OPEN ACCESS
IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. **8** (2013) 035001 (3pp) doi:10.1088/1748-9326/8/3/035001

SYNTHESIS AND REVIEW

Environmental impact of wind energy

J Mann[1] **and J Teilmann**[2]

[1] Department of Wind Energy, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark
[2] Department of Bioscience, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark

E-mail: jmsq@dtu.dk and jte@dmu.dk

Received 28 May 2013
Accepted for publication 3 June 2013
Published 3 July 2013
Online at stacks.iop.org/ERL/8/035001

Abstract
One purpose of wind turbines is to provide pollution-free electric power at a reasonable price in an environmentally sound way. In this focus issue the latest research on the environmental impact of wind farms is presented. Offshore wind farms affect the marine fauna in both positive and negative ways. For example, some farms are safe havens for porpoises while other farms show fewer harbor porpoises even after ten years. Atmospheric computer experiments are carried out to investigate the possible impact and resource of future massive installations of wind turbines. The following questions are treated. What is the global capacity for energy production by the wind? Will the added turbulence and reduced wind speeds generated by massive wind farms cool or heat the surface? Can wind farms affect precipitation? It is also shown through life-cycle analysis how wind energy can reduce the atmospheric emission of eight air pollutants. Finally, noise generation and its impact on humans are studied.

Keywords: offshore wind farm, benthos, birds, marine mammals, climate impact, wind energy, atmospheric models, life-cycle assessment

The production of electrical power from wind energy is growing exponentially with a doubling time of three years. Despite financial crises and rapidly changing political support for wind energy in various countries, the growth seen seems steady over the last couple of decades and shows minimal signs of exhaustion. Since the last focus issue in *Environmental Research Letters* related to wind energy (Mann *et al* 2008) China and the United States have passed Europe as the largest wind energy markets. At present, wind energy provides approximately 2% of the global electrical demand, while nuclear power covers 13%, but if the growth continues at the present rate (see figure 1) wind energy may cover a sixth of the global electrical energy demand a decade from now. New commercially competitive techniques to extract gas, so-called fracking, reduce the carbon dioxide emissions from electrical power generation (Hultman *et al* 2011), and could thus impact the growth of renewable energy in some markets, but it is strongly debated whether the technique has other adverse effects on the climate (Howarth *et al* 2012, Cathles 2012).

With this rapid growth it is timely to study the environmental impact of wind energy. The subject of this focus issue range from studies of wind turbine generated noise (Moorhouse *et al* 2011) and its impact on human health (Bolin *et al* 2011), over impacts on the marine ecosystem (Lindeboom *et al* 2011, Dähne *et al* 2013, Scheidat *et al* 2011, Teilmann and Carstensen 2012) to impacts on the atmosphere either through direct changes of wind speed and turbulent fluxes of heat (Adams and Keith 2013, Petersen *et al* 2013, Fiedler and Bukovsky 2011, Zhang *et al* 2013, Wang and Prinn 2011) or on the reduced emissions of carbon dioxide and other gases (Arvesen and Hertwich 2011).

Noise in air from wind turbines is mainly generated through interaction of turbulence with the blade and for

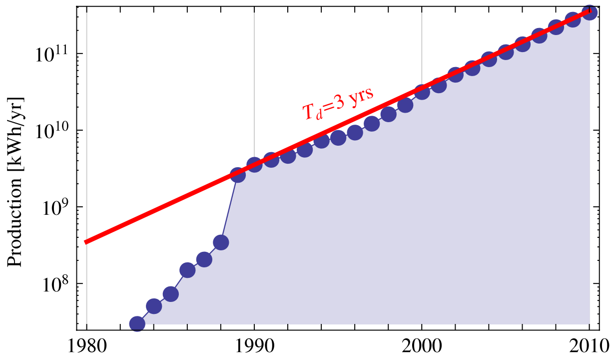

Figure 1. The global yearly production of electrical energy by wind turbines showing an exponential development over the last two decades with a doubling time of three years. Source: US Energy Information Administration.

smaller turbines also from mechanical vibrations. The review by Bolin *et al* (2011) shows that there is no direct health effect from turbine noise, but annoyance and sleep disturbances for turbine neighbors may occur and that these effects correlate well with the sound level. The sound levels are relatively low, but the pulsating nature of the noise increase the disturbing effect compared to a constant noise source of the same level (Pedersen and Waye 2004, 2008). Although building-mounted wind turbines will never have any significant impact on energy production and the price per produced kWh is comparably high, they have recently become more popular, and as Moorhouse *et al* (2011) show structure borne mechanical noise from the turbines is propagated into the buildings. The characteristics of the structure-borne noise is significantly different from the airborne.

The levelized cost of energy (LCOE) for new onshore wind farms is typically 0.06–0.14 USD kWh^{-1}, while for offshore it is 0.14–0.19 USD kWh^{-1} (IRENA 2012). Despite this several countries, most notably the UK, Germany and Denmark, invest heavily in offshore wind farms and 10% of all new installations in the EU are now offshore. One advantage of offshore wind energy is the lack of immediate neighbors which could lead to higher societal acceptance. However, we know from the Cape Wind project facing ferocious opposition from the local community that this is not always the case (Phadke 2010). The papers in this focus issue scrutinize the possible environmental effect mainly below the sea surface with somewhat contrasting results.

In the southern North Sea the effects of the first Dutch offshore wind farm, OWEZ, with 36 monopiles, were studied intensively from the bottom fauna (benthos) to the marine mammals before and after the construction (Lindeboom *et al* 2011). The results indicate no effects on the benthos between the foundations, while on the new hard substrate of the monopiles and the scouring protection, new species were found and a new fauna community was established. The recruitment of bivalve (mussels and other filter feeders) was not impacted. The fish community was highly dynamic both in time and space and with the method used, only minor effects was observed, although some fish species, such as cod, seem to find shelter inside the farm. Several bird species seem to avoid the park while others are indifferent or attracted. Although inconclusive, satellite telemetry showed that harbor seals seemed to avoid an area up to 40 km from the construction site when monopile foundations were driven into the seabed causing intensive sound pressure. After construction the seals were seen inside the wind farm. This is in line with a reduced number of seals observed on land during ramming 4 km from a seal haul-out in the Baltic (Edrén *et al* 2010).

Harbor porpoises have been given special attention in European waters due to their strict protection under EU Habitats Directive (EU 1992, Annex IV) and their unknown status caused by bycatch in gillnet fishery and other anthropogenic threats. The most disturbing effect may be the ramming of wind monopile foundations into the seabed. This creates some of the loudest sounds emitted and may be heard by these animals hundreds of kilometers away in deeper waters and are strong enough to cause physical damage at short ranges. A study on the first German offshore wind farm showed that fewer animals were detected up to 25 km from the ramming site and that the displacement period (up to 6 days) was positively correlated to the duration of the ramming (Dähne *et al* 2013). This is somewhat consistent with the only two similar studies by Tougaard *et al* (2009) and Brandt *et al* (2011) studying the effect of ramming in the two Danish wind farms in the North Sea. Both Scheidat *et al* (2011) and Teilmann and Carstensen (2012) have studied the effect on harbor porpoises over several years in two of the first large scale offshore wind farms in the world. Both studies did observations both before and after the installation of the turbines using acoustic data loggers placed on the sea bottom inside and outside the wind farm. Scheidat *et al* (2011) found a significant increase of 160% in the presence of porpoises 1–2 years after the wind farm was in normal operation, compared to the baseline period (the construction period was not studied). It was suggested that this could be caused by less ship traffic and more food due to the ban of fishery inside the wind farm. Teilmann and Carstensen (2012) studied the Nysted Offshore Wind Farm before, during and after the construction of the 72 gravity foundation wind turbines. A significant negative effect was found with 89% fewer porpoises inside the wind farm during construction and 71% fewer 10 years later compared to the baseline values. Although there are indications of a slight recovery, this is in clear contrast to the results from the Netherlands indicating that other factors interact with the farms and the ecosystems in highly unpredictable ways. Whether it is the longer construction time of the gravity foundations, differences in underwater noise levels, or difference in motivation to be in the area despite disturbing effects from the wind farm, that cause this difference is still to be studied.

The next group of papers is concerned with the effect of wind farms on the atmospheric circulation and exchange of gases. Adams and Keith (2013) address the global onshore wind resource by atmospheric mesoscale simulations that include a single huge wind farm situated in the Midwest of the United States. Simulations are done with various farm sizes and capacities of up to 10 TW, which is more than thirty times the all-time cumulative global capacity (0.283 TW, www.gwec.net), and covering areas up to half a million km^2. The main conclusion is that wind power production from such farms is limited to about 1 W m^{-1} which is a factor 2–4 less than previous studies. Adams and Keith (2013) claim that this limitation applies to wind farms down to a size of about 100 km^2. However, this is disputed by Petersen *et al* (2013) saying that this limitation should only apply to much larger farms.

Using explorative numerical experimentation Wang and Prinn (2011) show that a massive deployment of offshore wind energy covering a significant fraction of the total global energy consumptions will cause a slight (~0.2°) cooling of the ocean surface in areas with wind farms. This is in contrast to the situation over land where an earlier study by the same authors show a more significant surface heating (Wang and Prinn 2010). It is also found that, especially in European waters, the seasonal variation in wind energy production is substantial. The authors call for more detailed modeling with better parametrization of the interaction of the farms and the atmospheric to confirm their results. Exactly that issue is addressed in Zhang *et al* (2013) performing wind tunnel investigations of a model wind farm in wind tunnel where the floor of the tunnel is heated to simulate atmospheric stability. They find that the area-averaged change in surface heat flux relative to bare land is negative but small, but that locally, especially in the immediate vicinity of the individual turbines, changes in the surface heat fluxes may reach 12%. They hypothesize that this may have consequences for irrigation requirements and crop yields in agricultural areas. Using similar modeling as in Adams and Keith (2013), Fiedler and Bukovsky (2011) show that a massive 200 000 km^2 wind farm in the Midwest will increase the average warm-season precipitation with 1.0% in several states surrounding the farm.

Finally, Arvesen and Hertwich (2011) establish through life-cycle assessment the potential benefits of a ten-fold increase of wind energy. Blind extrapolation of figure 1 indicates that this could happen in ten years. They investigate the implications for eight air pollutants and find that all are significantly reduced when compared to fossil-based power. Their analysis is sensitive to the lifetime of the turbines, which they assume is 20 years for onshore and 25 years for offshore. The capacity factor, which is related to the siting of the turbines (Petersen *et al* 2013), is also important for the final figures as is the potential emission penalties due to the intermittency of the wind energy, which is not taken into account in the study.

It is a finding of this focus issue that the environmental impact of wind farms depends on the exact location. It is hard to extrapolate the long term impact on porpoises from one farm to another. Similarly, the impact on surface temperature of large wind farms depends on whether they are situated on- or offshore. A predictive model of the impact of offshore wind farms on various marine species it still not available. Likewise, the large scale models assessing the impact on atmospheric circulation and fluxes depend critically on good parametrizations of the flow and turbulence in the wind farm. These areas lack a strong experimental or observational basis and are recommended for further research.

Acknowledgments

We would like to thank all the authors of this focus issue, and the many reviewers who have contributed to the high quality of the contributions. We also thank the editorial staff and the publisher Guillaume Wright for efficient support.

References

Adams A S and Keith D W 2013 *Environ. Res. Lett.* **8** 015021
Arvesen A and Hertwich E G 2011 *Environ. Res. Lett.* **6** 045102
Bolin K, Bluhm G, Eriksson G and Nilsson M E 2011 *Environ. Res. Lett.* **6** 035103
Brandt M J, Diederichs A, Betke K and Nehls G 2011 *Mar. Ecol. Prog. Ser.* **421** 205–16
Cathles L M 2012 *Geochem. Geophys. Geosyst.* **13** Q06013
Dähne M, Gilles A, Lucke K, Peschko V, Adler S, Krügel K, Sundermeyer J and Siebert U 2013 *Environ. Res. Lett.* **8** 025002
Edrén S, Andersen S M, Teilmann J, Carstensen J, Harders P B, Dietz R and Miller L A 2010 *Mar. Mam. Sci.* **26** 614–34
EU 1992 *EU Habitats Directive. Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora* (http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31992L0043:EN:HTML)
Fiedler B and Bukovsky M 2011 *Environ. Res. Lett.* **6** 045101
Howarth R W, Santoro R and Ingraffea A 2012 *Clim. Change* **113** 537–49
Hultman N, Rebois D, Scholten M and Ramig C 2011 *Environ. Res. Lett.* **6** 044008
IRENA 2012 Renewable energy technologies: cost analysis series (wind power) *IRENA Working Paper* (Bonn: International Renewable Energy Agency) (www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-WIND_POWER.pdf)
Lindeboom H *et al* 2011 *Environ. Res. Lett.* **6** 035101
Mann J, Sørensen J N and Morthorst P E 2008 *Environ. Res. Lett.* **3** 015001
Moorhouse A, Elliott A, Eastwick G, Evans T, Ryan A, von Hunerbein S, le Bescond V and Waddington D 2011 *Environ. Res. Lett.* **6** 035102
Pedersen E and Waye K P 2004 *J. Acoust. Soc. Am.* **116** 3460
Pedersen E and Waye K P 2008 *Environ. Res. Lett.* **3** 015002
Petersen E L, Troen I, Jørgensen H E and Mann J 2013 *Environ. Res. Lett.* **8** 011005
Phadke R 2010 *Environ. Polit.* **19** 1–20
Scheidat M, Tougaard J, Brasseur S, Carstensen J, van Polanen Petel T, Teilmann J and Reijnders P 2011 *Environ. Res. Lett.* **6** 025102
Teilmann J and Carstensen J 2012 *Environ. Res. Lett.* **7** 045101
Tougaard J, Carstensen J, Teilmann J, Skov H and Rasmussen P 2009 *J. Acoust. Soc. Am.* **126** 11
Wang C and Prinn R 2010 *Atmos. Chem. Phys.* **10** 2053–61
Wang C and Prinn R G 2011 *Environ. Res. Lett.* **6** 025101
Zhang W, Markfort C D and Porté-Agel F 2013 *Environ. Res. Lett.* **8** 015002