Incorporating the visibility of coastal energy infrastructure into multi-criteria siting decisions

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ABSTRACT

Concern about the visibility of large infrastructure development often drives public opposition to these projects. However, insufficient analytical tools to assess visibility across a large number of alternate sites prior to siting typically results in the omission of visibility in multi-criteria siting processes, leading to inferior site selection and often costly litigation. This paper presents an approach for deriving visibility maps based on the location and duration of viewing by residents and visitors and demonstrates its use in illuminating tradeoffs by comparing these maps to wind energy value maps in the context of offshore wind energy development in the Northeastern United States.

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1. Introduction

Visual features on the landscape play significant and wide-ranging roles in people’s lives. Research has found links between nature viewing and many aspects of well-being [1,2], real estate prices and views [3,4], and a general public preference for natural and agricultural views accompanied by modest levels of development [5,6]. Recent high profile opposition to offshore wind farms in the U.S. and Europe has demonstrated how visual impacts can play a significant role in determining the level of public support for large scale development in sparsely developed land and seascapes [7–10]. Commonly standing 100 m or more, wind turbines are visible from as far as 30 km away [11]. The exposure that produces favorable wind conditions coincides with high inherent visibility and the potential for negative visual impacts to neighboring communities. Evidence from communities adjacent to land-based wind farms indicates that, while support for development is conditional on many factors [12], visibility concerns are consistently and frequently cited [13,14]. In coastal settings they are a top concern [7,15] and surveys have shown that coastal residents [16–18] and visitors [19,20] are willing to pay to site wind farms further from shore where they are less visible.

Public opposition to infrastructure development imposes a financial burden on local communities and developers via costly litigation and, in the context of wind energy, threatens the growth prospects of a globally important renewable energy source. Despite this, landscape-level siting decisions for wind energy development are largely conducted without formal consideration for visibility prior to the siting decision. While visual impact analysis has reached a remarkable degree of sophistication over the last 30 years [21], the post-hoc nature of this analysis means that site selection is missing potentially important impacts and tradeoffs related to visibility, resulting in social welfare losses even in the absence of litigation [22].

To incorporate visibility considerations into infrastructure siting requires inverting the traditional lens of analysis from assessing visibility from a given point source to assessing where people in the study area can see over the landscape. The 360° range of visibility from an observation point, commonly known as a viewshed, is limited by such factors as the acuity of the human eye, intervening topography, the curvature of the earth, and weather. In the fields of landscape planning and archeology, overall landscape visibility has been conceptualized by the term cumulative viewsheds, the aggregate visibility from multiple observation points [23]. This approach is beginning to attract attention in siting infrastructure [24,25]; however to-date it has been conducted only from the perspective of a handful of observation points—generally scenic overlooks and population centers.
This paper expands the cumulative viewshed approach to provide a more comprehensive accounting of where people are over space and time to significantly improve visibility estimates for planning in wind energy and other infrastructure siting decisions. This first requires information about places where people live and visit—two proxy datasets for where residents and visitors spend most of their time [25]. The locations of residences in the case study presented in this paper are based on maps created to enhance emergency response that combine both field surveys and orthophotography; however, many other potential data layers may be useful for this purpose. To estimate the relative spatial distribution of visitors to the study area (Fig. 1), the case study example here employs a global dataset of geotagged photos from a popular photo-sharing site that has been shown to provide an accurate proxy for the spatial distribution of visitation [26]. These relative visitation maps are calibrated to nominal visitation maps using surveyed visitation data to the area. While no dataset can ever fully represent the exact location, orientation, and duration of viewing for all viewers in an area, incorporating visitors is a novel addition to visual impact assessment that captures more of the inherent complexity in landscape viewing patterns. The residence and visitation data are inputs to a conventional viewshed algorithm that aggregates the resulting individual viewsheds to generate cumulative viewshed maps.

The context of a previously completed offshore wind farm sitting decision near Block Island, Rhode Island was selected as a heuristic demonstration of the core methodology of this cumulative viewshed approach and its use in multi-criteria spatial planning. Block Island is a small (25 km²) island located 21 km off the coast of mainland Rhode Island that is home to approximately 1000-year-round residents and a destination for over 30,000 people on a busy summer holiday weekend. The island is representative of many locations on the U.S. east coast and worldwide where favorable wind energy resources are located: it is close enough to potential wind farm locations such that visibility issues are a primary concern; it has a highly variable population throughout the year that is comprised of permanent residents, summer residents, and tourists; and finally, it has a high cost of energy that incentivizes locals to support wind energy projects [27,28]. A lengthy state-level planning effort [29] has led to the approval of a demonstration-scale wind farm that likely will be the first commercial offshore wind facility operating in the U.S. To demonstrate the use of these cumulative viewshed maps for siting, the outputs of a spatial wind energy value model are compared to cumulative viewshed maps where visibility is measured in viewer days, a quantitatively meaningful metric that accounts both for spatial and temporal variation in visibility across different categories of viewers. This flexibility of this siting approach is also demonstrated by drawing from the extensive visual impact literature to create cumulative visual impact maps that reflect viewers’ preferences. The methods demonstrated here expand the toolbox of planners to incorporate visibility into siting decisions for features with a visual impact, and in the specific context of offshore wind, allow for the comparison of tradeoffs between visibility, wind energy value, and other objectives as part of a multi-criteria spatial planning process.

2. Methods

2.1. Viewers

To characterize where people can see over space, a spatial inventory of viewers over the landscape is required. There are multiple potential data sources that can be used to spatially locate viewers based in residences, including orthophotography, tax assessment parcel maps, and maps created for public safety emergency response. This flexibility increases the applicability of this approach across a wide range of geographies. In the case of Block Island, the state of Rhode Island has an E-911 vector data layer for
use in public safety programs that spatially identifies all structures in Rhode Island that was created using field-verified orthophotography. It includes the number of stories for each structure and the street address, as well as classifications for whether it is a residential address or other class of structure. It also includes a sub-category of whether or not it is a seasonal versus full-time residence. From this data, all structures on Block Island were extracted and the dataset was further reduced by eliminating all structures that were not classified in the dataset as full-time residences.

Geotagged photos from the online photo hosting service Flickr (available via Flickr’s public API) were employed to assess the spatial distribution of where visitors or tourists aggregate. The global coverage of these photos, the ability to avoid time-consuming and costly surveys, and photos’ inherent linkage to visual landscape quality make them a useful data source in this context. A comparison of independent empirical visitation to 836 sites in 31 countries against observed imputed visitation from Flickr showed strong correlations, demonstrating that these data can be reliably used as a proxy for visitation [26]. Because visitors spend time in the waters surrounding Block Island for activities such as sailing, charter fishing, and transit from the mainland, all photos taken on Block Island or in the marine areas defined by a 60x60 km2 bounding box centered on Block Island were included.

This data includes the latitude and longitude, the user id, and the date the picture was taken. For the study area there were 11,088 photos over the years 2005–2012, comprising 1456 unique user days and 711 unique individuals. The median amount of days taking photos in the area per user is one day, with 64% of users falling into this category. Table S1 shows the distribution of user days for the dataset.

Wood et al. [26] found a strong correlation between user days and field observations of visitation at 836 recreation sites around the world, demonstrating that this dataset can be reliably used as a proxy for visitation. However, the raw number of observed photo-user-days significantly underestimates visitation, as naturally not all visitors to a location take pictures and upload them to this particular web service. The usefulness of these data is based rather in how it characterizes the distribution of visitors over space. Taken as a proxy for the distribution of actual visitors to the area, it can be combined with survey data on nominal visitation to provide quantitative estimates of visitation to different locations. Global Insight [30] provides data on the number of visitors to the island in 2009, indicating that there are 536,900 overnight visitors and visitors from under 50 miles, or 379,300 overnight visitors not including those from under 50 miles. Unfortunately the data are ambiguous regarding the distribution in the length of stay, so based on the observed flickr data the simplifying assumption was made that the median length of stay is one day as observed in the dataset (Table A.1). An additional assumption is that this field visitation data reflects not only visitation to the island but also to the surrounding waters. Much of the activity in surrounding waters, including passenger ferries, charter boats, and sailing is based out of the island so this is a reasonable assumption. To assign each viewpoint a number of total visitor days, the total number of visitors (536,900) were divided by the number of photos, therefore treating 11,088 photo locations from the flickr dataset equally and assigning each as representative of approximately 48.5 visitor days.

2.2. Viewer days and visual impact

Creating a quantitatively meaningful cumulative viewshed from input datasets for visitor and resident locations requires that the outputs of each viewed be in the same terms. There are many potential metrics that could serve as a potential common denominator between visitors and residents, and the choice should be informed both by how impacts are internalized by viewers and also more practical considerations such as data limitations, computing resources, and the nature of the questions or decisions that will be made with the results. Based on existing research and the limitations of available data, two approaches are presented here: using viewer days and a visual impact index as the output metrics for the cumulative viewed analysis.

For all locations (cells) in an area of interest, viewer days reflects the number of days each viewer can see that particular location and then sums those values across all viewers. This is a quantitatively meaningful output of landscape visibility that weighs residents’ viewing more than visitors’, addressing research that has found heterogeneous and time-variant visual impacts to different user groups [19]. Viewer days is also an intuitive and transparent metric that should be readily understood by policy makers and stakeholders, allowing involved parties to reflect on their visual preferences during the iterative stakeholder engagement process typical of nearly all successful spatial planning efforts [31].

To expand the viewer days concept from a visibility metric to a visual impact metric requires an understanding of viewers’ preferences for seeing development. Bishop and Miller [32] used a multiple regression analysis with standardized coefficients to examine how different predictors influence the visual impact of wind turbines, finding that distance has the largest effect. For the purpose of demonstrating a visual impact preference map in this cumulative viewed analysis, their regression results relating distance to visual impact are employed here, holding other variables at their sample means, yielding the following distance–impact relationship:

\[ I = 3.84 - 0.053D \]  

(1)

where \( I \) is the visual impact index that ranges from 1 (low impact) to 5 (high impact), and \( D \) is the distance of the wind turbines in kilometers from the viewer. In a cumulative viewed analysis, each individual viewed raster is weighted by this function prior to

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1 This left 1058 structures, a significant difference from the 514 occupied housing units identified by the 2010 U.S. Census. Without a spatial layer identifying the census housing units, the E-911 data is the best available resource to characterize the spatial distribution of year-round residences, even if it significantly overestimates their number. To partially address this, the 1051 full-time residents identified by the 2010 U.S. Census across all year-round residential units were evenly spread and each viewpoint received \((1051/1058)\times365 = 362.6\) viewing days per year. This approach captures the spatial distribution of the year-round residences. It includes the number of stories for each structure and the street address, as well as classifying each viewpoint a number of total visitor days, the total number of visitors (536,900) were divided by the number of photos, therefore treating 11,088 photo locations from the flickr dataset equally and assigning each as representative of approximately 48.5 visitor days.

2 Included in this analysis are the full-time residents of Block Island and visitors both on the island and in surrounding waters. Though the decision context explored here is siting a wind energy facility in the state waters surrounding Block Island, visitors recreating in the waters outside this area are included under the assumption that they also will be affected and may likely be tied to Block Island’s tourist economy. State waters to the north of Block Island extend to within 8 km of the mainland and generally should be included in an analysis of this type. However these viewers were not included for two reasons: first, while the particular case study gives context, the siting decision here has already been made and therefore this is a heuristic exercise to demonstrate the core cumulative viewed methodology; second, the wind energy analysis and visibility analysis made it clear that locations to the north of Block Island were inferior to those to the south. Adding in additional viewers that can only see the north side of the island would have done nothing to change the outcome of this (retrospective) policy guidance or advance demonstrating the approach.

3 By tracking individual users in the flickr dataset a finer temporal resolution could be created that breaks visitation time into hours; however, this level of detail has not been validated against empirical data and would still be reliant on the coarser field survey data for translation to total visitation time.
to being summed with other viewsheds. This process was automated using the InVEST Scenic Quality model, an open-source viewshed tool created specifically for weighted viewshed analysis [33].

2.3. Model runs

In the study area, one-meter resolution LiDAR point cloud data exists from which to derive elevation maps [36]. This data is from airborne LiDAR data collection done between April 21 and May 6, 2011. At this latitude, this date captures a point somewhere between no- and full-foliage, providing a reasonable median approximation of surface contours throughout the year. Using the ArcGIS LAS Dataset to raster tool, the point cloud data were processed into a one-meter resolution digital surface model (DSM) using binning interpolation with “maximum” cell assignment and natural neighbor void fill. Maximum biases the results to higher elevations by picking up higher elevation points that may be associated with trees and structures, important features to capture for a viewshed model. At this resolution the study area includes 5 billion pixels, a significant computational burden for over 12,000 individual viewshed runs using a raster-based viewshed tool like the ArcGIS viewshed tool, the chosen viewshed model for calculating viewer days. To reduce this burden, the DSM LiDAR data was resampled to 10 m using bilinear interpolation. While this reduces the fidelity of the data, it retains important surface features often missing in bare earth digital elevation modeling.

To be comparable to the 20-year time horizon of the wind farm the viewshed results were assumed constant across years and multiplied by a factor of 20. A common refractivity coefficient of 0.13 is used for all viewshed runs to correct for distortions based on the Earth’s atmosphere. Each individual’s maximum viewing radius is set at 30 km for the planned 175 m tall (turbine + rotor) Alstom 6.0 MW turbines in the demonstration wind farm [11]. Viewpoints representing visitors were assumed to extend 1.55 m vertically above grade, eye-level of the average U.S. citizen (1.55 m:1.69 m in height − .14 m for the distance between the top of the head and the eyes). Viewpoints for residents were placed on top of structures with no above-grade adjustment. This approximates (with a slight upward bias) the view from top-floor windows of these properties, a likely representation of the best and largest view from each property [37,38].

Wind energy value is given as the lifetime net present value (NPV) of the approved wind farm configuration for all potential siting locations in the study area, as estimated using the InVEST Wind Energy model ([33,39], see Appendix). Due to both the high cost of financing offshore wind energy projects and the high cost per megawatt for demonstration-scale projects, the NPV for this particular wind farm configuration is negative throughout the study area.

3. Results and discussion

As the case study is a state-level decision for siting offshore wind energy, here the analysis is restricted to the state waters surrounding Block Island. Comparing spatial maps of visibility, given in viewer days, and wind energy value side-by-side show that the demonstration-scale farm was sited in a favorable location for the two criteria of interest (Fig. 2). Locations to the south and southeast of the island provide higher NPV for a farm of this design and also result in lower visibility due to the spatial distribution of viewers and the geomorphology of the southern part of the island. Tradeoffs between NPV and visibility can be visualized by representing siting locations as a scatter plot (Fig. 3). Points below or to the left of the outer envelope in the lower plot indicate locations where either visibility or NPV could be improved at no cost to the other. The outer envelope of points forms the efficiency frontier for siting this wind farm configuration in the state waters surrounding Block Island. Sites on the frontier represent optimal combinations of visibility and wind NPV, and the concave negative slope indicates the rate of tradeoff between the two in the set of optimal solutions. Maximizing NPV comes at little cost to visibility when moving from −$11.5 million to −$10 million, but further gains in NPV quickly increase the visibility of the farm. Although the planned farm location is very close to the frontier, the plot shows that an increase in NPV of roughly $0.75 million could come
at no cost to visibility. Similarly, a reduction of a million viewer days could come at little cost to NPV. These are relatively small gains compared to many of the other locations that could have been chosen for this wind farm, which reflects well on the exhaustive planning process that resulted in this location being chosen despite not having the advantage of the cumulative viewedshed model or the wind energy value maps.

For demonstrating impact-weighted cumulative viewsheeds, the InVEST Scenic Quality model was run with a coarser 100 m DSM (resampled from the 1 m DSM) and only using the residence viewpoints. Other values were held constant from the viewer days cumulative viewedshed analysis. The results (Fig. 4) demonstrate the visual impact of the demonstration scale wind farm across space. As each pixel represents the cumulative visual impact at that location, the values are no longer on a 1–5 scale as they are summed. To the extent that the application of visual preferences for offshore wind turbines from a study done elsewhere apply to Block Island, this map demonstrates the decay of negative visual impact at increasing distances from island residences. Bishop and Miller [32] assessed visual preferences for offshore wind turbines by surveying attitudes about hypothesized predictors that influence the perceived visual impact of offshore wind turbines, such as contrast, distance from the viewer, rotor motion, and demographic characteristics. Unsurprisingly, many of these factors played a role. Demographics poses a particularly difficult challenge for creating visual impact maps, versus visibility maps, in the presence of heterogeneous populations. There is considerable remaining research necessary to integrate preference weighting into visual impact analysis, and this visual impact exercise also abstracted from important landscape context concerns which are still being formalized in the literature [9,41]. Nonetheless, the cumulative viewedshed framework presented here is adaptable to the use of visual impact indices and monetary value functions from willingness-to-pay surveys [16,17,19,20] as this research progresses.

It is important to note that the analysis here is concerned only with visibility and the visual impacts of infrastructure development, not the entire suite of values that may be associated with an undeveloped (or lightly developed) landscape. The concept of “value” in economics is categorized by use and non-use value. Visual impact is a type of use value, as the observer directly experiences a change in their well-being from viewing a landscape. Non-use value is commonly associated with wilderness and empty spaces—people value these and would be willing to pay to keep them wild (for example by prohibiting wind farms), even if they never plan to visit these locations. It is important not to conflate these sources of value – see the seminal paper by Walsh et al. [42] on non-use value and wilderness for more on this distinction. Estimating other use and non-use values arising from (the lack of) development in a landscape is challenging but is supported by other methods from more than 30 years of research in economics.

Cumulative viewedshed results, regardless of the chosen output metric, should be considered only as estimates of landscape visibility. A primary reason for this is the process for attributing the spatial and temporal attributes of viewers in the study area. This will always provide an imperfect measure of the exact location and duration of time spent viewing the landscape. Another important reason for this is that viewedshed algorithms are computationally intensive and this burden increases exponentially as the resolution of the inputs increases. This is a critical issue in cumulative viewedshed modeling when thousands of individual viewedshed runs are required across all the observation points. Current software and hardware limitations require that some sacrifices in accuracy must be made to run a cumulative viewedshed analysis, one of the major reasons that this type of analysis is under-studied.

A key advancement of this cumulative viewedshed approach is the fast and accurate production of landscape visibility maps prior to siting decisions, a crucial missing capacity for planning at a time when more than three dozen countries worldwide are starting or continuing to develop marine spatial plans in reaction to expanding use of coastal waters [43]. Marine aquaculture in particular is another visually sensitive and quickly growing use that is being deliberated globally without advance consideration for visual impacts. While it has been introduced in an offshore wind
energy siting context, the cumulative viewedesh method here is general and can be used in any siting decision where visual impacts are a concern, from negatively perceived features such as低调, surface mining, timber clearcuts, and electrical infrastucture to positively perceived features like monuments and parks. This approach is especially useful in areas where siting decisions are non-trivial from a visibility perspective, such as when the geomorphology or distribution of viewers varies significantly across space, a condition that holds at many coastal wind energy installations.

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Appendix A. Supplementary material

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