Offshore Wind Turbine Visibility and Visual Impact Threshold Distances

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Potential visual impact on coastal lands has emerged as a major concern in the development of offshore wind facilities in the United States and Europe. Optimal siting of offshore facilities requires accurate knowledge of the relationship between distance and the visibility of wind turbines. Past assessments of offshore wind turbine visibility were based on smaller turbines and facilities in use at the time and underestimate visibility for current projects, which use more and larger larger turbines. This study is a preliminary assessment of the visibility of offshore wind facilities in the United Kingdom. Study objectives included identifying the maximum distances the facilities could be seen in both daytime and nighttime views and assessing the effect of distance on visual contrasts associated with the facilities. Results showed that small to moderately sized facilities were visible to the unaided eye at distances greater than 42 km [26 miles (mi)], with turbine blade movement visible up to 39 km (24 mi). At night, aerial hazard navigation lighting was visible at distances greater than 39 km (24 mi). The observed wind facilities were judged to be a major focus of visual attention at distances up to 16 km (10 mi), were noticeable to casual observers at distances of almost 29 km (18 mi), and were visible with extended or concentrated viewing at distances beyond 40 km (25 mi).

Environmental Practice Page 1 of 17

The Energy Policy Act of 2005 provided the United States (US) Department of the Interior's Bureau of Ocean Energy Management with the authority to issue leases for renewable energy facilities on the Outer Continental Shelf. In 2009, the bureau released a new regulatory framework for reviewing and approving proposed offshore wind projects. In 2010, the department announced the *Smart from the Start* initiative to facilitate offshore wind development in federal waters by streamlining the approval process for proposed projects, implementing a leasing framework that includes identification of wind energy areas along the Atlantic Outer Continental Shelf, and moving aggressively to process offshore transmission applications (US Department of the Interior, 2010a). These actions demonstrate the federal government's commitment to promoting and accelerating commercial US offshore wind development. Many states are also actively seeking to encourage offshore wind development in waters under their jurisdiction. Although no utility-scale offshore wind facilities are currently located in US federal or state waters, development proposals have been submitted in more than 10 states, and active projects exist in 4 (OffshoreWind.net, 2010).

The large-scale deployment of offshore renewable energy seems inevitable; equally inevitable is that some offshore wind projects will face significant public opposition because of potential visual impacts. As the US begins large-scale deployment of offshore wind energy facilities, an important challenge developers and regulators will face is to minimize potential visual impacts to important coastal scenic, historic, and recreational resources; tribal properties and treasured seascapes; commercial interests dependent on tourism; private property of coastal residents; and the quality of life for millions living and working along the coasts.

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Visual impacts from offshore wind facilities have been a long-standing public concern in Europe and are quickly emerging as an important issue for US offshore wind development (National Oceanic and Atmospheric Administration, n.d.). Public and tribal concerns about visual impacts were major factors in the years-long delay of the Cape Wind Energy Project, which finally was approved for development in 2010 (US Department of the Interior, 2010b). Visual impacts have recently emerged as major concerns for offshore wind energy development in the Great Lakes and were cited as a factor in Ontario's recent moratorium on all offshore wind energy development along its entire Great Lakes coastline, as well as for projects in Texas (Clark, 2011; Mahony, 2011; National Oceanic and Atmospheric Administration, n.d.). As additional projects are proposed, visual impacts will certainly be a key issue in determining the ultimate success of offshore wind projects in the US as the need to protect local interests and landscape quality is balanced with the need to respond to changing energy policies that promote renewable energy development (Phadke, 2010).

The seascape visual impacts associated with offshore wind facilities are without precedent; the facilities are very large, with enormously tall structures having colors and geometry that contrast strongly with natural seascapes. The synchronized sweeping movement of the massive blades during the day and the synchronized flashing of the lighting at night contribute to the facilities' visibility over very long distances. These impacts are extremely difficult to mitigate, and the only truly effective means of reducing the impacts in a seascape is to site the facilities away from sensitive visual resource areas and viewing locations. Because distance is so important to reducing or avoiding impacts, an accurate understanding of the relationship between distance and the visibility of utility-scale offshore wind facilities in real settings is critical to the optimal siting of new facilities.

Over the past 20 years, several authors have studied proposed or operating facilities to explore the distance-visibility relationship for onshore and offshore wind turbines. The results were subsequently applied in visual impact analyses for proposed facilities. The visibility limits specified in these studies were sometimes used to determine the area of potential effects, to set the maximum radii for viewshed analyses, and to evaluate potential impacts likely to be observed at various distances from the proposed facility—one of the key elements of the analyses.

The use of these previous results to inform visual impact analyses for wind projects is appropriate when the proposed projects are similarly sized projects that involve similarly sized turbine models. A long-term, ongoing trend of developing and deploying larger wind turbines in larger facilities, however, is well documented for both onshore and offshore projects (Kessler, 2011), and visibility limits calculated for older wind facilities with fewer and smaller turbines could be invalid for the larger facilities and turbines currently being deployed.

Offshore wind turbines have increased substantially both in height and in rotor diameter in the last decade, and continued growth in size is predicted. Turbines exceeding 187 m (613 ft) in height (to blade tip) are already in production (ClimateWire, 2011; European Wind Energy Association, 2011b; Vestas, 2011; Weber, 2011), and even larger turbines are under development (European Wind Energy Association, 2011a; Kessler, 2011). Similarly, since the 1990s, the number of turbines deployed per project also has increased greatly, from a few or a few dozen turbines to several hundred turbines per facility today. Even larger projects are in the planning stages (Johns Hopkins University, 2011). As the early distance-visibility studies do not account for turbines or projects of these sizes, it is inappropriate to use limits of visibility established in these studies as the basis for current visual impact assessments. Clearly, impact assessments and siting decisions must rely on accurate, up-to-date knowledge regarding the visibility of today's offshore wind facilities.

This article presents the results of fieldwork undertaken to assess (a) the visibility of utility-scale offshore wind facilities currently operating in actual seascape settings and (b) the effects of distance and variable atmospheric and lighting conditions on offshore wind turbine visibility. The fieldwork was undertaken as part of a larger effort to develop the Visual Impact Evaluation System for Offshore Renewable Energy, a geographic information system–based software tool for developing accurate, highly realistic visualizations of offshore renewable energy facilities (including wind technologies) for use in visual impact assessment. The fieldwork was conducted by staff of the Environmental Science Division of Argonne National Laboratory, the University of Arkansas Center for Advanced Spatial Technologies, and the Bureau of Ocean Energy Management. Because there are no utility-scale offshore wind facilities in the US, the United Kingdom (UK) was chosen as the study site.

Literature Review

A standard approach to quantifying visibility is to determine the farthest distance at which a large, black object can be distinguished from the sky at the horizon. This distance estimate typically is referred to as the *visual range*. Distance between the viewer and the viewed object, properties of the atmosphere, the intensity and distribution of light, characteristics of the observed object, and properties of the human eye all influence the visual range (Hyslop, 2009) by affecting the ability to perceive the contrast between a viewed object and its background.

Over the last 20 years, several studies have been conducted in the UK and mainland Europe to explore the visibility of onshore and offshore wind farms. An early analysis of the effect of distance on onshore turbine visibility was conducted for the Penrhyddlan and Llidartywaun wind facilities in Wales in the early 1990s (European Commission, 1995). The authors of this study suggested that in conditions of very good visibility, at a distance of 20 km [12.4 miles (mi)], turbines with tower heights of 30 m (98 ft) and rotor diameters of 28 m (92 ft) would be invisible to the naked eye. This distance (20 km) became a standard measure for the visibility of turbines and was used in various environmental assessments to determine their visual impact.

Subsequent evaluations of the visual impact of onshore wind facilities often used standard guidelines for determining the farthest distance at which a wind turbine was visible. One such standard includes a division of the landscape into three areas—a distant area (a radius of over 10 km), an intermediate area (a radius of 1–10 km), and an immediate area (a radius of less than 1 km). In the distant area, wind turbines would be visible, but the nearest objects generally would dominate perception. However, in an "empty" landscape, the wind turbines could become the visual focus of observers. In the intermediate area, wind turbines would dominate the space because of their height and movement. In the immediate area, wind turbines would be extremely dominant because of their size and the rotational movement of the blades (Jallouli and Moreau, 2009; University of Newcastle, 2002).

In response to the trend toward larger turbines, various UK government agencies sought to determine the potential impacts of wind turbines out to 30 km (18.6 mi), an expansion beyond many of the typical guidelines. In response, Bishop (2000) developed an Internet survey in which paired animations of wind turbines were shown to respondents; one depicted a rotating turbine and one an expanding tower. Bishop suggested that modeling potential impacts out to 30 km (18.6 mi) was justified. However, he suggested that effects beyond 20 km (12 mi) might be rare and would depend on exceptional viewing conditions, a result similar to the findings in Wales.

To date, no systematic US study specific to onshore wind turbine visibility has been published. However, the ongoing investigations and repeated observations of onshore wind facilities reported here suggest that turbines are visible at greater distances than was previously noted in published research.

To address the seascape issues surrounding offshore wind developments, the Scottish Natural Heritage commissioned an assessment of the visual sensitivity of the Scottish seascape. A portion of this study focused on determining the distance at which wind turbines were visible. As a starting point, Scott et al. (2005) began with a review of existing guidance. Among these documents was the UK Department of Trade and Industry's strategic environmental assessment for offshore wind. As part of this review, the authors suggested that if a wind facility were sited 0–8 km (0–5 mi) from shore, a high visual impact would occur; at 8–13 km (5–8 mi), 13–24 km (8.1–14.9 mi), and more than 24 km (>14.9 mi), visual impacts would be moderate, low, and insignificant, respectively.

To test these standards, Scott et al. (2005) made observations from a ferry and determined that details on shore were clearly visible at a distance of around 30 km (19 mi) in clear, sunny conditions. As a result of these observations and previous guidance, the distance for visual analyses was extended to 35 km (21.7 mi) as a precaution.

Bishop and Miller (2007) also tested the impact of distance on offshore turbine visibility in a formal analysis including an assessment of a wind facility at three different distances [4, 8, and 12 km ($2\frac{1}{2}$, 5, and $7\frac{1}{2}$ mi)], in five different lighting and weather conditions, and in two movement conditions. Unlike previous analyses of visibility, Bishop and Miller argued that contrast between the turbines and the sky backdrop was just as important as distance in determining wind turbine visibility and needed to be quantified. Their research involved the creation of simulations and surveys to determine the visibility of the turbines. Their findings suggested that, in all atmospheric and lighting conditions, impact declined with distance and increased with rising levels of contrast.

Additional research for both onshore and offshore turbines has been conducted to determine the influence of blade movement in conjunction with distance. Studies of onshore wind facilities have suggested that motion can extend the

Table 1. Offshore wind facilities observed, facility descriptions, and onshore viewpoints

Wind facility	Description	Viewpoints/distance to facility/elevation[a]
Barrow	30 Vestas V90/3000; 3.0 MW 75-m hub height; 90-m rotor diameter 90 MW total installed power One offshore substation	V1: Walney Island, 11.5 km/10 m
Burbo Bank	25 Siemens SWT-3.6-107; 3.6 MW 83.5-m hub height; 107-m rotor diameter 324 MW total installed power	V2: Formby Point, 8.2 km/4 m V3: Clieves Hill, 18.4 km/57 m V4: Crosby Marina, 7.4 km/7 m V5: Leasowe Castle, 7.9 km/17 m V6: Thurstaston Common, 14.1 km/85 m V7: A55 Footbridge, 24.6 km/256 m V8: Point of Ayr, 16.7 km/8 m V9: Prestatyn Nova Center, 21.9 km/5 m
Greater Gabbard	140 Siemens SWT-3.6-107; 3.6 MW 78-m hub height; 107-m rotor diameter 504 MW total installed power	V12: Greater Gabbard Viewpoint, 31.0 km/6 m V13: Orford Castle, 29.7 km/13 m V14: Felixstowe Seafront, 34.2 km/8 m V15: Felixstowe Road, 34.4 km/9 m V17: Naze Tower, 41.0 km/48 m
Gunfleet Sands	48 Siemens SWT-3.6-107; 3.6 MW 75-m hub height; 107-m rotor diameter 172.8 MW total installed power One substation	V13: Orford Castle, 43.9 km/13 m V14: Felixstowe Seafront, 27.8 km/8 m V16: Landguard Fort Beach, 22.2 km/4 m V17: Naze Tower, 14.1 km/48 m V18: Great Holland, 10.1 km/21 m V19: Greensward, Friston-on-Sea, 10.9 km/13 m V20: Great Holland County Park, 7.7 km/8 m V21: Clacton Pier Area, 6.8 km/13 m V24: Reculver Castle/Towers, 38.6 km/6 m V25: Coldswood Road, 42.3 km/47 m
Kentish Flats	30 Vestas V90/3000; 3.0 MW 70-m hub height; 90-m rotor diameter 90 MW total installed power	V22: Bayview Road/Windmill Road, 12.8 km/48 m V23: Clapham Hill, 13.5 km/62 m V24: Reculver Castle/Towers, 10.4 km/6 m V28: Haine Road Roundabout/Margate, 22.5 km/54 m
Lynn and Inner Dowsing[b]	54 Siemens SWT-3.6-107; 3.6 MW 85-m hub height; 107-m rotor diameter 194.4 MW total installed power	V10: Candlesby Hill, 16.9 km/59 m V11: Skegness Beach Lagoon Walk, 5.5 km/4 m
North Hoyle	30 Vestas V80/2000; 2.0 MW 67-m hub height; 80-m rotor diameter 60 MW total installed power	V2: Formby Point, 25.7 km/4 m V5: Leasowe Castle, 21.1 km/17 m V9: Prestatyn Nova Center, 7.9 km/5 m
Rhyl Flats	25 Siemens SWT-3.6-107; 3.6 MW 75-m hub height; 107-m rotor diameter 90 MW total installed power	V2: Formby Point, 39.2 km/4 m V5: Leasowe Castle, 34.1 km/17 m V6: Thurstaston Common, 32.0 km/85 m V9: Prestatyn Nova Center, 13.9 km/5 m
Thanet	100 Vestas V90/3000; 3.0 MW 70-m hub height; 90-m rotor diameter 300 MW total installed power One offshore substation	V24: Reculver Castle/Towers, 28.6 km/6 m V26: Fort Lower Promenade, 15.3 km/11 m V27: Fayreness Hotel, 12.3 km/20 m V29: Marina Road, Margate, 15.8 km/20 m
Walney Island	102 Siemens SWT-3.6-107; 3.6 MW 80- to 90-m hub height 107- to 120-m rotor diameter 367.2 MW total installed power	V1: Walney Island, 17.0 km/10 m
Ormonde	30 REpower 5M; 5.0 MW 90-m hub height; 126-m rotor diameter 150 MW total installed power	V1: Walney Island, 9.5 km/10 m

[a] Viewpoint elevation; includes 2 m added to ground elevation to account for observer height.
[b] Two neighboring developments combined into one by Centrica Renewable Energy Limited.
Source: Wind Power (2011).

viewshed of wind turbines to beyond 8 km (5 mi) (Tsoutsos et al., 2007). The University of Newcastle (2002) reported that blade movement could be detected up to 15 km (9.3 mi) in clear conditions, but that a casual observer would not notice blade movement beyond 10 km (6.2 mi). As will be shown, the findings of our present study suggest that the actual distance for blade movement visibility is much greater than was indicated in these previous studies.

Several US offshore wind evaluations have focused on the proposed Cape Wind Energy Project. For evaluation of visual impacts, Environmental Design and Research (2006) used three distance zones [0–10 km (0–6 mi), 10–19 km (6–12 mi), and 19–29 km (12–18 mi)] to determine the potential visibility of wind turbines from the shoreline of Nantucket Sound. These zones are similar to those used for onshore evaluations. The visibility was documented as a percentage of the total mileage of the shoreline that would have potential views of the wind turbines. The results indicated that the turbines would be visible from 99% of the Nantucket Sound shoreline at distances of 0–10 km (0–6 mi), from 71% of the shoreline at 10–19 km (6–12 mi), and from 66% of the shoreline at 19–29 km (12–18 mi). This study did not evaluate impacts beyond 29 km (18 mi) or seek to determine the maximum distances at which turbines would be visible.

The visual impacts of aviation obstruction lighting and marine navigation lighting have remained largely unaddressed in research; however, Scott et al. (2005) acknowl-

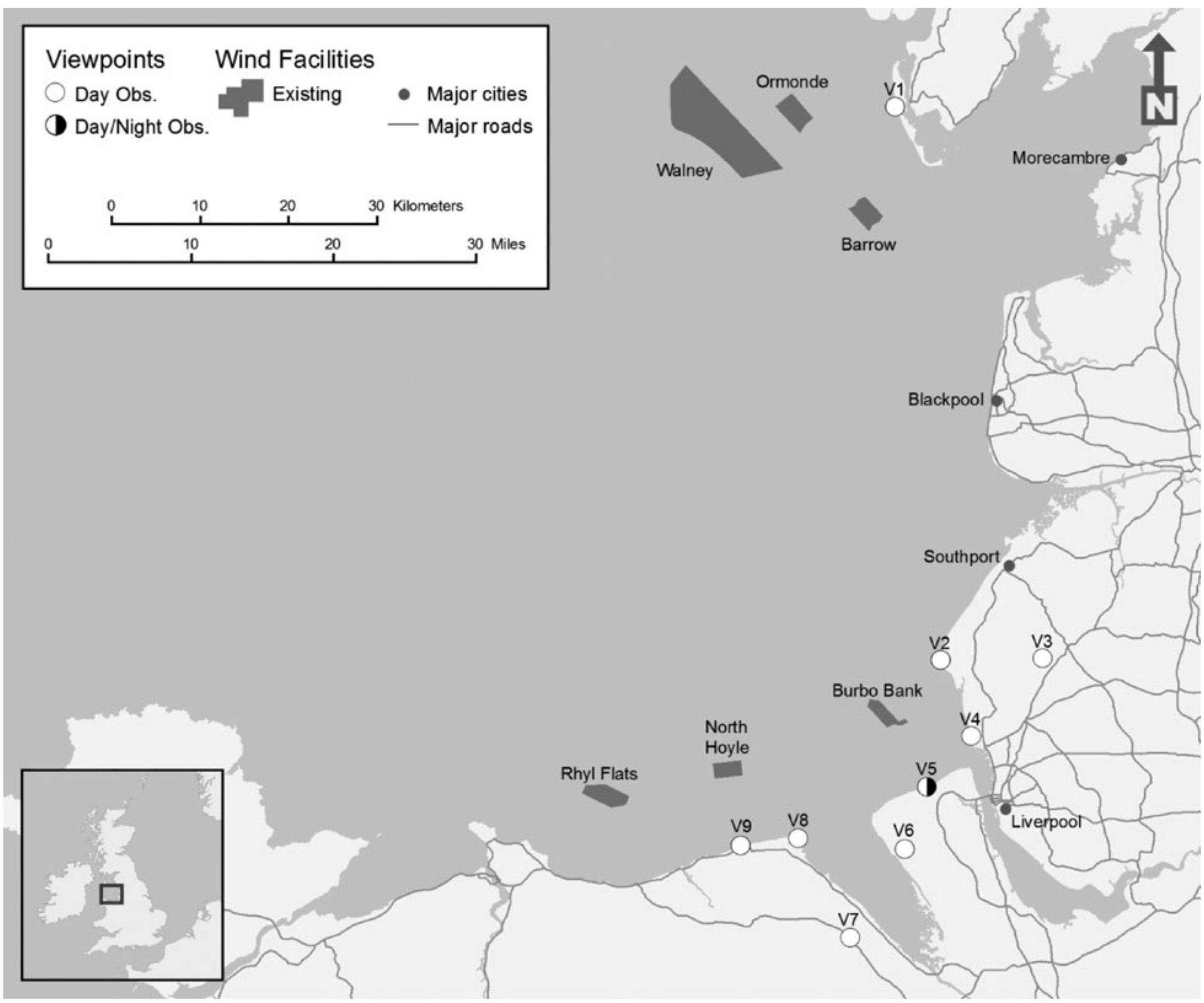

Figure 1. Irish Sea offshore wind facilities and onshore viewpoints.

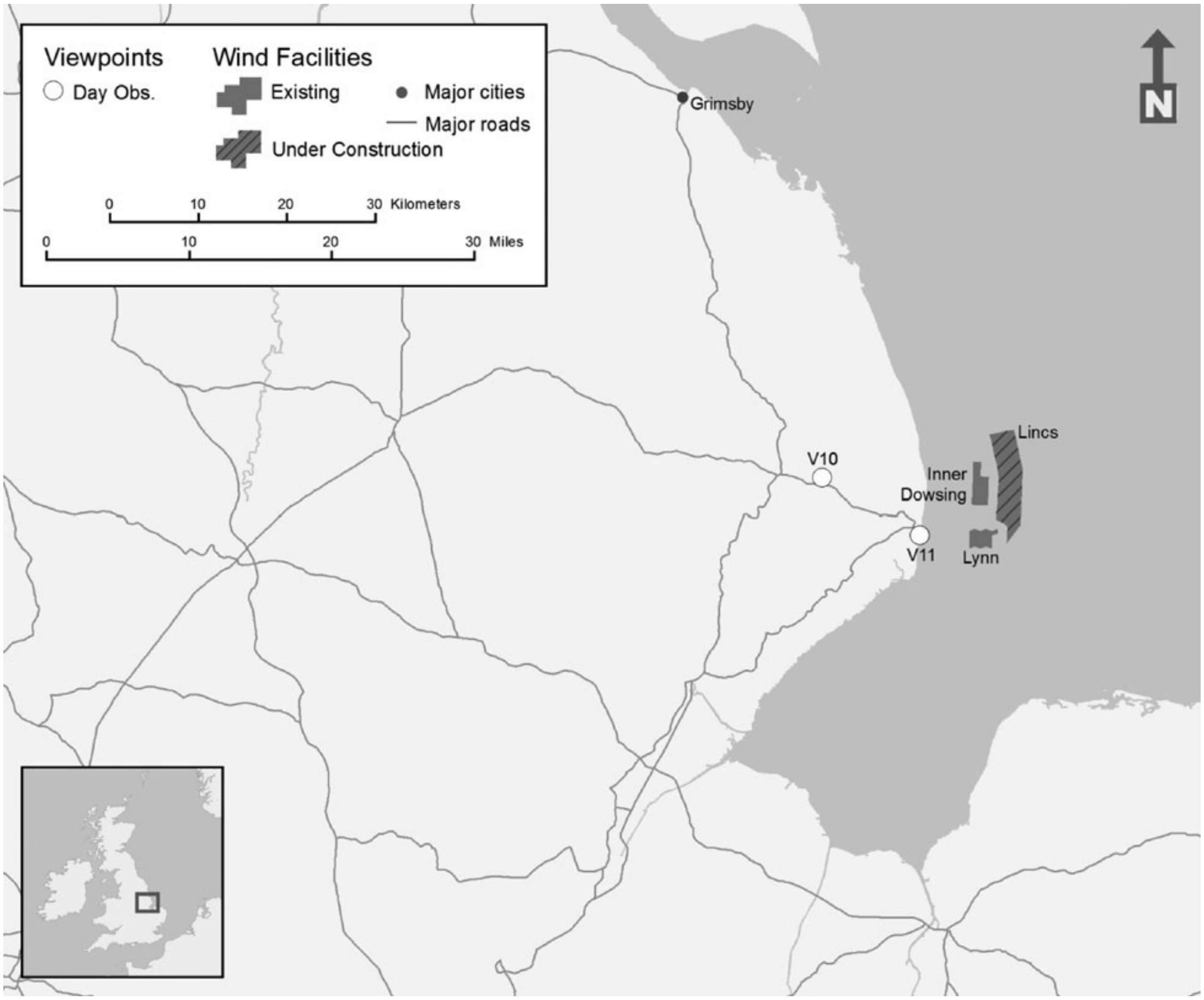

Figure 2. North Sea offshore wind facilities and onshore viewpoints.

edge that in some settings wind facility lighting could cause significant impacts at night because of changes in the character of the seascape. In a study conducted for the Cape Wind environmental assessment, the authors stated that, in evaluating the realism of night-sky impact simulations for the visual impact assessment, staff found aviation obstruction lighting on an operating commercial wind facility to be clearly visible at distances of 16–21 km (10–13 mi); visibility at longer distances was not evaluated. The authors further stated that the marine navigation lighting for Cape Wind "has a range of approximately 2 nautical miles" (Environmental Design and Research, 2003). As will be discussed, our present study shows that the visibility distances for both aviation obstruction lighting and marine navigation lighting are much greater than 16–21 km (10–13 mi).

Methodology

The fieldwork for this study was conducted in three regions of the UK from August 24 to September 1, 2011. Participants included a landscape architect, a geospatial visualization developer, and an archaeologist. A total of 49 daytime observations of 11 offshore wind facilities were made from 29 onshore locations, and 6 additional observations were made at night. The facilities observed were located in the Irish Sea near Liverpool, the North Sea near Skegness, and in or near the Thames Estuary. The facilities ranged from 25 to 140 turbines and were located within 6.0–52.0 km (3.4–32.3 mi) of the viewpoints. Viewpoints for the observations were chosen to represent key observation points used for the original preconstruction visual impact analyses in the facilities' environmental assessments. The facilities observed, the viewpoints, and the distances from the viewpoints to the facilities are listed in Table 1; maps of the facilities and viewpoint locations are in Figures 1–3. Elevations for the observations varied from near sea level for shots taken from beaches to 256 m (840 ft) for an inland hill. Observation elevations are included in Table 1.

For each observation, single-frame photographs and panoramic sequences were taken at a variety of focal lengths; at many locations, short videos also were recorded to capture the motion of the turning blades. Data recorded included descriptions of the location of the viewpoint; weather, general lighting, and visibility conditions; and the backdrop content and color. In addition, observers collected information about the solar azimuth and elevation, the layout and height of the visible turbines, the shading and/or sunlight on the turbines, and the overall lighting angle. If observed, information about aviation and marine navigation marking/lighting was included, as well as whether blade movement or other transitory effects were noted. For nighttime observations, additional data collected included the number, type, and cycle of the aviation and/or marine lighting.

Visibility assessments for the facilities were also made for 39 of the observations, by using a methodology developed for the Visual Impact Threshold Distance Study—a study for the US Department of the Interior, Bureau of Land

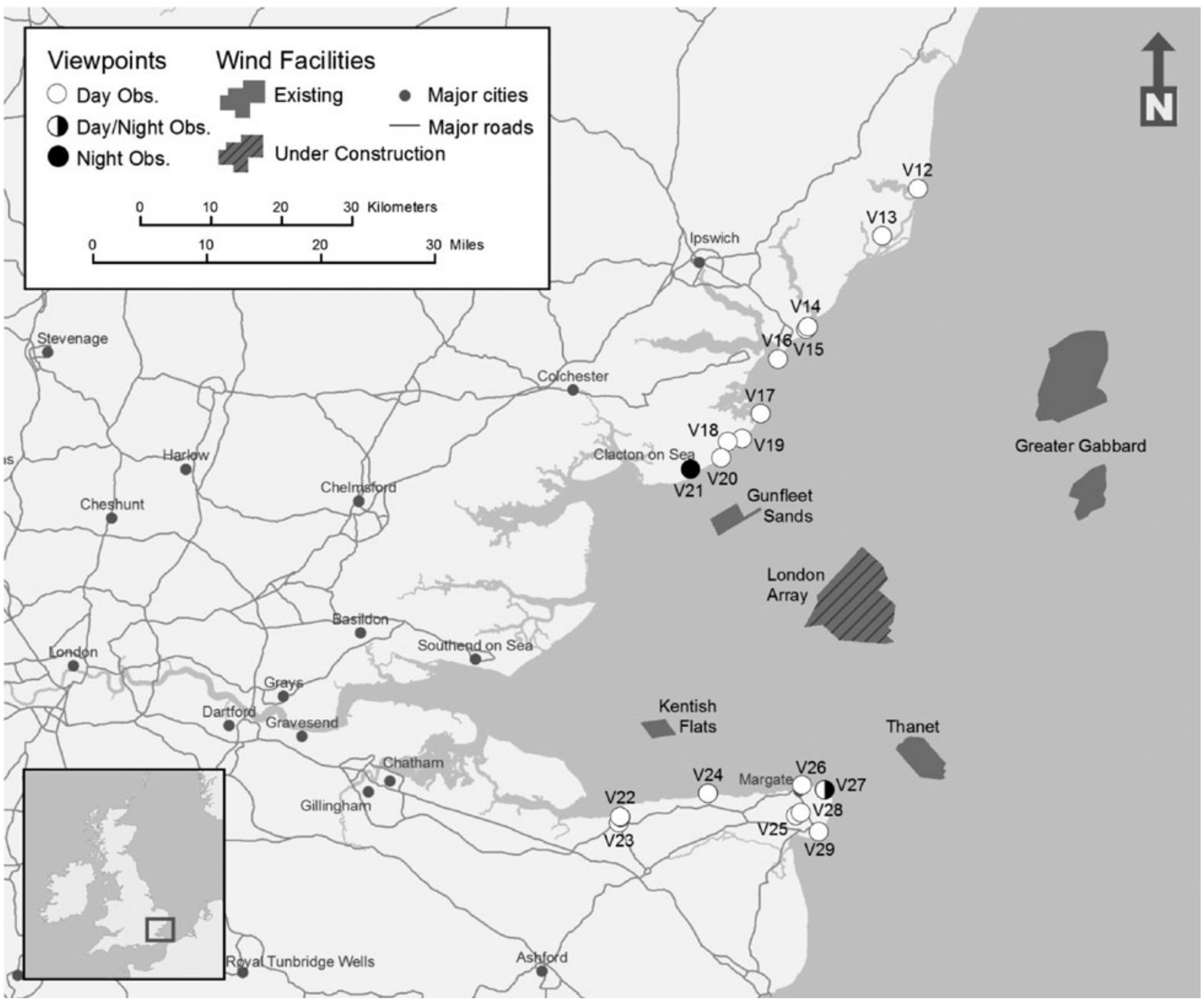

Figure 3. Thames Estuary offshore wind facilities and onshore viewpoints.

Table 2. Visibility Rating Form instructions used to rate visibility of offshore wind facilities

Visibility Rating Form instructions	
Visibility rating	**Description**
Visibility level 1. Visible only after extended, close viewing; otherwise invisible.	An object/phenomenon that is near the extreme limit of visibility. It could not be seen by a person who was unaware of it in advance and looking for it. Even under those circumstances, the object can be seen only after looking at it closely for an extended period.
Visibility level 2. Visible when scanning in the general direction of the study subject; otherwise likely to be missed by casual observers.	An object/phenomenon that is very small and/or faint, but when the observer is scanning the horizon or looking more closely at an area, can be detected without extended viewing. It could sometimes be noticed by casual observers; however, most people would not notice it without some active looking.
Visibility level 3. Visible after a brief glance in the general direction of the study subject and unlikely to be missed by casual observers.	An object/phenomenon that can be easily detected after a brief look and would be visible to most casual observers, but without sufficient size or contrast to compete with major landscape/seascape elements.
Visibility level 4. Plainly visible, so could not be missed by casual observers, but does not strongly attract visual attention or dominate the view because of its apparent size, for views in the general direction of the study subject.	An object/phenomenon that is obvious and with sufficient size or contrast to compete with other landscape/seascape elements, but with insufficient visual contrast to strongly attract visual attention and insufficient size to occupy most of an observer's visual field.
Visibility level 5. Strongly attracts the visual attention of views in the general direction of the study subject. Attention may be drawn by the strong contrast in form, line, color, or texture, luminance, or motion.	An object/phenomenon that is not large but contrasts with the surrounding landscape elements so strongly that it is a major focus of visual attention, drawing viewer attention immediately and tending to hold that attention. In addition to strong contrasts in form, line, color, and texture, bright light sources (such as lighting and reflections) and moving objects associated with the study subject may contribute substantially to drawing viewer attention. The visual prominence of the study subject interferes noticeably with views of nearby landscape/seascape elements.
Visibility level 6. Dominates the view because the study subject fills most of the visual field for views in its general direction. Strong contrasts in form, line, color, texture, luminance, or motion may contribute to view dominance.	An object/phenomenon with strong visual contrasts that is so large that it occupies most of the visual field, and views of it cannot be avoided except by turning one's head more than 45° from a direct view of the object. The object/phenomenon is the major focus of visual attention, and its large apparent size is a major factor in its view dominance. In addition to size, contrasts in form, line, color, and texture, bright light sources and moving objects associated with the study subject may contribute substantially to drawing viewer attention. The visual prominence of the study subject detracts noticeably from views of other landscape/seascape elements.

Form designed and developed by Argonne National Laboratory.

Management, to assess the effects of distance and atmospheric variables on the visibility and visual contrast levels of onshore wind facilities (Sullivan et al., 2012). The visibility assessments consist of numeric ratings on a scale of 1 to 6, scored on the visibility of a wind facility within its landscape/seascape setting and for the weather and lighting conditions at the time of the observation. The *visibility rating* is an observer judgment made by comparing the wind facility in view with language described on a visibility rating form that accounts for the visual characteristics of the wind facility appropriate to each rating level. Photographs were not used for visibility ratings; the ratings were conducted through naked-eye observations of the facilities in the field.

The rating scale is based on the US Bureau of Land Management's Visual Resource Management system (US BLM, 1984)—specifically, the Visual Contrast Rating (US BLM, 1986), which is used to predict the visual contrast of a proposed project with the surrounding natural landscape. The visibility rating form was customized for use with existing rather than proposed facilities. The form also included several open-ended questions soliciting information from the observer to justify, explain, and/or expand upon the numeric visibility rating. The visibility ratings and instructions used by the observers to rate visibility are reproduced in Table 2.

Visibility ratings of 1 or 2 would generally correspond with low levels of visual contrast in the framework of the Visual Contrast Rating, ratings of 3 or 4 would correspond with moderate levels of visual contrast, and ratings of 5 or 6 would correspond with high levels of visual contrast.

Each observer completed a separate visibility rating form for each observation, rating the visibility and answering the questions for each form independently without consulting the other observers. Observers could discuss their ratings after each observation but were not allowed to change the ratings once the form was completed.

Figures 4–6 are photographs of the Burbo Bank wind facility in the Irish Sea near Liverpool (see Figure 1 for facility location) taken during the visibility rating process for this facility. The photos, taken at different distances and in different lighting conditions, illustrate how distance and lighting affect visibility of offshore wind turbines. Burbo Bank is a relatively small wind facility with 25 Siemens SWT 3.6-MW wind turbines. The turbines have a hub height of 83.5 m (274 ft) and a 107-m (351-ft) rotor diameter, for a total height at blade tip of 137 m (449 ft).

Figure 7 is a photograph of the much larger Thanet wind facility near the mouth of the Thames Estuary off the coast of Kent (see Figure 3 for facility location). The Thanet facility consists of 100 Vestas V90/3000 3-MW wind turbines. The turbines have a hub height of 70 m (230 ft) and a 90-m (295-ft) rotor diameter, for a total height at blade tip of 115 m (377 ft).

Figure 4. Burbo Bank wind facility photographed from Leasowe Castle Golf Course (Viewpoint V5 in Figure 1), approximately 7.9 km (4.9 mi) from the closest turbine. The turbines are sidelit from the left but largely shaded. Visibility rating = 5.00. Equivalent 35-mm focal length = 57 mm.

Figure 5. Burbo Bank wind facility photographed from Thurstaston Commons (Viewpoint V6 in Figure 1), approximately 14.2 km (8.8 mi) from the closest turbine. The turbines are sidelit from the right, with 19 turbines in full sun, 6 partly shaded. Average visibility rating = 5.00. Equivalent 35-mm focal length = 55 mm.

Results

As already noted, a total of 49 daytime observations of 11 offshore wind facilities were made from 29 onshore locations, and 6 additional observations were made at night. Weather and visibility conditions varied widely during the 10 days allotted for fieldwork. Most days were partly to mostly cloudy; 1 day included significant, prolonged rainfall; and 3 days were sunny, although, for 1 of those days, fog at sea obscured visibility of the designated wind facilities entirely. In general, visibility was judged to be good, though many observations included low contrast levels between shaded wind turbines and cloudy-sky backdrops.

A total of 98 visibility rating forms were completed for 39 of the 49 daytime observations, and the form data were entered into a database for analytical purposes. For 21 of the 39 observations, three observers completed visibility rating forms; for 17 of the 39 observations, two observers completed forms; and, for the remaining observation, one observer completed a form. Caution should be used in interpreting the results of this preliminary assessment because biases could have been introduced by having a small number of observers with differing levels of visual acuity and potential individual biases, as well as a small number of observations for each wind facility.

Analysis of the visibility rating data indicated very good agreement between the raters. In many cases, the observers gave identical numeric visibility ratings, and in the vast majority of cases with three observers, at least two of the three were in agreement. In only two cases did observers differ in their numeric rating by more than one point; in

Figure 6. Burbo Bank wind facility photographed from Point of Ayr (Viewpoint V8 in Figure 1), approximately 16.7 km (10.4 mi) from the closest turbine. The turbines are fully shaded. Average visibility rating = 3.13. Equivalent 35-mm focal length = 52 mm.

one of these cases, the ratings were not made at exactly the same time; clouds that had shaded the turbines moved in the few minutes between evaluations, such that the ratings were made in different lighting conditions.

Analysis of the visibility rating data indicates a gradual drop-off in ratings with distance; the change is nonlinear, perhaps because of variability in lighting, contrast of the wind turbines with the background, facility size and layout, blade orientation and rotation rate, and various other factors that affect visibility in real landscape/seascape settings. Figure 8 is a graph of the relationship between distance and the visibility rating for all daytime assessments, regardless of weather and lighting conditions. The drop-off in visibility with distance was consistent regardless of weather, sun angle, blade movement, or blade orientation (although there was some variation in slope), suggesting that distance is indeed a prime determinant of visibility for a given design, size, and color of wind turbine.

Although caution is warranted because of the relatively small number of observations, the results suggest that, at a distance of approximately 16 km (10 mi), visibility drops below a rating of 5, indicating that, beyond this distance, the observed wind facilities were not a major focus of visual attention. At a distance of approximately 29 km (18 mi), visibility drops below a rating of 3, indicating that, beyond this distance, the observed wind facilities would likely not be noticed by a casual observer.

The observations made during this study suggest that, under favorable but not exceptional viewing conditions, moderately sized offshore wind facilities may frequently be visible at distances exceeding 35 km (22 mi); in this study, they were visible at a maximum distance of 44 km (27 mi) (Gunfleet Sands, Viewpoint V13, elevation 13 m). It should be noted that objects on the horizon may be seen at greater distances from elevated viewpoints because the screening effect of earth curvature is affected by viewer and target height. As would be expected, at these distances, the wind facilities were barely visible. However, when atmospheric conditions and lighting angles resulted in higher contrasts between the turbines and the sky backdrops, the facilities were judged likely to be seen easily by casual observers as

Figure 7. Thanet wind facility photographed from Fayreness Hotel (Viewpoint V27 in Figure 3), approximately 12.3 km (7.6 mi) from the closest turbine. The turbines are backlit in the early morning. Average visibility rating = 5.00. Equivalent 35-mm focal length = 57 mm.

far away as 29 km (18 mi) for a relatively large wind facility (100 turbines). Smaller wind facilities (25–48 turbines) were generally judged to be easily visible at distances of 22–25 km (14–15 mi).

With few exceptions, regardless of facility size or lighting conditions, on days with good visibility conditions, offshore wind facilities were judged to be major foci of visual attention at distances of 16 km (10 mi) or less, suggesting potentially high levels of visual impact for sensitive viewers. That these distances are greater than those reported in previous studies is likely a function of the long-term trend toward larger facilities with more and larger turbines than were assessed in previous studies.

Turbine blade movement was visible at distances as great as 42 km (26 mi) in 42 of the 49 daytime observations (Gunfleet Sands, Viewpoint V25, elevation 47 m) and was observed routinely at distances of 34 km (21 mi) or less. Contrary to expectations, lighting conditions, sun angle, and apparent contrast between the turbines and the sky backdrop did not substantially affect the likelihood of observing blade motion; blade motion was visible at distances beyond 30 km (19 mi) regardless of sun angle, lighting conditions, or contrast levels. Again, these distances are greater than those reported in previous studies.

Blade motion was noted by at least one observer as a major contributor to contrast levels for 24 of the 42 observations where blade motion was visible. All observers noted blade motion as a major contributor to contrast levels for 12 observations, one of which was at a distance of 34 km (21 mi) (Greater Gabbard, Viewpoint V14, elevation 8 m). Of the 24 observations where blade motion was judged to contribute substantially to visual contrast, 15 (62%) were at viewing distances of 16 km (10 mi) or less, suggesting that blade motion may contribute relatively more to visual contrast at shorter viewing distances.

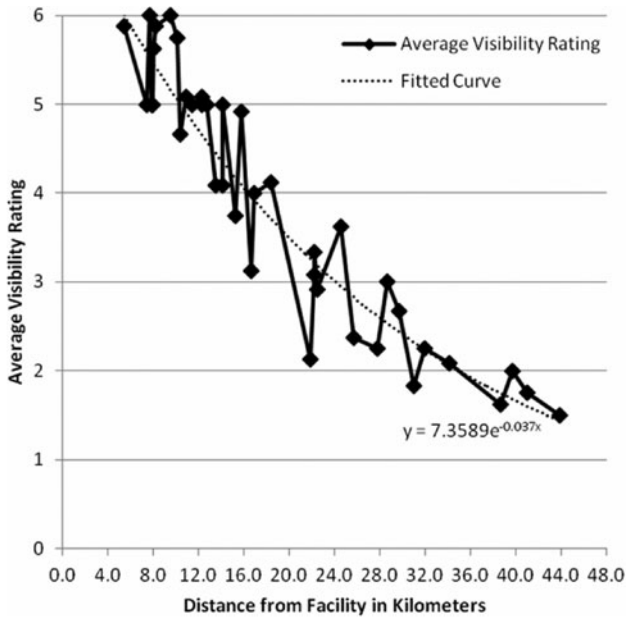

Figure 8. Offshore wind facility visibility-distance curve for 39 daytime observations of 11 offshore wind facilities in a variety of lighting conditions. The average visibility rating (y-axis) decreases as a function of increasing distance from the facilities (x-axis).

The base of each wind turbine tower must be painted yellow as an aid to marine navigation. The paint is reflective because it is designed to be easily seen, and it can contrast strongly with the white of turbine towers and dark sky or sea backgrounds. The yellow was noted as visible in 18 of the 49 study observations and at 8 of the 11 wind facilities observed, at a maximum distance of 17 km (11 mi) (Walney, Viewpoint V1, elevation 10 m). Marine paint was not stated to be a major contributor to visual contrast but was described as easily visible at distances up to 13 km (8 mi).

Our informal, qualitative opinion is that the photographs taken in the field generally show lower visual contrast levels than were actually observed during the visibility ratings. The photographs show lower contrast and less detail than was actually apparent in the naked-eye observations, and they do not capture the blade motion that attracted the visual attention of observers in the field.

Six observations were at night. Moderately sized offshore wind facilities were visible for long distances at night, with the red flashing aviation obstruction lighting visible at just under 40 km (25 mi) (Thanet, Viewpoint V27, elevation 20 m). At these long distances, the lights were not as bright as other lights visible at sea at the time but were recognizable as wind facility lights because of the spatial configuration and flashing. At a distance of 21 km (13 mi), both red aviation obstruction lighting and amber marine navigation lighting were visible at one facility, as seen from an elevated viewpoint (North Hoyle, Viewpoint V5, elevation 17 m). At shorter distances [7–12 km (4–7 mi)], amber and/or white marine lights and red aerial lights were visible for all observations and judged to be a major focus of attention within the visible seascape, in part because of the variable flashing rates and contrasting colors of the different lighting types. In some cases, at these shorter distances, the lights were judged to detract from seaward views, depending on the number and brightness of other visible lights and structures in the views. Although visibility ratings were not made for nighttime observations, an observer noted that lighting on a 30-turbine facility was bright enough to be visible from the interior of a normally lit room at a distance of 21 km (13 mi). Figure 9 is a nighttime photograph of Thanet Wind Facility (100 turbines) taken from Fayreness Hotel (V27 in Figure 3, elevation 20 m).

The visibility ratings for the fieldwork did not explicitly address cumulative effects when multiple offshore wind facilities are in view simultaneously from a given observation point, but the potential significance of the cumulative effects was noted by project staff, and local inhabitants mentioned this concern in several unsolicited comments. Because of the large size of offshore wind facilities, the existence of multiple facilities close to the observation point might limit the possibility for views of the seascape that do not include wind turbines, which some local inhabitants reported as a negative visual impact.

Figure 10 depicts another important type of cumulative visual impact: multiple wind facilities in a single line of sight. In this instance, two wind facilities at different distances from shore [Walney and Ormonde (viewed from V1 in Figure 1)] are visually juxtaposed so that the turbines appear to be interspersed. The line of sight is perpendicular to the long axis of the turbine arrays in both facilities, maximizing visibility of the turbines. Furthermore, one of the wind facilities (Ormonde) uses steel-lattice quadruped foundations that are partially visible projecting above the waterline and add substantially to the visual contrast of the turbines. The differing turbine size, style, and spacing between the two facilities create visual discordance that the observers felt strongly attracted and held visual attention.

Figure 9. Thanet wind facility photographed from Fayreness Hotel (Viewpoint V27 in Figure 3) at night, approximately 12.3 km (7.6 mi) from closest turbine. Most of the white lights visible in the photograph are marine navigation lights; red lights are aviation obstruction lights. The bright light in the center of the photograph is an offshore substation. The photograph is slightly overexposed.

Conclusion

This preliminary study has clearly shown that even small offshore wind facilities of a few dozen turbines can be seen easily at distances exceeding 25 km (15 mi) and that moderately sized facilities of 100 turbines are seen easily at distances of 35 km (22 mi) or even farther, in a variety of weather and lighting conditions. At distances of 14 km (9 mi) or less, even isolated, small facilities will likely be a major focus of visual attention in seaward views, again in a variety of weather and lighting conditions.

To date, most assessments of potential visual impacts of offshore wind facilities have identified lower levels of visibility at a given distance than the results of this study suggest. This is likely a result of reliance on earlier field studies of smaller turbines and facilities than are currently in use.

Applying visual ranges for those smaller turbines and facilities to today's technology might result in a systematic underestimate of the visibility of offshore wind facilities. Ultimately, this could result in siting of facilities close enough to sensitive visual resource areas and sensitive viewing locations to result in major visual impacts to these receptors. This, in turn, could engender stakeholder opposition that will delay or halt deployment of some offshore wind facilities. As nations move toward offshore siting of multiple wind facilities of hundreds or even thousands of large wind turbines, the visual impacts will increase dramatically, with significant potential cumulative impacts. Accurate knowledge of visibility of current and future wind

Figure 10. Ormonde (foreground) and Walney (background) wind facilities photographed from Walney Island (Viewpoint V1 in Figure 1), approximately 9.5 km (5.9 mi) from the closest turbine in the Ormonde facility and 17.0 km (10.6 mi) from the closest turbine in the Walney facility. Ormonde turbines are mounted on quadruped structures. An offshore substation is at center left. Equivalent 35-mm focal length = 157 mm.

technology as deployed at current and future scales will be even more critical to optimal siting.

It is essential to our national and global well-being to move toward less carbon-intensive energy sources, including offshore wind resources. Doing so in the most environmentally and socially responsible manner is also essential, if for no other reason than that failure to do so will invariably result in strong opposition from parties having an interest in or commitment to protecting potentially affected resources. Large-scale deployment of offshore wind facilities will involve major changes to the visual qualities of seascapes, from treasured views at national seashores and at historic and tribal properties to the everyday sea views of residents and visitors in coastal communities. Complete, accurate knowledge of the potential impacts to the nations' coastal visual resources is essential to achieving important national energy goals while fully considering ways to minimize potential environmental and social impacts.

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