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Abstract

Among the measures discussed as remedies for CO_2 emissions reduction renewable energies are prominent as they already provide marketable alternatives to fossil fuels. This holds true especially for wind power, which has multiplied more than twelve-fold on the global scale from 4,800 MW to over 59,000 MW between 1995 and 2005. This is the highest growth rate compared to all other sources of renewable energy. However, is this impressive expansion expected to continue in the near future? Although wind power as a clean technology helps to combat global warming and, as a renewable energy reduces the dependency on the supply of exhaustible fossil fuels, it is not without flaws. There are concerns over adverse effects on human beings, on wildlife and on the landscape. This paper discusses the limits for wind power generation and highlights important conflict areas that may roadblock further expansion of wind power and thus its potential to combat global warming.

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1. Introduction

Latest data on climate change have proven, again, the vast increase of greenhouse gas (GHG) concentrations in the atmosphere since pre-industrial times. At last GHG emissions have risen by 70 % in terms of their global warming potential between 1970 and 2004. Thereof, CO_2 represents by far the lion's share. Subdivided into different sectors, the largest growth in global GHG emissions in that period was measured with 145 % in the energy supply sector. Moreover, the growth of GHG emissions on the global scale is expected to continue over the next decades, if the existing climate change policies and development practices will not be altered (IPCC 2007, 2-4). Given the tremendous negative effects of global warming, these figures once again show the absolute necessity for mankind to make every endeavour to further cut down GHG emissions.

Among the instruments, measures, policies, practices and technologies discussed as remedies for CO_2 emissions reduction and climate change mitigation, renewable energies are prominent, particularly in the short and medium run until 2030 as they are already commercially available (IPCC 2007, 13, 17). This holds true especially for wind power, which has exhibited an impressive development over the last two decades and which is expected to maintain its growth path at least in the near future. However, this expansion challenges the prevailing practices of land use and causes new problems in terms of adverse environmental and spatial effects. This paper aims at discussing the major effects and presenting ecological-economic modelling as an innovative interdisciplinary approach for assessing and balancing these effects in order to minimize conflicts over site selection for wind energy plants (WEP).

The paper is organized as follows. *Section 2* refers to the promotion of wind energy as one of the key elements of climate policies in Europe, especially in Germany. In *section 3* we briefly discuss the natural, technological and legal limitations for the further development of wind energy production. In *section 4* we identify five main areas of conflict caused by the expansion of wind power generation, namely the visual impact on the landscape, impacts on wildlife, in particular birds and bats, emissions like noise, shadow and reflections, grid integration, and land consumption. Finally, in *section 5*, we draw conclusions and identify research priorities for the development of sustainable land use practices.

2. Promotion of wind energy – a key element of climate policy

Since energy supply contributes more than other sectors to the atmospheric GHG concentration it is also the most important lever to counter global warming. Basically, energy policy possesses three options for climate change mitigation which can be combined with each other:

- Enhancement of energy efficiency in all sectors of the economy,
- Upgrading of combined heat and power (CHP) generation, and
- Substitution of fossil fuels by renewable energies, which are biomass, geothermal energy, hydropower, solar energy, and wind power.

In principle, each of these three policy options can be applied to each of the three different types of energy, though they are more or less appropriate regarding these types, which are

- electricity,
- heat, and
- fuel.

Thereof, the electricity sub-sector is of particular importance in the short term, because it offers a great potential for the avoidance of CO_2 emissions as well as it provides marketable alternatives to fossil fuels in the form of renewable energies, primarily wind power (Nitsch 2007, 10; see also Nitsch 2007a). In the decade between 1995 and 2005 wind energy has multiplied more than twelve-fold on the global scale, from 4,800 MW to over 59,000 MW. This is the highest growth rate compared to all other sources of renewable energy. Up to now more than 50 countries all over the world have established wind power as a resource in their electricity sectors. In absolute figures, Germany is the leading country with an installed capacity of 18,428 MW in 2005, followed by Spain (10,027 MW), the USA (9,149 MW), India (4,430 MW), and Denmark (3,122 MW). In relative terms, however, Denmark has the largest wind power industry with a 20 % proportion of the country’s electricity supply. Whilst the countries of the European Union experienced the greatest expansion of wind turbine installations to date, the United States and Canada have caught up at last. Moreover, new markets have emerged more recently in South America and Asia, e.g. in India and China, which both reached record levels of expansion in 2005 (Aubrey et al. 2006, 5, 9). In Germany wind energy accounted for 5.4 % of power consumption in 2005. Due to wind power the overall contribution of renewable energies to power consumption (10.4 %) more than trebled since 1990 (Nitsch 2007, 9,10; see also Nitsch 2007a).

The story behind the impressive growth of the German wind power industry since the early nineties is a massive promotion of renewable energies by the German Government, mainly by means of statutorily warranted financial incentives. First of all, the "Electricity Feed Act" (*Stromeinspeisungsgesetz, StrEG*) was enacted in 1991 which gave the initial impulse to develop the market for electricity from renewable energies in Germany. However, the big push was given with the replacement of this law by the "Renewable Energy Sources Act" (*Erneuerbare-Energien-Gesetz, EEG*) in the year 2000. The EEG works via two associated mechanisms in the form of obligations imposed on electricity companies. First, a fixed allowance per kWh differentiated according to the type of renewable energy and the year of implementing the power plant which is payable to the supplier of electricity from renewable sources. Second, the obligation to purchase the electricity generated from renewable sources with priority. After these provisions were effective, in 2001 the annually installed wind energy capacity quintupled in terms of MW compared to the mid-nineties and the accumulated installed wind energy capacity jumped over the benchmark of 10,000 MW. However, this growth was also enabled through technological progress, i.e. an eightfold increase of the average wind turbine capacity within ten years (Jansen et al. 2005, 2), which was stimulated by the EEG *vice versa*.

3. Limits for the further development of wind energy production

The remarkable expansion outlined in section 2, of course, is not boundless. In this section we distinguish three kinds of limitations: natural, technological and legal. The first limitation is given by nature, whereas the second and third limitations are man-made. These limitations pose two questions: Firstly, is it possible to identify a sufficient amount of land to meet the demands of a growing wind power industry and thus the goals of climate policy (problem of land scarcity)? Secondly, is - respectively to which extent is - the available land suitable for wind power generation at all (problem of adequate site selection)?

3.1 Natural wind regime

As a renewable energy source, wind power depends on the natural flow of air masses in the atmosphere, which is fundamentally a result of the inhomogeneous warming of the earth through periodical solar irradiation in combination with the rotation of the earth. Therefore, wind energy is an indirect form of solar energy. On the global scale, wind resources are plentiful and distributed across all continents and most of the regions of the world. More detailed studies carried out so far on this subject concentrate mostly on Europe and the United States. In all they revealed a particular high wind energy potential in North America and the northern parts of Europe. Furthermore, Tasman Island in Australia and the southern tip of South America have constantly strong winds (see Aubrey et al. 2006, 23). Yet, the key feature of the wind is its discontinuity. Temporal fluctuations of wind force occur from year to year, season to season, day to day, and day to night. Spatial differences can be observed between coast and hinterland, lowlands and mountains, with regard to natural cover and urbanization, and so on. Largely, there are two factors which shape the variation of the wind flow – the latitude of a given location and the distribution of land and water that surrounds it (Hau 2006, 451-468).

This is the reason why large scale wind data are insufficient by far when it comes to the utilization of the wind flow to generate electricity. Even regional annual average wind speed data, which are common meteorological information, are not adequate for the site selection of wind energy plants. What is necessary is the detailed knowledge of site-specific wind characteristics, i.e. the frequency distribution of average wind speeds measured in short intervals of, e.g., 10 minutes in defined altitudes, which requires long-term research over at least ten years (Hau 2006, 459). In Germany, e.g., this was provided through the “Scientific Measurement and Evaluation Programme (WMEP) within the ‘250 MW Wind’ project”, a long-term investigation not only of wind conditions, but also of climatic and external electrical influences on WEP in use. For evaluation purposes, the 1,500 WEP sites included in the WMEP were distinguished according to four topographical categories – coastlines and islands, unwooded North German lowland plains, wooded North German lowland plains, and low mountain regions up to 1,100 m above sea level. From the wind data recorded in the period between 1993 and 2005 regional differences can be easily identified. Overall, the pattern shows that fluctuations of the wind force from year to year occurred in all four categories. Yet, although these fluctuations were more salient at the coastal sites, the rank order in terms of wind force remained always the same, i.e. every year the highest wind-power averages (in units of W/m²) were observed along the coastlines and islands (168 W/m²), followed by the low mountain regions (101

W/m²), then the unwooded North German lowlands (81 W/m²), and lastly the wooded North German lowlands (62 W/m²) (Durstewitz et al. 2006, 38-9). Adequate data on the natural wind regime is thus one of the crucial elements for site selection. Moreover, since the natural wind regime can not be shifted by humans across space problems of land scarcity and site selection can only be solved by altering the man-made boundaries.

3.2 State of the technology

Unlike wind resources, technological constraints are subject to progress through man-made efforts such as research and development. The exploitation of a given wind force is much higher today compared to the beginning of modern wind power generation in the mid-eighties of the last century.[1] This applies for site-specific cases as well as with respect to countrywide and global wind power potentials. Starting with average capacities of 30 kW and rotor diameters no more than 15 m, the most prominent market, the German market, today is dominated by 2 MW wind turbines with rotor diameters of 100 m and more, i.e. an increase of capacity by the factor of almost 70 in around 20 years. In the same period, average hub heights of newly installed wind turbines have also risen from 30 m up to more than 100 m (Durstewitz et al. 2006, 30-1; see also Wizelius 2007, 115). With regard to height a simple heuristic holds true: the higher the turbines the higher the energy output. Thus, not only higher wind energy yields can be earned at potential WEP locations but also higher CO_2 reductions. Moreover, by using the state of the art technology, formerly unsuitable locations can now be utilized for further wind power generation.

This remarkable achievement is due to a number of small evolutionary steps, principally weight reductions, improvement of materials and design simplifications which applied to nearly all of the main WEP components like tower, hub, nacelle, rotor blades, generator, gearbox, yaw system, transformer etc. Despite the enormous technical progress already achieved so far, further advances can be expected, because wind power generation is a comparatively young technology. The outcomes of future research and development are estimated in terms of durability, yield increases and production cost reductions as well as alleviations in manufacturing, transportation and assembling of wind turbine components and also improvements of product safety (Hau 2006, 728-9). Nevertheless, the further extension of hub heights and rotor diameters for on-shore wind turbines is limited because of the associated high costs as

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[1] The history of wind power probably reaches 3,000 years back, at first well-documented is a windmill in Persia in the year 947, and in Europe windmills were established from the end of the 12th century on (Wizelius 2007, 7).

well as domestic transport restrictions at least in Europe (cf. Jansen et al. 2005, 17). Further limitations are given by legal interferences.

3.3 Legal land use restrictions

In addition to technological restrictions, legal bounds on land use are further anthropogenic limitations. Whereas technology is a matter of human endeavour in terms of research and development and afflicted with uncertainties, legal land use restrictions are a deliberate reflection of the political will of a society (a nation state, a province, a county or a municipality). Since manifold human activities are bound to the use of land and, hence, compete for a scarce resource, these conflicting demands are subject to legislation at the respective different governance levels. Basically, in Europe the designation of sites for the installation of wind turbines is administered through building and planning laws, but immission control and nature conservation laws just as well. Three conflict dimensions which are central to land use planning in general, do also apply in the context of wind energy. These are conflicts of interests between private actors and the public, national versus local concerns and (long-term) environmental goals opposite to (short-term) economic goals (Khan 2003, 565).

In Germany – with regard to installed capacity world’s leading country in wind energy production so far - land scarcity is most prominent. Consequently, one of the goals of sustainable development is to restrict land consumption to a maximum of 30 ha per day by 2020 (http://www.bmu.de/files/pdfs/allgemein/application/pdf/nachhaltigkeit_strategie.pdf). To assure land use for wind power generation most of the regional planning bodies in Germany now confine the erection of wind turbines by zoning regulations to designated areas which then are privileged to this specific purpose. Thereby, WEP are restricted to areas which should minimize negative impacts on local ecology and keep a sufficient distance from human settlements to protect residents from noises, reflection and shading effects caused by WEP. Apart from zoning, the erection of wind turbines strictly is subject to approval according to the building codes of the 16 German states. The scope of the required approval procedures (building permit, immission control, environmental impact assessment) on the one hand depends on the number of WEP at a specific site, i.e. a single plant requires less approval than wind farms with 3 to 20 or even more plants (Maslaton/Zschiegner 2005, 102-111). On the other hand, authorities at different levels give advanced recommendations regarding wind turbine heights and/or distances to residential areas which can have significant effects. As shown for selected municipalities in Germany, an extension of the minimum distance to houses from 500 m at 1,000 m (as e.g. recommended in the German state of Lower Saxony) reduces the potential for using the state of the art technology (with regard to the replacement of old technology usually termed as *repowering*) by 67 % (Rehfeldt/Wallasch 2005, 66). Legal interferences may thus restrict the full deployment of technological development and hence the potential of WEPs to contribute to greenhouse gas reductions.

4. Windpower on the upswing? - Main conflict areas

Wind power is a clean technology as (among others) it avoids the emission of CO_2 and helps to combat global warming. Furthermore, as a renewable source of energy it helps to reduce the dependency on the supply (and suppliers) of exhaustible fossil fuels. Nevertheless, despite its undoubted benefits, wind energy is not without flaws. Problems concern adverse effects on human beings, on wildlife, and on the landscape. A further technical matter refers to the integration of wind power into the grids of electricity companies, and, finally, a fifth concern is the consumption of land due to the installation of wind turbines.

4.1 Effects on humans: noise, shadows and reflections

Humans can be negatively affected by wind farms through noise, shadows and reflections. Wind turbines in operation emit two different kinds of noise. Firstly, there is a mechanical noise coming from several components inside the nacelle – the generator, the yaw drive, the gearbox, and few other moving parts. Secondly, an aerodynamic swishing sound is caused by the rotating blades. The swishing sound level is wind-induced and depends on the speed of the blade tips. It dominates over the mechanical sound level, as the latter noise in modern wind power plants *“has been eliminated by sound-absorbing materials in the nacelle, better precision in the manufactured components and damping.”* (Wizelius 2007, 158). Wind turbines can produce sound emissions in the range from 95 to 108 dBA which equals the sound level in a discotheque. However, this occurs only under certain conditions at wind speeds between 3 – 4 m/s and 8 m/s. Furthermore, as the sound level decreases with an increasing distance from its source, what matters to people is not the sound emission but the sound immission. It is calculable for different distances using standard calculation models, if emission levels and hub heights are known. Therefore, the usual way to avoid problems caused by noise is to keep sufficient distances between houses and wind turbines (Wizelius 2007, 158-61). In Germany, e.g., sound immissions up to 35 dBA are allowed in residential zones, i.e. wind turbines should at least be placed 500 – 1,000 m away, depending on hub height and rated power (cf. section 3.3 of this paper).

Other disturbing effects which wind turbines impose on humans are shadows, stroboscopic effects and reflections. They occur under certain weather conditions when wind turbines are sited unsuitably in relation to nearby houses. The reflections can be coped with rather easily by the use of proper coating material. Shadows appear corresponding to the length of an object on sunny days, but are diluted with distance and due to the opaqueness of the air. A shadow moves with the run of the day from sunrise to sundown from the west through the north to the east of a given location and alters its path in the course of the year in accordance with the four seasons. Shadows are longer in winter than in summer and in the mornings and evenings than at noon. As these patterns are well known it is possible to calculate the path of the shadow for each location on earth very precisely. Consequently, shadows can be avoided to a large extent by means of appropriate siting which is normally fulfilled by adherence to the aforementioned sound immission limits. As a result, *"if houses are 500 meters away from the turbine none will get shadow flicker for more than two short periods of the year, and this for a maximum of 20 minutes per day."* (Wizelius 2007, 161). Moreover, shadows from moving rotor blades can be averted by means of individual turbine regulation, i.e. a temporary cut-off.[2]

4.2 Impacts on wildlife

Another major concern over wind power is its impact on wildlife. Most notably, this concerns birds and bats, whereas mammals or other animal species and their habitats are hardly if at all affected by wind turbines. Bird species can be impacted by wind turbines in terms of habitat losses, disturbances to breeding and foraging areas, and collision risks. An evaluation of over 100 studies conducted on this in 10 countries (but mostly in Germany) concludes that *"… no statistically significant evidence of negative impacts on populations of breeding birds could be found. … The impact of wind farms on non-breeding birds was stronger. … There was no evidence that birds generally 'habituated' to wind farms in the years after their construction. … There is evidence for the occurrence of a barrier effect in 81 bird species. … However, the extent to which the disturbances due to wind farms of migrating or flying birds influences energy budgets or the timing of migration of birds remains unknown."* (Hötker et al. 2006, 6-7). Altogether, scaring effects obviously apply to few non-breeding subspecies of geese and

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[2] Another adverse light effect comes from the red flashlights which are set up on the top of wind turbines (in Germany for example in cases where the total height of a turbine exceeds 100 m). Again, the remedy here is to keep a sufficient distance.

waders, whereas most birds seem to attune to wind farms within a reasonable time (Wizelius 2007, 157).

Examinations of occurred instances indicate that collision rates are influenced by the type of habitat and correspondingly bird species are affected to varying degrees. Bird fatalities in consequence of collisions with wind turbines mainly happened at wind farms close to wetlands, where most of the casualties are gulls, and on mountain ridges, where raptors are affected most frequently. Bats fall prey to collisions with wind turbines during their migration period from late summer to autumn but normally not in their breeding season. Although the collision risk for birds and bats increased somewhat with the size of wind turbines a statistical significance of this effect was not measured. Nevertheless, even small increases in mortality rates can cause significant population decreases (Hötker et al. 2006, 7). This creates need to qualify the negative impacts on birds and bats. So far, several studies have shown that bird mortality due to windmills is fairly low compared to bird deaths caused by oil spills along shores or avian collisions with other man-made structures like buildings, power grids, road vehicles, and telecommunications towers (see Aubrey et al. 2006, 33).

Besides, there are means available to reduce the adverse affects of wind power on birds and bats. These comprise, first and foremost, the siting of wind mills, which should avoid, e.g., wetlands, mountain ridges with high populations of birds of prey, important habitats for highly sensitive non-breeding birds, or migration routes of large flocks of birds. Anyway, many of those critical sites are excluded from wind power projects from the outset because of national nature conservation regulations. What matters too is the on-site configuration, i.e. turbines should be placed in line with the main flight directions of birds and not across. The fact, that today’s wind turbines turn much slower than previous ones also adds to reduced collision risks. Another means is the construction of tube towers instead of lattice ones (although, the lattice method of construction is inevitable for hub heights from 140 m on). Moreover, a deliberate repowering could mitigate negative impacts on birds and bats, if it is used to replace great numbers of small wind turbines with limited numbers of taller wind turbines, possibly at less problematic sites than today (Hötker et al. 2006, 7). However, the potential for repowering is highly contingent on turbine height and distance regulation (cf. sections 3.2 and 3.3., above). Moreover what deserves to be mentioned, too, is the fact that in the long run global warming is much more threatening to birds than wind power because it alters habitats in a way that they become uninhabitable for a number of indigenous bird species (Aubrey et al. 2006, 32).

4.3 Visual impact on the landscape

According to a number of surveys in Germany and elsewhere in Europe, the dominant concern about wind energy, probably, is the visual impact that wind turbines impose on the landscape (e.g., Egert/Jedicke 2001, 375; Khan 2003, 566). As Strachan/Lal (2004, 561) put it:
“Clearly, wind turbines are large, tall and highly visible structures with elements that can influence the visual or aesthetic impact of a wind project including:

- *landform and landscape characteristics*
- *the spacing, design and uniformity of the turbines*
- *markings on the turbines and with how the turbines relate to the skyline*
- *supporting structures including service buildings and ancillary components like power lines*
- *access infrastructure such as roads.”*

What’s more, according to Kahn, the most appealing sites with regard to wind force quite often are also particular scenic places in the open landscape (Khan 2001, 566). Landscape architects classify wind turbines as bulky infrastructure facilities with superior spatial requirements in terms of function, extent and disturbance potential. Beyond the outskirts, tall technical buildings like WEP cause a loss of scale and an alienation of surface areas. They also can destroy scenic textures and the outlines of the landscape. Hence, conflicts over wind energy especially arise, where it rivals existing spatial functions and uses, e.g. local recreation or tourism (Egert /Jedicke 2001, 373). What is remarkable in this context, the bulk of surveys carried out so far dealt with newly planned WEP sites. Existing WEP locations are rarely to be found as objects of investigation. Although rejection of and protest against wind turbines from some of the local residents often occur prior to the installation, it is not for sure that these negative attitudes perpetuate once a WEP is under operation for a couple of years. In principle, it is similar to waste disposal sites which are necessary for the society as a whole but evoke routine ‘not in my backyard’ resistance from the locals. Still, only surveys conducted after the implementation of a wind farm really can show whether the problem of acceptance persists in the long run or could be solved as indicated by recent studies (Egert/Jedicke 2001, 373-6 and Strachan/Lal 2004, 561).

Albeit the visual impact on the landscape cannot be totally averted, neither by means of technology nor regulation, they can be alleviated by an intelligent siting of wind turbines, i.e. *“to minimize the visual dominance of turbines and to site them in ordered groups that follow the outlines of the landscape … and concentrate siting in a few geographical areas that are clearly separated from each other, leaving the majority of the landscape free from turbines.”* (Khan 2001, 572). Moreover, the adverse affects of wind power on the other hand must be confronted not only with areas of unspoiled nature or pleasing landscapes, but with the negative impacts that other infrastructure facilities, in particular energy developments do have on the landscape, for instance open cast coal mining or coal, gas and nuclear power stations. Furthermore, wind turbines can be easily dismantled, which allows for a relatively quick return to the previous stage of the site (Aubrey et al. 2006, 29 and Wizelius 2007, 158).

4.4 Grid integration

A major technical issue for the utilization of wind power is its connection to the grid and its integration into the existing electricity supply system. National power systems usually consist of different grid levels which are linked together through transformers. A transmission grid with high and highest voltage levels connects to large producers, transmits huge amounts of power and bridges long distances, domestic as well as cross-border. A number of regional and local distribution grids with lower voltage levels deliver the electricity to the consumers. From the grid operators’ point of view two features are of particular importance regarding wind energy compared to conventionally generated energy: the fluctuations of the fed in power which is subject to the variations of the wind speed and direction, and the decentralized supply from a vast number of far-scattered small plants instead of the customary concentration on few very large power plants which connect to the transmission grid (Durstewitz et al. 2006, 60). As electricity already is a perishable commodity, the distinct attributes of wind energy add to this problem, i.e.: *“Wind energy can’t be used for base loads, since the production varies. Nor can it be used as regulating power, since the energy from wind turbines cannot be increased with demand. Nor can it be used as peak power, for the same reason.”* (Wizelius 2007, 210).

In fact, for several reasons the problems are not that big as they might appear at first glance. First of all, there is a smoothing effect resulting from a great many wind turbines located in different regions with diverse wind conditions which are aggregated at a system level. Also, variability is not unique to wind energy but is routine day-to-day business in the electricity industry, since the consumers' demand for power changes permanently, often with high amplitudes, and unscheduled outages occur in conventional power plants, too. In addition, because of the necessity to constantly balance supply and demand, power systems already have regulatory and back-up capacities which serve as primary or secondary reserves and can, in principle, also be used for the integration of higher amounts of wind power. In Central Europe, e.g., this also includes possibilities to import/export electricity from/to neighbouring countries via the Integrated European Grid. Furthermore, much of the problem could be solved by means of short-term (hourly as well as daily) forecasting of wind power output, which has significantly improved in recent years. However, these mitigating factors are effective only up to some threshold level of wind power penetration, beyond which the grid infrastructure needs to be adapted and upgraded. According to different statements in the literature this threshold lies in the range from 10 to 20 % on a national scale (e.g., Wizelius 2007, 213 and Aubrey et al. 2006, 24 respectively). Finally, the integration of wind power even on a large scale seems to be technically feasible, but requires a considerable capital investment[3] as well as the removal of institutional barriers and distortions (Aubrey et al. 2006, 23-7; Durstewitz et al. 2006, 61-6; Jansen et al. 2005, 64-74, Wizelius 2007, 213-7).

4.5 Land consumption

With respect to the land demanded for a substantial development of wind power two points should be borne in mind. On the one hand, it seems plausible that the placement of a great deal of wind turbines in the open countryside would require the utilization of lots of acreage, albeit there are two counterbalancing aspects: Firstly, replacing old by new technology (repowering) allows generating the ongoing energy output by fewer land demand. Secondly, land consumption by WEPs must be weighed against the land demand of conventional energy sources along the whole chain of production. On the other hand, although the land actually covered for the foundation, access roads, transformer, cable runways and auxiliary equipment of a wind farm is relatively small, however, the total area exhausted by a wind farm is far-reaching because of its visual impact on the landscape. The spatial dimension of the visual impact is highly controversial since generally accepted methods of calculation do not exist yet (Schmitt et al. 2006, 406). In the literature, estimates of land consumption owing to wind power differ considerably. A study conducted in the UK, e.g., calculated 0.018 up to 0.49 ha covered land per MW wind power compared to 0.16 ha/MW for a nuclear plant (see Wizelius

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[3] For Germany, e.g., Jansen et al. 2005, 68, calculated a cumulative amount of approx. 12 billion Euro until the year 2020. Above that a major challenge to facilitate the integration of more significant amounts of wind power in the future is the development of effective storage technologies, e.g. based on hydrogen.

2007, 153-4). The study also points out that the configuration of turbines inside of a wind park (the number and lengths of lines and rows) significantly influences the demand of land. Furthermore, the study arrives at the conclusion that 99 % of the area spanned by a wind farm *“can still be used as before”*, so double use like wind farming and crop growing or cattle grazing is possible (ibid.).

Recently, Schmitt et al. (2006) presented a new method of calculation to estimate the total land consumption as a result of wind power throughout Germany. The authors start from the assumption of a continuum of land demand caused by wind turbines which is terminated by two extremes: on the one hand, the visual impact of a turbine representing the maximum spatial strain and, on the other hand, the foundation of the turbine, including its auxiliaries, representing the minimum. For comparison, the authors then present two more methods of calculation: the horizontal circular area underneath the blades (CAUB) which yields a magnitude not far from the minimum, and the toppling distance circular area (TDCA) which is much larger as it adds the hub height to the blade width in the formula. Schmitt et al. argue that the CAUB as well as the TDCA are insufficient since they focus on single wind turbines. In contrast, the method developed by Schmitt et al. is based on the identification of wind farms and the proposition that the entire land occupied by a wind farm (including the spaces between the single turbines) is lost for any other constructional uses. Thereby, the amount of land spent is delimited by the outer turbines which shape the wind farm. Consequently, the method of Schmitt et al. results in magnitudes between the TDCA and the Maximum.

The application of the method first of all requires the demarcation of wind farms. To this end, using geographical information systems, Schmitt et al. locate wind turbines throughout Germany and draw circles of 500 m radius around each turbine. Then, by definition, they merge all overlapping and tangential areas in one and the same wind farm, which yields a definite number of virtual wind farms. Next step is the determination of the land demanded for a single wind farm. It is determined through the entire acreage within the boundary of a wind farm which is defined by the individual outboard toppling distances of its outer turbines. Finally, by summation Schmitt et al. calculate a land demand for existing wind power plants in Germany of 50,911 hectares (17.8 ha/MW) in 1998 which almost trebles the TDCA value and would represent 1.2 % of Germany’s entire settlement area in that year. For the year 2005 Schmitt et al. (2006, 407-8) even estimate 331,000 hectares (18.2 ha/MW) which would represent 7.2 % of the settlement area. However, it is rather doubtable whether the basic argument of Schmitt et al. – to weigh up wind power against other constructional uses – is reasonable. Because wind turbines are mostly erected in the open country side or rather agricultural areas which are generally not designated for other constructional uses, this land is never used up by wind power but allows complementary land use like agriculture. Accordingly, in line with the conclusion of Schmitt et al., there is ample scope of interpretation regarding the land consumption due to wind energy.

5. Conclusions and outlook

The ongoing climate change will further on exert continuous pressure on politics as well as on the economy to counteract global warming, i.e. to cut GHG emissions, particularly CO_2. Among the most effective remedies is the substitution of fossil fuels with renewable energies. Thereof, wind power offers the greatest potential in the short and medium run in terms of CO_2 avoidance and efficiency. On this account, in many countries of the world the future expansion of wind power is as likely as not, despite of its few limits and flaws. However, this will involve, especially in the densely populated countries of Europe, an increasing pressure on land use, at least in hot spots where wind conditions are good. If, at the same time, the adverse effects of wind power are sensible as well it is straightforward that disputes over the land demand of the wind power industry increase as well. The more so as up to the present generally accepted methods of calculation do not exist, an area that deserves more study in the future. Moreover in face of contradictory environmental objectives it requires sophisticated tools and methods to assess and balance the positive and negative effects of wind power. This should reveal the trade offs at issue at different spatial places of allocation as a pre-requisite for identifying adequate space for wind power generation and selecting the sites in the most sustainable way.

In Germany, the Federal Ministry of Education and Research (BMBF) within the framework programme "Research for Sustainability" (see http://www.bmbf.de/en/4815.php) supports these goals by funding the project “Strategies for Sustainable Land Use in the Context of Windenergy”. This project aims at the evaluation of the aforementioned impacts – externalities – of different modes of wind energy production, reflecting the use of different technologies for wind power generation and the spatial configuration of turbines among others. Using an ecological-economic modelling framework that integrates knowledge from different disciplines and sophisticated economic valuation methods in combination with an advanced geographical information system landscape related impacts of wind power production are assessed and contrasted with societal preferences for wind power generation in two selected regions of Germany, Western Saxony and Northern Hesse. For further details see http://www.ufz.de/index.php?de=14638). If the development of this innovative tool becomes effective, this should help not only to identify land to satisfy the demand of a growing wind power industry but also to mitigate conflicts by means of site selection. Moreover the results of such an analysis will show whether given man-made limitations, especially the identified legal land use restrictions, may act as a stumbling block for the desired expansion of wind power as a means to combat global warming.

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