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HOW WIND POWER LANDSCAPES CHANGE: AN ATTEMPT TO QUANTIFY VISUAL IMPACT ON LAND USE AND RESIDENTS IN NORTHERN JUTLAND, DENMARK

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ABSTRACT

Following 25 years of continuous development, Danish wind energy landscapes are going to face changes. Ceased on-shore construction, unresolved re-powering and stalled regional planning characterize the situation overshadowed by off-shore development. One of the factors inhibiting development appears to be planning uncertainty regarding the future impact on landscapes. Visual impact has seldom been an issue so far, but growing turbine size and less local involvement may change this. This paper presents a deterministic approach of quantifying percieved visual impact on landscapes and population, taking into account that there is no clear threshold for perceived visual impact. A raster-based geographical information system (GIS) has been used to build a regional landscape model for Northern Jutland County, which is used to assess visibility of turbines in the period of 1990 to 2010. Multiple viewsheds are computed for a variety of thresholds of visual impact, and since overlaid with population and land use data. The results indicate that the construction of new turbines replacing 40% of the old turbine stock and raising the installed capacity by 20% will not add to the comparative impact in general. However, the pattern of visibility will become askew, and the present homogenous distribution of visibility will disappear. This skewness, together with changing ownership and receding local involvement, could eventually lead to lower popular acceptance of wind power.

INTRODUCTION

Wind energy plays an important role in the Danish energy system. More than 5,300 turbines produced 20% of the net national electricity production in 2005, contributing significantly to cut CO_2- and other emissions to the environment. It is apparent that this development has altered the visual perception of landscapes. As the aim is to double the share of wind power during the next two decades, “wind power landscapes” will continue to change.

The overall good acceptance of wind power is foremost helped by institutional factors: many residents and neighbours to wind power plants are economically involved in co-operatives. Wind power is widely considered a green source of energy creating jobs and boosting development. And a transparent, local planning process has regulated the number and size of wind power projects. These directives have maintained a positive public opinion throughout the entire period (Krohn and Damborg, 1999).

Yet a crossroads may be reached soon. On-shore construction of new turbines has ceased a couple of years ago and re-powering schemes necessary to renew the ageing stock of turbines have stalled. While focus seems to be on offshore projects, regional planning fails to act as a driving force for sustained on-shore development (Jersild, 2004), and, essentially, feed-in conditions for new turbines have become substantially poorer. In addition, local participation in wind power projects declines with growing projects and old co-operatives phase out. These factors may change the perception of visual impact in the near future.

In Northern Jutland with its many old turbines large-scale decommissioning is due: Until 2010, 30 % of the currently operating wind turbines and 12 % of the total generator capacity will end their lifetime, while until the year 2020, 95 % of the turbines and 88 % of the installed power will have disappeared (DEA, 2006) if no new turbines are going to be built, see fig. 1. With decreasing number and increasing size, changes in landscape prominence and visual impact might become apparent. New turbines replacing decommissioned capacity will change landscape as well. About 100 turbines of 2-3 MW are needed to replace 860 turbines in the next 15 years.

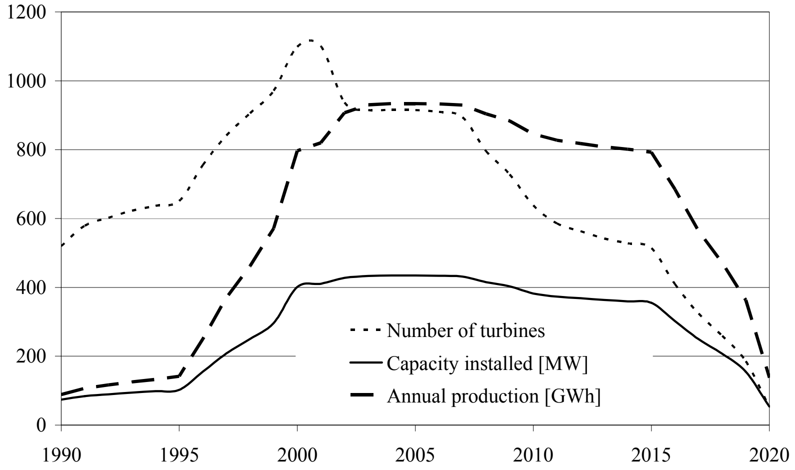

Figure 1: Projected development of turbine count and capacity in Northern Jutland. If turbines are not replaced after ended technical lifetime of 20 years, there will be a significant decrease in production after 2015.

While visual impact has played a minor role so far, increasing turbine size and less local economical involvement may remove the basis for public acceptance and ultimately lead to a change in public opinion. The public decision for or against continued on-shore wind power development thus requires a quantification of the changes the Danish wind energy landscapes will undergo.

MATERIALS AND METHODS

Computer-aided assessment of visual impact is carried out with methods related to multiple viewshed analysis, where the number of visible turbines is summarised for cells in a raster-based elevation model by means of line-of-sight analysis. A generic, raster-based GIS allows for this rudimentary sort of quantification, not accounting for these factors required for a more objective assessment of visual impact: different land use (e.g. in dense forests the visual impact is zero); the sensitivity of viewers (some viewers tolerate more than others); the location of viewers (people might tolerate less impact at their residence); the statistical likelihood of visibility influenced by weather etc.; and the partial shading of objects in a non-binary real landscape. True objectiveness cannot be achieved due to several reasons: digital elevation models are insufficient in detail and precision; partly transparent landscape elements such as hedges are excluded; viewer location, sensitivity and preoccupation are very subjective; and year-round climatic conditions are too complex to include.

The measure of visual impact - and consequently every attempt of quantification - depends on the eye of the beholder. Local people involved in a wind energy project accept a higher measure of physical exposure than perhaps visitors or residents with no economic involvement (Toke, 2005). Quantification of visual impact will therefore include a significant bias.

This paper tries a multiple deterministic approach to resolve and quantify the likely visual impact on landscapes and residents. An approach motivated by the work of Shang and Bishop (2000) and Bishop (2002) was developed, see Möller (2006) for details. Wind power development was described for the years 1990, 1997, 2003 and 2010. A visibility weight on the landscape was calculated with cumulative viewsheds, in which thresholds limit the effectively perceived distance to turbines, derived as a function of their angular dimension. Angular dimensions establish a close to linear relation between turbine size and distance. Dimensions of 1000, 500, 250, 100 and 50 square minutes of arc have been used to limit the radius within which they are assumed to create visual impact. A large angular size translates to a high threshold for perceived visual impact, while a declining angular size means that a spectator becomes less tolerant to wind turbines.

Study area

Northern Jutland county has a population of 495,000 (2004) and an area of 6,200 km^2. Adjacent to the Baltic and the North Sea, the county is divided by the Limfjord waters, see fig. 2. Glacial landscapes with characteristic valleys in the central North and South, strips of sand dunes in the North and flat former sea bottom in several areas compose the natural landscapes. Elevation is between 0 and 133 m with an average of 24 m. Land use is divided according to table 1. Good wind power resources have resulted in more wind turbines built at an earlier point of time than elsewhere and hence an older turbine stock, see Table 2. Towns house about 70% of the population, rural areas and villages the rest.

Land use type	**Area [km2]**	**% of total**
Agriculture	4,000	65%
Natural landscapes	808	13%
Forests	661	11%
Cities, towns, villages	416	7%
Other, including water	183	3%
Transport	127	2%
Total	*6,194*	*100%*

Table 1: Land use statistics for Northern Jutland County the dominance of agricultural land. Forest coverage is slightly less, natural landscape area is more than national average.

	Northern Jutland	Denmark
Number of turbines	910	5,284
Total capacity [MW]	434	3,111
Average age, years	8.8	7.7
Average capacity [kW]	477	589
Turbines per area [1/km2]	0.147	0.123
Capacity [kW] pr capita	0.876	0.579

Table 2: Comparing turbine number, capacity, age and density in Northern Jutland and Denmark as a whole reveals a more capacity, higher density and age in this part of the country.

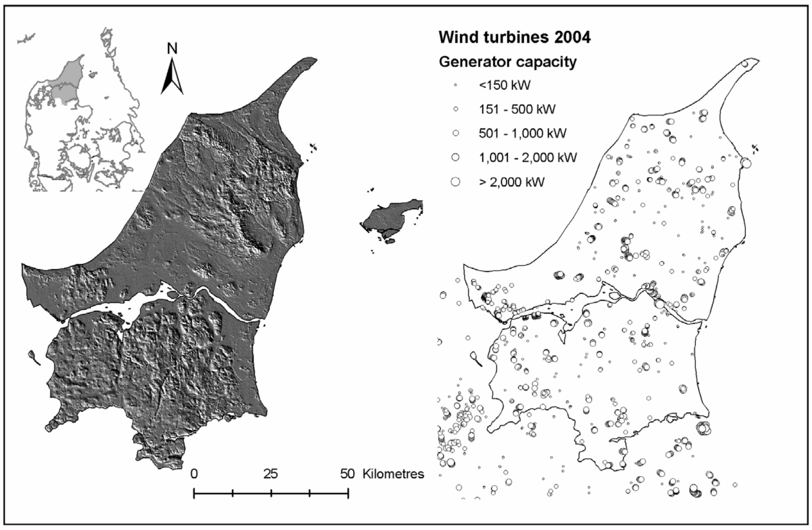

Figure 2: Northern Jutland County features good locations for wind energy. The left map shows a hill shade map with important landscape. Right map: numerous wind turbines are located in the country; many of the smaller ones will end their lifetime in the next decade.

The number of turbines in the county has peaked with 1,100 in the year 2000, followed by decommissioning and replacement; see figure 1. From 2005 on, the number is foreseen to decrease even more, and assuming that no new turbines are installed, the installed capacity will be reduced increasingly. A likely scenario will be 50 new turbines of 3 MW in existing planning zones, replacing older machines unsuitably located. Recent regional wind power planning of 2001 and 2005 seeks to concentrate turbines in parks and remove poorly located single turbines in sensitive landscapes (Northern Jutland County, 2001 and 2005).

Quantification of visual impact

Visual impact is difficult to quantify objectively; see e.g. Hutardo et al. (2004), Wood (2000) and Bishop and Karadaglis (1996). A wind turbine visible from a location does not itself produce an impact. Distance to turbines, their size and number, paint and structure, weather conditions, how often, how long, and where people are faced with turbines make quantitative visual impact assessment extremely difficult and uncertain. However, comparative studies could include a bias to accommodate in particular the subjective factors, and improve comparability in a simplified landscape model. A suitable bias can be the angular dimension, see Shang and Bishop (2000).

Visual exposure can be quantified in a raster-based GIS by the geographic overlay of viewsheds with landscape types or population count, summarising land use area or population numbers for cumulative numbers of visible wind turbines. Although not quantifying the absolute exposure, this establishes a benchmark for comparison.

A landscape constructivist approach is applied, constructing a physical landscape model from digital elevation and land cover data. Uncertainty has to be dealt with (Appleton and Lowett, 2003; Daniel, 2001; Erwin, 2001) by using a cautious approach in a what-if manner: for a known topography the visibility of existing wind turbines is computed with sensitivity of observers to smaller or larger turbines.

Cumulative viewshed analysis by means of GIS

Viewshed analysis of wind turbines (Manwell et al., 2002) uses lines-of-sight between turbine and observer locations in an elevation model to create viewsheds (Burrough and McDonnell, 1998). Cumulative viewsheds establish a measure of visual impact, summarising turbines visible in each landscape cell. Viewshed analysis is binary: an object is either visible or not, excluding ‘fuzzy’ perception of visibility in a landscape with trees, buildings and hedges. With these many diversions from reality, it is a great leap from a simple data-driven model in the Cartesian space to actual, perceived visibility and even the psychological visual impact, as discussed in van Leusen, (2002). Uncertainty is not only influenced by the quality of the input data and by the algorithm used. The naïve application of the standard viewshed algorithm can therefore not be recommended. The visibility model has to contain as many of the factors that induce uncertainty as possible.

The GIS software ArcGIS 9.0 by ESRI with Spatial Analyst has been used for this study (ESRI, 2001). The DEM used is based on ‘DDH® Land’ of 1999, by COWI Geographical Information and IT, with a grid resolution of 20 m (COWI, 2004). This DSM has been resampled to a 100 m resolution for manageable CPU time, and smoothed with a focal mean function in order to reduce noise. Edge effects are avoided by including turbines and topography 50 km outside the case area.

Adjusting the threshold of perceived visual impact

Smaller turbines are seen over shorter distances than bigger ones. The distance at which a turbine is perceived is limited using cut-off distances. The angular dimension is a proxy for intensity of the stimulus and sensitivity to the stimulus (Shang and Bishop, 2000). The cut-off radius was calculated for all turbines as a function of its cross-sectional size and a chosen angular dimension (Möller, 2006). Threshold levels in the range of 50 to 500 square minutes of arc are suggested by Shang and Bishop (2000), excluding atmospheric effects. The offset of the turbine against the surface of the Earth is given by the either 1 or 2 rotor blades simultaneously visible above hub height, making hub height a good reference elevation. The observer offset was uniformly set to 2 metres.

Modelling population distribution and type of landscape

Population data was readily available from public registers, linking socio-demographic data to residence. The new Danish standard square grid with statistics aggregated to anonymous grid locations was used with the highest possible 100 m resolution (MEM, 2001) for the year 2002. Types of landscapes are mapped in a vector land use map available through the Area

Information System (AIS) of the National Environmental Research Institute (NERI, 2000), converted to a grid with 100 m resolution and reclassified to the landscape types included in table 1.

Zonal statistics and evaluation

The superimposition of population and land use data with cumulative viewsheds has been implemented with a zonal statistics function in ArcGIS, summarising values of a value grid within each of the individual zones in a zones grid. The cumulative viewsheds form zones grids, where each instance of a number of visible turbines is understood as a zone. The largest zone has normally the value zero, while the highest possible number of zones is equal to the total number of wind turbines. The values summarized in the zonal statistics are population count and land use area. The results of each visibility scenario (4 years times 5 angular sizes) were written to tables and imported to a spreadsheet for graphical and further statistical evaluation.

RESULTS

Overall visibility of wind turbines

Figure 3 shows increasing visibility of turbines in time and by angular size. In the years from 1990 to 2000 and for angular dimensions of 50 to 250, the higher number of turbines results in a more even pattern of visibility than after the year 2000, where concentration of turbine visibility becomes evident, resulting in greater visibility in some locations and lower visibility in others. A visual pattern evolves, which seems askew and polarised. Smaller angular size seems to reflect local topography, while large angular size results in patterns mainly influenced by distance to turbines.

A statistical interpretation of visibility

The total visibility count is calculated as the sum of the turbines visible in each landscape cell. Visibility depends on the angular size assumed. Figure 3 already suggests a steady increase in total visibility for each of the angular sizes. Figure 4 reveals that visibility curves break in 2003. With smaller angular dimensions applied, visibility decreases, while higher angular dimension results in a continued, albeit slower increase of visibility. Visibility of turbines increases for angular dimensions of 250 to 1,000 square minutes of arc, which is the case for large or close by turbines.

Figure 5 shows the average visibility of turbines by land use category for an angular dimension of 100 square minutes of arc. Average visibility grows until 2003; after which it remains constant. While two thirds of the land is agricultural, the number of turbines visible in average on agricultural area is less than 40 % higher than in towns, on roads and railroads and in forests, together comprising 30 % of the area. Oppositely, natural areas see a rather low visibility count. After 2003, agricultural areas see fewer turbines, forests a few more, while visibility in natural landscapes and other areas will remain on the same level.

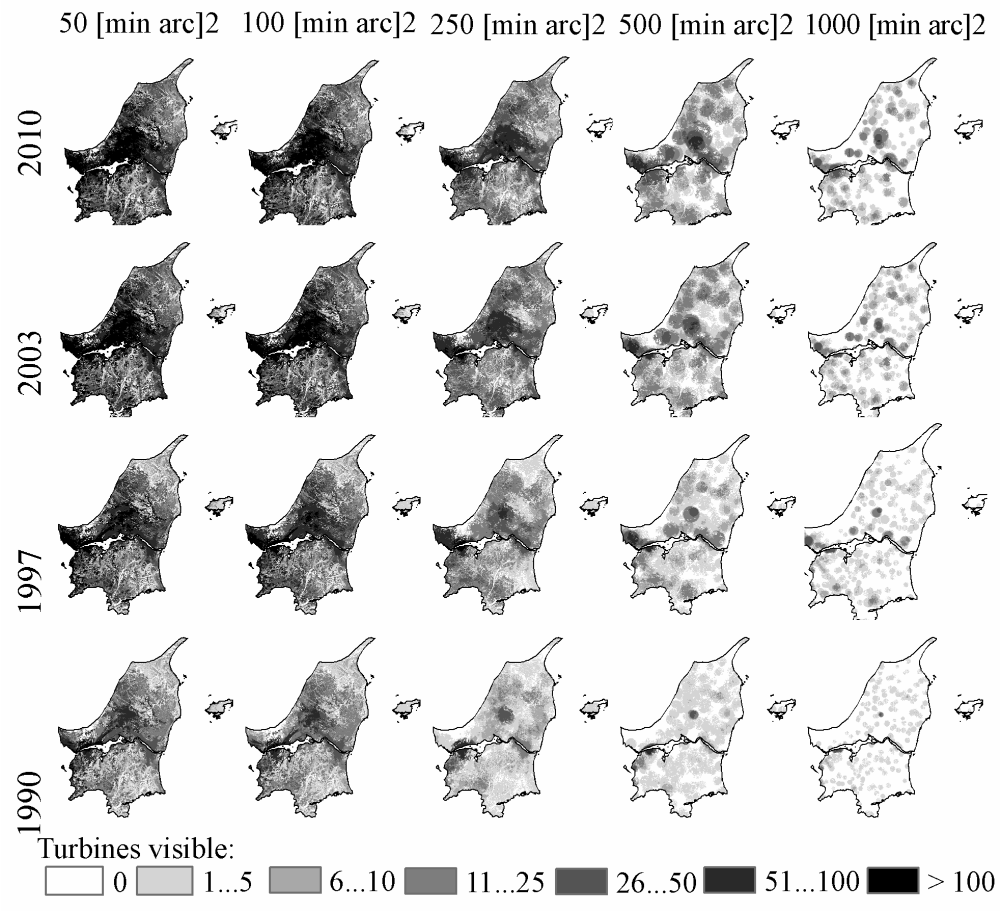

Figure 3: The resulting viewsheds for four selected years and five different angular dimensions reveal significant changes in turbine visibility.

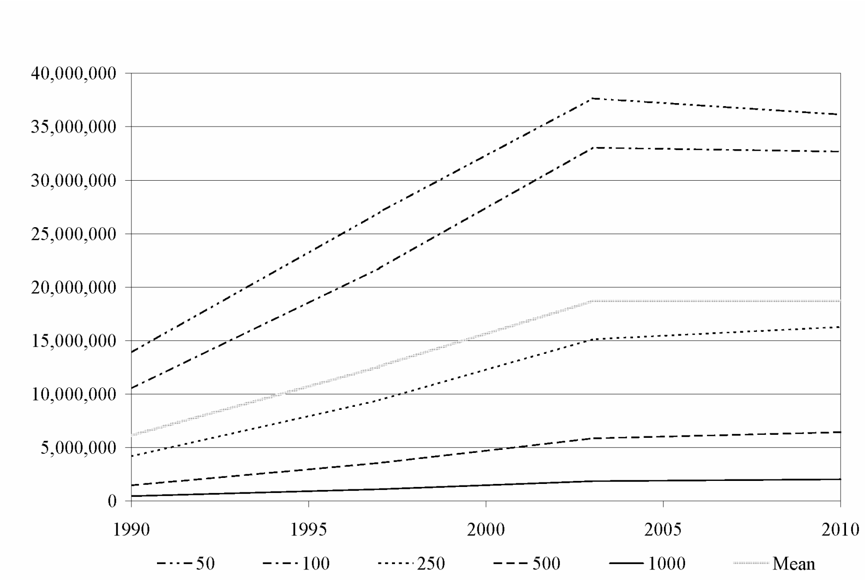

Figure 4: Development of total visibility in the study period for five different angular dimensions. Total visibility is the sum of cell count by number of turbines.

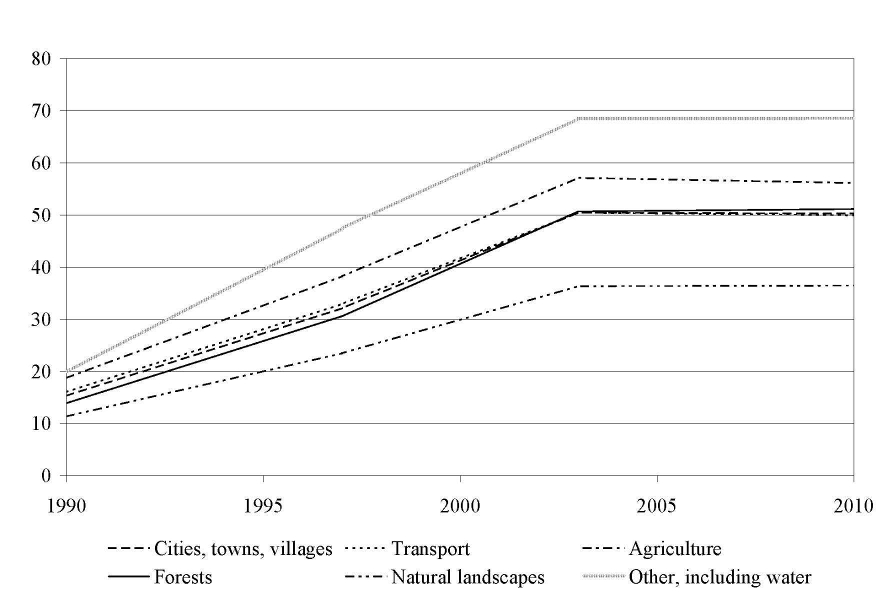

Figure 5: Average turbine visibility (100 square minutes of arc) by landscape category. Visibility grows with number and size of turbines until 2003. Landscapes are unevenly impacted.

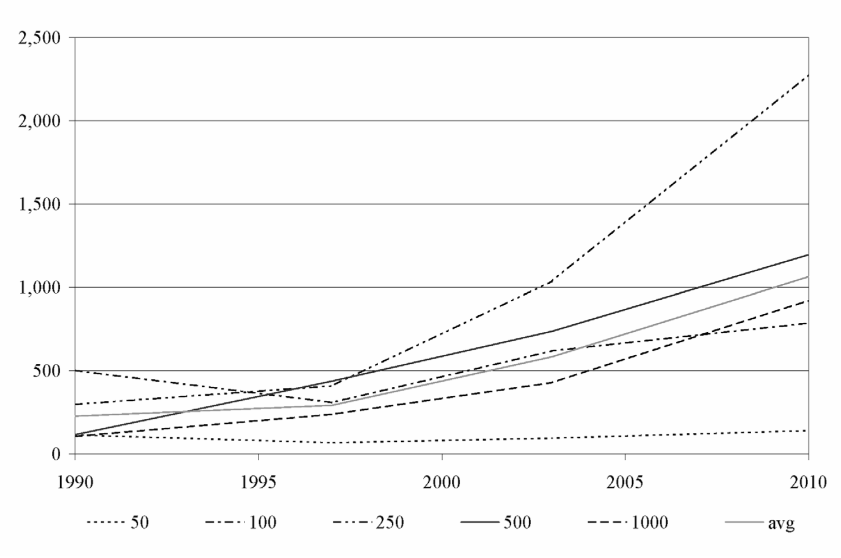

Figure 6: The median of wind turbine visibility count reveals skewness of visibility distribution. Growing median values indicate increasingly large turbines causing a less homogenous pattern of visibility.

Skewness of geographical patterns

Many locations see few or no turbines at all, while in some places cells many turbines are visible. Histograms of all 20 viewsheds reveal in different degree that the geographical patterns of visibility are skew. Measuring skewness using the median of these frequency distributions, the median grows with time for almost all angular dimensions, indicating that increasingly large turbines are causing a more homogenous pattern of visibility, see fig. 6.

Skewness also depends on angular size. With the smallest angular dimension of 50 square minutes of arc the distribution appears more skew; increasing turbine size has little influence. Skewness is smallest with a moderate angular dimension of 250 square minutes of arc. This is consistent with the viewshed maps in figure 3.

Overlay of visibility and population

The larger the angular dimension, the less people do see many wind turbines. A lower impact threshold due to smaller angular sizes increases the percentage of people who can see more turbines. Temporally, for all angular sizes it can be seen that the share of population exposed to visual impact gets smaller, except in the last years of the study period. The difference between the years 2003 and 2010 is not as high as in earlier time steps. The results also tell that in the years from 2003 to 2010 the tendency of ever decreasing proportions of people who see no turbines at all is reversed.

DISCUSSION

An overlay of 20 multiple viewsheds with landscape and population data in the period 1990 to 2010 reveals that visibility caused by smaller turbines is reduced, while visibility of large turbines is amplified: visibility decreases for the less tolerant observer and increases for the tolerant. Reasons are growth of visibility with turbine height by the factor √ 2, and the landscape topography, where a 100 m turbine dwarves most of the hills in that area. Despite most new turbines will be erected close to sea level, they will be visible in large parts of the county.

Assumed a generally positive image of wind power has existed in the 1990's, smaller tolerance levels could be applied for this period, resulting in an evenly distributed visibility of generally lower levels. Development since 2003 and onwards will bring along a net decrease in turbine number, meaning that landscapes will see less visual impact in total.

The used methods, data and models in this study have simplifications and inaccuracies due to a complex reality. Uncertainties arise due to divergence between the line-of-sight model and the real world visual processes, as well as the input parameters and geographical data used.

To mention a few methodological reflections, van Leusen (2002) suggests distance decay functions to improve models of this kind. This is not possible with the viewshed software used here. Bishop (2002) urges to include atmospheric effects and contrast to background in such a study. While atmospheric haze has not been included because visibility measures were to be worst case, there was no satisfactory way to model contrast of wind turbines against their background by means of GIS. Toke (2005) argues to include social factors such as ownership and local involvement. This would have partly been possible for the situation in the 1990's, when most turbines were owned by local cooperatives, but not for current projects.

Scale is important: the smallest units in the model are raster cells with 1 hectare size, excluding as possible shading objects landscape elements smaller than 100 metres. Population data by 1 hectare means that the precise location of persons is not known. The question where precisely a person is exposed, how often etc. can not be answered with this model or any other more detailed.

Changes in landscape and population such as migration, afforestation and urban development were excluded. Rotational speed of turbines was not included as a model parameter, although smaller, faster rotating turbines are more likely to draw attention than larger, slowly rotating. Atmospheric effects such as haze and scattering were not included as these values highly depend on weather conditions, and can change with time as several other factors in this study.

CONCLUSIONS

Regional studies of quantitative visual impact of wind turbines have never been carried out in Denmark. Despite the difficulties in designing an objective method, this study could contribute to the overall goals of planning by quantifying in particular the temporal changes in visual impact.

Removing 400 plants and replacing them with 50 new at three locations will not increase the overall visual impact, except in areas already subject to high visual impact. The rather equal distribution of turbines the 1990's resulted in evenly distributed and moderate impact, while in the years to come a larger geographical variation of wind turbine visibility will be seen. In some areas people will not see windmills as a part of their daily environment, while others living elsewhere will see more. Likewise, some natural landscapes will be more exposed than others, which might influence their value in public. This could be crucial for the acceptance of wind power. Two of the factors influencing acceptance are landscape value and local financial involvement. 13% of the county is semi-natural landscapes (natural grassland, heath, marsh and moors), which will see higher visual impact. If multi-megawatt projects can not be realised as co-operatives, the opinion will turn against wind power. Main reasons seem to be the proposed regional planning areas, concentrated at just three sites in the county. Originally been conceived to save precious landscapes, they might achieve the opposite.

To be able to further quantify this hypothesis, the studies presented here need to be supplemented with measurements of individual thresholds in order to apply a more definite cut-off distance for viewshed analysis.

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