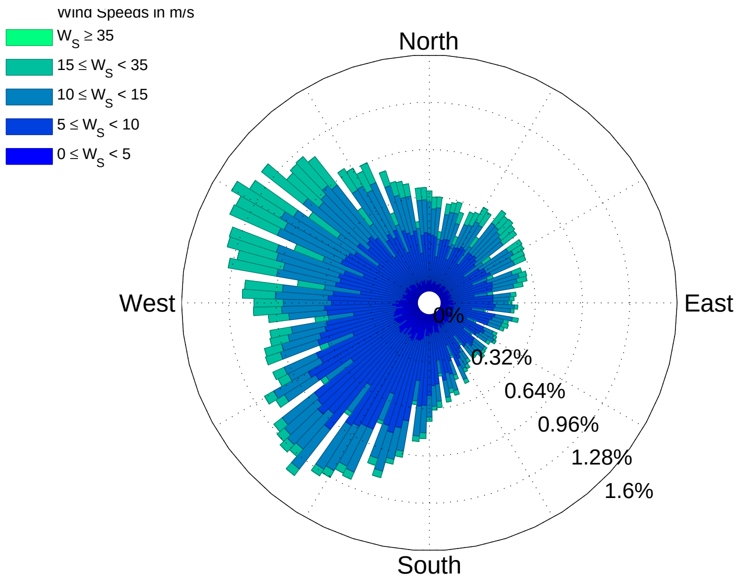

Figure 8. Wind rose for usable wind speeds at WIS Station 63101 from 1992 to 2012 at hub height 110 m.

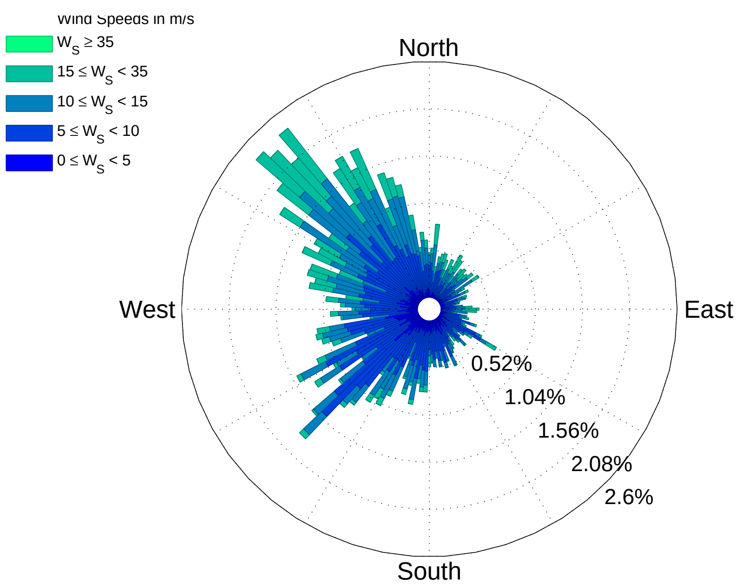

Figure 9. Wind rose for usable wind speeds at WIS Station 63101 in 1980 at hub height 110 m.

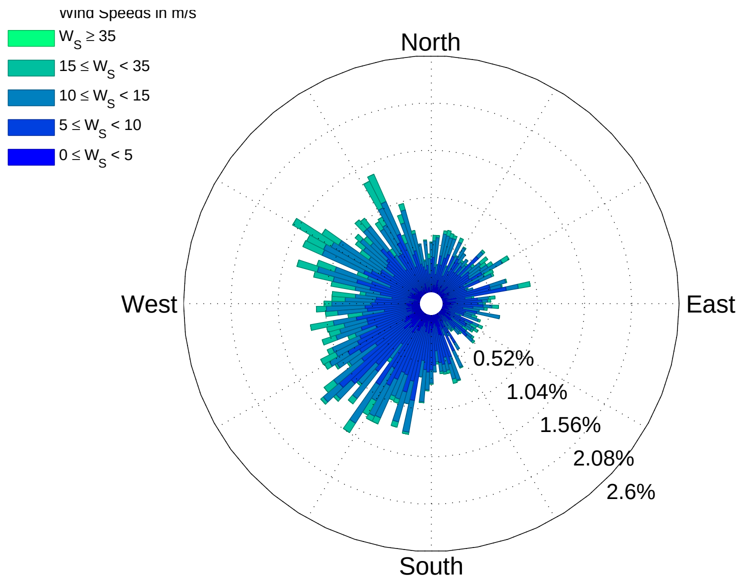

Figure 10. Wind rose for usable wind speeds at WIS Station 63101 in 2012 at hub height 110 m.

to 2012 to represent long-term conditions with minimum data requirements. Figure 11 shows the similarity to the usable wind rose at Station 63101 from 1992 to 2012. The linear regression of usable winds over 33 years from 1980 to 2012 provides an average trend of 0.0015 m/s with a 95% confidence interval varying between -0.000001 m/s and 0.00298 m/s per year. This upper value is half of the value of the average trend identified from the usable wind data at WIS Station 101 located further offshore. The upper value is used for the simulations. This usable wind trend is 0.059 m/s over 20 years, the life time of a wind farm.

Genetic Algorithm set up

All scenarios are simulated using O'Reilly et al.'s (2013)[63] objective function parameter values for comparison with these results. The weighting factor w_1 is set to 1 so that the non-monetary terms ecological and fishery constraints are excluded. Therefore, the objective function reduces to:

$$WiFSOF = \frac{1}{PR} \tag{9}$$

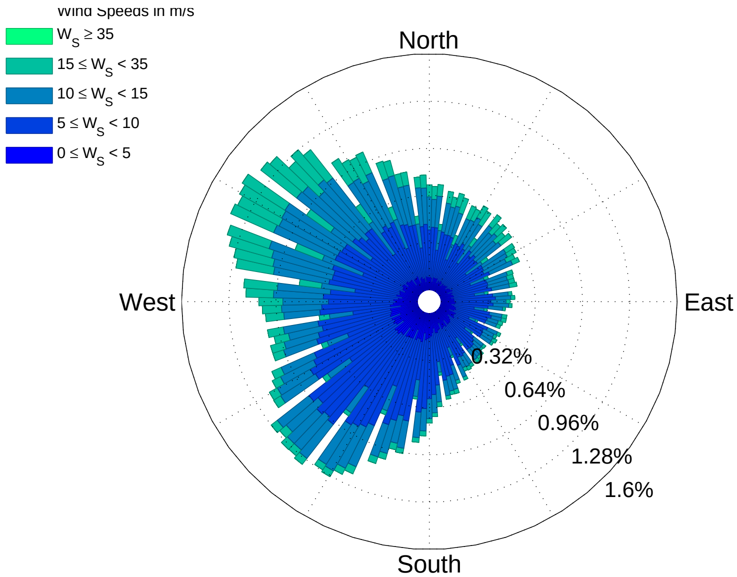

Figure 11. Wind rose for usable wind speeds at WIS Station 63095 from 2008 to 2012 at hub height 110 m.

Table 5. Genetic Algorithm parameters

Site	Generation	Populations	Sub-populations
REZ	400	32	4
South Lease	1,200	32	12
North Lease	1,400	32	14

Minimizing the objective function leads to the maximum net revenue. The first runs of simulation 2 at the REZ were conducted with 1,000 generations to test convergence of the WiFSOF. After that, the Genetic Algorithm was run for 400 generations, 32 populations and 4 sub populations. For the South Lease, 12 sub-populations and 32 populations are created and the run takes 1,200 generations. The North Lease requires 1,400 generations, 32 populations and 14 sub-populations to converge. The settings of the Genetic Algorithm are presented in table 5. In simulation 5 and 6 turbine interconnection costs are excluded from the algorithm first to set a higher importance to the wake calculation. The second approach includes interconnection cost as siting constraint.

While optimizing the AMI the interconnection cost are calculated with a Prim Algorithm[68][69] to find the shortest possible connection of all turbines. The Prim Algorithm was validated by application to the REZ. Computational time is reduced by excluding the trend in the usable wind velocity from the wake calculation. Testing this method at the REZ leads to a 0.02% loss of produced power. This simplification was considered acceptable and implemented in the AMI zone in order to keep the computational time in a reasonable time frame (days versus weeks).

1.5 Results and Discussion

1.5.1 Renewable Energy Zone

Base case

Optimum solutions were found for 5 distinct locations. One solution is shown in figure 12. The cable interconnection costs pull the turbines together while the wake effect pushes the devices apart. The turbines are placed in areas of low foundation cost. Extractable power has no significant influence since the resource is approximately equally distributed over the zone[63]. Figure 13 shows that all locations are sited in the area of the lowest WiFSI of the REZ. The East part of the REZ with a higher index is avoided due to high foundation cost. The map was created for macrositing purposes in Grilli et al. (2013)[11] with the initial formulation of the WiFSI. Compared to the layout which was developed by Deepwater Wind, the optimized solution would save $17 Million over a lifetime of 20 years due to the reduction of wake effects[63].

Sensitivity to time series length

The first runs were operated with 1000 generations to test convergence for the long-term usable wind rose. Five examples are shown in figure 14. Most runs quickly reach a local minimum of the WiFSOF after 200 generations while only in

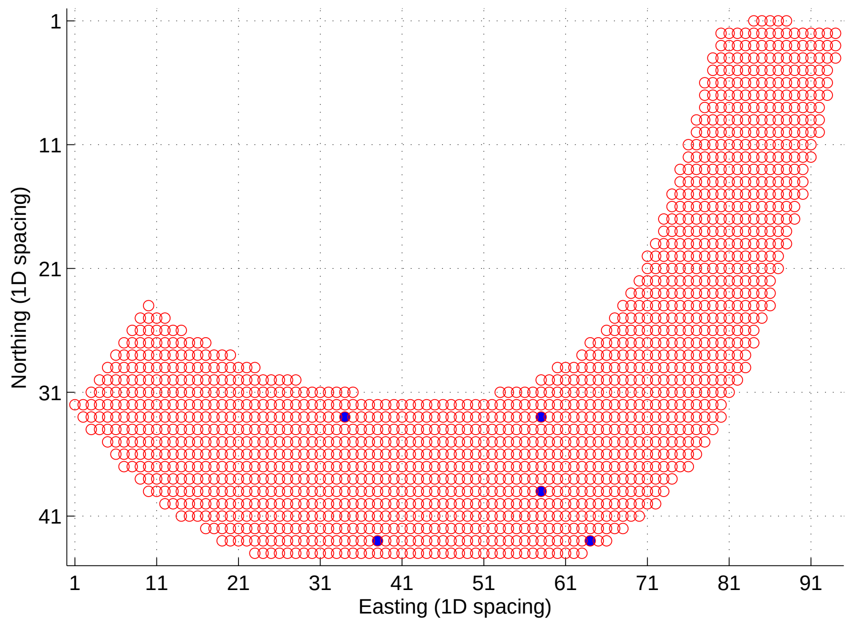

Figure 12. Optimum layout (blue) in simulation 1 for the base case at the Renewable Energy Zone (REZ) applying the usable wind rose at the Block Island Meteorological Tower from 2008 to 2012[63].

a few runs the index decreases more slowly but determines a better layout at the end. After 400 generations already 99.57% of the total revenue of the layout after 1000 generations is achieved. This percentage is considered as an insignificant difference. All subsequent runs were conducted with 400 generations to reduce computational time and for better comparison with the results of the base case optimization.

With the same settings as for the wind scenario of O'Reilly et al. (2013)[63] the optimized turbine locations change as a function of the length of the time series used. While five clear turbine siting zones are identified in the base case, two additional zones appear in simulation 2 (20 years time series). In parallel, each zone widens (Figure 15). In simulation 3 (33 years time series) (Figure 16), a similar behaviour is observed. In contrast to the constant shape of the turbine

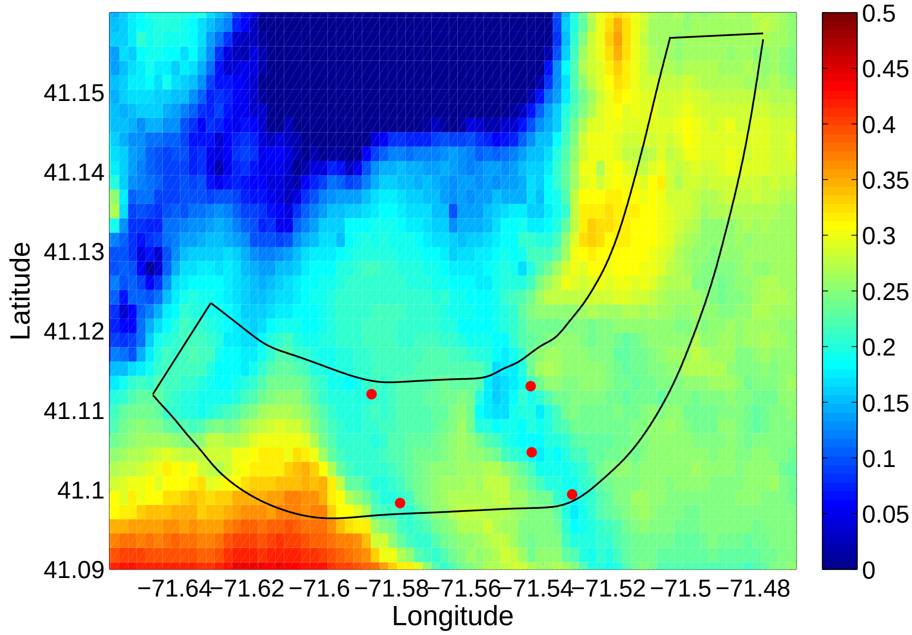

Figure 13. Map of the Wind Farm Siting Index (WiFSI) (color shading) excluding ecological and fishery constraints at the Renewable Energy Zone (REZ) (outlined in black) with optimum turbine locations (red) of the base case in simulation 1.

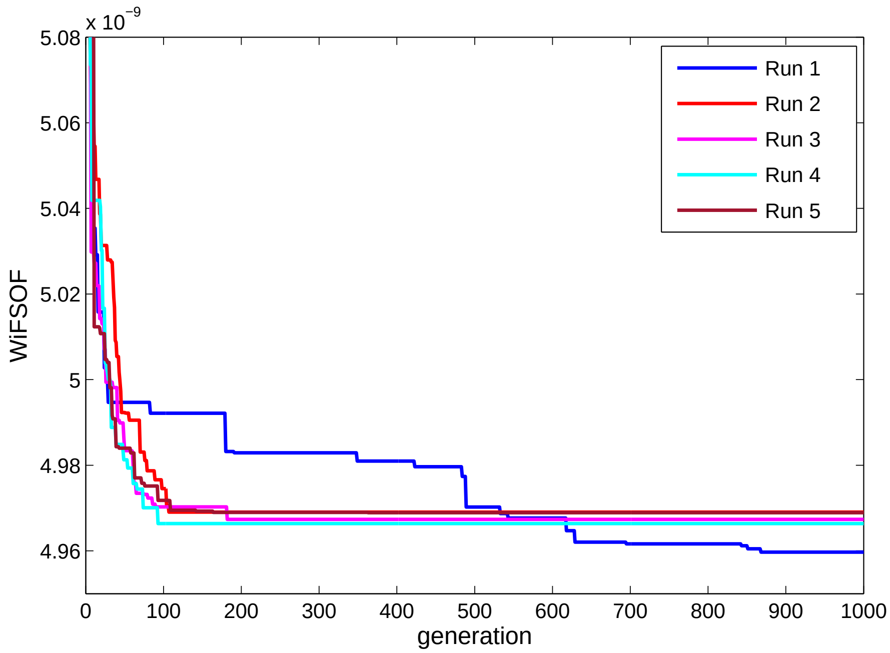

Figure 14. Convergence of the Wind Farm Siting Index Objective Function (WiFSOF) in simulation 2 applying the usable wind rose at WIS Station 63101 from 1992 to 2012.

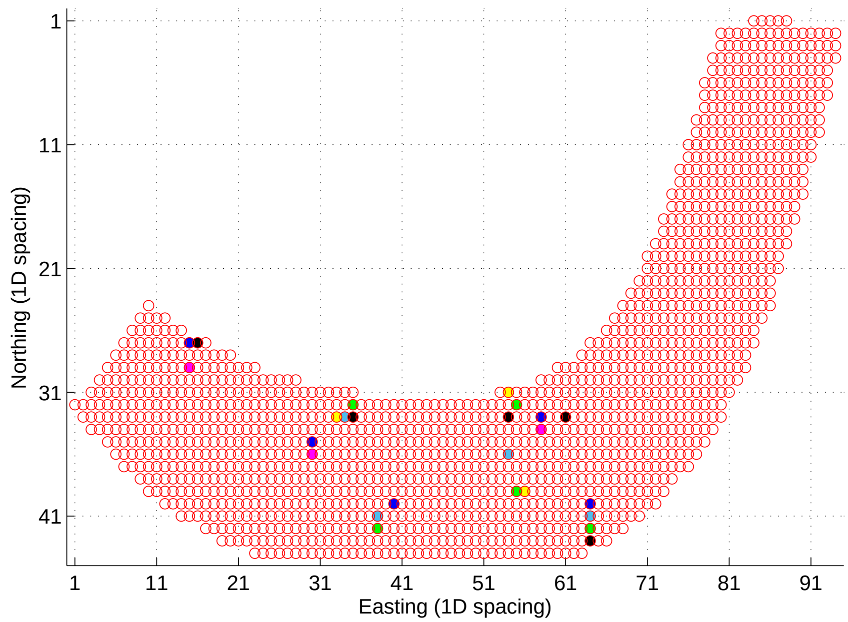

Figure 15. Optimum layouts in simulation 2 at the Renewable Energy Zone (REZ) applying the usable wind rose at WIS Station 63101 from 1992 to 2012. Each color-set represents one optimum layout.

layouts of the base case layout, the inclusion of more data from previous years leads to six different combinations of turbine locations. The implementation of the shorter wind time series, the youngest five years from 2008 to 2012 (Figure 16), leads to 3 different layouts.

Net revenue is in the same range about \$201.41 million for all three simulations 2 to 4 which is in average 1.1% lower than the results of the base case. Lower feeder and higher interconnection cost are identified for the runs with the usable wind roses of WIS Station 63101. The mean of the results from the different simulations is presented in table 6.

The presence of more optimum turbine sites for longer time series reflects the increase of occurrence of directional sectors which are weakly represented

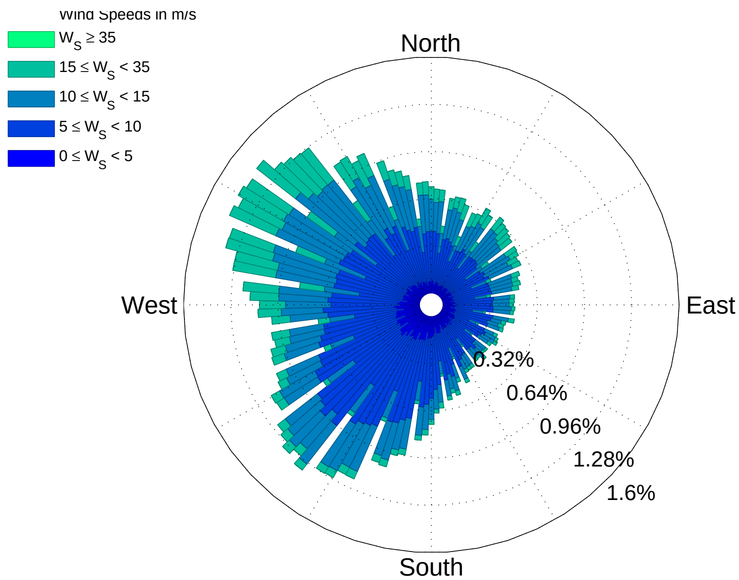

Figure 16. Wind roses for usable wind speeds at WIS Station 63101 from 1980 to 2012 at hub height 110 m.

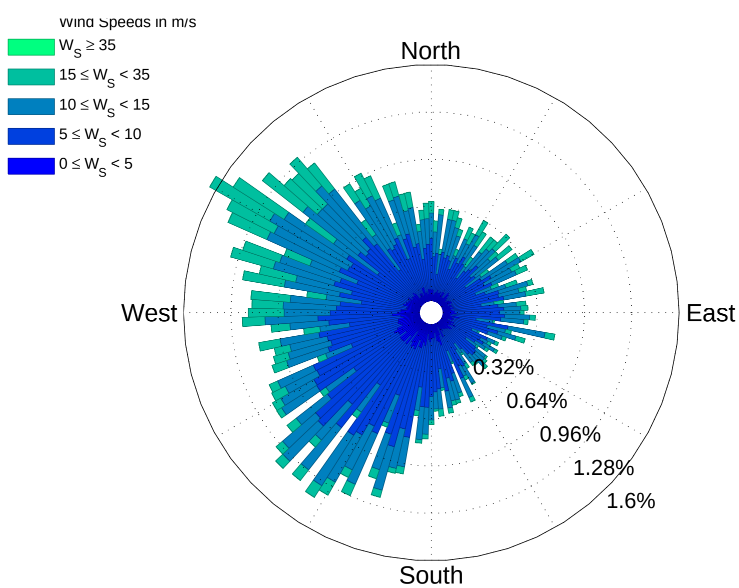

Figure 17. Wind rose for usable wind speeds at WIS Station 63101 from 2008 to 2012 at hub height 110 m.

Table 6. Results simulation 1 to 4 with cost in $ million

No.	Description	Total revenue	Installation cost	Produced power
1	Standard	203.55	56.14	259.69
1	optimized with standard, results calculated with wind rose 1992-2012	200.94	56.14	257.08
2	1992-2012	201.31	57.66	258.98
3	1980-2012	201.51	57.75	259.26
4	2008-2012	201.43	57.73	259.17

in the short-time series. The short-term usable wind rose based on three years of measurements at the Block Island Meteorological Tower shows two distinct frequency peaks for the Northwest and Southwest direction. The long-term WIS usable wind roses with 20 or 32 years of data show less significant peaks since all other directions grow in occurrence over time. This leads to more options in placing the turbines optimally without being located in the wake of another. Optimal turbine locations are more variable and larger optimum siting areas appear.

The 2008 to 2012 usable wind rose was selected to include the minimal five years of wind data to obtain a representative sample of synoptic conditions and to reflect the most recent wind climate. Its shape is more similar to the long-term usable wind rose of 1992 to 2012 than to the three year Block Island Meteorological Tower wind rose. This reflects differences in wind micro-climate at the site of the Block Island Tower and the offshore WIS Station. The layout solutions for the five year usable wind rose are closer to the long-term optimized wind farms.

The determination of several solutions to one optimization problem offers various options for soft constraints. The user is able to choose between layouts based on societal or political preferences. Although the optimization might exclude ecological and fishery cost, a layout with low EI or FI could be chosen or visual concerns could be solved without significant losses in total revenue.

The decrease in revenue using the long-term usable wind roses is misleading. Total revenue is calculated assuming that the wind conditions described by the used wind rose actually occur over the wind farm life time of 20 years. The base case wind rose does not represent long-term wind conditions as was shown by comparison of figure 7 and 8. Consequently, the base case placement of the turbines does not remain optimal over the life time of the wind farm. The expected real life revenue is lower. Calculating the total revenue of the base case layout by applying the usable wind rose from 1992 to 2012 leads to a loss of \$2.61 million. This is 1.28% less compared to the previous usage of the usable wind rose of the Block Island Meteorological Tower.

Long-term wind roses present a more realistic picture of the wind conditions of a site. Calculated revenue is expected to reflect a realistic picture of net revenue. Consequently, the wind data collection for a wind farm project should cover the longest time period possible to avoid over-representation of yearly or monthly variations in the wind. The time period which shows few changes in the respective wind rose when more years are added is required as minimum for the optimization process.

The various simulations with usable wind roses over varying time periods show the importance of the consideration of exact wind conditions. Changing the wind velocity and direction as simulated by the different wind roses leads to a different

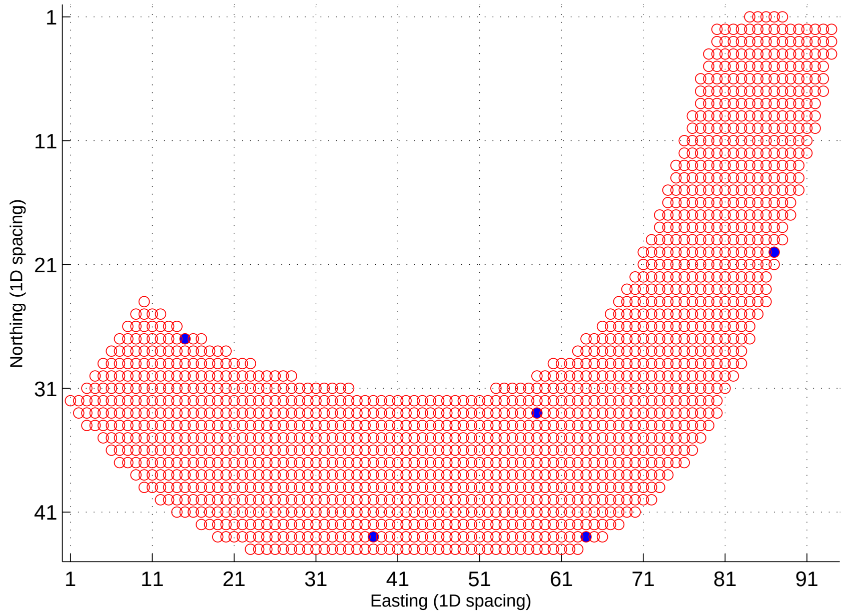

Figure 18. Dominant optimum layout (blue) in simulation 5 at the Renewable Energy Zone (REZ) excluding interconnection cost applying the usable wind rose at WIS Station 63101 in 1980.

optimum layout. Consequently, a farm optimized with fragmentary wind data will produce an inaccurate estimation of the wind farm revenue. Considering trends in usable wind speed and directions therefore becomes of great interest.

Changing wind direction

The application of the usable wind rose of 1980 without turbine interconnection cost results in six turbine siting zones with four different possible combinations. The dominant layout with 60% of occurrence in the results is shown in figure 18. The optimum layouts of the usable wind rose in 2012 also shows six zones where only one has a totally different position compared to scenario 1980. The dominant layout with 80% of occurrence is found similar to the usable wind rose of 1980. Mean total revenue is $199 million for both cases with similar values for produced power and installation cost.

Despite the usable wind probability distributions being different, the optimized layouts are similar when interconnection cost are excluded. The three Southwest turbine locations remained the same throughout all runs although the wind direction was changed. Excluding interconnection costs do not emphasize the constraints due to wind direction in the siting. In contrast, without the influence of the interconnection costs which pull the turbines together, the individual locations spread over the whole area without any distance constraints. Wake effects become unimportant over the long distances and the effect of changing wind direction is not visible in the layout.

Repeating the simulations including interconnection costs results in different layouts. For winds in 1980 figure 19 shows that the turbines are more likely to line up perpendicular to the dominant wind direction Northwest although these likely high winds are rated down to 15 m/s. Optimizing for the usable wind rose of 2012 leads to turbine zones (Figure 20) which are are more similar to the results of O'Reilly et al. (2013)[63]. The reason might be the usage of a similar wind distribution from 2009 to 2012. The turbines are mainly arranged in two rows perpendicular to the Southwest direction although the usable wind rose does not show a clear dominance in that direction (Figure 10). Setting the respective wind conditions constant for 20 years, both layouts produce a total revenue of \$201 million each (Table 7).

Assuming the layout optimized for the usable wind rose of 1980 but applying the long-term usable wind rose from 1980 to 2012 results in a loss of produced power and total revenue of \$0.86 million or 0.33% over 20 years. When the usable wind

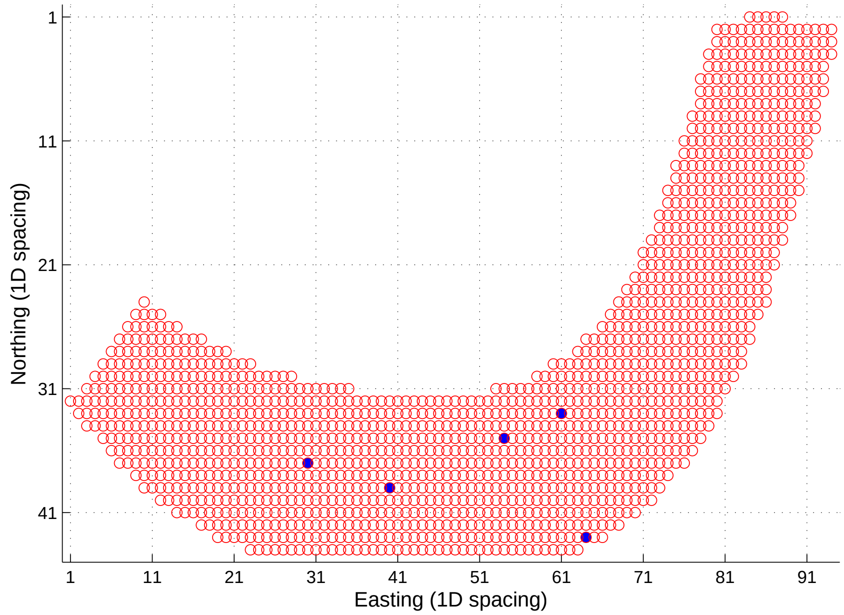

Figure 19. Optimum layout (blue) in simulation 5 at the Renewable Energy Zone (REZ) applying the usable wind rose at WIS Station 63101 of 1980.

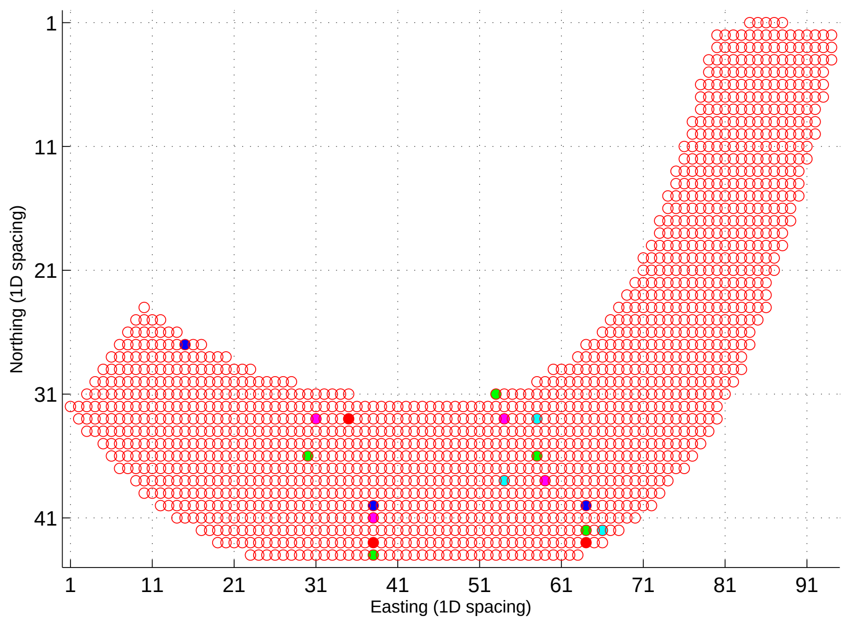

Figure 20. Optimum layouts in simulation 6 at the Renewable Energy Zone (REZ) applying the usable wind rose at WIS Station 63101 of 2012. Each color-set represents one optimum layout.

Table 7. Results of simulation 5 and 6 in $ million

No.	Description	Total revenue	Installation cost	Produced power
5	1980	201.85	58.35	260.1
6	2012	201.85	57.62	259.47
5	optimized 1980, results 1980-2012	200.98	58.25	259.24
5	optimized 1980, results 2012	200.08	58.25	258.33
6	optimized 2012, results 1980	200.17	57.62	257.79

rose of 2012 is applied to the 1980 layout, total revenue is reduced by $1.76 million or 0.89%. A similar reduction is observed when the 1980 usable wind rose is applied to the layout resulted in an optimization assuming a 2012 usable wind rose.

Different wind roses result in different layouts. The more significant the variation in the wind rose, the more noticeable is the difference in the turbine locations. Assuming the same wind conditions as the farm was optimized for, different layouts can produce the same revenue. However, the application of real life wind conditions with changing wind direction leads to reduced revenue over time. The determination and consideration of future changes of wind direction in an optimization process gains importance.

Trend in usable wind velocity

The turbine locations converge towards the same locations as the one obtained for the base case in simulation 1 (constant wind speed) (Figure 21). The averaged installation costs remain constant but mean produced power increases by 2.17%. Total revenue increases to $209.07 million compared to $203.55 million in the base case.

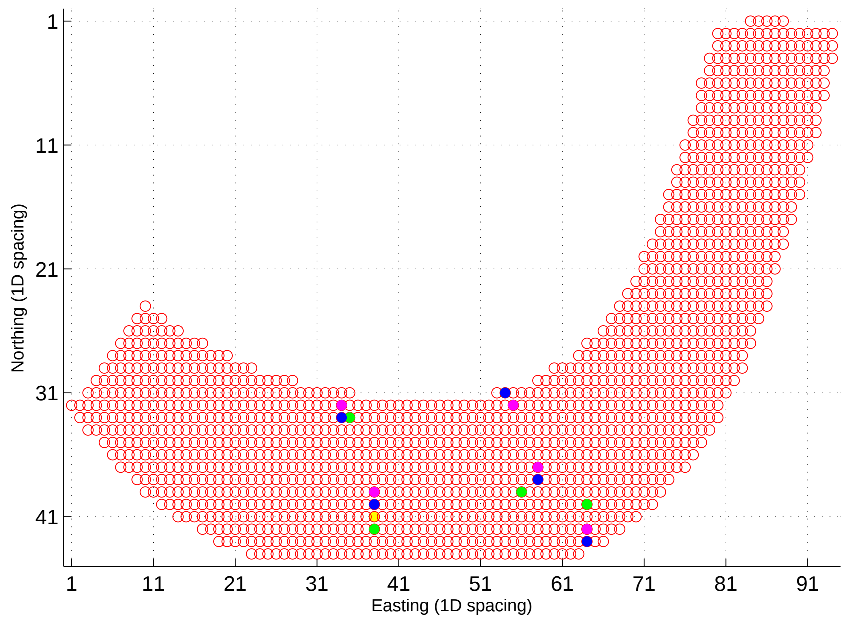

Figure 21. Optimum layouts in simulation 7 at the Renewable Energy Zone (REZ) applying the usable wind speed trend to the usable wind rose at WIS Station 63101 from 2008 to 2012. Each color-set represents one optimum layout.

Table 8. Results simulation 1 and 7 in $ million

No.	Description	Total revenue	Installation cost	Produced power
1	Standard	203.55	56.14	259.69
7	Trend Standard	209.07	56.37	265.44

The application of a positive trend to the usable wind velocity results in an increase in power production while the turbine locations remain quasi identical. A higher trend magnitude might have a larger effect on the layout since the wake effect will increase with higher wind velocity. However, this effect may not play a large role for wind farm siting since measured wind trends have been found considerably small[51][52][53].

1.5.2 Area of Mutual Interest

Base case at the South Lease

Figure 22 presents the dependence of the WiFSOF to number of generation for three optimizations for the South Lease. Over the first 200 generations the index decreases rapidly. After 600 generations the WiFSOF remains approximately constant. Regarding the total revenue of the first run, the change over generations is less significant. After 100 generations, revenue is already 98.78% of the revenue after 1,200 generations. This is a loss of $47.96 million. 38 turbines are changing location before reaching the final generation. From generation 1100 to 1200, still 4 turbines are replaced and revenue is increased by $1.52 million or 0.04%. Figure 23 shows the layout for generation 100, 600 and 1200. The first layout contains more central turbine locations. The longer the optimization process, the more turbines are placed at the North and West border of the siting area.

Optimizing the South Lease mainly results in placement of turbines at the borders of the area. Locations are similar for all runs at the West and the Northwest border of the large as well as the small part of the lease. Few devices are placed at the Eastern border. A higher variance of turbine locations occurs at the North and South borders. However, turbines are often distributed in successive rows in a 45° angle to the grid axis (Figure 24). Turbine clustering is not as clear as during

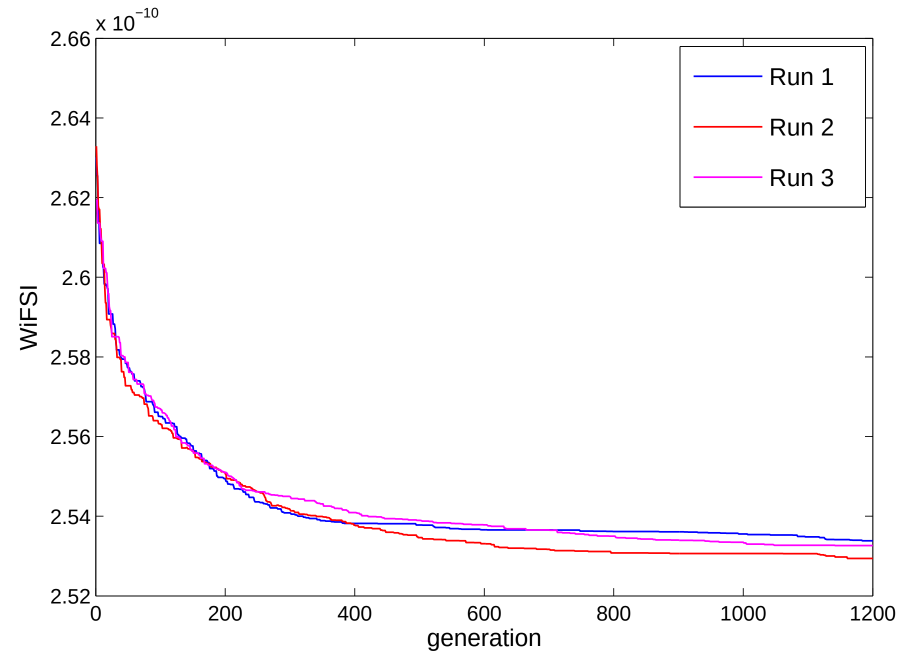

Figure 22. Convergence of the WiFSOF in simulation 8 at the South Lease applying the usable wind rose at WIS Station 63095 from 2008 to 2012.

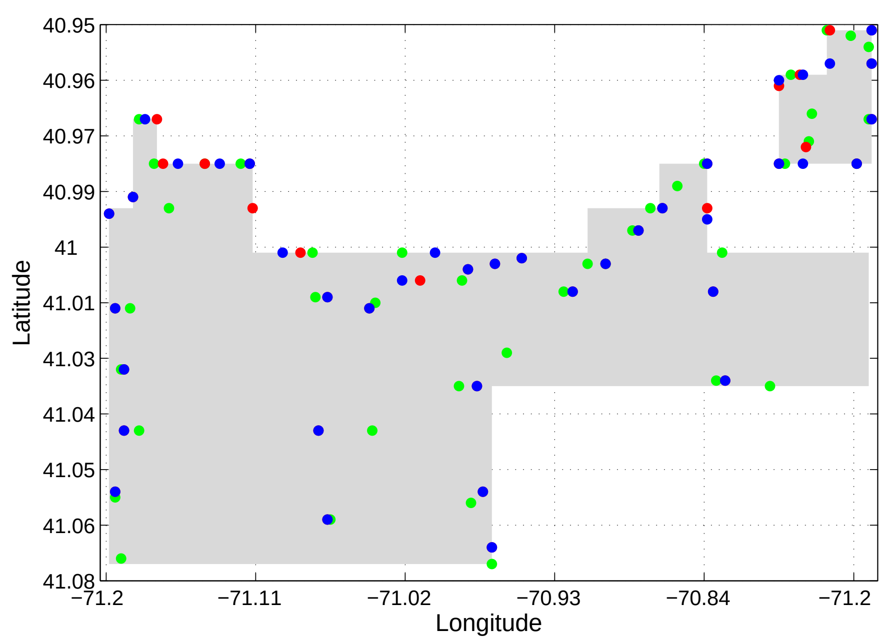

Figure 23. Convergence of layouts in simulation 8 at the South Lease (grey) applying the usable wind rose at WIS Station 63095 from 2008 to 2012: after 100 generations (green), 600 (red) and 1200 (blue).

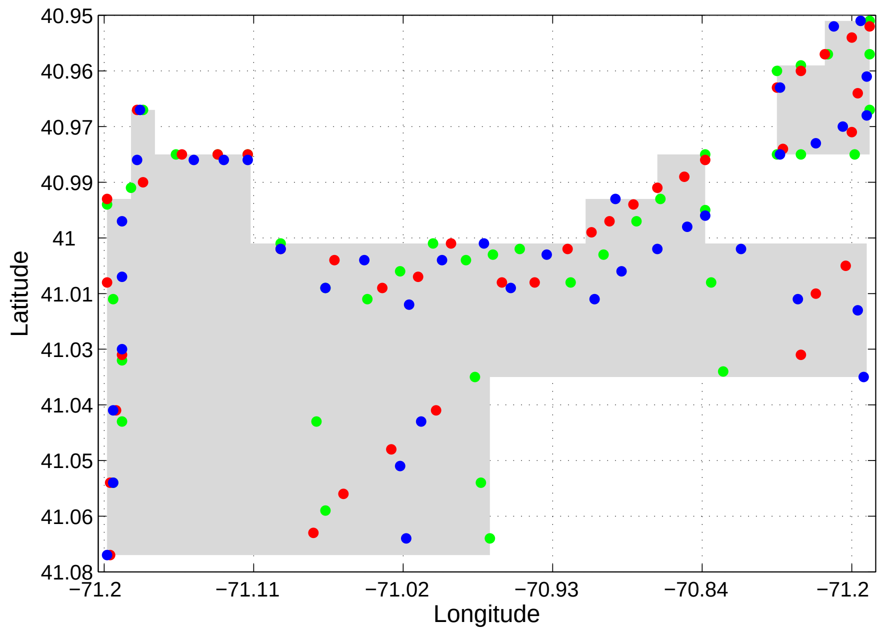

Figure 24. Optimized layouts in simulation 8 at the South Lease (grey) applying the usable wind rose at WIS Station 63095 from 2008 to 2012. Each color-set represents one optimum layout.

Table 9. Results simulation 8 to 11 in $ billion

No.	Description	Total revenue	Installation cost	Produced power
8	South Lease Standard	3.95	0.95	4.91
9	South Lease Trend	3.99	0.97	4.95
10	North Lease Standard	5.99	1.14	7.14
11	North Lease Trend	6.05	1.15	7.20

the optimization of the REZ. All runs end in the same range of produced power and installation cost resulting in an average total revenue of $3.95 billion (Table 9).

Base case at the North Lease

The dependence of the WiFSOF to number of generation when optimizing the North Lease shows the typical shape for convergence. The layout at 100 generations has 49 different turbines compared to the final layout. The optimization produces

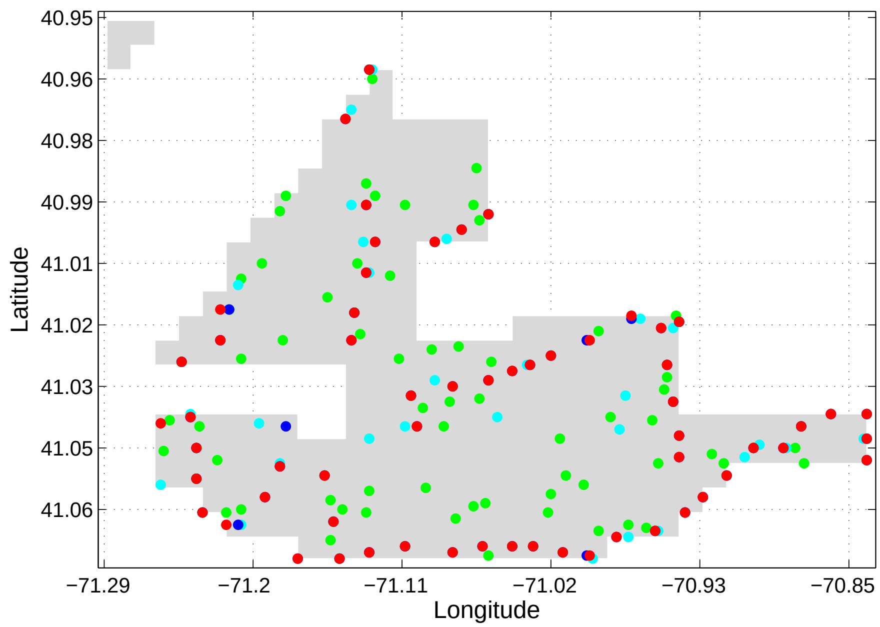

Figure 25. Convergence of layouts in simulation 10 at the North Lease (grey) applying the usable wind rose at WIS Station 63095 from 2008 to 2012: after 1400 generations (red), 900 (blue), 400 (light blue), 2 (green).

an additional revenue of $88.85 million or 1.49%. After 1000 generations only four turbines change location. This is a difference in total revenue of $2.06 million or 0.004%. Figure 25 shows that the higher the generation number, the more likely the turbines align at the borders of the lease. The small allowed area in the Northwest is avoided as well as the Northwest border. Only three rows of nine devices do not follow a border. Net revenue is $5.99 billion for the final layout (Table 9).

Trend in usable wind velocity at the South Lease

Applying the trend in usable wind velocity leads to a similar layout as the one obtained in simulation 8 (no change in wind resource over time) (Figure 26). Individual optimum sites are difficult to identify since several possibilities are shown for

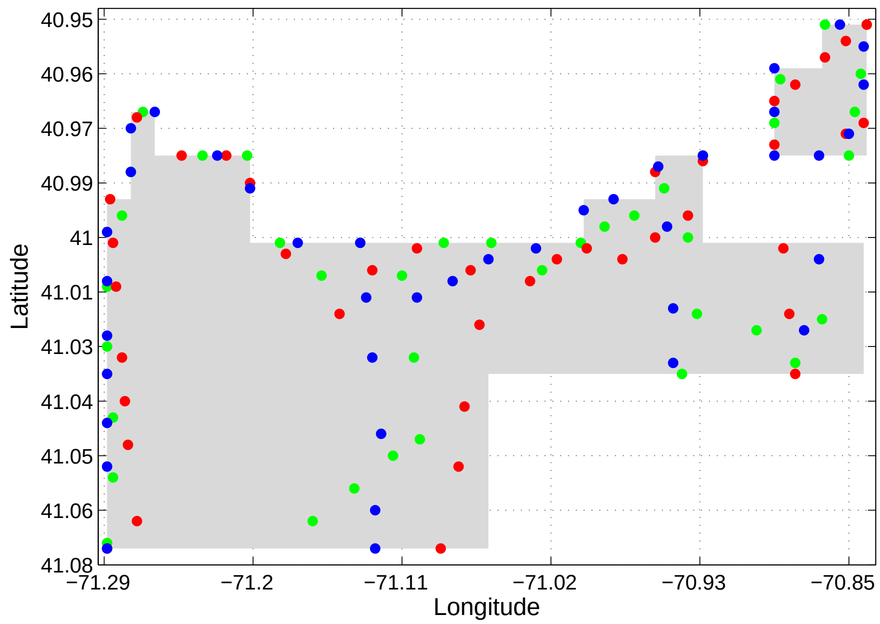

Figure 26. Optimized layouts simulation 9 at the South Lease (grey) applying the usable wind rose at WIS Station 63095 from 2008 to 2012 with the implementation of a usable wind speed trend. Each color-set represents one optimum layout.

each turbine. In addition, the trend was excluded from the wake effect to maintain a reasonable time frame in computational time. However, the rows at the West border and Northwest edge as well as the successive rows in a 45°angle provide a distinct pattern. Produced power and installation cost are in the same order of magnitude for all runs and result in an average total revenue of \$3.99 billion. The increase of total revenue due to the trend is of the order of 1% corresponding to \$37.55 million. The power production rises by \$47.20 million.

Trend in usable wind velocity at the North Lease

Figure 27 shows the optimized layout with the implementation of the trend in usable wind speed compared to the base case optimization in simulation 10 with constant wind. The similarity of the layouts is not as obvious as for the REZ. Still, turbines align at the borders of the site except the Northwest border and the

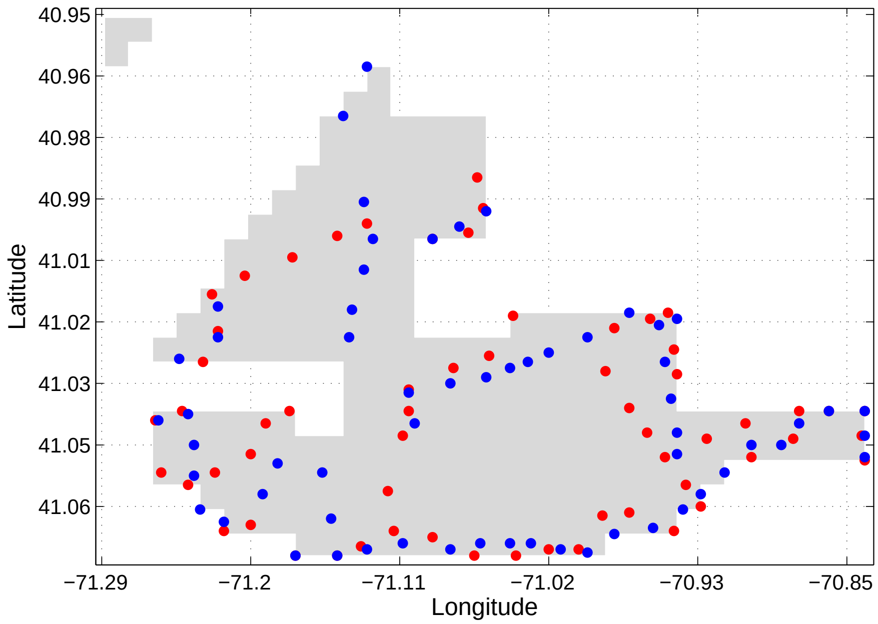

Figure 27. Optimized layouts in simulation 10 at the North Lease (grey) applying the usable wind rose at WIS Station 63095 from 2008 to 2012: constant wind (blue) and implementation of a usable wind speed trend (red).

central area is mainly avoided. Four rows of 14 turbines are placed across the area. The angles of the rows vary. Total revenue is \$6.05 billion which is an increase of \$56.87 million or 0.95%.

Discussion

The optimized layouts for the base case simulations are not as similar to the layouts of the simulations with the trend in usable wind speed as in the REZ. This is due to the increase of variables from five to 40 and 60 devices and of possible turbine locations from 1,494 in the REZ to 12,431 in the South Lease and 17,952 in the North Lease of the AMI. The several options of available optimized layouts offer flexibility in societal or political preferences.

The optimization of the North as well as the South Lease shows the placement of the turbines along the borders of the siting area. At the South Lease the South border is left out while at the North Lease, the Northwest border is avoided. In both areas few turbines do not follow a border. At the South Lease, those are mainly aligned in successive rows in a 45° angle which is perpendicular to one of the dominant wind directions. At the North Lease, the rows are either in a 90° or 0° angle. There is no clear connection to the dominant wind directions.

Figure 28 shows a map of the WiFSI over the AMI. The map was created for macrositing with the initial formulation of the index in Grilli et al. (2013)[11]. The placement of the turbines can be explained regarding favourable siting areas with a low WiFSI. At the South area, the South border as well the middle is avoided due to the worst index in the whole area. The devices are placed at the borders where the WiFSI is lower. Many turbines are set up at the small Northeast area because the best WiFSI values of the South Lease are located there. The high index of the South Lease is due to high foundation cost (Figure 29) resulting from increasing depths to 60 m (Figure 31) although wind speed is high (Figure 30).

At the North Lease, the Northwest border is avoided due to a high WiFSI. The index results from the highest foundation cost in the area due to the local geology characterized by terminal moraines. Unlike to the South Lease the index in the center of the area is not as high. The wake effect and the cable interconnection cost mainly influence the placement of the turbines at the borders. O'Reilly et al. (2013)[63] showed that turbines tend to spread over the whole siting area when interconnection cost are not included. In that case, the power lost due to wake effects decreases. In contrast, turbines cluster at one point at a specific site when wake is excluded but interconnection is the major constraint. At

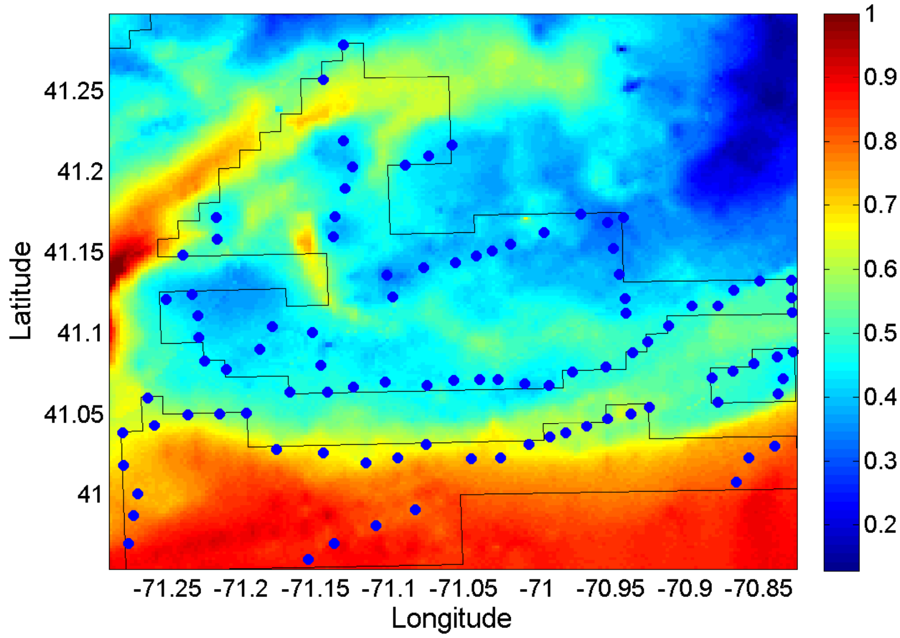

Figure 28. Map of the non-dimensional Wind Farm Siting Index (WiFSI) (color shading) at the Area of Mutual Interest (AMI) with the borders of the North and South Lease (outlined in black) as well as optimum turbine locations (blue).

the North Lease, the cable costs constraint leads to small distances between each turbine and its neighbours by placing them in rows. The wake effect is expressed through distance maximization between each row. The distance between the turbines is restricted by the zone borders and the number of turbines.

Both AMI zones were optimized separately to reduce computational time. The layout of the leases changes when optimized together. Areas of high foundation cost would still be avoided but interconnection cost and wake effect would change the overall shape of the turbine layout.

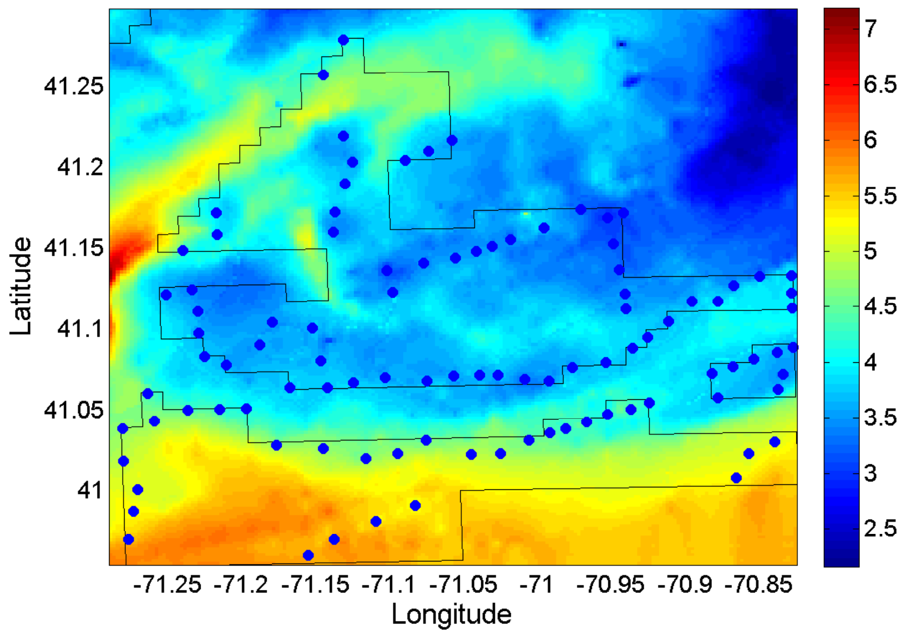

Figure 29. Map of technological cost (TC) (color shading) in $ million at the Area of Mutual Interest (AMI) with the borders of the North and South Lease (outlined in black) as well as optimum turbine locations (blue).

1.5.3 Comparison

Installing the turbines of the optimized layouts of the North and South Lease would cost $2.09 billion and produce power for $12.05 billion. Assuming the trend in usable wind velocity, net revenue increases from $9.94 to $10.04 billion. This increase is 1.0% or $94.42 million.

Table 10 compares costs and income per turbine for both leases. At the North Lease each turbine leads to an average revenue of $99.86 million. At the South Lease income per turbine is $98.74 million. The same difference of approximately $1 million per turbine is stated for the implementation of the trend. Average installation cost per turbine is less for the North Lease due to lower water depth (Figure 31). The South Lease outweighs higher installation cost with a higher power production per turbine because of higher wind velocity (Figure 30).

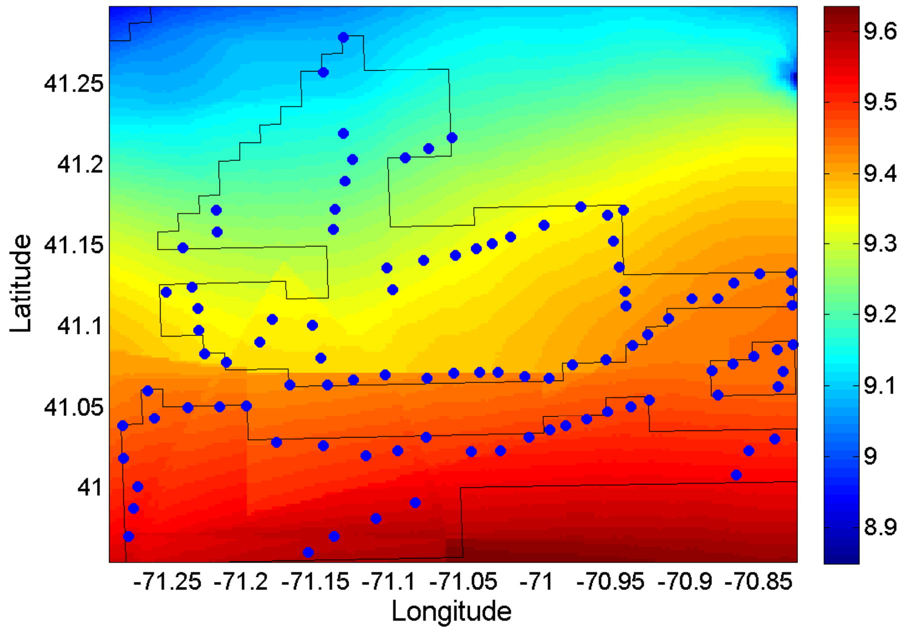

Figure 30. Map of wind speed (color shading) in m/s at the Area of Mutual Interest (AMI) with the borders of the North and South Lease (outlined in black) as well as optimum turbine locations (blue).

Optimizing the REZ with wind data from a different station as the AMI but the same time period from 2008 to 2012 leads to 60% less total revenue per turbine. Installation cost is cut in half but produced power is only 42% of the power of the AMI. It has to be considered that different types of turbines have been used for the REZ and AMI. On the one hand, the Siemens 6MW used at the REZ is 5 m taller and rotor diameter is 4 m longer than the Alstom Haliade 6MW used at the AMI. The range of usable wind speed of the Alstom device is also 1.5 m/s lower. In addition, its rated wind speed is 2.5 m/s lower. On the other hand, efficiency of the Alstom turbine is higher (Figure 2). The difference in efficiency as well as the higher extractable power at the AMI result in the high produced power per turbine at the North and South Lease.

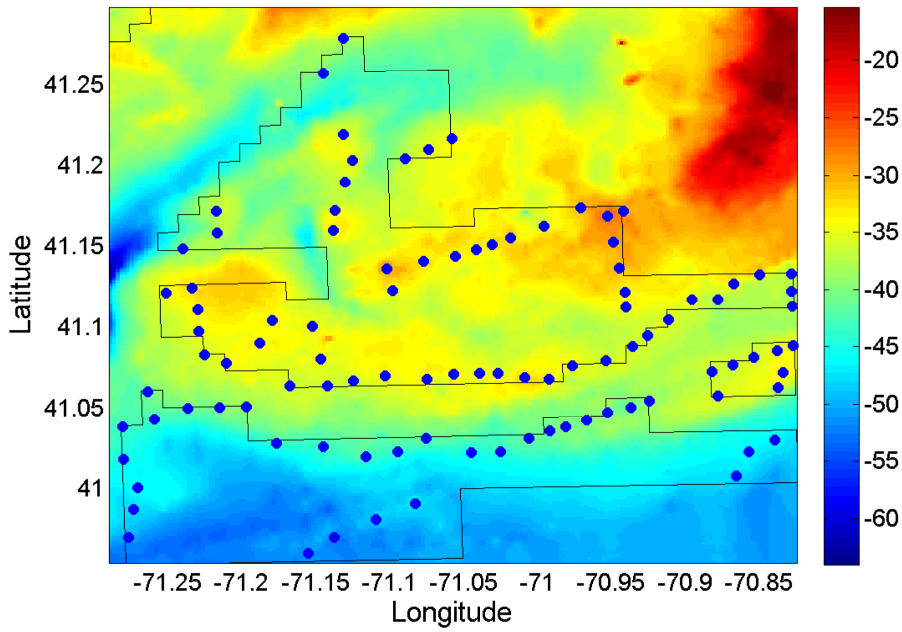

Figure 31. Map of water depth (color shading) in meter at the Area of Mutual Interest (AMI) with the borders of the North and South Lease (outlined in black) as well as optimum turbine locations (blue).

Table 10. Cost and revenue per turbine in $ million

No.	Description	Total revenue	Installation cost	Produced power
1	REZ 2009-2012	40.29	11.55	51.83
7	REZ Trend 2008-2012	41.81	11.27	53.09
8	South Lease Standard	98.74	23.93	122.667
9	South Lease Trend	99.68	24.18	123.85
10	North Lease Standard	99.86	19.10	118.96
11	North Lease Trend	100.81	19.24	120.05

For all results it has to be considered that the applied usable wind rose only effects the wake calculation. The wind power resource at the sites is constant for all simulations. Only produced power is changing according to the wake loss due to the relative positions of the turbines. In addition, the applied usable wind rose is assumed to be representative for the entire life time of a farm.

1.6 Conclusions

This study determined the sensitivity of a wind farm layout and its total revenue to wind time series length, wind direction and usable wind velocity trend. O'Reilly et al.'s (2013) [63] model was updated with the implementation of a usable wind speed trend in the calculation of the produced power and the wake effect. The model was applied to a large wind farm siting area. The update includes also the implementation of a Prim Algorithm for the calculation of cable interconnection between the turbines at large wind farms. Computational speed was increased by restructuring of the model.

Applying wind probability distributions which were collected at the same site but during different time periods leads to different optimization results. The number of possible layout options increases with wind time series length. If the number of possible turbine locations increases, even more optimum layout options are available. Turbine locations form rows perpendicular to the dominant wind direction if present. Sensitivity of the layout to wind time series length and wind direction is significant. The impact on the total revenue is smaller but recognizable. This is because all other constraints as foundation cost and extractable power remain the same for all simulations while only the wind direction changes. In contrast to that, the implementation of a trend in usable wind velocity does not result in a significant change in the turbine layout but has a a higher impact on the total revenue. A positive trend leads to an increase in produced power while installation cost remain the same. Total revenue rises.

A long-term wind prediction over the life time of a farm is necessary to determine the optimum layout and expected total revenue of a site. Short-term wind probability distributions are not representative for future wind conditions. Their application does not result in the optimum layout for a wind farm over its entire life time. Real life income might be less than predicted total revenue. In contrast to that, long-term predictions include changes in the wind resource i.e. direction and velocity. Applying changes in the wind direction leads to wind farm designs which minimizes the impacts of the changing wake effect expansion. In contrast to that, considering the trend in usable wind velocity is not significant for finding optimum turbine locations as long as the trend is small. High trends increase the extent of the wake effect and are expected to change the layout. The implementation of the trend is therefore only necessary in economic models when expected produced power can be calculated more accurately. Economic decision can be taken regarding the decrease or increase of total revenue due to a negative or positive trend respectively.

Future work should focus on the validation of the wind farm siting model. Model results could be compared to data collected at the Block Island Wind Farm which is currently under construction. Calculated produced power is validated with values of power produced at the Block Island Wind Farm. The one-dimensional WAsP Model can be compared to measurements of the wake decay behind the operated turbines. The influence of changing wind direction as well as speed could be observed with data of the produced power for short as well as long time periods.

Further research is required for the optimization of the AMI. More runs where constraints such as wake effect or interconnection costs are excluded are necessary to determine their sensitivity to the layout. The optimum number of turbines at the AMI could be found to maximize total revenue. Ecological as well as fishery costs could be included in an optimization. The resulting layouts show options for the usage of the marine resources when environmental, economic and social impact are considered.

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