Local wind energy as a new commons – evidence by quantitative geographical analysis

B. Möller[1]

Abstract

Wind energy is a limited local resource with potential for public ownership and can hence be considered a commons if wind turbines are installed by common bodies and the produced energy is commonly accessible. Wind turbine ownership as well as the reduced environmental impact of electricity production is a potential economic benefit to communities. The cost for community, apart from installation and operation, is mainly the visual impact of wind turbines.

While many point at off shore wind installations to solve acceptance problems of land based wind energy, on shore wind energy is still more feasible. Low investment costs, proven technology and – particularly interesting for the study of the commons – a significant potential as a common good managed locally by common bodies.

Protests against land based wind turbines can be considered a result of unequal distribution of ownership and visibility. Empirical evidence shows that shareholders in a wind energy project have fewer complaints about visual impact than people with no ownership. Improving management of the new common wind energy should therefore address questions of location and ownership.

The question addressed here is whether locally owned wind turbines have a future in a technology scenario where wind turbines continuously grow in size, making them less attractive to local communities for reasons of higher visibility, higher total project costs, and less easy organisation.

Quantitative geographical analyses in a raster-based geographical information system are used to model visual impact of actual turbines on local population. Possible ownership is identified by means of population density and distance functions. Finally a statistical link is established between visibility and ownership in order to identify the future chances for locally owned, economically feasible and socially accepted wind energy development.

The results indicate that the current approach of locating wind turbines may increase alienation and polarisation, while a different planning approach based on resource economics could lead to better local acceptance.

Keywords: *Wind energy, visual impact, resource economy, geographical analysis, GIS*

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[1] Sustainable Energy Planning Research Group, Department of Development and Planning, Aalborg University, Denmark. Email: berndm@plan.aau.dk

Introduction

Wind energy is the fastest growing source of power generation in Europe, comprising 40% of all power plant capacity installed in the EU in 2007 (EWEA, 2008). Exponential growth over two decades has increased the share of electricity generated from renewable, low-impact wind energy resources to considerable numbers. But in many places, development has come at a cost. Visual impact on valuable landscapes as well as socially inexpedient investments and ownership structures are among the main miscalculations made during the frenzied ‘gold rush’ of wind energy development’s first years.

Since land-based wind turbines are meeting increasing protest and planning restrictions, off-shore installations seem to be the solution. However, high costs, high risks and long lead times for projects could outweigh the benefits of higher output and lower visibility.

As wind energy is an efficient means to prevent global warming by reducing carbon emissions from power generation, and wind turbine development is highly distributed geographically, one could take a different view on the installation and operation of wind turbines. Wind energy can be considered a public good, or a commons, even in the classical sense where private profit within a community is made by commonly managing and utilising wind-rich areas, which are unfit to use otherwise, or which are used for purposes that go well with wind turbine development, such as agriculture. Another characteristic of a commons is the limitedness of a resource, which is also the case for wind energy as there are a limited number of good locations. As with many other natural resources, wind energy shows a characteristic of increasing costs of utilisation with cumulative amounts of resources used.

A commons is furthermore characterised by making common use of marginal lands which need proper management in order to avoid land degradation. Land is thus a limited resource, and land management becomes a necessity to maintain productivity. Translated to wind energy, this means that land with a good wind regime is a limited resource, which can yield profit to local communities when properly planned and managed, and when owned commonly. If the local community shares an interest in using nearby wind resources to create local income; to maintain landscape beauties; and to contribute to sustainable energy supply of future generations, then all factors seem to be in place to construe wind energy as a commons.

But what happens if wind energy is over-utilised by such a local community? First of all, there will not be a direct degradation of land that threatens future wind power generation. The ill effect of over-utilisation will be that landscapes themselves get degraded visually. Local people may see the necessity of income generation as something more important than how landscape looks. Problems will occur when people, who have no benefit from wind energy, complain about this development; as well as visitors, people from outside, and tourists. The latter case poses a competing use for the land, although studies from Denmark have shown that wind energy development may enhance the green image of a tourist destination (Krohn and Damborg, 1999). A negative attitude towards wind energy development nearby is often brought forward by people without benefit from wind energy development, or people who are envious.

Visual impact from wind turbines is restricted to the local areas surrounding wind farms. Dependent on the ‘lay of the land’, local topography and land cover greatly reduces the visibility of turbines, while visual impact is influenced by landscape value, the observer’s attitude, the visual pattern of wind turbines, as well as the distance to the turbines. It is impossible to map visual impact objectively.

Visual impact is limited to the lifetime of wind turbines. Landscapes will recover completely from visual impacts the day inexpediently located wind turbines are removed. Also, technological development should be considered in the assessment of negative effects on landscapes. Experience from Denmark, a country where wind energy has been harvested commercially since the late 1970’s, shows that wind energy landscapes change. Many small turbines are replaced with few, large installations, a development that has both positive and negative effects on landscapes and the public acceptance of wind energy development. A general tendency throughout the entire period of commercial wind energy development is the constant increase in turbine size, see figure 1.

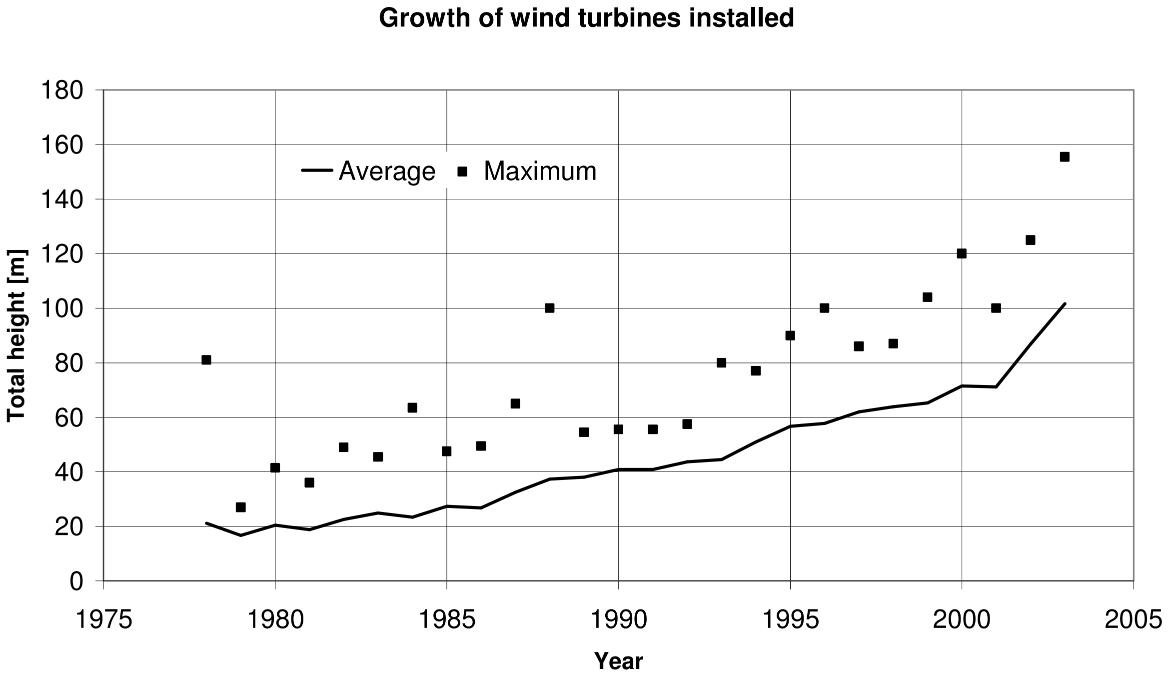

Figure 1: Growth of wind turbine size as indicated by total height from ground to tip. The figures are derived from a national register of all turbines in the country. While turbines have grown at a steady pace in the 1980s and 1990s, in recent years their development in size has accelerated.

This paper seeks to present quantitative evidence for the discourse on renewable energy generation versus landscape protection using spatial modelling of wind turbine visibility and distance, distribution of population and turbine ownership. A digital landscape model is prepared for Northern Jutland in Denmark, a region where wind energy development was pioneered. Spatial statistics of visibility and population are used to suggest that wind resources are best managed as commons.

Methods

The methodology needs to meet four objectives. Firstly, the resources and costs of wind energy generation under assumptions of area suitability need to be quantified in terms of marginal costs of cumulative resources. This is important because the economy of wind energy projects is almost entirely dependent on the optimal utilisation of the best wind regimes. Hereby an assessment of the economical potential as a proportion of the theoretical wind energy potential is given.

Secondly, intervisibility as a proxy of likelihood of visual impact caused needs to be mapped regionally as a continuous surface, and areas excluded from wind energy development need to be charted. This serves the purpose of limiting the physical resource base to the theoretical wind energy potential.

Thirdly, distance to wind turbines needs to be modelled, in order to weigh visual impact by distance and to locate those areas, where wind turbines and local communities are neighbours and hence potential sources of conflict or commonly managed wind resources.

Finally, a combination of resources, costs, visibility and distance should yield a means to cautiously weigh economic gains, environmental impact and landscape consumption.

During times the overall paradigm of planning wind turbines in Denmark has been to utilise the best locations first, aiming at the least possible costs of generation under constrained area availability. Large parts of the country are ‘blacklisted’ from wind energy development, such as urbanised and forested areas, coastal strips, areas of natural interest and conservation, as well as a large variety of buffers to built-up areas, infrastructure etc. Then, by ‘white-listing’ zones where wind energy could be developed, the area available has been limited even further. Interestingly, there never seems to have been an analytical means to prioritise investments by expected economic gain versus environmental loss. The application of geographical information systems (GIS) has so far been restricted to mapping and spatial planning, rather than a means for spatial modelling of resources, costs and constraints for development.

The current planning approach for land-based wind energy in Denmark (Agnolucci, 2007) favours re-powering schemes to replace older, poorly located or paid-back turbines with new turbines yielding much better energy output per area consumption, and at lower costs. The market for re-powering is significant: of the current 5,100 turbines (January 2008 data), about 1,000 will approach the end of their useful lifetime within the next 5 years, and roughly 2,000 turbines will have to be replaced due to age within the next 10 years. Replacement of older turbines will make much better use of suitable areas, reducing the landscape consumption by annual energy output by at least a factor 5 from more than 0.1 km^2/GWh/year for the average of plants built in the early 1980s, to less than 0.02 km^2/GWh/year for wind turbines installed today, see figure 2. These figures have been derived by approximation of the area consumption as a function of the rotor diameter, divided by the annual average energy production, both of which are recorded for all individual wind turbines in (DEA, 2008).

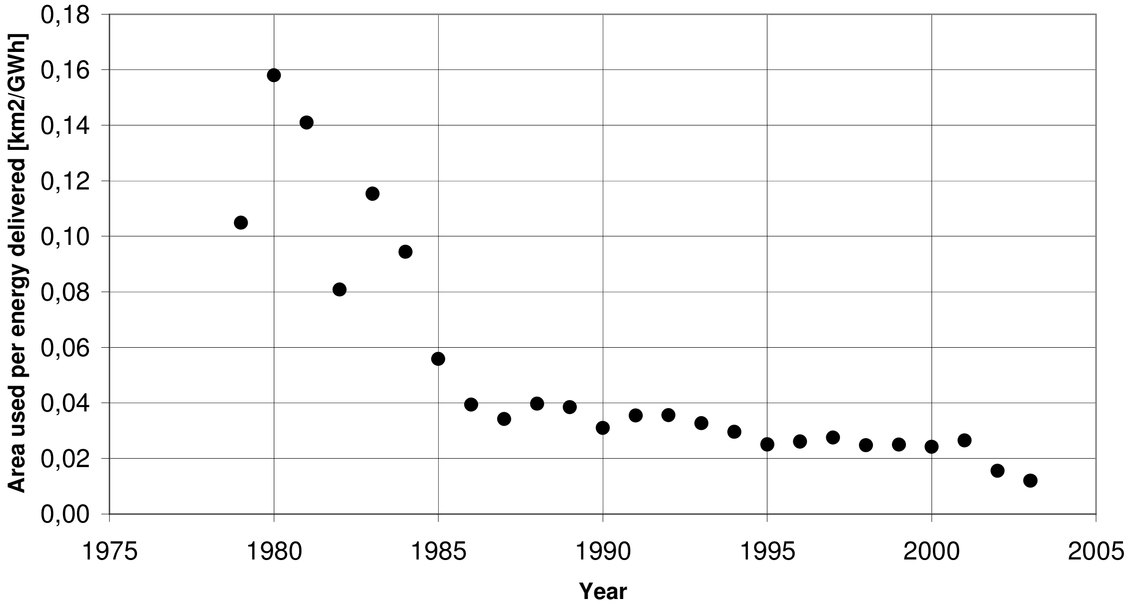

Figure 2: The specific area consumption of wind energy production has been greatly decreased as turbines have increased in size and capacity. Area requirements (A) have been assumed a function of rotor diameter (D) of turbines installed in subsequent years (A ≈ D^2 *25) and recorded energy production by year.

Finding locations for re-powering, however, has proven to be equally difficult. Hardly any areas are left suitable in the process. The compulsory environmental impact assessment (EIS) of remaining wind park sites is critical. The former county administration of Northern Jutland has ruled out all proposed sites in the year 2005 as a result of negative EIA, which seems to demonstrate that finding locations for new turbines might not be a matter of objective choices alone.

Visual impact, wind turbine size and ownership, as well as social acceptance are related. Changes in ownership can be observed in Denmark, as locally and cooperatively owned turbines reach their end of useful lifetime and are often replaced by corporately owned projects. Neighbours to proposed wind turbines increasingly raise protest; and a number of cases have been reported, where wind turbine development has been said to impact property value.

Several authors argue that local ownership would guarantee local acceptance (Hvelplund, 2006; Toke, 2005; Toke *et al.*, 2008). Meanwhile, it can be clearly demonstrated from the turbine inventories maintained by the Danish Energy Authority (2008) and EMD (2008) that (a) the share of local ownership is decreasing as many smaller, (b) cooperatively owned turbines built in the 1980s are less influent on the landscapes and (c) larger, privately or corporately owned turbines increasingly dominate the environment, see figure 3.

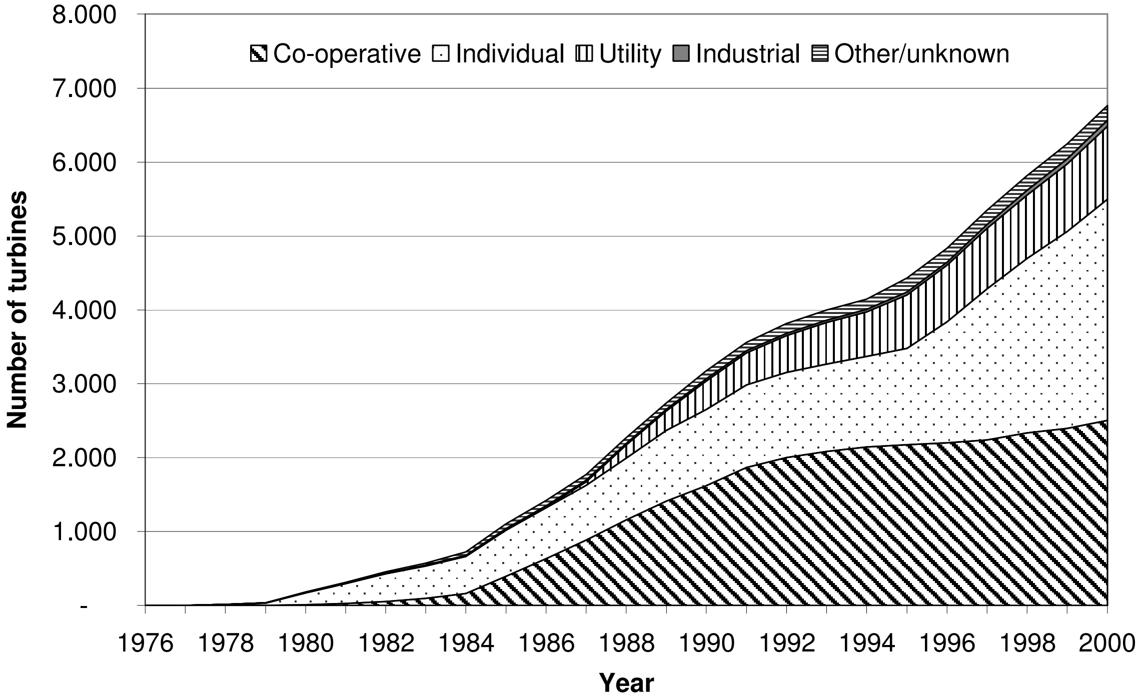

Figure 3: Ownership of wind turbines in Denmark has changed considerably since the early days. The diagram shows the number of wind turbines erected in each year by ownership. Development in the 1980s was dominated by locally owned co-operatives, while private individual ownership took over in the late 1990s. Data beyond the year 2000 is not available.

Visibility and wind energy economy seem to be causally connected: exposed locations are essential for wind turbines, because obstructions like hills, forests or buildings reduce energy production. Ideal locations seek to minimise landscape roughness in a distance up to 5-10 km, where visibility normally is highest. In Northern Jutland landscapes, dominated by glacial geomorphology, topography clearly is expected to influence both visibility and energy output, see figure 4. The challenge is thus to find locations with good wind regimes and low visibility at the same time.

This paper uses the concept of intervisibility for wind energy planning. When two locations are visible from each other, they are intervisible. Intervisibility is not a property of landscape, but the effect observation has on landscapes. Intervisibility quantifies in a deterministic way how visible a location is from all other locations. It is therefore assumed independent of the actual visual impact caused by existing or planned wind turbines, and could be used as a measure of the likely sensitivity of a location to wind turbine development in its neighbourhood. Intervisibility is however dependant on the observer and the observation process (Readinger, 2002).

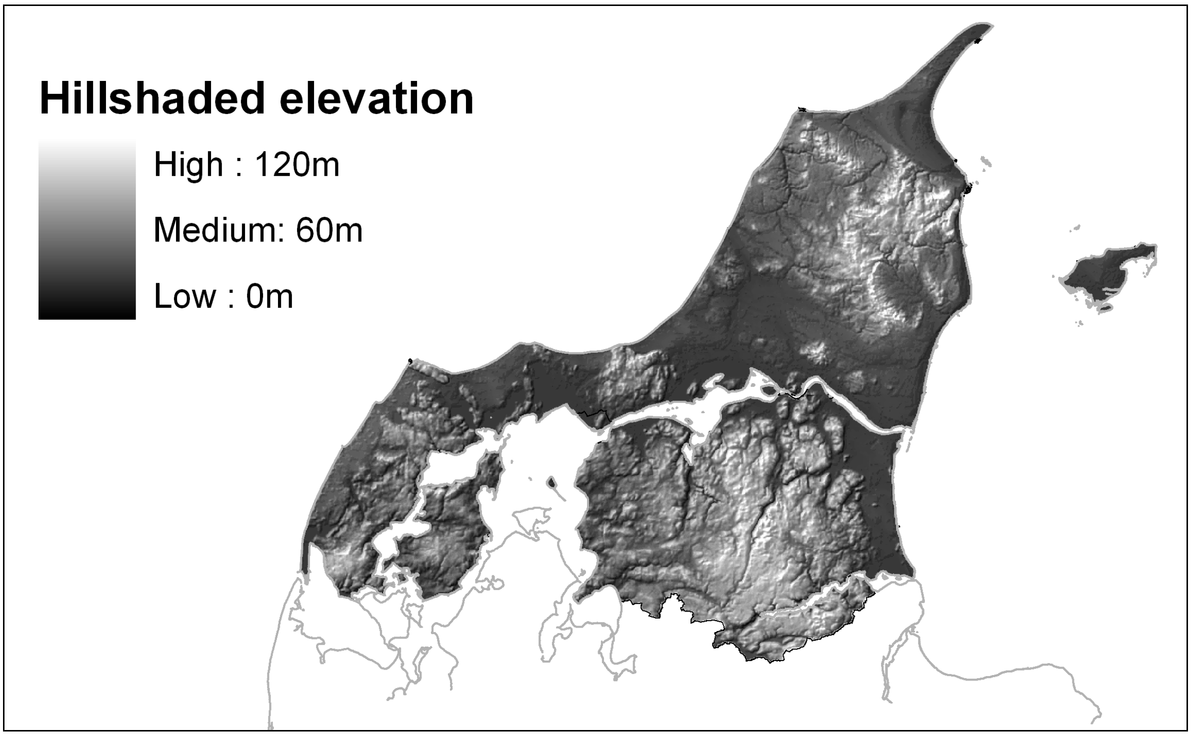

Figure 4: Hill-shaded elevation model of the Northern Jutland region, which has been chosen as case area for this study. The landscape is rather diverse and composed of hills, valleys, flats and open water areas.

Intervisibility can be quantified in a raster-based GIS as the number of landscape cells, which are visible by line of sight analysis from each landscape cell. The visibility count is influenced by the topography (absolute and relative elevation) of a locale. Intervisibility could therefore be used as a measure of visual exposure of locations in a region, practically as a data layer to be used for further analysis in a GIS. Using spatial statistics, pairing an intervisibility map with a wind resource map and a map of wind energy costs, the effectiveness of intervisibility mapping as an environmental-economic planning tool shall be analysed.

Intervisibility is practically always restricted by atmospheric phenomena (haze, rain, daylight etc.), landscape inventories (land cover, single obstructing objects, partly transparent objects etc.) and the eye of the beholder (some locales comprise a higher landscape value than others; and some observers are more sensitive than others). While some of these factors simply have to be neglected because of the complexity any adaptation to the real world brings along, others could be addressed in order to make these spatial models more realistic, and to approximate to quantitative analysis. One way of improving quantitative analysis in the field of viewshed analysis has been tried in an earlier study (Möller, 2006), while this paper uses the concept of spatial autocorrelation to a higher degree. Spatial autocorrelation is also referred to as spatial interaction or the notion of distance decay and has been used, among others, by Skov-Petersen and Snizek (2007). It includes the quantitative conception of the general phenomenon that distant objects have less influence on a process than objects located nearby (Getis, 2007). Spatial autocorrelation therefore establishes a mathematical function of diminishing influence by increasing distance. It could be used in the context of this paper to ascertain the visibility of turbines as a function of their distance, thereby effectively incorporating the not-in-my-back-yard

(NIMBY) argument, which seems to have gained much influence recently, but also the more general quantification of likely visual impact in larger proportions of landscape.

Model development

The study has made extensive use of GIS, including software for GIS-based analysis and geographical data. GIS were used as an analytical tool and modelling environment, as well as for preparing input data and for the interpretation and presentation of results. As GIS software, ArcGIS 9.2 by the Environmental Systems Research Institute (ESRI) was used, including the Spatial Analyst extension for raster-based modelling. The ModelBuilder graphical modelling environment was used for consistent and replicable design of spatial models. All geographic data were used within the same geodetic datum, European Terrain Reference System 1989 (ETRS89) and projected in the Universal Transverse Mercator (UTM) system. References to data royalties are given in the text.

Modelling intervisibility

Visibility maps are produced using surface analysis tools in a raster-based GIS, where line-of-sight analysis (LOSA) is a standard procedure. LOSA draws lines-of-sight between an observer location and all centroids of cells in a raster-based digital elevation model (DEM). If no obstacle obstructs the view, a value 1 is added to an observer location's visibility score, otherwise a value 0. The result is a regional map quantifying visual exposure from a given observer location (Burrough and McDonnell, 1998). An intervisibility map is an expansion of this concept, as it performs LOSA from all locations to all locations in a region. The result is a continuous map of the visibility of each location. It is an incredibly time-consuming process, which renders a map which, one produced, needs no further alteration or recalculation.

A DEM was derived from a 10m raster (KMS, 2007) by bilinear resampling, which smoothes the landscape and keeps values within the range of existing values. In military applications of intervisibility, choice of raster resolution is crucial for accuracy and computation effort. Reducing cell size by factor c results in c^2 times the number of cells and in c^4 times the number of LOSA calculations. Accuracy is mainly determined by the DEM resolution. Smith et al. (2006) have studied agreement between DEM resolution and output quality. Tests carried out for a small proportion of the Northern Jutland case area with a "typical" representation of landscape types, reveal that local landscape features disappear and landscape diversity is disregarded with increasing cell size.

It was found that within environmental impact assessment, high detail and accuracy are not necessarily requisites for this type of analysis. Intervisibility becomes less differentiated for increasing raster resolution. Large cell size overestimates the intervisibility of landscape, reduces small scale variations of landscape and works like a filter. The smaller the cell size, the larger is the influence of smaller objects. A trade-off has to be found between the importance of objects such as buildings and forests and the computation efforts. Due to the large range of values of the produced intervisibility maps, and the incorporated autocorrelation and distance decay, even a reduction of detail does not affect the final result very much. It was therefore assessed that a raster resolution of 500m would allow for reasonable computation times. The resulting surfaces were then interpolated bi-linearly to 200 m in order to match the wind resource map. The bilinear interpolation results in smoother surfaces deemed better for planning purposes, but not necessarily expressing true intervisibility.

The calculations involving 2.4 billion LOSA calculations in between 49.000 grid cell centroids of a 500 m raster take between 2 and 11 hours for intervisibility analyses with variable cut off radii using a Pentium Centrino computer with 1.8 GHz and 2 GByte RAM. Alternative, time-saving algorithms as in Sansoni (1996) and Mills *et al.* (1992) were not considered.

Viewshed analysis allows for setting the height above ground for observers and the observed locations. Observer height was set to 2 m, while the observed locations received a height of 100 m, which is the hub height of wind turbines currently used. Although wind turbines are higher than that adding half the rotor diameter, the hub height was chosen because it comprises the centre of visibility of a wind turbine. Because of the large difference in height, errors due to the coarse raster resolution become less apparent around the source. The law of geographical scale, where the relative difference between largest and smallest objects is more relevant than the absolute size of the smallest objects, supports this choice.

A crude implementation of distance decay and spatial autocorrelation of decreasing visibility by distance was achieved by the arithmetic overlay of several intervisibility surfaces derived for specific cut-off distances. The choice of a cut-off radius effectively reduces the influence of remote locations to local visibility. This makes sense because wind turbines, in a completely flat landscape, become practically invisible at large distances, as shown by Shang and Bishop (2000). But visibility and sensed visual impact are not simply inversely proportional to distance: although modern turbines are taller, they are also more slender and their slower rotation is deemed to reduce visual impact further.

Since no earlier studies in this field yield suggestions for mathematical functions of visual distance decay, and empirical or field studies are impractical, the simplest form of a distance decay function was chosen: I = 1/d, where I is the impact, d the distance. This fits well with observations made by Bishop (2002), who distinguished certain thresholds where, at a certain distance, visibility became visual amenity. A recent study by del Carmen Torres *et al.* (2007) points into similar directions, thereby entirely relying on expert knowledge.

A combination of viewshed analysis and distance decay was not found available in commercial GIS software. But using the cut-off distance of standard viewshed tools, combined with an arithmetic overlay, maps with different cut-off radii can be added and divided by the number of input grids to produce an approximation to a decay function. Using this approach, a composite intervisibility map was prepared for the Northern Jutland region by adding normalised intervisibility grids prepared for distances of 2 km, 5 km, 10 km, 20 km, 50 km and infinite with the weights for these distances. The maximum distance across the region is 193 km, but most coasts are less than 100 km apart. As the added intervisibility surfaces are in geometric intervals, their arithmetical sum forms an inverse linear function; see figure 5.

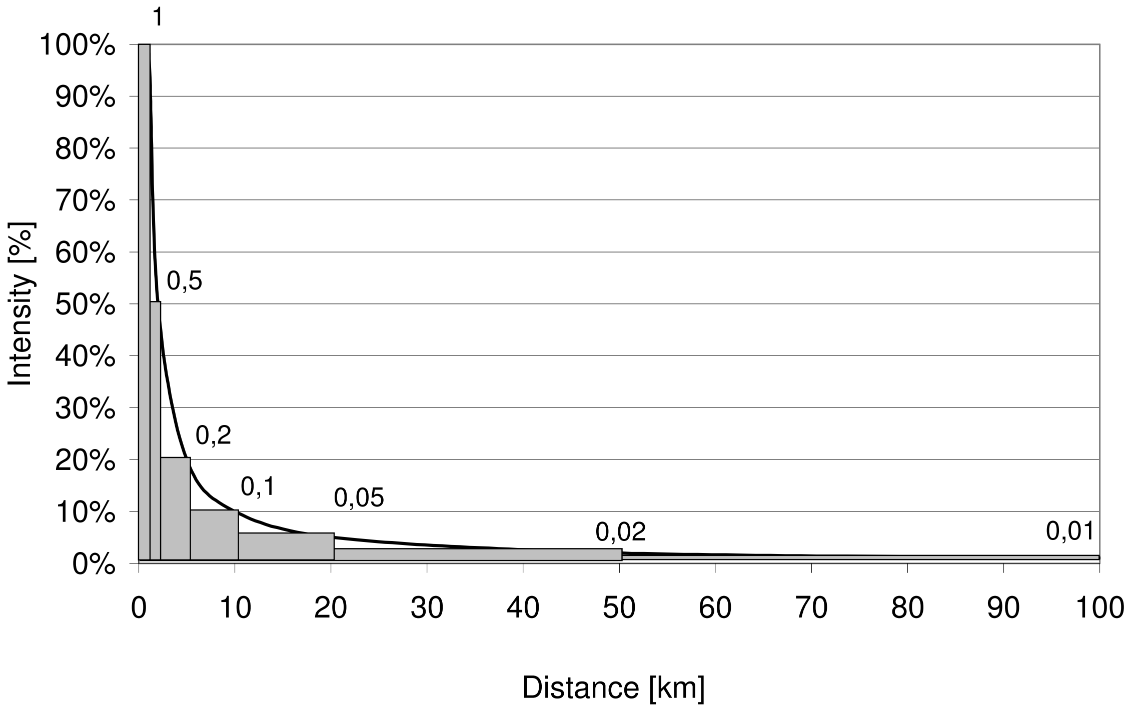

Figure 5: Approximation of a distance decay function I = 1/distance by composite intervisibility maps. Six intervisibility maps were prepared for the cut-off radii 2, 5, 10, 20, 50 and 100 km with the intensity valued shown in the diagram.

Viewshed analyses are prone to border effects if the visibility of turbine locations from a neighbour region is neglected. Hence a buffer of 50 km was added to the input DEM, leaving only contributions less than 10 % out of the analysis. The resulting experimental area covers 14 200 km^2, excluding sea and inland waters. The area of the region itself is 7 617 km^2. An analysis mask has been applied, covering Northern Jutland region alone, while the extent of the analysis also covers inland waters and contributions from nearby islands across the sea.

Distance to wind turbines

Distance to the nearest wind turbines registered by the Danish Energy Authority can be calculated using a Euclidean distance tool, which calculates the distance as the crow flies between each landscape location and the nearest wind turbine. This results in a measure of proximity to all existing turbines, regardless their size and their numbers. Since larger turbines and those arranged in parks induce a higher visual impact than smaller, single turbines, another method needs to be applied. A kernel density function calculates the number and size of turbines within a given distance and applies weight to these factors, which decreases by the square root of distance. Figure 6 shows a kernel density map prepared for the wind turbines in the region, using a 10 km search radius, the total turbine height as the population field, and a quadratic kernel function.

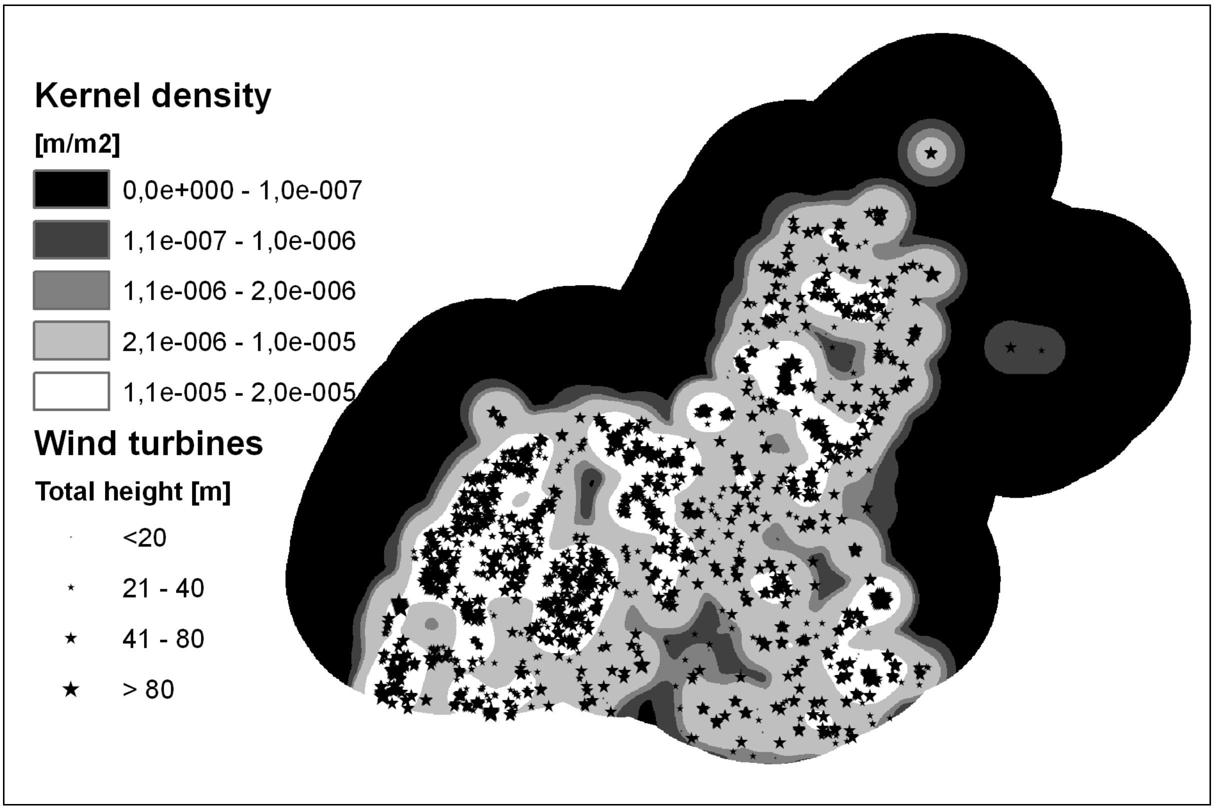

Figure 6: The kernel density of wind energy development in the region shows centres of wind energy development as well as areas with lower densities hence lower likelihood of visual impact.

Costs of wind energy generation

To assess the relation between wind regime and visibility, a wind resource map was prepared with Wind Resource Mapper by EMD International, which uses topographical information and local influences, following the Wind Atlas (WAsP) methodology (Petersen *et al.*, 1981). Energy production of a 2 MW turbine with 80 m rotor diameter on a 100 m tower was calculated for a 200 m grid resolution, see figure 7. Although the sizes of future turbines probably will be in the order of 3 MW, the smaller size has been chosen because better production prognoses exist. The area requirements of larger turbines might be smaller, but the costs will most likely be in the same order. Since the costs of producing electricity decrease nonlinearly with increasing wind resources (Morthorst, 1999), it was necessary to calculate the costs of production as a function of energy production and area consumption. The required land area for a turbine can be approximated by spacing of turbines in main wind direction by 7 times the rotor diameter, and 4 times the rotor diameter perpendicular to the main wind direction. For an 80 m diameter wind turbine this results in an area consumption of 16 ha, which means that a 200 m grid sized 4 ha/cell may contain up to 0.5 MW/cell. This is an average value for turbines in parks with regular grid spacing. Other configurations yield a better or worse utilisation of area, for smaller or larger wind parks.

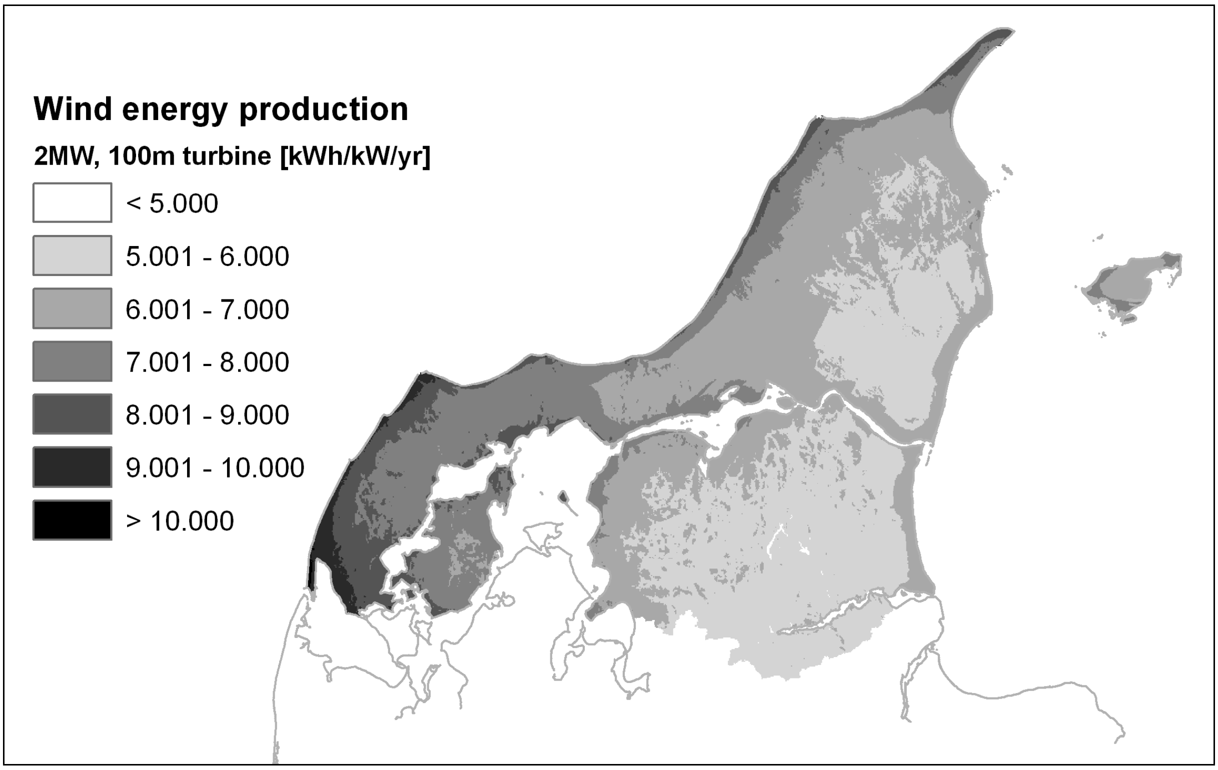

Figure 7: A wind resource map for the case area. The raster map with a resolution of 200m shows the production of a 2 MW wind turbine with 80 m rotor diameter and 100 m hub height. The map was produced using the Wind Resource Mapper software by EMD International, which is based on the wind atlas software WaSP by Risø.

Investments, operation and maintenance costs were kept constant for all locations. Land rent was excluded from this study, especially because experience shows that land rent depends on the planning permissions achievable for a given location. Net income was set to zero in this study, by letting the net present value (NPV) be nought after 20 years of operation. This results in a balanced cost calculation with neither gains nor losses, hence expressing the costs of wind energy generation to society.

Further input to the cost calculation is derived from the technology catalogues of the Danish Energy Authority, an authoritative source for socio-economic calculations of energy systems (DEA, 2005). Investments of turbines including auxiliary installations, grid connection etc. were set to be 0.75 M€ / MW; operation and maintenance costs are 8.50 € /MWh electricity produced in average through the lifetime; and a lifetime of 20 years was chosen. The interest rate was set to 3% and 6% respectively to include alternatives for the assessment of future investment from a shorter and longer termed perspective. The resulting map of balanced wind energy generation costs shows values from 22 to 36 €/MWh (3% discount rate) and 33 to 57 €/MWh (6% discount rate) for wind regimes of 6.7 to 10.1 m/s in 100 m height, see figure 8, which also shows the supply curves of wind energy including the exclusion of areas unsuitable for wind energy exploration, see next chapter. The initial inclination of the supply curve reflects the fact that the highest wind energy potential comes from a rather small area, which is soon exhausted and succeeded by less attractive locations. The curve will eventually flatten out. The curve hence is useful for assessments of the most optimal locations of wind energy utilisation.

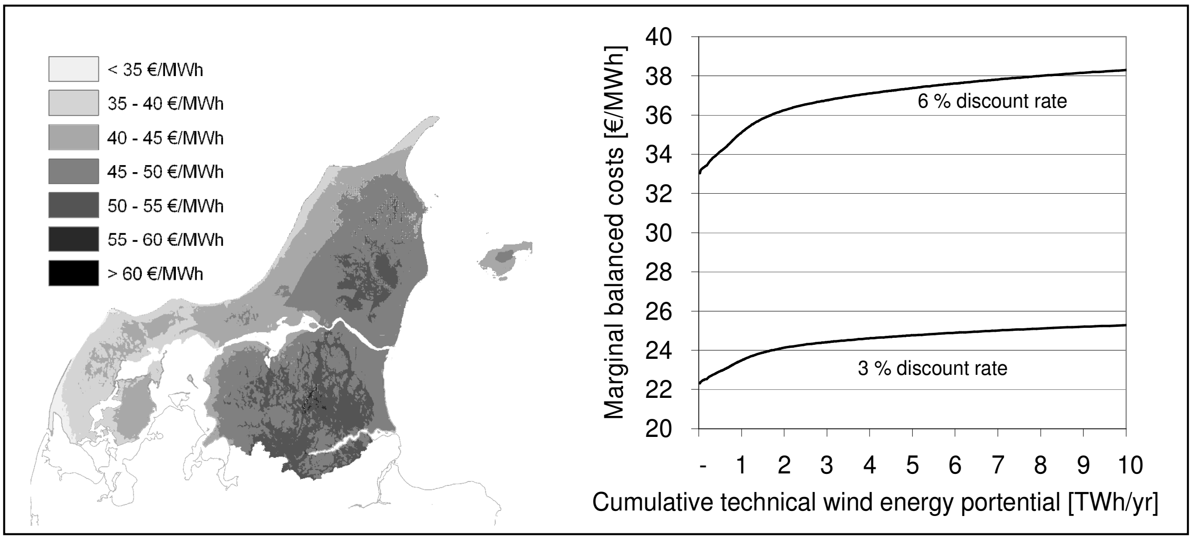

Figure 8: Left: a wind cost map for Northern Jutland (here shown for 6% discount rent) reveals pristine wind resources in a small area at the west coast, and good locations along the remaining western costs and some inland locations, with production costs much lower than average. Right: the supply curve of wind energy, restricted to the first 10 TWh out of a total of 113 TWh, shows the marginal balanced costs of wind energy generation. The curve is steepest until a potential of about 2 TWh, which is twice the resource utilised today.

Area exemptions due to planning

Wind turbines can obviously not be built in cities, towns and villages, in nature reserves or forests as well as other areas exempted from this type of development. These locales are consequently removed from the analysis. Buffers, an important part of current planning, are used differently than in regional and municipal planning as the model works with gridded raster data instead of discrete vector data. The resulting geometrical errors may be critical in local context, but less so on a regional level because smaller areas, which could form the locations for single wind turbines or small groups, will not be detected by the model. And since the aim is to find locations for larger groups at a regional scale rather than detailed local planning, this shortcoming is deemed insignificant.

Only land used for agriculture, including ploughed fields and pastures are included as potential locations in the model. The data base used comprised a detailed land use map prepared by the National Environmental Research Institute (Groom and Stjernholm, 2001) with a recommended scale of 1:25,000. Alternatively, the European CORINE data set (EEA, 2008) could be used, but it lacks detail as the smallest polygon is the same size as the raster resolution used here. The coastal protection zone as well as the natural reserves in the NATURA 2000 catalogue and other protection themes, see table 1, was accessed from the governmental environment geodata portal Miljøportal (MIM, 2008).

The nine individual vector data layers were merged and converted into raster data sets with 200m cell size with the values “1” for areas where wind turbines cannot be built and “nodata” for all other cells. The resulting raster is used as a mask, which only returns values where cells have a value other than “nodata”.

	Area within NJ [km^2]	Area within NJ, % of total
EU Ramsar areas	240	3,15%
EU bird protection area	578	7,59%
EU Habitat areas	830	10,90%
National conservation areas	471	6,18%
Proposed national conservation	115	1,51%
Pristine nature areas	1	0,01%
Protected nature areas	1.176	15,44%
Antique church protection lines	99	1,30%
Forest protection lines	1.843	24,20%

Table 1: Areas where planning and natural protection rules out the possibility to develop wind energy in Northern Jutland. Some of these areas overlap, and it should be observed that only land areas are included. Bird protection and Ramsar areas typically include water surfaces.

Built-up areas need a buffer of 500 m, which was approximated using a focal maximum function, which expands the neighbourhood of built-up areas with 3 cells.

The resulting exemption dataset, see figure 9, is used as a mask in the analysis in order to exclude locations considered inappropriate for wind energy development. The mask is used consequently for all analyses of resource, costs and intervisibility overlay, while each of the inputs to the overlay procedure is prepared for the entire landmass for the sake of better visual interpretation.

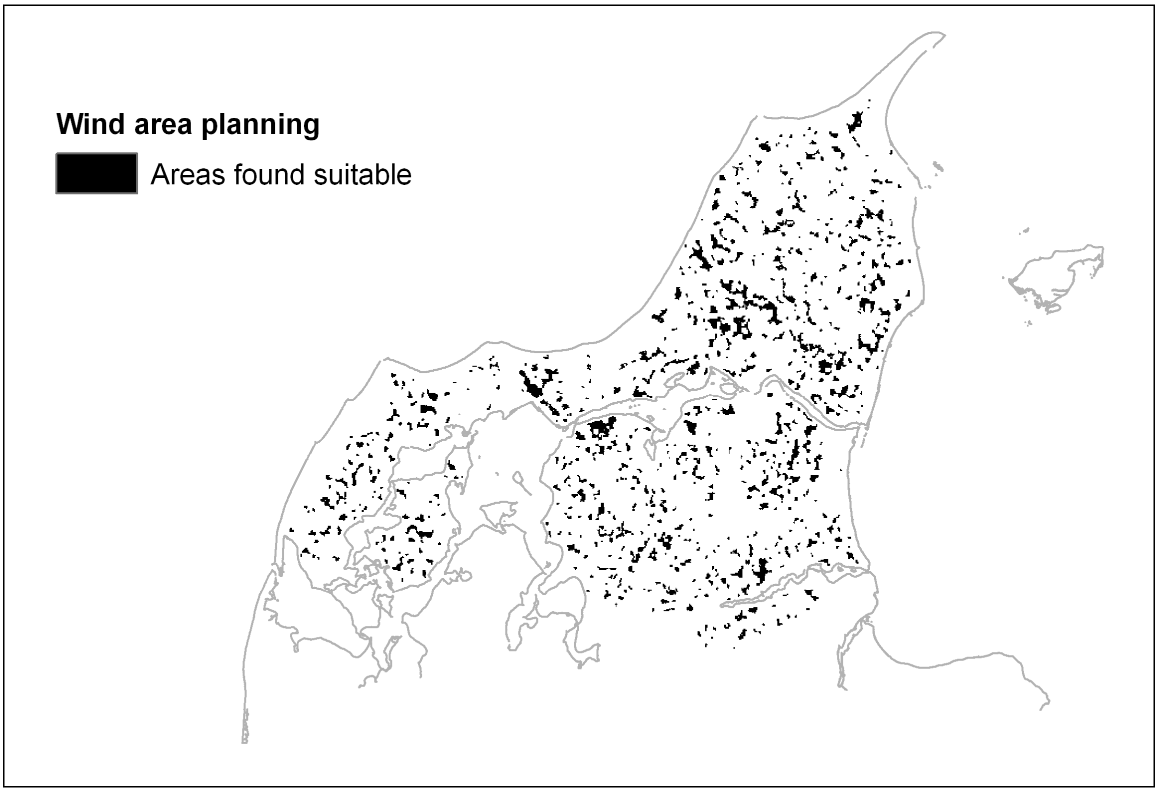

Figure 9: Areas which were found theoretically suitable for wind energy development, found by subtracting various exemption zones and buffers from agricultural land. The remaining area is 703 km^2, equal to 8.9% of the land area.

Table 2 shows a breakdown of the remaining areas after each of the spatial analysis processes applied.

	Area [km^2]	Area [%]	Remaining area [km^2]	Remaining area [%]
Total land area	7 617	100%	7 617	100%
Agricultural areas	5 081	67%	5 081	67%
Areas protected by planning	2 956	39%	4 164	55%
Built-up areas and buffer	5 626	74%	881	12%
Coastal strip buffer	360	5%	840	11%
Majority filter and size > 4ha	703	9%	703	9%

Table 2: Areas suitable for wind energy development have been derived through a raster-based analysis, where generally suitable agricultural areas were excluded by Boolean overlay if planning, built-up area buffers and coastal buffers were in the way. The remaining areas were majority filtered to exclude narrow strips. Areas smaller than 4 hectare were removed. The remaining areas comprise 9% of the land mass in the region.

Combination of planning data, visibility, wind regime and costs

The overlay analysis uses a zonal statistics function, where values are summarised for a number of specified zones. Zones are here understood as integer values of the cost variable: balanced costs of power production, intervisibility or land demand. For each of the zones the available wind energy resource is summarised and the result is exported to a table for further processing in a spreadsheet. Here, the specific costs are multiplied with the resource to acquire the total costs. Total costs and wind resources are accumulated, and the marginal costs are plotted against the cumulative wind resource in an x,y-diagram, forming a supply curve.

Interpretation of results

First, in order to test intervisibility as a location criterion for commonly managed wind turbines, geo-statistical analyses with costs maps, visibility maps, exclusion areas and population count were carried out combining the input variables by zonal statistics.

It can be demonstrated from combining wind energy generation costs and intervisibility maps that it is not necessarily apparent that good wind resource locations are highly sensitive to visual impact because of good visibility. From an analysis of area availability and the costs of supply it can be seen how degrees of intervisibility as a criterion affect the costs of utilising wind energy. When normalising visibility and wind resources on a 0 to 100 scale, visibility is rather low in most locations with good wind regime.

It becomes furthermore evident that intervisibility of landscape locations is not evenly distributed across more or less densely populated areas. Locations such as peninsulas and islands, despite their exposure, have generally lower visibility than large and flat areas. It can be seen from the intervisibility map in figure y that hilltops expectedly have high visibility, but small available areas and a lower wind regime than planes. Coastal areas along the West coast have low visibility compared to their surroundings, but a high wind energy potential, making them obvious locations to build turbines that are highly productive but little visible. Unfortunately these areas are all under heavy natural protection, and for good reasons.

A quantification of the economic effects of using visibility as a planning criterion is therefore required. A supply curve is shown in figure 8, which visualises the amount of wind energy from all agricultural areas excluding areas that are protected. The supply curve was created by plotting visibility over accumulated wind resources, using the spatial statistics from the overlay of both themes. The regional supply curve establishes a mathematical relation between the wind resource supply in Northern Jutland and the “costs” connected with visual impact. It can be seen that the vast majority of wind resources in the area are available at rather low “costs” of visibility.

Discussion

Every exclusively data-driven approach is doubtful to produce results applicable in a real situation. Any outcome of this study therefore needs field testing and a backup of empirical data to be applicable. The work presented here needs to be used in praxis, ideally in a participatory planning situation where various stakeholders align their interests by means of the proposed model.

The methods themselves have been used earlier in another context and within different disciplines, and are fully documented in literature. They allow for adaptation to various contexts and geographical settings. The supply curve approach is generic in a sense that it is applicable for analysis of various impacts and resources.

The intervisibility analysis is the most resource intensive part of this study and seemingly the one most error-prone. The limitation to a raster resolution of 200-500 m brings along that the results of this study are not useful for detailed local planning, and that a considerable uncertainty should be allowed for any interpretation of results. It may be possible with networked computing or super computers to improve the raster resolution, but this may only lead to better results locally, while the regional outcome is assumed to be the same. Since remote locations have a significantly lower weight than visibility contributors nearby, the error in line of sight analysis due to coarse raster resolution, errors in elevation values and even the missing landscape inventories are believed to be of much less significance than for the analysis of intervisibility in e.g. military applications.

The analysis of spatially distributed costs of wind energy has not been attempted this way before, despite the good data base comprising of a detailed wind resource map and well-documented costs of wind energy generation. There are a few shortcomings and caveats related to the park layout and the site-specific costs. Wind turbines are usually arranged in parks, where shading reduces their average efficiency by as much as 15 %. This has not been taken account for specifically, but by applying a general loss factor. The variation of site specific costs originates in higher or lower costs of grid connection, foundation and road building, while land rent deliberately was excluded. There are, however, no indications for a general lower suitability of wind energy locations on the grounds of remoteness to the public grid and to roads, and the overall geology is rather alike across the region without tendencies towards more or less expensive foundations.

The exclusion of zones where wind energy is not possible because of unalterable land use, nature conservation or planning issues bears a few error sources due to the coarse raster approach. The effect is that possible wind turbine locations are subject to uncertainty. The conversion of discrete polygons of land use to continuous raster fields causes the loss and gain in equal proportions because the criterion for conversion is 50% cell area. Another source of error is the neglect of buffer areas smaller than 200 – 300 m, caused through the raster conversion.

The data base for the modelling process is judged to be authoritative. Partly it consists of the best available elevation and other topographical data available in Denmark; partly it is based on governmental data used in public administration and law enforcement. The wind resource map is thought of as the so far most reliable source for wind energy resources. Finally, the land use map is the most current available, but the choice of land use classes available for wind energy planning is subject to revision, as a few more classes might be added.

Conclusions

It is difficult to quantify to which extent a commonly managed wind resource reduces visual impact while at the same time utilising local wind resources optimally. Any project might be visible but a spectator will not necessarily see it as such. Visibility is affected by differences between model and reality, by physical effects such as atmospheric haze, by the frequency of spectators and by landscape inventories such as vegetation.

It can be demonstrated that the areas with high concentrations of wind turbines are not necessarily the areas with the highest potential for local investment. The largest part of wind resource is available in remote areas, and even in a rather densely populated country like Denmark there are few spots where wind resource and population seems to be the cause for problems with wind energy sensed by a larger part of population. There seems to be a natural cause for commonly managed wind energy in rural areas.

This work in progress shows that wind resources and visibility as drivers of and limits to local wind power development as commons are not necessary contradictions. They are unique landscape properties and need therefore to be analysed for each region in question. Intervisibility of landscape locations seems to be efficient to tell apart areas where turbines are likely to be seen from many other locations. The spatial overlay with wind resources allows for an assessment of the areas that need to be “sacrificed” for preservation of precious landscapes. The visual and arithmetic overlay alone, however, does not allow for an economic assessment or, if this path is followed, for a prioritisation of land use for wind energy development contra preservation.

What the cost curve tells is that most wind resources in the area, excluding those located in areas that are subject of protection and preservation, are not exposed to high visibility and therefore may very well become subject to a commons style their management approach. The highest visibility in the area was computed for some flat areas in the central planes and for hilltops. If setting a threshold for acceptable visibility, the cost curve can in its final version reveal a relation between acceptable visual impact and the costs of wind energy generation. It seems there is good cause to believe that the economically attractive potential for commonly managed wind resources in local areas is considerable.

The ongoing research needs to include a more detailed DEM in order to include many local effects in the hilly landscapes of Northern Jutland. The economic calculation of wind energy costs as a function of wind resources needs to be improved as it cannot deal with the specific costs related to small, locally owned wind parks. Area consumption calculations need to be improved as well. The spatial statistics applied in this paper, essentially used to test the correlation between land use, visibility and wind regime, need further refinement. The expected outcome will be a more thorough analysis of intervisibility as a suitable criterion for location of future wind turbines.

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