centre for
sustainable
energy

2nd edn, June 2017

Common concerns about wind power

Common concerns about wind power (2nd edn)

Written and researched by Iain Cox.

Centre for Sustainable Energy, June 2017
Written and researched: 2015

The Centre for Sustainable Energy is a national charity committed to ending the misery of cold homes and fighting climate change.

We share our knowledge and practical experience to empower people to change the way they think and act about energy.

We are based in Bristol although most of our work has relevance and impact across the UK. Our clients and funders include national, regional and local government agencies, energy companies and charitable sources.

PHOTOS: istock.com (cover/p4, p2, p94, p126), Shutterstock (p26, p32); pexels.com (p82), Jasja Dekker (p86), Changhua Coast Conservation Action (p104), Rachel Coxcoon (116)

centre for
sustainable
energy

OFFICE	3 St Peter's Court Bedminster Parade Bristol BS3 4AQ
PHONE	0117 934 1400
EMAIL	info@cse.org.uk
WEB	cse.org.uk
TWITTER	cse_bristol
CHARITY	298740
COMPANY	2219673
FOUNDED	1979

Contents

Introduction

Welcome to the second edition of the Centre for Sustainable Energy's Common Concerns about Wind Power. The first edition (2011) is our most widely accessed publication both in print and online. It's popularity reflects the need for a document that helps the interested reader, faced with a mass of conflicting information, to weigh up the likely impacts of wind power in their locality. We hope this update continues to provide an independent guide to the issues, backed up by hundreds of peer-reviewed papers and a dozens of government studies.

Every chapter from the first edition makes a reappearance, in many cases supplemented by new evidence that allows us to give more detailed and nuanced consideration to those issues. The second edition contains several new chapters covering topics that were not being widely discussed when the first edition was being prepared.

Of all renewable energy sources, wind power occupies a unique place due to a combination of two attributes: technological preparedness (wind is still best placed of all existing renewable energy technologies to contribute the electricity needs of the UK whilst simultaneously reducing its carbon emissions), and the fact that it is inherently site specific (making wind turbines strikingly visible additions to often previously undeveloped landscapes). The increasing presence of wind farms across the country means that communities everywhere will continue needing to address the issues surrounding wind power. Changes to government planning policy in 2015 mean that onshore wind developments cannot now proceed without a site first having been allocated in a local or neighbourhood plan. This publication, therefore, should provide a comprehensive grounding in the facts for local authorities and communities as they undertake the development of local policies with regards to wind power and renewable energy in general.

And of course wind power continues to be a highly contentious and politically charged issue. This is not helped by articles in the UK media that continue to repeat misstatements which are clearly contrary to the evidence and can easily be refuted, or by emotive language and the tendency to 'cherry-pick' evidence to present a one-sided view.

Equally, keen proponents of wind power are often too quick to dismiss any problems raised, levelling the charge of 'nimby' at anyone who speaks out against planned developments. While not necessarily willfully dishonest, both sides of the debate can be accused of reporting expediently to further their point of view.

In this updated and extended publication, we hope that pertinent research continues to be presented in a manner that leads to informed discussion. As before, this edition of Common Concerns about Wind Power relies heavily on academic peer reviewed publications and expert reports. Reading this is not intended to be the end of an interested person's research: rather, it should encourage further reading around the subject and the casting of a critical eye on the source of information. Casual assertions that unambiguously state wind power is good or bad without any supporting evidence should be judged accordingly. As is demonstrated throughout this document, the reality is frequently more complicated than that. The agendas of vested interests too often mean these subtleties are lost and the subject descends into acrimonious debate.

What this document aims to show is that, implemented as part of a progressive energy portfolio, wind power can significantly reduce both the UK's carbon footprint, and its dependence on fuel sources that may become less secure in the future, or that present a costly and unacceptably hazardous legacy for future generations.

However, wind power is not appropriate everywhere and can impact communities in different ways. We hope that, by publishing this research, communities themselves will engage constructively with the best available evidence to judge if there is a place for wind turbines in their own locality. To empower communities to make these decisions demands a more mature and responsible approach from the media, the wind industry and pressure groups on both sides of the debate.

Rachel Coxcoon,
Centre for Sustainable Energy, June 2016

Chapter 1

Wind turbines and energy payback times

Summary

The harnessing of wind for the generation of electricity may rely on a renewable source of energy, but it must also prove to be sustainable. All systems for converting energy into usable forms have energy requirements themselves, where energy must be invested in the myriad activities necessary for extracting and shaping materials, transport of parts and fuel, building and maintaining power plants and associated infrastructure, and decommissioning or upgrading the site. In its very broadest sense, some even include the expenditure of capital and labour as part of the energy investment. The amount of energy involved in the manufacture, construction, operation and decommissioning of wind farms is often voiced as a concern over whether wind turbines should be used at all. Since the capture and generation of any usable form of energy requires energy to be invested, the question is really one of how effectively the generating plant returns energy back to its users (i.e. society) in relation to the energy invested.

There are a number of ways of answering this question, but all these methods essentially seek to present information in a way that is useful in understanding how society can obtain sufficient surplus energy to make its investment worthwhile. In every case, the evidence shows that wind turbines perform well in this regard, often being the most effective of the renewable energy sources after hydropower, and in most situations being comparable or superior to conventional thermal electricity generation (i.e. fossil fuel and nuclear power). Overall, wind is relatively effective – for example, modern wind farms on average return 18 times the energy invested in them over their lifetime – but specific cases have returned lower values, and many very high estimates are born of optimistic projections for electrical output or fail to incorporate certain inputs that count as invested energy. Nonetheless, the modern, larger turbines (>1 MW) typically employed in wind farms today will 'pay back' the energy invested in less than a year, in some cases in less than six months. Over the remainder of its 20 to 25-year lifespan, the wind turbine will continue to return useful surplus energy in the form of electricity back to society.

What is this based on?

Since the Industrial Revolution, the phenomenal growth and development of global society has been a story of vast surpluses of energy.[1] These surpluses have been provided by fossil fuels, and the years since the end of the second world war have seen explosive growth driven by a global economy underpinned by oil (in later years accompanied by natural gas). As readily available reserves of oil have been depleted since 1900, this glut of available energy has steadily fallen, and the energy obtained through the extraction, refinement and delivery of oil and gas fuels to where they can be used is now less than half what it used to be only four decades ago, and this downward trend will continue.[1,2]

Although global reserves of coal continue to see a healthy energy return that has changed little since the 1950s (although energetically favourable extraction is very region-specific), increasing knowledge about the profound environmental and health implications of continued coal extraction and combustion means that it is viewed as one of the least sustainable fuels. One far-reaching environmental concern is climate change, caused largely by rising levels of greenhouse gases in the atmosphere. The prodigious consumption of fossil fuels by humans has been the single largest contributing factor to rising levels of CO_2 (a major greenhouse gas), and this fact has also made the quest for alternative sources of energy even more pressing.[3]

The current dependency of the world's economy on oil and gas has prompted much debate about when these resources might run out.[2] This is not meant in the purely literal sense of there being no more oil in the ground, but instead seeks to asks when society must invest so much energy into extracting and delivering oil that the useful energy obtained is no longer worthwhile. Economic indicators such as market price and cost-benefit analysis often fail to adequately assess future resource issues, such as when depletion of a finite resource (e.g. oil and gas) means a sufficient surplus of useful energy is no longer available.[4] Even if the geological deposits do not physically run out, increased energy expenditure to extract lower-quality oil and natural gas, combined with the necessity of opening up new deposits, will entail greater environmental impacts due to resulting emissions and habitat degradation.

To get around these problems, a practical metric to describe the level of energy surplus is applied, known as energy return on investment (EROI), which measures the net energy balance of an 'energy gathering' system. Although it is complex variable that can take into account many different factors, the basic formula for EROI is commendably simple:

$$\text{EROI} = \frac{\text{Energy returned to society}}{\text{Energy required to get that energy}}$$

At its most basic, the denominator and numerator can be expressed in the same units of energy, so giving a ratio with no units. For instance, an EROI of 10:1 ('ten to one') tells us a given process or system yields 10 joules for every 1 joule that is invested. Hence, an energy resource with a high EROI is considered a more useful or productive resource than one with a lower EROI. The EROI measurement can be a helpful indicator of the value of an energy source for several reasons. Not only does EROI provide a numerical output that can be easily compared with other energy sources, but, since it indicates the net level of useful energy that is delivered to society, it can be used as a proxy for assessing how much economic development is possible from the energy delivered, i.e. it can capture the quality of the resource.[5] This is often reflected in how useful energy is finally delivered in the system, and is one of the factors that complicates EROI analysis. Consider, for example, the delivery of a lump of coal to your house compared to mains electricity. Although both forms may contain the same amount of energy (in joules), the electricity is cleaner and more flexible at point of use than the coal; subsequently, you would be more productive consuming the electricity for your daily activities than using coal, and the greater value is reflected in the price paid for electricity.[6]

The quality aspect of EROI provides useful insights into the historical development of energy resources. Consider the typical EROI values for major energy sources given in Table 1.1. By looking at how EROI levels have changed over the course of a century, it has become increasingly clear that major fossil fuel resources are declining in quality, since EROI levels have been dropping steadily since the 1970s.[1] In the USA, which has always been one of the world's largest oil-producing nations, the EROI for a barrel of oil has declined by two-thirds since the 1970s, dropping from 30:1 to 10:1.

Natural gas data are typically aggregated with oil production, because the two energy sources are extracted from the same wells. However, data from more recent nonconventional natural gas deposits (Canadian tar sands, and 'tight gas' desposits in the USA) show a similar range of values, and a pattern of declining returns as the best resources are rapidly exploited (see Table 1.1).

The fall in EROI means that either more energy is needed to deliver a given amount of useful energy, or that the energy gain from what is currently invested is less than it used to be.[5] This has important implications for modern society, since it indicates that, despite rising prices that might drive increased exploration and extraction, or rising levels of gross production (e.g. more oil is drilled), the inevitable reduction in the quality of fossil fuels – as measured by EROI – means that these will soon no longer be viable resources to exploit as their EROI approaches a ratio of 1:1.[1,7] Even coal, which dropped from an EROI of 80:1 to 30:1 by the 1950s before returning to 80:1 in the 1990s, has only avoided this trend of declining EROI via the exploitation of lower-quality deposits that rely on cheaper surface mining. As can be seen in Table 1.1, when the value of energy is taken into account, i.e. the value of primary fuel compared to electricity, and we consider coal-powered electricity, the EROI for coal falls to less than 25:1. The detriment to climate, the environment and public health that this renewed extraction brings with it is one important factor not captured by EROI.[1]

This looming 'net energy cliff' will have a profound impact on global society. The abundance of surplus energy made available from energy sources with historically high EROI ratios has been fundamental to technological and cultural development, and maintaining EROI over a certain level is key to the improved quality of life and well-being of modern civilisation.[8] For instance, when the total energy cost of extracting and delivering useful energy to the final consumers is considered, a ratio of 3:1 EROI is calculated to be the 'bare minimum', but this would leave little surplus for other societal activities – essentially, much of society would be invested in helping deliver this energy and to maintaining fundamental services like the growing and transportation of food.[4,8] The threshold for maintaining greater well-being and quality of life (as measured by a combination of indices, such as the Human Development Index, health expenditure, and female literacy rates) is estimated to be in the range of 20:1 to 30:1 EROI. It is interesting to note that the upper value (30:1) represents a 'saturation point' above which additional surplus energy offers no further improvements to society.8 This is perhaps an indication of how profligate many modern societies have been with their historically high rates of fossil fuel consumption over the course of the previous century, when energy was abundant and, seemingly, never-ending.

In the case of wind power, the energy investment includes: manufacturing and transporting wind turbine components; constructing, connecting, operating and maintaining the wind turbine facility (this may be multiple turbines on a wind farm); and the final decommissioning of the site and recycling of the used components.[9] Note that the energy invested in the wind

Table 1.1 A range of illustrative EROI values for various energy carriers, divided between primary fuels (unshaded) and electricity (shaded).

Energy carrier	Average EROI, i.e. *x*:1 (energy$_{out}$/energy$_{in}$)	Comments
Primary fuels		
Oil	35	Global average
Oil & natural gas	30 11–18 10.1	U.S. domestic production in 1970s U.S. domestic production by 2005 U.S. domestic production by 2010
Natural gas	38 20 30	Canada domestic production 1993 Canada domestic production 2009 U.S. domestic production 2005
Shale oil	5	Conventional oil derived from shale formations. Initial high EROI values from U.S. extraction in the 1990s declined rapidly once 'sweet spots' were depleted
Tar sands crude oil	2–5	Note that low EROI of tar sands will lower average of oil and gas industry as a whole
Oil shale	1.4	Oil shale is a low-grade oil precursor, not to be confused with 'shale oil'
Electricity		
Oil-fired electricity	3.7–10.6	Higher value based on oil EROI of 30 (see oil & natural gas above)
Coal-fired electricity	12.2–24.6	Note EROI for coal alone (80:1) not included as it has limited use without further energy conversion
Nuclear-powered electricity	5–15	May be underestimated due to outdated processes studied
Wind-powered electricity	**18–20**	Data from meta-analysis of global wind farm installations. Larger modern turbines have higher EROI values
Solar p.v. electricity	6–12	Covers several types of modern photovoltaic (p.v.) systems. Generation based on average insolation for southern Europe
Hydropower	84	By far highest EROI with some values reported above 100, but resource geographically constrained

Figures derived or calculated from data in references 9, 15, and 16. The final EROI for solid fuels used to generate electricity or heat are based on well-head, mine-mouth or farm-gate values multiplied by typical thermal conversion efficiencies of primary energy inputs. In contrast to all renewable energy sources, fossil fuels and nuclear power use entirely non-renewable sources of energy both upstream and at point of use.

turbine and associated infrastructure is a mix of primary energy inputs and energy carriers. What this means is that primary energy inputs, such as oil, gas or coal, have been used alongside forms of energy, e.g. such as refined oil products and electricity, that themselves have been converted from primary energy inputs. For example, primary energy inputs (combustion of coal) may be used in heat-intensive processes like steel manufacture, whereas electricity may be used elsewhere in the supply chain in the manufacture of aluminium or to operate machinery during assembly.[1]

These primary energy conversions are another key complicating factor in energy ratio calculations, since the energy inputs have differing values depending on whether they are primary fuels or energy carriers (like electricity) that themselves are the result of energy conversions.[5] Each conversion step will require an energy investment, and accounting for these energy balances in a meaningful way in relation to the final useful energy delivered is very important. Of particular relevance to renewable energy systems is the fact that the energy gathering process itself consumes some of the energy being extracted, i.e. the system needs energy to make energy.[10] This 'autocatalytic' nature of energy generation (a product of the process is used in the process itself) means that the mix of energy types invested in a power plant assume great importance if it is a source of renewable energy. For example, if the EROI is lower than the 3:1 minimum mentioned above, then the renewable energy system is effectively being subsidised by fossil fuel consumption rather than creating a surplus of renewable energy itself.[4] This is clearly counterproductive if the aim is to have a sustainable (and low-carbon) means to generate energy.[5]

There are two important points to consider when assessing the net energy return for wind power. First, wind turbines generate electricity only. As we have seen, electricity is a high-value form of energy in terms of its usefulness to society.[5] The EROI equation can be written more specifically for a wind turbine, since it is producing a high value energy carrier from primary energy inputs invested:

$$\text{EROI} = \frac{\text{cumulative electricity delivered to society}}{\text{primary energy inputs invested}}$$

One can see that if, for instance, the primary energy inputs to generate electricity in the manufacturing process could be reduced due to greater deployment of renewable electricity generation (e.g. from wind turbines already operational), then the EROI will be improved. Remember, of course, that the EROI does not account for other benefits, like large reductions in greenhouse gas emissions and other pollutants due to displacing coal-fired electricity.[1] However, many studies also report energy investments as primary energy inputs, although wind turbines will return energy in the form of electricity only.[11] Because of this, the issue of whether the energy cost of wind turbines should be adjusted to electricity equivalents is still debated, and serves to illustrate the complexity of defining energy flows in national energy infrastructures.[10,11]

The other consideration is during the operational lifetime of the turbine, where the input of energy (wind) that generates the energy output (electricity) requires no further 'gathering' once the turbine is in place.[12] This means that the vast majority of the energy investment for wind power is an upfront cost.

Rather than calculate the return over the lifetime of the power plant, which EROI measures, it is often useful to look at how soon the operating plant 'pays back' the energy invested in it – the energy payback time or (EPT).[13,14] Note that EPT can be related to EROI, but they are not interchangeable. The EROI is time dependent – whether you run your wind turbine or coal-fired power station for two or 20 years makes a big difference to how much energy the plant will generate over its lifetime, whereas it will require the same energy investment to build and decommission it regardless. In the case of a fossil fuel-fired plant, however, the lifetime also makes a big difference to the amount of fuel that needs to be extracted and delivered for conversion to electricity. The energy flow for a wind turbine is neglible by comparison since the wind is 'free', so once the energy invested in building, operating and decommissioning is paid back, the energy delivered to society as electricity is a net gain.[12] This is why EPT is often used as a measure of how efficient renewable energy sources are, because the initial energy payback period is all that needs to be accounted for, after which point the turbine returns energy until the day it is shut down.

Once we know the EPT for a wind turbine, we can relate it EROI by accounting for the lifetime of the plant.[14] The EPT measures how long it takes to 'replace' the energy embodied in the wind turbine (including decommissioning), so we can simply take EROI to be equal to the operational lifetime divided by the EPT:

$$\text{EROI} = \frac{\text{lifetime in years}}{\text{EPT}}$$

What is the current evidence?

There are a wide range of values for EROI and EPT that have been found for wind turbines around the world. A recent report by the IPCC, based on published literature reviews that had amassed data from many operational and projected wind turbines, found that EROI values ranged from 5:1 to 40:1, and EPT ranged from as little as five or six weeks up to one-and-a-half years (the typical lifespan of the turbine was 25 years).[13] There are several issues with arranging so much disparate data from turbines together, and it is not surprising that these values exhibit a wide spread.

One of the most fundamental issues with any EROI analysis, whether fossil fuel or renewable energy system, is that of boundaries.[15] Establishing system boundaries clearly is the most important part of a net energy analysis, and it can be difficult to meaningfully compare EROI values for different energy resources if different direct and indirect energy costs are included or excluded.[5] For instance, a meta-analysis of published EROI studies encompassing data from 114 wind turbine projects found EROI values ranging from 1:1 up to a (somewhat astonishing) 126:1; such a wide spread, the authors argued, is due to the subjective nature of the boundaries set by the investigators, which omitted certain indirect energy costs.[9] The average EROI for all turbines was 25:1, but when only operational data was included this fell to 20:1. On the other hand, much of the data was derived from old, small turbines that are not indicative of modern turbines that have capacities of several megawatts. The same meta-analysis demonstrated a clear relationship between increasing turbine size and higher EROI values.[9] A different study that analysed figures published for 26 wind turbines of varying sizes also arrived at a mean EROI of 20:1.16 Most studies agree that the global EROI average for wind power is currently 15:1 to 20:1 for turbines that have a 20 to 25-year operational lifetime.[9,13–16] Moreover, the general data trend suggests that the EROI is steadily improving as more and more newer, larger wind turbines come online, including large offshore arrays.[9,14,15]

Some published studies have reported EROI values in excess in of 30:1, which, given performance capabilities for wind technology currently, or soon to be, deployed, are likely to be optimistic scenarios for planned turbines that assume favourable capacity factors (see chapter 4, ‘Efficiency and capacity factors of wind turbines’) or reflect wind farms located in areas that have higher than average wind speeds.[17] This issue has been highlighted by several researchers, and it is worth remembering that the EROI is generally downgraded when real operational data is used alone (viz. the change from 25:1 to 20:1 above).[1,9] Real-world data also tends to incorporate wider system boundaries, as mentioned above, and more stringent application of energy costs due to associated infrastructure and buffering capacity (see chapter 5, ‘Intermittency of wind turbines’) tends to result in lower EROI ranges.[9,16,17] This issue is also evident in published assessments of nuclear power, as it is claimed that unrealistic assumptions concerning reactor performance and uranium enrichment can lead to under- or overestimates of EROI.[14,17] Looking further ‘upstream’ in the nuclear supply chain, it can also be seen that mining and processing are important contributing factors to nuclear power’s overall primary energy input.[18] The decreasing quality of global uranium resources is likely to have an increasing impact on the energy inputs required to extract this fuel at the level required to satisfy future global nuclear expansion.[19] This introduces a certain element of risk when relying on nuclear power to supply a large proportion of future carbon savings, because a significant increase in primary energy inputs will have a subsequent knock-on effect of increasing GHG emissions.[18]

Given the context of replacing electricity generated from non-renewable sources, it is instructive to compare the performance of wind turbines with conventional and other alternative energy sources. Illustrative values are shown in Table 1.1. As can be seen from Table 1.1, EROI values for fossil fuels have steadily declined over the last century, in contrast to wind power, which, as we have seen, tends to improve as larger, more modern turbines come into operation. Data over time show that the decline seen with fossil fuel resources can be surprisingly rapid, as can be seen from values for oil and natural gas deposits in the USA and Canada (see Table 1.1). Despite the promise of new, unconventional sources of fossil fuels – tar sands oil, shale oil and dry (‘tight’) natural gas – many recent fields that were initially highly productive have already apparently passed their peak.[1,6,16]

Finally, relating the EROI of wind power to EPT suggests that wind turbines on average will pay back their energy investment in a little over five months.[13] The authors of Kubiszewski et al. found that EPT for turbines between 0.5 and 1.5 MW in size ranged from 95 to 193 days (i.e. roughly three to six months); operational data alone suggested EPT is slightly more than four-and-a-half months.[9] However, it is worth bearing in mind that the wind turbines in question had relatively high EROI values, and it is likely some assumptions were made in the reports analysed that excluded indirect energy inputs. Another review of 20 published studies suggested similar ranges for EPT, quoting a median (note, not the mean) of roughly five-and-a-half months, with a spread of 3.4 to 8.5 months.[20] Other recent values for large turbines (3.0–4.5 MW) give an EPT of seven to ten-and-a-half months.[11] The author of this review also points out that EPT would be extended if the primary energy invested had to be paid back in electricity equivalents, although this ‘worst case’ scenario would entail an EPT of roughly 20 months over the course of a 25-year operational lifetime.

Conclusion

Wind turbines are capable of generating low-carbon, high-value electricity by harnessing the natural energy flow provided by wind. Before such a energy gathering system can become operational, however, there is an energy ‘cost’ that is involved, because the manufacture and transport of components, site construction, operation and maintenance, and the ultimate decommissioning stage, all require energy to be invested. The value of a generating system is how much useful energy is returned to society. This can be expressed via the ratio of energy return on energy invested (EROI), although this deceptively simple equation hides a great deal of complexity. Generating systems are embedded in the wider energy infrastructure, which encompasses, at its widest, energy investments made at all stages of extraction, transport, conversion and delivery of energy in various forms. Historically, the extraction of fossil fuels has delivered abundant energy surpluses (high EROI values), but these have steadily declined as the most readily available resources have been depleted.

The non-sustainable nature of conventional energy generation, coupled with the far-reaching negative effects their use has on the environment and public health, has made the need to find alternative, renewable sources of energy particularly pressing. Maintaining the present level of development in modern society has been estimated to require a certain ‘bare minimum’ level of EROI for any energy resource, estimated to be 3:1. For civilisation to enjoy the full benefits of technological and cultural development that has characterised developed countries in the modern age requires a higher level, in the region of 20:1 EROI, unless society is willing to reduce present levels of consumption and use what energy is available more efficiently.

Wind power is able to offer an EROI level comparable, even superior, to present-day conventional generating systems. Existing operational data suggests an average EROI for wind of 18:1 to 20:1, and the increasing prevalence of larger, more modern turbine designs is likely to raise this average in the future. By comparison, present-day oil and natural gas resources have EROI values between 10:1 and 18:1 (Table 1.1), and industry trends means these values are likely to decline, even when taking newly exploited resources in North America into account. Coal has a higher global average of 28:1. It is noted that open mining in certain regions has seen the EROI for coal return to historically high levels (80:1), although these are lower-quality resources and involve significant environmental impacts. Typical values for nuclear power suggest an EROI of between 5:1 and 15:1, although some argue that this relies on older data that does reflect more modern techniques. The mining of uranium is essential for the nuclear industry, and thus it uses a non-renewable fuel supply chain that will become more and more depleted similar to the history of fossil fuel extraction.

Because renewable energy sources like wind rely on natural energy flows, almost all of society's energy investment is considered an upfront cost. Hence, a useful indicator of the efficiency of wind turbines is the energy payback time (EPT), which is the time it takes for a turbine to supply an amount of energy equal to the energy embodied (or invested) in it. It is important to remember that EROI and EPT are related, but not directly interchangeable. Published studies on typical modern wind turbines (capacities of 0.5 to 4.5 MW) show the EPT ranges from as little as three-and-a-half months to just over ten months. A wind turbine has an operational lifetime of 20–25 years, which means it will take just one to four per cent of its lifetime to repay the energy invested in it. Over its lifetime, a modern wind turbine would be expected to return at least 20 times the energy invested in it as renewable electricity.

References

1. Hall CAS, Lambert JG, Balogh SB. EROI of different fuels and the implications for society. Energy Policy. 2014; 64:141–52.
2. Murphy DJ, Hall CAS. Energy return on investment, peak oil, and the end of economic growth. Ann NY Acad Sci. 2011; 1219(1):52–72.
3. Bindoff NL, Stott PA, AchutaRao KM, et al. Detection and attribution of climate change: from global to regional. In: Stocker TF, Qin D, Plattner G-K, et al., editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC. Cambridge, UK and New York, USA: Cambridge University Press; 2013. 867–952.
4. Hall CAS, Balogh S, Murphy DJR. What is the minimum EROI that a sustainable society must have? Energies. 2009; 2(1):25–47.
5. Murphy DJ, Hall CAS, Dale M, Cleveland C. Order from chaos: A preliminary protocol for determining the EROI of fuels. Sustainability. 2011; 3(12):1888–907.
6. Cleveland C. Net energy from the extraction of oil and gas in the United States. Energy. 2005; 30(5):769–82.
7. Dale M, Krumdieck S, Bodger P. Net energy yield from production of conventional oil. Energy Policy. 2011; 39(11):7095–102.
8. Lambert JG, Hall CAS, Balogh S, Gupta A, Arnold M. Energy, EROI and quality of life. Energy Policy. 2014; 64:153–67.
9. Kubiszewski I, Cleveland CJ, Endres PK. Meta-analysis of net energy return for wind power systems. Renew Energy. 2010; 35(1):218–25.
10. Giampietro M, Sorman AH. Are energy statistics useful for making energy scenarios? Energy. 2012; 37(1):5–17.
11. Davidsson S, Höök M, Wall G. A review of life cycle assessments on wind energy systems. Int J Life Cycle Assess. 2012; 17(6):729–42.
12. Wall G. Life cycle exergy analysis of renewable energy systems. The Open Renew Energy J. 2011; 4(1):72–7.
13. Sathaye J, Lucon O, Rahman A, et al. Renewable energy in the context of sustainable development. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 707–90.
14. Modahl IS, Raadal HL, Gagnon L, Bakken TH. How methodological issues affect the energy indicator results for different electricity generation technologies. Energy Policy. 2013; 63:283–99.
15. Murphy DJ, Hall CA. Year in review—EROI or energy return on (energy) invested. Ann NY Acad Sci. 2010; 1185(1):102–18.
16. Lambert J, Hall C, Balogh S, Poisson A, Gupta A. EROI of Global Energy Resources: Preliminary Status and Trends. Report No. DFID 59717. Syracuse, NY: State University of New York College of Environmental Science and Forestry; Nov 2012. 40 p.
17. Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A. Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. Energy. 2013; 52:210–21.
18. Warner ES, Heath GA. Life cycle greenhouse gas emissions of nuclear electricity generation: systematic review and harmonization. J Ind Ecol. 2012; 16:S73–92.
19. Englert M, Krall L, Ewing RC. Is nuclear fission a sustainable source of energy? MRS Bull. 2012; 37(04):417–24.
20. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.

Chapter 2

Materials consumption and life cycle impacts of wind power

Summary

In addition to the concept of energy investment and energy return on that investment (see chapter 1), one other property of wind power that is fundamental to its role in providing sustainable energy is the material flow involved in their manufacture and operation. From an environmental perspective, all energy infrastructure comes at a cost. Although electricity generated from wind does not require fossil fuel combustion, wind turbines and their associated connections still require significant quantities of steel, copper, aluminium, and other more rare metals, in addition to concrete for wind turbine foundations and fibreglass and resins for the blades. Processing and manufacturing these materials requires energy, which contributes to greenhouse gas emissions, not to mention the requirement to physically extract the necessary mineral resources used in the manufacture of these component materials. Finally, although it is possible to recycle many of the materials used to construct turbines, this does not occur to the extent estimated in many life cycle impact assessments, and some materials (notably concrete and specialised plastics) cannot be effectively recycled at all with present technology. These are challenges that will become increasing pressing for the wind industry due to the rapid expansion of built infrastructure in recent years and projected future growth, which will result in very large numbers of turbines nearing the end of their useful life in the next few decades.

Wind turbines are a good example of modern society's sophisticated material requirements in the context of sustainable development, since they are integral to the provision of low-carbon electricity, but must operate under increasingly stringent resource availability so that broader environmental goals can be realised. Although its material requirements are significant, wind power is still one of best-performing energy technologies from an environmental perspective, with lifetime greenhouse gas emissions just 5–10% of those from fossil fuels.

What is this based on?

The continuing global expansion of wind as a source of electricity reflects its increasing competitiveness in terms of cost and the maturation of the onshore wind industry in particular. In 2012, the level of newly installed wind power capacity surpassed that of any other renewable energy technology, and some countries like Denmark generated 30% of their annual electricity needs from wind alone, with other regions seeing record generation peaks.[1] In the UK, along with a steady year-on-year increase of onshore wind installations, the growth in offshore wind has resulted in half of all renewable electricity generated across the country in 2013 being from wind power, which is 8% of the UK's total electricity supply.[2,3] This strong growth and the vast potential of offshore wind resources means that wind power is likely to form the cornerstone of society's transition away from predominantly fossil fuel-fired electricity generation.[4]

Although the advantage of wind power is that it relies on a renewable source of energy (the kinetic energy in wind flows), this does not mean that a wind turbine is free from non-renewable resource demands and the emissions related to the production and consumption of those resources.[5] Since mitigating rising atmospheric greenhouse concentrations is one of the key aims of moving to renewable energy sources, most studies on the costs associated with wind turbines are focused on the energy consumed and resulting carbon dioxide (CO_2) emissions.[6,7] However, the material resources themselves, which for wind turbines includes cast iron, steel, copper, aluminium, concrete, fibreglass-reinforced plastic and epoxy resin, are subject to supply chain constraints, and one must not forget that these resources are locked up in the wind turbine structure for the duration of its operational lifetime, which will place constraints on material flows to other sectors.[8]

Although these bulk materials are unlikely to run out in the near future, the rapid growth of the wind industry (and renewable energy in general) will place selective pressure on national and global manufacturing supply chains. More broadly, continued global economic growth and development across all industries will mean that the eventual strain on these finite resources may well present a severe impediment to a sustainable and secure future.[9,10] Even if the materials do not physically run out, increased energy expenditure to extract lower-quality mineral ores and the necessity of opening up new deposits will entail greater environmental impacts due to resulting emissions and habitat degradation. It is important to remember that the curtailment of these resources will affect every endeavor of modern society, so this is a constraint within which the wind industry must operate rather than an issue precipitated by the expansion of wind power per se.$_{11}$ Nevertheless, there are certain materials for which future wind turbine construction specifically will place greater demands: these are metals known as *rare earth elements,* which are essential for many large, modern turbine designs that employ permanent magnets.[8,12]

What the preceding discussion illustrates is that the need to recycle and reuse raw material stocks will become ever more pressing, but the present situation is that many metals are not recycled on global markets at a sufficient rate to be considered sustainable.[13] This largely reflects modern society's lack of incentive to sacrifice short-term economic gains for material efficiency, even though there are several long-term benefits in terms of increased resource security for nations, lower emissions of pollutants and greenhouse gases, less environmental degradation, and lower levels of finite resource depletion.[9] As far as wind power is concerned, establishing industry standards for recycling materials from turbines upon decommissioning is sorely needed.[14] Although the superior perfomance of wind turbines in comparison to fossil fuels with regards to greenhouse gas emissions and overall energy use is not in serious dispute,[5–7] the exploitation of finite mineral resources and use of non-recyclable materials needs to be properly assessed to ensure a true picture of wind power's sustainability is drawn.[15] This will be critical in optimising wind energy's contribution to climate change mitigation over the next century.[16]

What is the evidence?

Wind turbine structure and material needs

The turbine and substructure is the predominant source of material and energy consumption when considering wind power.* The energy expenditure and overall emissions that result from building a wind turbine and its foundation typically make up at least three-quarters of its lifetime environmental impact, with resources for the turbine itself dominating for onshore wind, whereas the resource burden is shared more equally between turbine and foundation for offshore installations.[5,7,16] The particular design requirements for turbines have changed over the last decade as larger turbines become the norm. Even in 2009, less than 10% of wind turbines were over 2.5 megawatts (MW) in size, yet this had increased to more than 35% by 2012, with many projections for an even greater proportion of significantly larger turbines (around 5 MW) thanks to the rapidly expanding offshore sector.[1,17] Increasing size leads to greater stress on gear mechanisms and increased maintenance requirements,[18] and this has pressured the industry to invest in designs of lower weight and with fewer moving parts.[4,8] One important outcome of this is an increase in turbines that employ a permanent magnet, which allows for a direct-drive system with no gearbox mechanism.[19] There are many types of permanent magnet available, but one in particular offers a superior combination of magnetic field strength combined with lower weight and size – it is a neodymium-iron-boron alloy (often called NdFeB or NIB), and it is central to much of the discussion surrounding potential shortages of rare earth elements and the expansion of wind power (discussed under Critical Raw Materials below).[17]

Both Table 2.1 and 2.2 outline the major material requirements for typical modern wind turbines. Note the way in which the data are presented between the two tables, with lifetime resource consumption of raw materials per unit of electricity generated over the turbine's lifetime (Table 2.1), and the construction materials required to build a new turbine per MW of capacity (Table 2.2). This highlights two important features of any life cycle assessment for energy technologies. First, similar to the principle of energy returned compared with energy invested (see chapter 1, 'Wind turbines and energy payback times'), the operating lifetime of a wind turbine will determine how much electricity it produced in total before it is decommissioned, but the material needed to build the turbine in the first place will be the same regardless of how long it operates for. Second, the increasing size of modern turbines means that less material is required for each unit of generating capacity, not only because improvements in materials technology and design can optimise materials efficiency as the industry evolves, but also because larger turbines can extract more energy from the wind (this is discussed in chapter 4). Indeed, the move away from smaller turbines by the industry to a standard commercial size of several megawatts (at least) has seen the environmental profile of wind turbines markedly improve when measured per kilowatt-hour of electricity produced.[6,7,16] There is some evidence, however, that the rate of improvement slows significantly once the megawatt 'threshold' has been passed, although the general positive trend continues.[5]

Critical raw materials

Since the 1990s, wind turbines have gotten larger and the penetration of wind into national power systems has grown, which has necessitated several changes in the design principles behind generator technology. This has been largely driven by the need to better integrate with

---

* The concept of energy expenditure and energy flow over the lifetime of a wind turbine is discussed in Chapter 1. This chapter deals with material flows and thus the material 'by-products' from wind energy are included here, namely greenhouse gas emissions. The reader should keep in mind that energy and material flows, and the overall emissions that result, are intertwined, but they have been separated for the sake of this discussion.

Table 2.1 Estimated consumption of raw materials used in wind farms as a function of lifetime supply of electricity (values taken from refs. 20–22)

Turbine size used (type)	1.65 MW	3MW	3 MW (offshore)	3 MW (PM)
Resource	Estimated lifetime consumption (g/kWh)			
Water	38	51	49	27
Stone	3.6	3.5	<0.1	nd.
Quartz sand	0.12	0.59	0.34	0.24
Limestone	0.33	0.1	0.13	0.13
Clay	0.02	0.05	0.03	0.18
Rock salt (NaCl)	0.14	0.08	0.05	0.14
Iron	0.99	0.04	0.42	nd.[a]
Zinc	nd.	0.01	0.04	nd.[a]
Aluminium	0.01	<0.01	0.01	nd.[a]
Manganese	nd.	0.01	0.01	nd.[a]
Copper	nd.	<0.01	0.01	<0.01
Lead	nd.	nd.	<0.01	nd.[a]
Chromium	nd.	<0.01	nd.	<0.01
Rare-earth ore	n/a	n/a	n/a	0.1
Hard coal	1.11	0.64	0.74	0.52
Lignite	0.23	0.34	0.32	0.69
Crude oil	0.71	0.54	0.63	0.64
Natural gas	0.53	0.42	0.38	0.73

g/kWh, grammes per kilowatt-hour; MW, megawatt; nd., no data; PM, permanent magnet

All values based on turbine lifetime of 20 years, although it is feasible larger wind turbines will have longer operational lifespans than this.[21,22] Turbines onshore unless otherwise stated. Note fossil fuel consumption is based on energy resources used to extract and process metals and other mineral resources before they can be used in construction.

[a] Data given as unprocessed ore rather than elemental metal so direct comparison not possible.

Table 2.2 Summary of major materials required for construction of wind turbines based on installed capacity in megawatts (MW)

	Materials required per MW installed capacity (tonnes/MW)						
Turbine	Stainless steel	Cast iron	Copper	Concrete	Fibreglass	Nd in magnet	Misc.[a]
1.5 MW onshore, gearbox, wound rotor[b]	115	23.9	2.5	590	9.8	0	8.1
3.0 MW 'next-gen.' turbine on- and offshore, mixed generator technology[b]	103	20	3	402	6.8	0.04	9.3
3.0 MW onshore, PM generator[c]	96	21.7	1.8	298	~7-8	0.04	~10

DFIG, double fed induction generator; Nd, neodymium (27% by weight of NdFeB permanent magnet; Nd is a rare earth element); PM, permanent magnet

[a] Includes aluminium, thermoplastics and other polymers, epoxy resins, lubricants and other materials.

[b] Estimates from ref.8 based on generic 'current generation' (1.5 MW) and 'next generation' (3 MW) turbines rather than a specific turbine model. Note the next-gen. turbines are assumed to make more use of composite materials and approximately 20% of installed turbines will contain a PM generator, with the remainder being DFIG (a type of wound rotor generator).

[c] This is based on life cycle impact assessment for a specific model (see ref. 22). Note estimates for fibreglass and miscellaneous categories are approximations made to fit with categories from ref.8 (see rows above). It is estimated that using a neodymium magnet in this model can save around 10 tonnes of steel per turbine (see ref.15).

the grid, so that wind turbines can operate at variable speeds and cope with dips in grid voltage, and also to improve the cost-effectiveness of larger turbines through lowering the weight and size of the generator, power converter and gearbox mechanisms, and minimising the level of maintenance required.[†] [4,19] There are several different ways in which these aims can be realised, but one of the most effective devices that assists with this overall goal is the use of a permanent magnet.[‡] Neodymium-iron-boron (NIB) permanent magnets combine higher magnetic field strength with low weight, thus making them ideal for high-torque applications where space and weight must be minimised. This means NIB magnets are of especial importance to renewable technologies, such as electric motor vehicles and wind turbines.[17]

On the periodic table, neodymium is grouped as a lanthanide; along with scandium and yttrium, the lanthanides are classed as rare earth elements. Of a total of 17 rare earth elements, 10 of these are of ongoing commercial interest, although it is conceivable that more will find uses given the increasingly specific and exacting demands of modern materials technology.[11,12] Rare earth elements are so-called because of their geological dispersal rather than their lack of abundance – this simply means concentrated ore deposits do not exist and therefore these elements have been mined as a by-product of larger deposits of useful commodities, typically iron ore.[23] Indeed, until commercial uses were found for these elements they were typically treated as contaminants or waste products.[24]

Permanent magnets used in wind turbines typically contain neodymium and smaller quantities of another rare earth element, dysprosium (this latter element is added to NIB magnets to improve their performance at higher temperatures). The supply of both of these materials is considered critical over the next decade, due to the concentration of viable deposits in one region (China mines 95% of the world's supply) at a time when demand for clean energy technologies is growing rapidly.[12,17] In fact, wind turbines are a relatively small contributor to this supply bottleneck. For instance, the demand for neodymium and dysprosium consumption due to electric vehicle manufacture is higher than for wind turbines.[12] By far the biggest driver of consumption, however, is the extraordinary volume of rare-earth magnets used in the electronics sector: around 75% of global stocks of neodymium used today are in personal computers and audio equipment, and these also contain the largest dysprosium stocks.[25] The type of use will have important implications for the future sustainability of some of these critical materials. Since rare earth elements are used in comparatively large quantities per device in wind turbines and electric vehicles, they are more amenable to recycling; recovering these precious metals from electronics, however, requires specific knowledge of how each device is manufactured to enable precision dismantling, none of which routinely occurs today.[12,24,25] The vast majority of in-use rare earth element stocks are therefore destined to be lost from the material flow 'loop' thanks to the high growth and turnover of the consumer electronics market.

Despite the advantages of permanent magnets in wind turbine design, recent spikes in global prices due to Chinese export restrictions at a time of growing demand have prompted governments and the wind industry to reassess wind turbine design and deployment in an attempt to reduce their reliance on rare materials.[23] There are several alternatives to current designs that use permanent magnets, a proven one being the use of 'hybrid drive' generators, which employs a single-stage gearbox with a smaller permanent magnet. This type of design evolution can result in less maintenance needed thanks to the lower number of gears involved when compared to a conventional turbine gearbox. At the same time, a hybrid drive can reduce neodymium use compared with turbines that use direct-drive permanent magnet systems from 186 kg per MW installed capacity to just 62 kg/MW, and the small amount of dysprosium used will also see the same proportional drop.[17,19] More conventional generators can also be used that do not need permanent magnets, thanks to updated designs that eliminate parts subject to wear and tear (e.g. 'brushless' induction generators, although not all designs have been commercially proven for MW-rated turbines).[19] Finally, one must remember that existing generator and gearbox designs are still effective and in constant use.

Since the early days of expansion in the 1990s, when there were higher than expected failure rates for some component parts (surprisingly, and contrary to expectations, these failures were rarely related to gearbox assemblies), there has been a steady reduction in failure rate to the point where the reliability of wind turbines is comparable to that of gas turbine generators.[26] As the industry learns how best to

---

[†] Staying online during a low-frequency voltage dip is know as 'fault ride-through capability', and most national grids in Europe now regard this as mandatory for new wind installations. The use of variable-speed generators allows the turbine electrical output to be better synchronised with the grid connection, and fault-ride through can be facilitated by using power converters. The generator, gears and power converters are the main contributors to the overall weight and size of the wind turbine nacelle, so maximising efficiency is key. One obvious way to reduce size and weight is to remove the gears altogether, as is achieved with direct-drive designs; this has an additional advantage in reducing maintenance requirements.

[‡] Normal high-power generators rely on an electrical current passed through the field coils to create the necessary magnetic field around the rotor. Strong permanent magnets can maintain a persistent magnetic field without the need for a power supply to the coil; by mounting permanent magnets on the rotor shaft, the generator also becomes synchronous. Both of these features enable fault ride-through and improved grid connectivity, and reduces many of the parts in a conventional generator that are subject to wear.

implement the most effective preventive maintenance, this reliability is likely to improve further; thus, the range of designs available to the industry means that is better placed to cope with critical materials shortages should they arise.[19,26,27]

Life cycle greenhouse gas emissions

Finally, what are the implications of these material requirements? There are many life cycle assessments (LCAs) for wind power that have been published in the last few decades, which seek to quantify the environmental impact of wind energy, especially with regards to the greenhouse gas emissions it produces for every unit of electricity it generates. The LCA can be subject to different results for emissions or energy used, based simply on the methodology applied to deriving the inventory of energy and material inputs – all LCAs for energy technologies are subject to these differences, wind energy among them.[15] A very recent review, which sought to aggregate and analyse many different published LCAs for wind energy, usefully filtered many studies due to criteria such as lack of completeness, not directly presenting impacts in the form of greenhouse gas emissions, being outdated, quoting secondary sources, or only focusing on CO_2 to the exclusion of other greenhouse gases.[16] A summary of the findings is presented in Table 2.3.

The average rate greenhouse gas emissions (in CO_2 equivalents per megawatt-hour) is roughly 34 kg $CO_{2\text{-}eq}$/MWh (see Table 2.3). This is in line with a broader review by the IPCC that looked at LCAs published over a longer period, which found the emissions value to be grouped between 8 to 20 kg $CO_{2\text{-}eq}$/MWh, with some outliers as high as 80 kg $CO_{2\text{-}eq}$/MWh.4 Another recent meta-review of energy technologies also found a similar range for wind power, this time ranging from 3 to 41 $CO_{2\text{-}eq}$/MWh.28 However, Table 2.3 also reveals that the value for offshore is lower overall when compared with onshore (19 vs 39 kg $CO_{2\text{-}eq}$/MWh); this also follows the same pattern found in the IPCC report.[4,16] Despite the greater material requirements for offshore wind due to larger turbine and foundation structures, the increased electricity production means overall emissions are lower per MWh.

One can also see the importance of lifetime estimates in Table 2.3, because when LCA results are grouped by age in five-year increments we see almost a two-thirds drop in the emissions rate between 20 years and 30 years (from 41 to 25 kg $CO_{2\text{-}eq}$/MWh). As we saw when considering energy invested (Chapter 1), because the inputs for wind power are predominantly upfront (i.e. only a small fraction of the total material and energy inputs are required once a turbine is built and operating) an extended lifetime means more electricity is produced for only a neglible increase in total emissions.

What is clear from the many LCA studies available is that wind performs significantly better than fossil fuel-powered electricity. Using the figures presented in Table 2.3, wind power has emissions roughly one-tenth of those of natural gas (34 vs 350–443 kg $CO_{2\text{-}eq}$/MWh)

Table 2.3 Summary of findings from review of 22 studies dealing with LCA of wind power systems. Data from Nugent and Sovacool (2014), Energy Policy, 65:229–44

	Greenhouse gas emissions (kg CO_2eq/MWh) contributed by each stage of a turbine's life				
	Overall total (n=39)	Extraction, processing & manufacture	Construction	Operation	Decommissioning (incl. recycling)
Mean	**34.1**	43.0	14.4	14.4	-11.6
Median	**12**	12	8.3	2.4	-3.3
s.d.	**67.2**	77.0	21.2	26.3	18.8
	Greenhouse gas emissions (kg CO_2eq/MWh) based on whether turbine is onshore or offshore				
		Onshore (n=31)	Offshore (n=6)		
Mean		38.9	18.9		
	Greenhouse gas emissions (kg CO_2eq/MWh) based on operational lifetime of turbine Estimated lifetime of turbine (years)[a]				
	20 (n=26)	**25 (n=3)**	**30 (n=4)**		
Mean	40.7	28.5	25.3		

kg CO_2eq/MWh, kilogrammes CO_2 equivalents per megawatt-hour; n, sample size; s.d., standard deviation

[a] This shows data when categorised by average operational lifetime of the turbine. Note that offshore wind turbines typically have an estimated operational lifetime of 30 years and are therefore mainly represented by this longer time frame; in contrast, the 20-year lifespan is typical of onshore wind turbines.

and anywhere from one-twentieth to one-thirtieth that of electricity from hard coal (34 vs 660–1050 kg CO_{2-eq}/MWh).[16,28] An in-depth LCA of nuclear power arrived at average emissions of 66 kg CO_{2-eq}/MWh; but the studies that were included, even after a stringent selection process, differed widely in assumptions about the full life cycle processes for uranium fuel, such as estimates of the quality of uranium ore, the energy intensiveness of the enrichment method and the effort required to treat spent fuel and decommission plants.[29] Indeed, although well-established as an energy commodity, uranium fuel can also be considered a critical material, since any expansion of the global nuclear fleet in the next century will require a substantial construction effort and the exploitation of new, as yet undiscovered, uranium deposits.[30]

What are the implications of these emissions figures? Take the UK's present level of carbon emissions from the electricity sector, which is 450 kg CO_{2-eq}/MWh, on average. Projected installed capacity for wind power is expected to generate roughly 51 GWh per annum by 2020. This would save over 22 million tonnes (Mt) of CO_2, or around 15% of the present-day electricity sector's total emissions.[31] Taking into account the less carbon-intensive nature of the UK's generating portfolio by 2020, largely due to less carbon-intensive coal-fired generation,[§] these savings may be lower, but will still be in the region of 20 Mt CO_2.[32]

Other life cycle impacts

In addition to greenhouse gases and their effects on climate change, LCA methodology takes into account other pollutants, attempting to present these in a meaningful way to allow a comparison of overall environmental effects.[15] These effects are typically categorised under several impact indicators: acidifcation, eutrophication, particulates, photochemical oxidants, ecotoxicity and human toxicity. Many of these impacts are caused by fossil fuel combustion releasing particulate matter, sulphur dioxide (SO_2), nitrogen oxides (NO_x) and other chemicals. It is important to account for these impacts, since the extraction and processing of the raw materials needed for wind turbines will rely to a large extent on energy from fossil fuels in the present energy infrastructure.[5] Over their lifetime, wind turbines produce much lower levels of particulates and the pollutants responsible for acidification and eutrophication (primarily SO_2 and NO_x), typically in the order of one-tenth or even one-hundredth of that emitted by electricity from fossil fuels.[28,33,34] It is acknowledged, however, that a more detailed analysis of toxic emissions is needed as many LCA models are incomplete in this regard, a problem which extends to LCAs for all energy technologies, both conventional and renewable.[5] This is especially important if the proportion of wind turbines employing rare-earth magnets increases, because the ecotoxicity of rare-earth mining can be significant when compared to bulk metal commodities on a per weight basis.[35] In addition, there is currently little that can be done to recycle the composite fibreglass and plastic materials used for construction of the blades in a turbine. The environmental impacts of these materials if placed in landfill are significant, and the wind industry is experimenting with recycling these products to be used as filler material or heat-treating them so that fibreglass and synthetic resins can be used in other industrial processes.[5,14] Unfortunately, at present, these avenues have met with limited success.

Finally, coming back to the material requirements of different energy technologies, the level of resource depletion is another important indicator of sustainability (this is often termed 'abiotic depletion' because it is focused on mineral resources). The level of resource depletion can be mitigated to a sizeable degree (up to 70%) through effective recycling and reuse of core construction materials used in a wind turbine.[14] At present, however, it is known that many LCAs for wind turbines apply recycling rates for metals used in construction that are not indicative of the real world.[13] A common misconception is the level of recycled steel incorporated into construction stock, which is generally considered to be overestimated in LCAs for wind, often stated in excess of 90% when the recycled content is typically less than 50%.[5,13,15] For rare metals the current recycling rate is practically zero.[13] This is due, to some extent, on there being no market for it, but largely because the consumer electronics industry uses the lion's share of such metals, which presents a considerable obstacle to effective recycling on account of the intricacy of components and a lack of mandates to persuade manufacturers of such products to husband these resources effectively.[24] In comparison, the wind industry is well-placed to implement an effective 'closed loop' for many of the rare metals used in turbine generators, since the larger components are more amenable to recycling and the renewables industry does not operate along the lines of fast product turnover and rapid obsolescence seen in the consumer electronics industry.[5,24,25]

Conclusions

Like any energy infrastructure, wind power requires significant quantities of material for construction, notably iron, steel alloys, aluminium, copper and fibreglass. In addition, some modern turbine designs make significant use of rare earth metals, for which there are expected to be critical bottlenecks in supply over the coming decade. One should bear in mind that

---

[§] This is based on an approximation from DECC's projected gas/coal mix (see ref.32, p.39), and taking into account the Emissions Performance Standard that will limit coal-fired plants to 450 gCO_2/kWh. This gives average carbon emissions from combined gas and coal-fired generation of 409 tCO2/GWh in 2020.

the wind industry is not the sole driver of material demand, or even the largest. Global demand for all energy technologies is increasing at a phenomenal rate due to the continued economic expansion of countries such as China and many developing nations. Where specific material requirements exist, like that for rare earth metals, other industries predominate, not least the already large consumer electronics market and the burgeoning electric vehicle sector.

Material consumption will increase over the short-term if the wind industry, and the renewables sector generally, continues to expand following current projections. This will create supply constraints for some critical materials, although the range of existing alternative options for turbine generator design allows some adaptations to be made in the face of resource constraints and rising prices. The extensive literature on life cycle impacts shows that wind energy, in terms of greenhouse gas emissions and other indicators, has one of the best environmental profiles of any generating technology, and is far superior to fossil fuel-powered electricity in particular. However, the present rate of recycling for the vast majority of metals, both rare and non-critical, is very low across all sectors. It is imperative that more action is taken in this regard. With its sustainable credentials and a central role to play in the world's future energy mix, the wind industry is must take a strong lead in improving recycling and materials efficiency as the number of turbines worldwide continues to increase.

What are the implications of wind energy's material requirements? Despite these short-term increases in materials consumption, the need to accelerate the transition to renewable energy technologies is the more pressing need, because the lag time between reductions in greenhouse gas emissions and the stabilising of global temperatures means any delay of even a decade will increase the likelihood that extreme climate effects will be unavoidable over the next century.[36,37]

It has been shown that the short-term increase in material and energy use resulting from widespread implementation of renewables will pay dividends by the second half of this century, as overall environmental impacts from energy supply will be considerably reduced.[33] Greenhouse gas emissions alone could be more than 60% lower when compared with a 'business as usual' scenario, and this from just 39% of the world's electricity being generated by a mix of wind, solar and hydropower. Thus, although it is likely to lead to a short-term increase in consumption of certain materials, the expansion of wind and other renewables now will help guarantee the wider benefits of a sustainable energy future by the middle of the 21st century.

References

1. REN21. Renewables 2013 Global Status Report. Paris: REN21 Secretariat; 2013. 176 p.
2. 'Renewable electricity capacity and generation (ET 6.1)', Statistics: Energy trends section 6: renewables, Department of Energy and Climate Change, Excel spreadsheet www.gov.uk/government/uploads/system/uploads/attachment_data/file/323527/et6_1.xls (last updated 26 Jun 2014), accessed 21 Jul 2014.
3. 'Fuel used in electricity generation and electricity supplied (ET 5.1)', Statistics: Energy trends section 5: electricity, Department of Energy and Climate Change, Excel spreadsheet www.gov.uk/government/uploads/system/uploads/attachment_data/file/323524/et5_1.xls (last updated 26 Jun 2014), accessed 29 Jul 2014.
4. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.
5. Arvesen A, Hertwich EG. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. Renew Sustain Energy Rev. 2012; 16(8):5994–6006.
6. Kubiszewski I, Cleveland CJ, Endres PK. Meta-analysis of net energy return for wind power systems. Renew Energy. 2010; 35(1):218–225.
7. Raadal HL, Gagnon L, Modahl IS, Hanssen OJ. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. Renew Sustain Energy Rev. 2011; 15(7):3417–3422.
8. Wilburn DR. Wind energy in the United States and materials required for the land-based wind turbine industry from 2010 through 2030. USGS Scientific Investigations Report 2011-5036. Denver: U.S. Geological Survey; Jun 2011. 22 p.
9. Allwood JM, Ashby MF, Gutowski TG, Worrell E. Material efficiency: providing material services with less material production. Phil Trans R Soc A. 2013; 371(1986):20120496.
10. Graedel TE, Erdmann L. Will metal scarcity impede routine industrial use? MRS Bull. 2012; 37(4):325–331.
11. Graedel TE, Harper EM, Nassar NT, Reck BK. On the materials basis of modern society. Proc Natl Acad Sci USA. 2 Dec 2013 [epub ahead of print], doi:10.1073/pnas.1312752110.
12. Alonso E, Sherman AM, Wallington TJ, et al. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ Sci Technol. 2012; 46(6):3406–14.
13. Graedel TE, Allwood J, Birat J-P, et al. What do we know about metal recycling rates? J Ind Ecol. 2011; 15(3):355–366.
14. Ortegon K, Nies LF, Sutherland JW. Preparing for end of service life of wind turbines. J Clean Prod. 2013; 39:191–9.
15. Davidsson S, Höök M, Wall G. A review of life cycle assessments on wind energy systems. Int J Life Cycle Assess. 2012; 17(6):729–42.

16. Nugent D, Sovacool BK. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy. 2014; 65:229–44.
17. DOE. Critical materials strategy. Report no. DOE/PI0009. U.S. Department of Energy; Dec 2011. 194 p.
18. Yang W, Tavner PJ, Crabtree CJ, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. Wind Energy. 2014; 17(5):673–93.
19. Polinder H, Ferreira JA, Jensen BB, Abrahamsen AB, Atallah K, McMahon RA. Trends in wind turbine generator systems. IEEE Trans Emerg Sel Topics Power Electron. 2013; 1(3):174–85.
20. Vestas. Life cycle assessment of electricity delivered from an onshore power plant based on Vestas V82-1.65 MW turbines. Randers, Denmark: Vestas Wind Systems A/S; Dec 2006. 77 p.
21. Vestas. Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines. Revised edition. Randers, Denmark: Vestas Wind Systems A/S; Jun 2006. 60 p.
22. D'Souza N, Gbegbaje-Das E, Shonfield P. Life cycle assessment of electricity production from a Vestas V112 turbine wind plant. Copenhagen: PE North West Europe ApS; Feb 2011. 87 p.
23. Hurd AJ, Kelley RL, Eggert RG, Lee M-H. Energy-critical elements for sustainable development. MRS Bull. 2012; 37(4):405–10.
24. Ayres RU, Peiro LT. Material efficiency: rare and critical metals. Phil Trans R Soc A. 2013; 371(1986):20110563.
25. Du X, Graedel TE. Global in-use stocks of the rare earth elements: a first estimate. Environ Sci Technol. 2011; 45(9):4096–101.
26. Tavner PJ, Xiang J, Spinato F. Reliability analysis for wind turbines. Wind Energy. 2007; 10(1):1–18.
27. Yang W, Tavner PJ, Crabtree CJ, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. Wind Energy. 2014; 17(5):673–93.
28. Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sustain Energy Rev. 2013; 28:555–65.
29. Sovacool BK. Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy. 2008; 36(8):2950–63.
30. Englert M, Krall L, Ewing RC. Is nuclear fission a sustainable source of energy? MRS Bull. 2012; 37(04):417–24.
31. DECC. 2010 UK Greenhouse Gas Emissions, Final Figures. London: Department of Energy & Climate Change; 7 Feb 2012. Statistical release No.4282. Available from: www.decc.gov.uk/en/content/cms/statistics/climate_stats/climate_stats.aspx [Accessed 28 July 2012].
32. DECC. Updated energy and emissions projections 2013. URN 13D/231. London: Department of Energy and Climate Change; Sep 2013. 50 p.
33. Hertwich EG, Gibon T, Bouman EA, et al. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc Natl Acad Sci USA. 6 Oct 2014 [epub ahead of print], doi:10.1073/pnas.1312753111.
34. Sathaye J, Lucon O, Rahman A, et al. Renewable energy in the context of sustainable development. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 707–90.
35. Hischier R, Wäger P, Hauschild M. Life cycle impacts of metals. In: Van der Voet E, Salminen R, Eckelman M, Mudd GM, Norgate T, Hischier R, editors. Environmental risks and challenges of anthropogenic metals flows and cycles. A report of the Working Group on the Global Metal Flows to the International Resource Panel. Nairobi: UNEP; 2013. 125–156.
36. Lenzen M, Schaeffer R. Historical and potential future contributions of power technologies to global warming. Climatic Change. 2011; 112(3-4):601–32.
37. Myhrvold NP, Caldeira K. Greenhouse gases, climate change and the transition from coal to low-carbon electricity. Environ Res Lett. 2012; 7(1):014019.

Chapter 3

Wind power costs and subsidies

Summary

Although it is argued that wind power is unfairly subsidised to make it more competitive with conventional forms of electricity generation, fossil fuels and nuclear power both benefited from government support in their early years of development, and continue to do so today. The transition away from an energy economy dominated by conventional fuels and centralised power distribution towards a more diverse set of renewable energy sources is essential to the development of a sustainable, low-carbon future, something that cannot be achieved within existing energy infrastructure.

Renewable energy subsidies are motivated by the need to displace fossil fuels within a power system that was never originally designed to accommodate renewables, creating a 'level playing field' for newer technologies and smaller producers in liberalized, competitive energy markets. In fact, the generating cost of onshore wind power is comparable to conventional generation, largely thanks to the opening created by financial support mechanisms, which started in the 1990s, which have allowed the wind industry to expand, gain experience, improve efficiency and performance. However, subsidies for onshore wind have were removed completely in 2016 due to the UK government's desire to set a cap on the total overall cost of subsidizing renewable energy through the Levy Control Framework. This unanticipated removal has had a detrimental impact on investor confidence in wind power in the UK and has the potential to undo some of the positive impacts of 25 years of investment in wind.

The UK is also a leader in offshore wind development, and higher subsidies for this form of generation reflect this maturing, but still relatively nascent, industry. Subsidies to renewables also acknowledge the benefits derived from removing the wider burdens placed on the environment by conventional generation; these burdens incur sizable costs for society as a whole. The majority of these costs are not internalised into the present-day costs of energy generated from fossil fuels and nuclear power, which obscures the true cost of conventional generation and reinforces its apparent competitive advantage over more sustainable sources of energy.

What is this based on?

Subsidies for renewable generation methods are not unique, in one way or another governments worldwide provide financial support to the energy industry, including fossil fuels and nuclear power generation. Readily affordable electricity generated by burning fossil fuels has been supported by governments and consumers because of the continual, rapid economic growth and development this has facilitated. Support for fossil fuels remains strong globally, with governments maintaining a range of measures to support consumption, through price reductions for the consumer, or production, through price guarantees for producers and through lowering the cost of production.[1,2]

Production subsidies for fossil fuels, which are the main tool used in industrialised countries, including the UK, are much less transparent than the more direct payments to renewable energy, and usually involve a complex arrangement of tax deductions and credits, capital expenditure write-offs, and liability protections, all of which vary between countries.[3] In addition, consumption patterns for energy derived from conventional sources are maintained by tax concessions to producers and consumers alike. Lowering prices for providers and end-users in energy markets discourages energy efficiency and creates a dependency, or 'lock-in', for particular fuels; thus, the development and commercialisation of alternative forms of energy that may be more beneficial cannot be fully realised.[3]

However, concerns about climate change mean that the UK government is committed to ambitious and legally binding targets for reducing carbon emissions in the energy sector.[4] Given the suitability of wind for generating renewable electricity and its availability in the British Isles, both onshore and offshore wind are likely to be the largest contributors in the generating sector to reaching these targets to 2030.[5,6] To make wind competitive, within an energy market locked-in to fossil fuel generation, government subsidy to promote investment, industry growth and R&D, to the point where the cost of wind is comparable to conventional generation methods, was the only option.

What is the current evidence?

The Non Fossil Fuels Obligation

The current subsidy system in the UK grew out of the non-fossil fuel obligation (NFFO). Growing concerns over the environmental impact of burning fossil fuels in the 1980s led many governments in Europe to begin investing in alternative energy sources or to expand programmes that had been instigated in response to the oil crises of the 1970s.[7] In the UK, the NFFO was introduced in 1990 and funded through the fossil fuel levy, which was set at 10% or 11% of consumers' bills between 1990 and 1996; however, the main purpose of the levy was to help prop up the nuclear industry that had been found unable to support itself following privatisation of the British electricity market.

Despite raising an average of £1.2bn a year from 1990 to 1996, renewable projects funded by the NFFO only received between 1% and 8.6% each year; the remainder went to support the nuclear industry. When the state-owned Nuclear Electric was privatised in 1996 the fossil fuel levy was reduced to 2.2% of consumer bills. When nuclear was removed from the NFFO scheme altogether the levy fell even further, ending at just 0.3% of customer bills by 1999, at which point it became the effective subsidy to the renewables industry. However, whilst the NFFO helped kick-start the nascent onshore wind industry in the UK, many renewable energy schemes awarded contracts under the NFFO were never realised because they were subsequently found to be uneconomic in practice.[8]

The Renewables Obligation

Realising it was not performing as planned, having failed to provide any significant investment to the renewable industry, the government replaced the NFFO with the Renewables Obligation (RO) in 2002. The RO intended to create a competitive market for renewable energy rather than directly setting the prices of MWh. By dictating that power suppliers must obtain a certain proportion of their electricity from renewable sources, it aimed at incentivizing investment in renewables. Accredited generators received a Renewables Obligation Certificate (ROC) for every megawatt of electricity produced from renewable sources, which they were free to sell directly to suppliers, along with their electricity, or on certificate trading markets to brokers.

The RO penalised the failure of suppliers to meet their quota of ROCS with a 'buy-out price', originally set at £30/MWh shortfall. Compliance was rewarded by recycling these penalties (known as the 'buy-out fund') back to suppliers in proportion to the number of ROCs they had submitted.[9] The regulator of the RO scheme is Ofgem, who recover their adminstration costs from the buy-out fund itself. These operating costs are minimal, amounting to £3.5m for administrating the RO in 2012/13, which is just 2% of the £164m eventually recycled from the buy-out fund back to suppliers.[10] The suppliers that paid the cost of non-compliance passed these costs to their customers; in the early days of the RO, the total pass-through costs to consumers was estimated to be 2% on the average domestic electricity bill, which subsequently rose to 3% (equivalent to £17 a year) by 2010.[11,12] Compare this to the NFFO fossil fuel levy that was set at 10%–11% between 1990 and 1996, almost all of which went to support nuclear power.[8] Despite the low impact of the RO subsidy on energy bills, customers saw their total bill rise considerably between 2008 and 2010, driven largely by a sharp increase in the price of natural gas rather than the subsidy framework itself.[12]

However, there is definitely evidence that suppliers were 'gaming' the system under the RO in its original form to achieve the most profitable balance between the buy-out fund and traded ROCs, which meant renewable quotas were consistently under-fulfilled whilst compliance costs were still being passed onto consumers.[9,12,13] Because the cost of both ROCs and the buy-out fund fluctuated, opportunities arose to save money by deliberately not purchasing ROCs and planning to pay directly into the buy-out fund. The government identified that the RO was encouraging this problem, and so introduced a 'guaranteed headroom' to the RO in April 2009, which added an extra percentage (around 8%–10%) to the obligation in excess of what the expected renewable generation was going to be. This new mechanism was an effort to do away with the incentive for suppliers to deliberately fall short of RO targets.[9]

Because the prices of ROCs weren't fixed, and fluctuated according to changes in the market, the RO tended to privilege well established and efficient technologies, such as onshore wind, over newly emerging technologies or less commercially viable ones. This, in turn damaged public relations as the demand for energy companies to ensure the best possible return led to them intensively developing onshore wind facilities (one of the most commercially viable technologies), many of which were unpopular with local residents.[3,14,25] Whilst the RO was more successful than the NFFO and provided quite generous subsidies for wind, comparing the amount of renewable capacity installed by unit cost the evidence suggests that the more direct feed-in tariff (FiT) subsidy method has delivered better results, with countries such as Germany and Denmark enjoying much higher rates of renewable deployment for comparable or less cost per unit capacity installed.[14,16]

The UK government took a more interventionist approach in 2009, by introducing technology banding into the RO scheme.[15] This meant that suppliers now received differing amounts of ROCs per MWh dependent on the type of renewable generation, more established technologies received fewer ROCs. These technology bands revealed the more established nature of onshore wind compared with offshore: until 2015 suppliers received 0.9 ROCs/MWh for electricity from onshore wind, but 2 ROCs/MWh from offshore wind.[6] Other low-cost and mature technologies get even less support, for instance, landfill gas projects only receive 0.2 ROCs/MWh. The differentiation between onshore and offshore wind highlights the progress that has been made within the wind industry, namely, that onshore wind has become established enough since the 1990s that generation costs have fallen dramatically, which has been reflected in a fall in subsidies worldwide (generation costs are discussed below).[17] A fall in the cost of offshore wind is projected to occur over the next few decades as the industry comes to grip with some of the unique challenges of operating in the open sea, and by 2017 the support for offshore wind will decline to 1.8 ROCs/MWh.[6]

It is important to note that this reduction in subsidy should not be presented (as some commentators are prone to do) as a display of falling confidence on the part of government in renewable energy; a cut in the subsidy rate was a clear indicator that onshore wind, at least, was increasingly becoming directly competitive with conventional generation and thus subsidy could be gradually curtailed.

The Levy Control Framework

The costs incurred by suppliers due to this mandatory legislation, the RO, can be seen as an indirect tax. In the same way that public spending is held accountable, the levy imposed by the RO scheme is considered as 'tax and spend'. To this end, a Levy Control Framework (LCF) was put in place as a cap on the total amount of money that could be raised and spent to support the RO and, importantly, its planned successor scheme, Contracts for Difference (CfD). The budgeting of support for renewables in this way is a sensible approach to attempt to control consumer costs as low-carbon schemes expand, but the inclusion of nuclear power under the 'low-carbon' umbrella in the new Contracts for difference (CfD) scheme may have drastic implications for the total amount of cash available to renewable energy. This is discussed further below.

Note that the spending limit set by the LCF was £7.6bn by 2020/21 in 2011/12 prices. However, the OBR, and Cornwall Energy both predicted an overspend of the LCF in 2015. It was this anticipated overspend that in part led to the rapid, unexpected policy change regarding support mechanisms, including the removal of subsidies for onshore wind a year earlier than planned.[18]

This unexpected removal of the onshore wind subsidy (relating to the introduction of the LCF) in 2016 has damaged investor confidence and may cause an increase in generation costs. It was previously anticipated that the subsidy would be gradually curtailed as the technology became more competitive, as has been the case in other European subsidy regimes.[18]

Contracts for Difference

The RO closed to new onshore wind projects from May 2016 and closed to all new generating capacity on 31 March 2017. Certain grace periods remain for onshore wind projects which have been subject to unavoidable delays. These last until March 2019.[25] The RO has been replaced by Contracts for Difference (CfD) meaning projects comissioned from March 2017 onwards will only be supported by CfD tariffs.

The CfD scheme is a further step towards technology-specific support, and an acknowledgement by the government that purely market-driven mechanisms do not encourage a diverse base of renewables, and have a tendency to support more established technologies.[9,19] Under CfD, renewable generators will receive a guaranteed tariff for their electricity that is dependent upon the technology used, this tariff level being termed the 'strike price'. Having an agreed strike price early in the development of a project allows for investor confidence as the finances of the project can be more confidently predicted. Crucially, once a project is built and starts operating, if the generator receives a wholesale market price for their energy that is above this agreed strike price, then they must pay back the difference.[19] This two-way mechanism is intended to prevent excessive profits that ultimately cost the consumer more and avoids technologies receiving more subsidy than is warranted, something that arguably resulted under the RO prior to its reform.[9,13,14,20]

The strike prices and the way in which they are implemented again reflect the gap in maturity between onshore and offshore wind. Offshore wind will receive a guaranteed strike price of 11.4-12p/kWh for 2016-2019. By contrast, the strike price for onshore wind is capped at 8.3p/kWh for 2016-2019. Furthermore, onshore wind generators must submit competitive bids as part of the process of their CfD allocation.[21,22]

The RO and the Feed in Tariff scheme combined (the latter covers smaller generators below 5 MW) were estimated to make up 6% of the average domestic electricity bill in 2013, although because of rising wholesale energy prices forcing total bills upwards this is equivalent to £37 a year (recall in 2010 £17 a year was 3% of the bill).[23] By 2020, the newer schemes introduced, including CfD, will also be operating, and the total subsidies are expected to add 9% to the average consumer's total energy bill. In fact, when all low-carbon energy initiatives and climate change policies are included (such as additional carbon costs generators have to pay) it is estimated these will make up 19% of the final energy bill, hence the LCF budget expanding to £7.6bn by this point.[6,23] However, these costs will be offset by a range of policies relating to energy efficiency and rebates for clean energy use that the government is introducing over the same period.* When offset by these related policies, overall energy bills are expected to be around 7% lower on average than they would have been without these policies.[24]

Has wind power been unfairly subsidised?

It can be seen from above that support for renewable energy does make a small but significant contribution to costs on the average consumer bill, although much of this extra cost was designed to be mitigated by policies designed to lower energy bills overall. In fact, when looking at the cost of generation, onshore wind costs are increasingly competitive with conventional generation, suggesting that the subsidy mechanisms used to date have broadly delivered their intentions. The average cost† of onshore wind generation is 10.1 p/kWh, compared to 8 p/kWh for a natural gas combined cycle gas turbine (CCGT, the most cost-effective form of generation in the industry).[26] Offshore wind remains relatively expensive at 12.2 p/kWh, a function of the industry's slow development over the past decade (it is set to grow very quickly in the UK over the next decade), challenging working conditions, and the fact that this less established technology has suffered from a general increase in set up costs that have affected all forms of generation to some extent.[27] The increasing competitiveness of onshore wind is a global trend and is largely due to the support mechanisms put in place by various governments that have seen the onshore wind industry grow and mature.[17]

There was evidence to suggest that the cost of onshore wind would remain competitive compared to conventional generation, and was likely to become one of the cheapest forms of electricity as fuel prices tend to increase and higher carbon costs are imposed on fossil fuels (this includes the cost of installing carbon capture storage in addition to carbon tax). However, the future of the onshore wind industry in the UK is now less certain as a result of the unanticipated, early closure of onshore subisides.[18] As for offshore wind, whilst subsidies remain, industry learning and a lessening of supply chain constraints should cause a drop in prices, with some predictions that it could be as low as 10 p/kWh by the year 2025.[28]

Indeed, wind generally is likely to be more competitive than nuclear power, even in European countries that have greater experience with running a nuclear fleet.[29] There is a risk that nuclear generation costs in the UK could rise significantly higher than those for onshore or offshore wind, up to 16 p/kWh[30] which would make it less competitive than wind but for a much greater subsidy burden on the taxpayer.

The approach by the UK government to nuclear development, which has offered a CfD strike price for the new nuclear reactor at Hinkley, runs the risk of leaving UK consumers with expensive electricity that is non-renewable for many decades (although nuclear is relatively low-carbon compared to coal). The deal made with the owners of the planned Hinkley reactor includes a 9.3 p/kWh strike price that is tied to the Consumer Price Index, which will run under the CfD scheme for 35 years (renewables are typically offered 15-year contracts, making this a much more generous deal than any wind development would be offered). In addition, £10bn of the construction cost has been underwritten with a government loan guarantee.[29] Because of the LCF imposing a limited 'pot' for total low-carbon energy projects, there is also the threat of large overspend on any nuclear development using up a large proportion of the money available, leading to a repeat of the failures seen with the NFFO more than two decades earlier, where renewables (wind included) were effectively crowded out by government support for nuclear.

Furthermore, if the wider costs to society were realised in the price of conventional generation methods end users would see that the price is much higher than it first appears.[31,32] These costs, termed negative externalities, include dispersal of pollutants to air and water, greenhouse gas emissions, environmental damage, health impacts and accident risk; they can vary from a local to a national to a global scale in their effects. These negative externalities are not factored into the cost of conventional generation such as coal and oil. However, many of the wider health impacts of energy sources have been documented for several decades at this point, and consequent revisions have closely followed developments in epidemiology to result in a broadly accepted and scientifically robust assessment.[33,34]

The most far-reaching assessment of national electricity generation pathways across 15 EU member states was by the ExternE project ('External Costs of Energy'), published by the European Commission. It found that the external costs of fossil fuel generation are significant in comparison to renewable sources of energy, in many

---

* These are numerous and include (or have included) the Carbon Emissions Reduction Target, Community Energy Saving Programme, Green Deal, Warm Home Discount, Products Policy, and initiatives for smart metering and better billing.

† Specifically, this is the 'levelised cost of electricity' (LCoE), which is the lifetime cost expressed per unit of energy produced over that lifetime. It is expressed in terms of present-day value, hence, LCoE values are 'discounted costs' because the costs and outputs today will not have the same value in the future.

cases doubling the cost of generation.[31] More recent analyses following the same principle have suggested that the cost of conventional generation with fossil fuels and nuclear is triple, even quadruple, the current costs.[32] Because they are not paid for by producers or consumers, these costs are passed on to society at large (often across national boundaries). The fossil fuel industry has continuously been shielded in this way from the true cost of its energy sources, since its earliest years, which effectively amounts to a staggering level of subsidy that would be unthinkable if it were suggested today as a means to support renewable energy sources.

Later impact assessments have also included ecological impacts such as climate change and acidification from emissions.[34] A salient point is that ExternE and derivative methodologies are subject to omissions of impact factor data where it is not readily available, and consequently have a tendency to produce lower values for external costs.[35] This is especially the case for climate change impacts, which are almost certainly underestimated given the artifical time horizons imposed on cost estimates (usually 100 years).[33] Indeed, it has been noted that many of the highest cost estimates from the ExternE studies that included climate change impacts were discounted because the range of estimates was so large that it could not be accurate (e.g. the true cost of coal-fired generation was found to be 100 times higher).[32,35] A review of the impact that the full life cycle of coal-fired generation has on the United States, considered conservative in scope because it discounted many of the wider ecological and atmospheric effects, came to the conclusion that the generation costs for coal should be considered two or three times the actual price per unit electricity.[36]

Conclusion

Wind power has experienced rapid development since the 1990s in terms of worldwide installed capacity, but it has also seen decreasing costs that have made it increasingly competitive with the leading conventional sources of generation. In the past, conventional sources of energy received large levels of state-sponsored support and were frequently nationalised. Over this long period of expansion and development, fossil fuel and nuclear-powered electricity generation became entrenched in modern energy infrastructures the world over. As governments and people became more aware of the detrimental impacts caused by high levels of extraction and consumption of non-renewable sources of energy, it has been realised that a transition to renewable energy sources is crucial if society is to continue developing on a more sustainable basis and avoid the worst effects of human-driven climate change.

Serious research, development and commercial deployment of renewables began in earnest in the UK during the 1990s, but this coincided with a period that also saw the widespread dismantling of nationalised generation and supply companies during the advent of liberalised (privatised) energy markets. Renewables have been faced with establishing themselves in this newly competitive marketplace, within which the incumbent conventional generators had long enjoyed uncontested dominance and benefit from an existing infrastructure that was never designed to accommodate the more distributed and variable forms characteristic of renewables. Thus, support for the nascent renewable energy sector has been necessary to ensure the industry and technology can become established and competitive, as was the case for all forms of conventional generation in their early days.

For onshore wind in particular, subsidies have achieved remarkable success in creating a low-margin and cost-competitive form of electricity generation, and it will play an important role in the decarbonisation of the generating sector as a whole. Indeed, in contrast to the success of onshore wind the sixty-year-old nuclear industry still requires comparable levels of support, and its costs are likely to climb at the same time as all forms of commercial wind power continue to fall. In addition, although fossil fuels remain the most cost-competitive, the nominal cost of these fuels excludes many negative externalities that, if accounted for, would push up the cost of generation substantially. By being able to pass on these wider costs to society at large, producers and consumers of fossil fuels benefit from what are effectively enormous subsidies.

Whether directly or indirectly, consumers in the UK have historically footed the bill for subsidies of all forms of energy, but given that large-scale renewable energy development has occurred following privatisation of energy markets these subsides have been increasingly transparent. Consequently, the impression is that renewables are unique in the level of subsidy they receive, but the more complex and unaccounted costs associated with conventional generation shows this is not the case. Even when at their highest level, consumer levies relating to alternative energy sources (under the NFFO) were almost entirely paid to the UK nuclear industry, a supposedly established and competitive form of electricity generation. Since these levies were replaced by the market-driven Renewables Obligation, renewable electricity has enjoyed a much higher level of support.

Whilst it is true that this level of support has arguably been in excess of the amount of renewable generating capacity delivered, the total contribution to consumer energy bills has been very small, within two or three per cent. The largest single driver of increasing energy costs for consumers has been the steady increase in fuel costs, and this is likely to remain the case when fossil fuels remain the dominant source of energy.

Through Contracts for Difference, the UK government is introducing a fundamental change to the national renewables subsidy mechanism that will align it more with feed-in tariff policies that have delivered greater expansion of renewables (for less cost per unit installed) in countries like Germany and Denmark. The removal of subsidy for onshore wind reflects its market maturity, however, it remains to be seen whether or not this will have the negative impact that is predicted on the development of the industry. Offshore wind continues to receive support, this may still stimulate a rapid and large-scale expansion of this sector, but the lack of investor confidence in onshore wind in the UK may have a domino effect on this industry too. Whatever happens with offshore wind it is unlikely to ever be as cheap as onshore wind.

The cut in subsidies to onshore wind a year earlier than planned have introduced a high degree of uncertainty in investment. Ostensibly the introduction of the LCF is intended to protect consumers from high fuel bills and create a secure investment environment; however, it is likely that the budgetary constraints imposed by the LCF will undermine both of these goals.[41] This, combined with the closure of the RO and the establishment of CfD means that UK energy policy has undergone yet another sea-change. It remains to be seen what the long-term effects of these changes will be, particularly in light of the 2016 referendum on membership of the European Union; the UK's relationship with EU law on renewable energy targets could fundamentally change. The short term effect has been to damage investor confidence and create confusion over how the government aims to meet its commitment to have 15% of energy come from renewable sources by 2020.[41]

As renewable electricity generation increases, subsidies will form a greater proportion of consumers' energy bills, although this cost will still be outstripped by increasing fossil fuel costs. Since renewable energy expansion goes hand-in-hand with national strategies to reduce household energy demand, the small increase in bills due to renewable subsidies will be offset by lower energy consumption. It is unlikely that future reductions in energy consumption will be able to compensate in a similar fashion for future increases in fossil fuel prices. Furthermore, as wind power comes to replace significant amounts of conventional generation, the wider external costs of conventional energy that society bears at present will lessen.

References

1. IEA and OECD. Developments in energy subsidies: the good, the bad and the ugly? In: *World Energy Outlook 2011*. Paris: International Energy Agency; Nov 2011. 507–40.
2. IEA. Global energy trends to 2035. In: *World Energy Outlook 2013.* Paris: International Energy Agency; Nov 2013. 55–98.
3. IEA, OPEC, OECD and World Bank [Online]. *Analysis of the scope of energy subsidies and suggestions for the G20 initiative.* Prepared for submission to the G-20 Summit Meeting, Toronto, Canada, 26–27 June, 2010; 80 p. [Last accessed 6 Feb 2014]. Available from: www.opec.org/opec_web/en/publications/1834.htm.
4. Department of Energy & Climate Change. *The UK Low Carbon Transition Plan: National Strategy for Climate Change.* URN 09D/716. London: The Stationery Office/TSO; Jul 2009. 230 p.
5. Toke D, Breukers S, Wolsink M. Wind power deployment outcomes: How can we account for the differences? Renew Sustain Energy Rev. 2008; 12(4):1129–47.
6. DECC. *UK renewable energy roadmap: 2013 update.* URN 13D/259. London: Department of Energy & Climate Change; Nov 2013. 76 p.
7. Mitchell C, Sawin JL, Pokharel GR, et al. Policy, financing and implementation. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Cambridge, UK and New York, USA: Cambridge University Press; 2011. 865–950.
8. Mitchell C. The England and Wales Non-Fossil Fuel Obligation: History and lessons. Ann Rev Energy Environ. 2000; 25(1):285–312.1.
9. Woodman B, Mitchell C. Learning from experience? The development of the Renewables Obligation in England and Wales 2002–2010. Energy Policy. 2011; 39(7):3914–21.
10. Ofgem [Online]. *Renewables Obligation: Annual Report 2012–13.* [Last accessed 4 Sep 2014]. Available from: www.ofgem.gov.uk/publications-and-updates/renewables-obligation-ro-annual-report-2012-2013.
11. DTi. 2005–6 Review of the Renewables Obligation: Preliminary consultation. URN 05/850. London: Department of Trade and Industry; Mar 2005. 68 p.
12. DECC. Estimated impacts of energy and climate change policies on energy prices and bills. URN 10D/719. London: Department of Energy & Climate Change; 1 Nov 2011. 81 p.
13. CSE. Renewable Energy Subsidy in the UK. Bristol: Centre for Sustainable Energy; Feb 2015. xx p.
14. Toke D. Renewable financial support systems and cost-effectiveness. J Clean Prod. 2007; 15(3):280–7.
15. Wood G, Dow S. What lessons have been learned in reforming the Renewables Obligation? An analysis of internal and external failures in UK renewable energy policy. Energy Policy. 2011; 39(5):2228–44.
16. Lipp J. Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. Energy Policy. 2007; 35(11):5481–95.
17. Badcock J, Lenzen M. Subsidies for electricity-generating technologies: A review. Energy Policy. 2010; 38(9):5038–47.
18. Lockwood M. The UK's Levy Control Framework for renewable electricity support: Effects and significance. Energy Policy. 2016; 97:193-201
19. DECC. *Planning our electric future: a White Paper for secure, affordable and low-carbon electricity.* (Cm 8099). London: The Stationery Office/TSO; Jul 2011. 142 p.
20. Steinhilber S, Ragwitz M, Rathmann M, Klessmann C, Noothout P. *Indicators assessing the performance of renewable energy support policies in 27 member states.* D17 Report. Munich: Fraunhofer-Gesellschaft; Oct 2011. 111 p.
21. DECC. *Electricity Market Reform: allocation of Contracts for Difference. A government response on competitive allocation.* URN 14D/113. London: Department of Energy & Climate Change; 13 May 2014. 40 p.
22. DECC. *Contract for Difference: Final allocation framework for the October 2014 allocation round.* URN 14D/328. London: Department of Energy & Climate Change; 1 Sep 2014. 56 p.
23. DECC. *Estimated impacts of energy and climate change policies on energy prices and bills 2012.* URN 12D/390. London: Department of Energy & Climate Change; Mar 2013. 96 p.
24. DECC. Estimated Impacts of energy and climate change policies on energy prices and bills 2014. URN 14D/386. London: Department for Energy and Climate Change; November 2014. 23p.
25. Ofgem [Online]. RO Closure. [Last accessed 21 Jun 2017] Available from: www.ofgem.gov.uk/environmental-programmes/ro/about-ro/ro-closure
26. DECC. *Electricity Generation Costs* (December 2013). URN 14D/005. London: Department of Energy & Climate Change; 19 Dec 2013. 62 p.
27. Heptonstall P, Gross R, Greenacre P, Cockerill T. The cost of offshore wind: Understanding the past and projecting the future. Energy Policy. 2012; 41:815–21.
28. National Audit Office [online]. Nuclear Power in the UK. 2016. [Last accessed 16 Jan 2017] Available at: www.nao.org.uk/wp-content/uploads/2016/07/Nuclear-power-in-the-UK.pdf
29. Boccard N. The cost of nuclear electricity: France after Fukushima. Energy Policy. 2014; 66:450–61.
30. Harris G, Heptonstall P, Gross R, Handley D. Cost estimates for nuclear power in the UK. Energy Policy. 2013; 62:431–42.
31. European Commission. External costs: research results on socio-environmental damages due to electricity and transport. EUR 20198. Luxembourg: Office for Official Publications of the European Communities; 2003. 24 p.
32. Sovacool BK. Renewable energy: economically sound, politically difficult. Electr J. 2008; 21(5):18–29.
33. Krewitt W. External costs of energy—do the answers match the questions? Looking back at 10 years of ExternE. Energy Policy. 2002; 30(10):839–48.
34. Bickel P, Friedrich R, Directorate-General for Research, editors. *ExternE: Externalities of Energy; Methodology 2005 Update.* Luxembourg: European Communities; 2005. 282 p.
35. Sundqvist T. What causes the disparity of electricity externality estimates? Energy Policy. 2004; 32(15):1753–66.
36. Epstein PR, Buonocore JJ, Eckerle K, et al. Full cost accounting for the life cycle of coal. Ann NY Acad Sci. 2011; 1219(1):73–98.

Chapter 4

Efficiency and capacity factor of wind turbines

Summary

It is sometimes alleged that wind turbines are inefficient because they only generate electricity '30% of the time'. This figure is based on the capacity factor for wind farms, but it is incorrect to equate this measure with operational efficiency. For instance, coal-fired stations in the UK run with a typical capacity factor of 40 to 55 per cent, but these are not described as generating electricity only 'half the time'. The capacity factor of a wind turbine is an important metric, but is only a partial indicator of performance. Operational capacity factors for wind turbines can broadly be said to result from the combination between local wind resource and wind turbine technology at any given site. Improved technology in the form of longer turbine blades and higher hub heights results in higher capacity factors at a given average wind speed. Likewise, high average wind speeds at a site result in better capacity factors for a given turbine when compared with a different site with lower wind speeds. In reality, wind farms are generating electricity around 85% of the time, using an energy source that is free and completely renewable. There is none of the thermal waste inherent in conventional power plants, so wind energy is converted to electricity very efficiently.

What is this based on?

Any device capable of generating power is given a capacity rating or nameplate capacity measured in watts. This is simply how much power the device can produce if operating at full load. Nameplate capacity can be viewed as an 'ideal' technical value, because it does not take into account how the power output is converted into useful energy, how much energy is used by the power plant itself, and any losses due to transmission; neither does it allow for interruptions due to maintenance, fuel shortages or lack of available energy resources.* For this reason, an important indicator of actual performance for a power plant is the *capacity factor.*

The capacity factor is the measure of actual output over time as a percentage of the theoretical maximum that could have been achieved over the same period, given the nameplate capacity.[1] The standard period is a year, which is divided into hours to allow for the fact that output is measured in multiples of watt-hours, for instance, familiar units like kilowatt-hours (kWh) and megawatt-hours (MWh). Thus:

$$\frac{\text{electricity generated during the year [MWh]}}{\text{(installed nameplate capacity [MW] at year beginning + installed nameplate capacity [MW] at year end)} \times 0.5 \times 8760 \text{ hours}}$$

This calculation is frequently mis-stated as a measure of generating efficiency. An average capacity factor of 27%–30% for UK wind installations (this is data from onshore and offshore installations since 2005 [2,3]) has led some commentators to declare that wind turbines 'only work 30% of the time'. But this confuses the issue of capacity factor and efficiency; that is to say, the average capacity factor of 28% does not mean wind turbines are 72% inefficient, or, to put it another way, that they run for less than seven hours every day. No generator is designed to run at full-load capacity continuously (if ever), and the capacity factors for conventional power plants that rely on thermal energy typically range between 40% and 65%.

What is the *efficiency* of wind turbines with respect to energy harnessed? In this case, the energy resource available is the kinetic energy found in natural wind flows. This kinetic energy must be extracted or 'gathered' via the placement of a turbine. Due to the law of conservation of momentum there is a theoretical upper limit to how much energy can be extracted from a wind stream passing over a turbine's swept area (the area covered by the turbine blades as they rotate). This limit, known as the *Betz limit*,† is 59.3% of the energy contained within the wind stream, and it acts as the theoretical upper bound of aerodynamic performance of turbine blades.[4] This 59.3% is often referred to as the 'maximum efficiency' of a wind turbine due to the wind in this case being described as a power input, but this is not correct. Rather, the Betz limit is a ratio of the theoretical maximum power that could be extracted by the face of a turbine over the power contained within the wind stream when no turbine is present. This seems

---

* A fuel 'shortage' may actually be the deliberate down-rating of a power station due to high fuel prices, which constrains the economically available supply (e.g. this situation occurred in the UK in 2012 due to high wholesale prices for natural gas – see ref.1). Lack of flowing water or wind would mean no available energy resource for a renewable power plant, such as a hydroelectric dam or wind turbine.

† More recently, this has been called the 'Lanchester–Betz–Joukowsky limit' to reflect the three scientists who all described this theoretical limit independently of each other between 1915 and 1920.

somewhat confusing, given that efficiency of a device is generally considered to be how much power can be extracted as a percentage of how much power is put in. In the case of wind power, however, if all of the kinetic energy from wind was extracted at the turbine face, the speed of the wind just the other side of the turbine would be zero. This body of dead air would act to block the wind coming behind it, and the windstream would therefore stop flowing. This is why the Betz limit is a limit, not a measure of efficiency: there must always be some movement of air past the turbine, so the actual energy 'available' to the turbine, i.e. the power input, will only be a fraction (59.3%) of the total kinetic energy in a windstream.[5]

In fact, a theoretical 'perfect' turbine face operating at the Betz limit would capture almost 89% of the energy available to it. A device that has an energy output that 89% of the energy input is very efficient indeed.[5] One should immediately realise that such a perfect turbine does not exist in reality! However, improved aerodynamic designs of modern turbines built since the mid-2000s have gotten within 84% of Betz's theoretical limit, and practical limitations of aerofoil drag means that this is unlikely to be surpassed.[4]

Once the wind flow is at the cut-in speed (this is when the turbine begins to generate electricity, usually 3–4 ms-1, see chapter 5, 'Intermittency of wind turbines') the rotating blades will transfer their rotational energy to the generator inside the wind turbine nacelle.[4] The nacelle is the housing that contains the gearbox, main bearings, generator and various electrical components (e.g. converters and control system). During the process of converting rotational energy to electricity via the generator, there are losses due to friction in the mechanical parts, electrical losses from components associated with the generator (e.g. the magnetic core and windings), and stray load losses.[6] However, the overall efficiency of these processes is generally very high, and climbs steeply between the cut-in speed and the rated speed (~11 ms-1) from around 50 to more than 90 or 95 per cent.[5,6]

What is the current evidence?

Medium to large-scale power generators typically have nameplate capacities given in megawatts (MW). To give a few examples for the UK: typical ratings for large coal-fired stations consist of several 400–600 MW units; combined cycle gas turbines (CCGT) can vary in size, but large units are typically in the 400–450 MW range; nuclear plants are in the range of 1,100 to 1,250 MW nameplate capacity; small gas/oil installations tend to be below 100 MW; and individual wind turbines are typically 1.5–3.0 MW onshore and 3–5 MW offshore, although capacity ratings for offshore turbines are likely to increase as commercial experience grows.[1,2] Recent data for years 2010–2012 are show in Table 4.1, showing total installed capacity for selected generating technologies alongside their annual capacity factors.

Since wind power relies on natural flows as its energy source, the marginal cost is close to zero.[7] What this means is that increasing power output is not a function of increased fuel inputs, so the cost of producing

Table 4.1 Capacity factors for selected conventional and renewable energy sources installed in the UK (data from refs. 1 and 2)

Year	2010		2011		2012	
Source of electricity generated	Installed capacity[a] (MW)	Capacity factor (per cent)	Installed capacity (MW)	Capacity factor (per cent)	Installed capacity (MW)	Capacity factor (per cent)
Conventional thermal stations	36,036	34.5	34,170	34.7	30,970	48.6
– of which coal-fired	23,085	40.2	23,072	40.8	23,072	57.1[c]
Nuclear stations	10,865	59.3	10,663	66.4	9,946	70.8[c]
Combined cycle gas turbine stations	33,305	61.6	32,389	47.8	35,320	30.4
Hydroelectric stations (large scale, natural flow)	1,453	24.2	1,471	39.0	1,471	35.8
– unchanged configuration basis[b]		26.1		41.5		35.3
Onshore wind	4,045	21.7	4,638	27.3	5,893	26.2
– unchanged configuration basis	21.6		27.2		25.6	
Offshore wind	1,341	30.3	1,838	36.8	2,995	35.2
– unchanged configuration basis		29.5		35.0		33.7

[a] Note that for renewable sources and smaller non-renewable plants the installed capacity is the declared net capacity (small generators typically make up <9% of total non-renewable sources); all other installed capacities are derived from the non-renewable stations of the major power producers and are listed in terms of transmission entry capacity.

[b] Capacity factor on unchanged configuration basis. This measure only uses capacity factors for plants that have operated throughout the calendar year. This excludes biases in capacity factor ratings due to the introduction of new installed capacity partway through the year.

[c] Closure of coal-fired and nuclear capacity through the year may have caused an upward bias in capacity factor rating. Similar accounting to the unchanged configuration basis used for renewables (see b above) is not carried out for non-renewables

additional energy (marginal electricity) is negligible. This makes the capacity factor of particular significance for wind power, because it is a significant driver of effectiveness in terms of cost to achieve stated goals – the main goal being the reduction of greenhouse gas emissions in the energy sector.[8] Annual capacity factors for the period 2005–2012 are shown in Table 4.2, and the average values for the whole period are also given. The main issue with wind power is that the varying levels of wind blowing at any one time across the UK region means that supply is intermittent (see chapter 5). This is why the annual capacity factor for onshore wind is around 27% and offshore is 31%, as seen in Table 4.2. Note that for conventional thermal stations the average capacity factor is 41%; for coal-fired plants, which make up the majority, the capacity factor is higher at 53%. As mentioned in the introduction, this does not mean that wind turbines work 30% of the time, or that coal-fired stations only work 'half the time'.

To see how capacity factors are arrived at using the formula described earlier, it is useful to see a few examples. A wind farm in North Ayrshire reported a total annual output 101,781 MWh electrical in 2013 from an installed capacity of 28 MW.[9] If all the wind turbines on this wind farm had operated at 100% of their nameplate capacity that would have generated 245,280 MWh (i.e. 28 MW × 8760 hours). By dividing the actual output over the year the resulting capacity factor, expressed as a percentage, is (101,781/245,280) × 100 = 41.5%. By comparison, a smaller wind farm in the south of Oxfordshire with an installed capacity of 6.5 MW managed to generate 10,369 MWh in 2013.10 This represents a much lower capacity factor of 18.2% (i.e. [10,369/56,940] × 100).[‡]

The above examples illustrate the central principle of output being dependent upon the local wind resource and the wind technology deployed at that locality. The first wind farm is situated in an upland area not far inland from the Firth of Clyde, and clearly has a superior wind resource to that of the Oxfordshire wind farm, which is built on a disused airfield in a much flatter area in central England. The nameplate capacity of the wind farms are 28 MW (N. Ayrshire) and 6.5 MW (Oxon.). One can imagine a larger array of turbines at the Oxfordshire site would increase total output due to a larger nameplate capacity, but the capacity factor is not likely to increase in a linear relationship with this output. Why is that?

Three things might take place with regards to raising the nameplate capacity: (1) the number of turbines is increased, (2) the the wind farm is 'repowered' using larger turbines, or (3) a combination of more, larger turbines is deployed. In option (1) each turbine will only generate electricity at the same capacity factor as before, but total output will go up since there are more units. In option (2), even though the turbines may be situated as before, their larger size means the turbine hub will be higher and the blades larger – the increase in height means more wind energy is available (average wind speed is faster as you go higher) and the swept area is greater (because the blades are larger); thus, more wind energy is available and it can be extracted more effectively. Finally, the obvious result of option (3) is that total output will increase further due to the combination of factors listed for the first two options.

All of the effects described above can be seen in the development history of the global wind energy sector. Since the late 1990s, the trend towards turbines with taller towers and larger swept areas has led to a gradual increase in capacity factors.[4] Another way of looking at steady improvement in capacity factors is the annual energy production per square metre of swept rotor area

Table 4.2 UK average generating plant capacity factors 2005–2012

Generating technology	Year	Capacity factor (per cent)								Median capacity factor	Mean capacity factor
		2005	2006	2007	2008	2009	2010	2011	2012		
Conventional thermal stations		46.1	49.4	44.3	39.3	33.2	34.5	34.7	48.6	41.8	41.3
– of which coal-fired		63.0	72.9	66.0	45.0	38.5	40.2	40.8	57.1	51.1	52.9
Nuclear		72.4	69.3	59.6	49.4	65.6	59.3	66.4	70.8	66.0	64.1
Combined cycle gas turbine stations		60.9	55.1	64.3	71.0	64.2	61.6	47.8	[b]30.4	61.3	56.9
Onshore wind[a]		26.4	27.2	27.5	29.4	26.5	[b]21.6	27.2	25.6	26.9	26.4
Offshore wind[a]		27.2	28.7	25.6	34.9	32.1	29.5	35.0	33.7	30.8	30.8
Hydroelectric stations (large scale)		37.5	34.8	38.2	37.4	38.4	[b]26.1	41.5	35.3	37.5	36.2

a Figures for wind from 2008 onwards are on unchanged configuration basis.

b These data can be considered outliers (based on interquartile ranges) but are included in the mean and median shown. Disregarding these values gives mean capacity factors of 60.7% (CCGT), 27.1% (onshore wind) and 37.6% (hydroelectric).

[‡] These two examples are: the Kelburn Wind Farm near Farlie, N. Ayrshire, consisting of 14 wind turbines each with a 2 MW nameplate capacity; and the Westmill Wind Farm in Oxon., consisting of 5 turbines each rated at 1.3 MW.

(kWh m-2) for a given wind resource site. Improvements of 2%–3% per year have been documented over the same period.[4] This has been helped by the development of more offshore wind arrays (the UK has the largest installed offshore wind capacity in the world as of 2013), because turbines are generally larger and the wind resource is typically more abundant and consistent.[2] Early offshore plants in the UK have been subject to a relatively high component failure rate, which has meant the average capacity factor (31%) has been lower than might be expected from the European average (35%–45%); thus, as experience grows within the industry and component problems are identified and resolved, the UK's offshore capacity is likely to rise.

Even for onshore wind, however, continuing improvements in performance are evident due to better tailoring of turbine design to specific sites, as opposed to simply installing turbines with higher power ratings.[11] For instance, increasing the height and rotor diameter of a 2.3 MW turbine will allow it to operate more of the time over a year (e.g. the wind speed at any given time may well be high enough to operate at 80 m even when it is too low at 50 m), and a higher proportion of that wind energy can be captured due to the larger swept area (so the turbine can get closer to the theoretical Betz limit, making it very efficient at extracting available energy). This will lead to both a higher power output and improved capacity factor, but without resorting to larger generators to achieve it. The maxim that 'bigger is better' certainly applies to wind turbine design, but the 'bigger' in this case does not necessarily entail larger generator ratings.

One interesting issue concerning the global trend for higher capacity factors is that as more modern turbines can extract more wind energy at a given site this makes low-quality wind resource sites more economically attractive (remember that the marginal cost of generation is negligible for wind).[4,7] Siting of wind farms in such areas will depress overall capacity factors nationally (or globally), and this is one reason why the average capacity factor does not necessarily increase linearly with increasing installed capacity and total output. Thus, one qualification that could be made is that turbine design has led to improvements in capacity factors for a given wind resource, but these performance enhancements are mitigated to some extent by the exploitation of inferior wind resources.[11] This illustrates the importance of balancing the economic and social needs of an area where a wind farm is developed with the fact that higher capacity factors are the most effective way to maximise output of renewable, low-carbon electricity, but appropriate sites are more physically constrained.[7] For instance, a community may benefit from a wind farm in terms of community ownership or community fund that derives income from wind power, even though the wind farm itself may operate at a sub-par capacity factor. Likewise, highly productive sites with high capacity factors, which means greater output of low-margin renewable electricity, may meet with opposition due to the visual or environmental impact a wind farm has when situated in a culturally or ecologically sensitive area (this social dimension is discussed further in chapter 8, 'Public acceptance and community engagement'.

As the discussion in the previous section outlined, wind turbines can capture available wind energy very efficiently, and use this to generate electricity with comparatively low energy losses.[5,6] Wind turbines have also demonstrated high availibility, with downtime due to outages or scheduled maintenance being less than 3% of operational times.[4,12] Furthermore, wind farms are operational – i.e. generating electricity – more than 80% of the time. Although this does not mean turbines are always at full capacity, periods of peak electricity demand in the UK do tend to coincide with average wind farm capacity factors of 38% to 44%, which is significantly higher than the overall annual average.[13] By comparison, fossil fuel-fired stations and nuclear plants rely on thermal energy from fuel to drive electrical generators as opposed to natural flows. The best efficiencies are found in CCGT generation with roughly 48% thermal efficiency, whereas nuclear and coal are around 36% to 39%.[1]

The more widespread deployment of larger, more efficient turbines means that these can operate for longer, because larger rotors means that lower wind speeds can be used to drive a generator. Provided the generator is not over-rated (i.e. nameplate capacity is too large) for a given wind resource and size of turbine, this means the turbine will operate closer to its maximum rating for more of the time, which means capacity factors will be higher.[11] Note this does not necessarily mean total output is higher, as discussed in the examples earlier, but improved capacity factors are a sign of optimal resource use within the bounds of acceptable turbine size and placement.

A good working knowledge of wind resources through annual, decadal, and even century-long forecasts means that developers and policymakers can assess the projected output of a site over its lifetime, and tailor the turbine design and rating accordingly to optimise capacity factors.[7,14] This is an area that is constantly being improved through new data. In some cases, as turbine height increases, it has been found that the available wind resource that can be extracted over an annual period is underestimated, meaning real capacity factors can be more than a third higher than projected.[14] A note of caution, however, should also be made. In the past many developers and advocates within the wind sector have consistently overestimated average capacity factors, giving misleading figures in the region of a 35% national average, something that has not been borne out by operational data so far.[7,15]

Conclusion

When discussing wind power, capacity factor is frequently equated with efficiency. This is not strictly correct, and paints a misleading picture of wind turbines lying idle in relation to conventional generating plants. In fact, wind power is a relatively high-efficiency form of electricity generation and modern turbine design means that an increasingly greater proportion of available energy is able to be extracted from natural wind flows. Modern turbines are able to extract almost 75% of the total available energy in a wind stream, and can convert rotational energy to electricity via a generator with very small losses. Conventional thermal plants (including nuclear) typically have thermal efficiencies of around 36%–39%, although this can be as high as 48% for the best combined cycle gas turbines.

Wind turbines in the UK typically produce electricity for 80% of the time or more, and only experience downtime for 3% or less of their operational lifetime. The periods of highest average capacity factors (38%–44%) tend to coincide with times of peak electricity demand. This means that a large percentage of demand during peak times can be met with a low-margin cost source of renewable electricity through wind.
Due to the low marginal cost of wind power, capacity factors are of great importance when looking at wind turbine performance, because lower capacity factors represent a missed opportunity to produce low-carbon electricity. A tendency of the wind sector to overestimate capacity factors by applying a misleadingly high national average across all UK sites means that expected output can fall below projections because wind farms are sited in low wind resource sites or turbines are not optimised to get the most out of what is available. Data since 2005 reveals that the average capacity for onshore wind in the UK is 27% and offshore is 31% (the latter is lower than the European average). An ever increasing amount of data from operational sites,[§] coupled with more sophisticated and efficient turbine designs, means that capacity can be more accurately forecast and wind farm developments designed accordingly. In addition, existing wind farms can be repowered to maximise wind extraction through more modern, larger turbines.

Globally, wind farms have followed a trend of increasing capacity factors, partially driven by an increase in average turbine rotor size and hub height, and partially by the increasing number of offshore farms that enjoy superior wind resources. However, a greater ability to capture available wind flows due to technological development has also meant more wind farms are sited in areas with sub-optimal wind speeds, thus depressing capacity factors. More experience and technical knowhow means that wind projects can increasingly be tailored to the characteristics of a site by varying the height, rotor diameter and blade type.

Given the quality of energy generated by wind – i.e. clean, renewable electricity – the location of turbines at less optimal resource sites is not necessarily problematic, but it does become an important issue if low capacity factor schemes are located where the environmental or social impact may be deemed too costly in relation to the scheme's projected overall performance. Likewise, where good wind resources exist and wind turbines are deemed an acceptable development, it is important to tailor the technology to harness that wind resource so that the benefits are realised as advantageously as possible.

[§] Data in the UK is relatively freely available thanks to data collected on behalf of the regulator for the Renewables Obligation scheme.

References

1. Hemingway J, Michaels C. Chapter 5 – Electricity. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 111–54.
2. Dagnall S, Prime J. Chapter 6 – Renewable sources of energy. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 155–89.
3. Dagnall S, Prime J. Chapter 7 – Renewable sources of energy. In: Digest of United Kingdom Energy Statistics 2010. London: The Stationery Office/TSO; 2010. pp.179–209.
4. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.
5. Aliprantis DC. Fundamentals of wind energy conversion for electrical engineers. Ames, Iowa: Department of Electrical and Computer Engineering, Iowa State University; 4 Nov. 2011. 50p.
6. Tamura J. Calculation method of losses and efficiency of wind generators. In: Muyeen SM, editor. Wind energy conversion systems: technology and trends. London: Springer-Verlag; 2012. 25–51.
7. Boccard N. Capacity factor of wind power realized values vs. estimates. Energy Policy. 2009; 37(7):2679–88.
8. DECC. Planning our electric future: a White Paper for secure, affordable and low-carbon electricity. (Cm 8099). London: The Stationery Office/TSO; Jul 2011. 142p.
9. 'Renewables Obligation Generators', Renewable Energy Foundation, Energy Data database <http://www.ref.org.uk/roc-generators> (last updated 20 Mar 2014), RID no. R00172SQSC, accessed 21 Jul 2014.
10. Ibid., RID no. R00190RQEN, accessed 21 Jul 2014.
11. Wiser R, Bolinger M. 2012 Wind Technologies Market Report. Report no. DOE/GO-102013-3948. Oak Ridge, Tenn: U.S. Department of Energy; Aug 2013. 89p.
12. Blanco MI. The economics of wind energy. Renew Sustain Energy Rev. 2009; 13(6-7):1372–82.
13. Sinden G. Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. Energy Policy. 2007; 35(1):112–27.
14. Kubik ML, Coker PJ, Barlow JF, Hunt C. A study into the accuracy of using meteorological wind data to estimate turbine generation output. Renew Energy. 2013; 51:153–8.
15. Jefferson M. Capacity concepts and perceptions – Evidence from the UK wind energy sector. IAEE Energy Forum. 2012, Vol.21, Second Quarter, 5–8.

Chapter 5

Intermittency of wind turbines

Summary

Weather patterns can be forecast with some degree of accuracy, which is crucial to balancing supply and demand in a power system that incorporates wind as a generator. Within a regional or national grid the electricity supply must be equal to the electricity demand at all times, something that becomes particularly challenging when relying on increasing levels of variable wind power output. This notwithstanding, the problem of dispatch, whereby electricity supply is constantly tailored to meet demand, is not new to the industry. Large and, at times, unpredictable swings in the grid system are already balanced on a daily basis. Whilst the short-term (hours to days) intermittency of traditional thermal generators is much lower than for wind farms, they are still prone to sudden unplanned outages. Given the large-scale, unitary nature of traditional thermal generators, the potential loss of power from such a plant exerts a continual risk on the grid that has to be supported by a network of balance response units, the cost of which can be significant. Smoothing out variable output from geographically dispersed wind farms across a grid presents novel statistical challenges for the transmission service operator, but they are challenges that are being met, and can be met in the future. Forecasts for wind speeds and wind power output already achieve a high level of accuracy, and these are steadily improving as more data is obtained and prediction methods are refined. More powerful forecasting tools will further reduce operating costs and improve security of transmission for the system operator, and will allow more competitive market trading for generators.

The projected share of wind in the generating sector will necessitate some financial costs to improve interconnectivity and to operate reserve capacity. However, many of the costs towards upgrading grid infrastructure are necessary in any case to replace ageing components and improve the UK's interconnectedness within the European electricity market, and many small renewable generators have been forced to pay the shared costs arising from the risks imposed by larger conventional generators on security of supply for some time. Contrary to popular belief, wind power does not need 'one-for-one' backup to allow for its intermittency – indeed, the fraction of reserve capacity needed is under one third of the installed wind capacity. A considerable capacity reserve already exists in the UK's national energy infrastructure to provide the security of supply as mandated by the transmission service operator, and the further expansion of a distributed network of wind farms will bring further benefits in terms of low-carbon, low-marginal cost electricity across the grid.

What is this based on?

One major disadvantage often stated for wind power is that it is not available as a smooth, uninterrupted supply, because wind itself is intermittent. For the transmission service operator (TSO) of a national power system, this is usually described in terms of traditional 'dispatchable' generators and the alternative 'non-dispatchable' generators that rely on intermittent natural flows. Although it is quite possibly the most important energy carrier in modern society, electricity cannot be efficiently or cheaply stored (unlike, say, fuel stocks or heat). Hence, electricity supply must be balanced with demand at all times; if it is not, then the power system may suffer excessive fluctuations in operating parameters, such as voltage and frequency, which can cause loss of load (i.e. electricity supply falls short of demand) and possibly damage expensive equipment or infrastructure. The key role of the TSO is to ensure the system can withstand any sudden events that may cause such disturbances, thus guaranteeing the system's reliability.

In the face of constantly changing customer demand, the TSO seeks to balance forecast demand with the projected generation offered in advance by the generators. The TSO relies on the ability of conventional thermal plant run by traditional generators to provide voltage regulation and frequency response services that help maintain stable transmission and distribution. When there is a mismatch between supply and demand, generators of conventional plant can act to 'ramp' up or down their supply of electricity. This is typically achieved by fossil fuel-fired plants, which will differ in efficiency, flexibility and cost depending on the exact type of plant. In some cases the TSO can also use parts of the grid infrastructure, such as interconnectors, to provide a degree of stability, but this capacity is limited.

Historically, peak electricity demand in the UK – and therefore peak supply – has been less than 80% of total national capacity. Maximum demand in 2012 fell on 12 December, and was just 70% of the UK's total capacity.[1] This is a good illustration of the spare capacity built into power systems. If the generating facilities and infrastructure were to run constantly at full load, i.e. where all available capacity was barely sufficient to meet demand, the system would not have the flexibility to cope with changes in customer usage (up or down) at the same time as providing for unforseen events that involve component failure or connection losses on the grid. Since the power system is designed to operate within its maximum total capacity, this helps ensure the system's adequacy, such that it is able guarantee sufficient electricity output to meet the aggregate demand of its customers at any given time, taking into account scheduled or unscheduled outages that may occur on parts of the system.

In a perfect world, the TSO would have access to wind forecasts that were 100% accurate, allowing it to schedule its dispatchable generating assets accordingly. But even if this were the case, it would not change the fact that the wind would still be variable – it is the variability that the TSO ultimately cannot control. Whilst short-term variability of conventional plant is much lower than that of wind farms, the TSO must allow for the fact that unforseen events resulting in loss of supply do occur and cannot be controlled. In many respects, variations in wind forecasts that look more than several hours ahead have a bearing on the grid's adequacy, because the power system is operating with spare capacity and potential mismatches can be hedged via spot-market trading and TSO scheduling.[2] The power system must, however, operate sufficient dispatchable reserve capacity at a given level of wind generation to allow for sudden changes in the short-term or very short-term (anything from minutes to a few hours) that may harm the system's reliability. The national grid already bears a significant risk from large conventional generators, which, should they suffer an unscheduled outage, can place considerable strain on the power system.[3] Thus, the variability of wind is a significant challenge, but it is not entirely unprecedented that the national grid must cope with large and instantaneous fluctuations on a regular basis.

The need to maintain and upgrade the UK's power infrastructure, which is an existing and ongoing challenge, must be combined with the need to transition to a low-carbon grid. Modern society cannot function without electricity, but neither can it afford to persist with its current inordinate reliance on fossil fuels. Thus, these challenges represent a 'social resource cost', where the move to a new type of flexible grid that can accommodate intermittent energy sources like wind is one cost that should be weighed against the cost of continuing along society's current trajectory of unsustainable energy consumption. It should also be remembered that wind is not the only renewable source of energy, and can work effectively alongside technologies that are not intermittent, such as biomass, tidal or geothermal.

What is the evidence?

Wind power on the national grid

The output of electrical power across the grid must exactly balance the demand, as the expense and inefficiency of current storage technology means there are only limited means to store excess electricity.[2] Before 2013, onshore wind had been the leading source of renewable electricity in the UK, increasing steadily year-on-year,[4] only pushed into second place briefly by the conversion of several large coal-fired units to biomass over 2012/13. This meant that biomass-fired electricity generation made up 34% of total renewable electricity, compared with 32% for onshore wind.

However, the continuing deployment of both onshore and offshore wind means that combined wind power generated more than half of all renewable electricity in the UK in 2013, amounting to 28,433 gigawatt-hours* (GWh), which was 8% of the total electricity supplied to the grid that year.[5,6] These figures represent a generation increase on the previous year of 40% for onshore and 52% for offshore wind. Over the same period this is an increase in installed capacity of 27% and 23% for onshore and offshore wind, respectively, bringing total capacity to 12.2 GW. This illustrates the continued strong growth of the wind power sector.

The National Grid estimates that the UK will have anywhere from 13 to 20 gigawatts (GW) of installed wind capacity by 2020, which would be a 16%–78% increase in installed capacity on 2013 levels.[7] The upper limit may be even higher if onshore or offshore developments are particularly favoured, and the figure does not include a potentially small but significant contribution from embedded wind turbines. These embedded 'private wire' turbines that are directly connected to properties do not typically supply electricity to the national transmission grid, but they do serve to reduce total load by meeting local distribution demand.

With these projections, it appears likely that wind power will be more than 20% of the UK's total installed capacity by 2020, and there may be times when wind generation will supply one-third to one-half of total demand.† Looking ahead even further to 2035, where installed wind capacity may be 51 GW or more, it is possible that there will be periods where electricity generation from wind will exceed the minimum demand on the grid.

---

* One gigawatt-hour (GWh) is 1 × 109 watt-hours. The more familiar kilowatt-hour (kWh) is 1 x 103 watt-hours; hence, 1 GWh = 1,000,000 kWh.

† In fact this is already happening. Wind power in the UK set a new record in December 2014 by meeting 43% of domestic electricity demand (see J. Kollewe, 'British windfarms set new power production record', Guardian, 9 December, 2014, www.theguardian.com/business/2014/dec/09/british-wind-farms-set-new-record).

No power plant supplies all of its theoretical maximum output as based on its rated capacity. The fraction of this maximum output that is actually generated over a given period is the capacity factor of the plant (see chapter 4). Taking present-day figures for the UK wind sector, this capacity factor will be around 29% overall, although the expected improvements in offshore wind performance means this present value is almost certainly going to rise above 30%. This means that by 2020 onshore and offshore wind could supply around 50,800 GWh per annum, cutting carbon emissions across the entire UK electricity sector by 15%.[8,9]

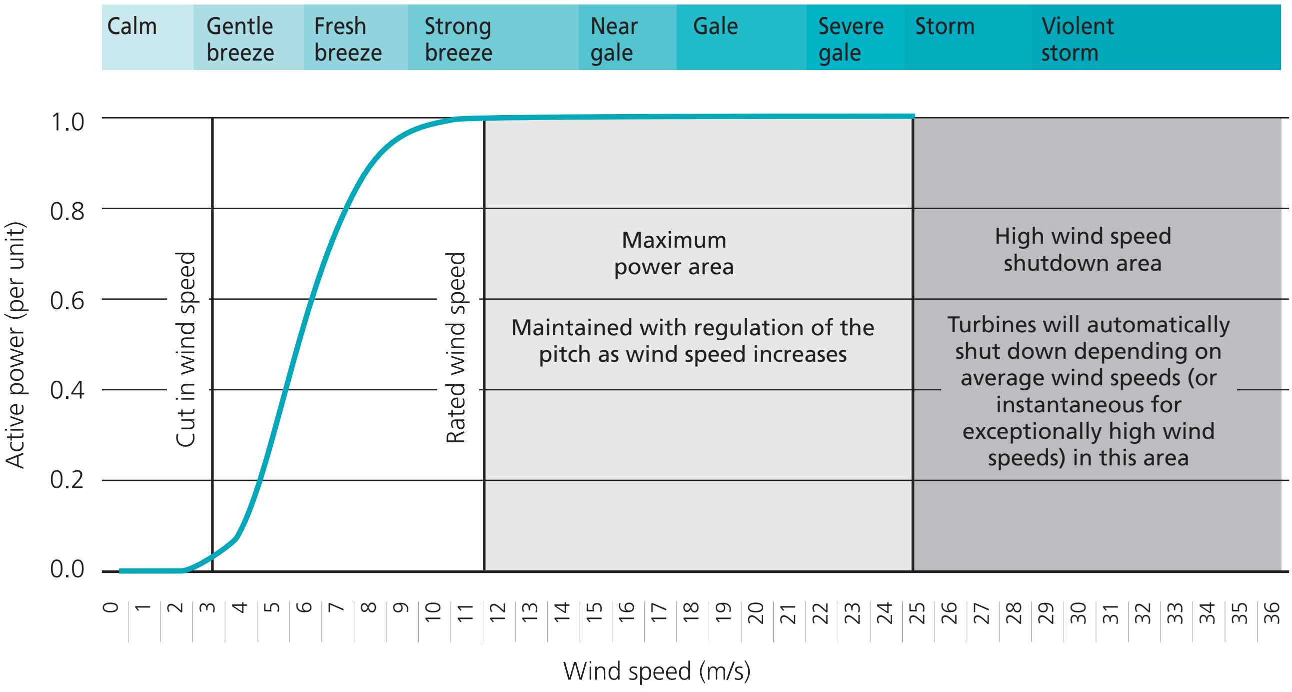
Predicting variability

However, there is no denying that wind is a variable power source. The output of a wind turbine ramps up or down depending on the speed of the wind (measured in metres per second, or m/s) and can be seen to follow a power curve, as illustrated in Figure 5.1. This typical power curve can be split into three regions. In the first region wind speeds are too low at less than 3 m/s (6.7 mph) and no power is generated. The second region begins at the cut-in speed, usually 3–4 m/s, at which point the turbine can extract useful energy from the wind. In this region, wind speed and power output are related through a cubic relationship, which means a small change in wind speed can result in a large change in power output – note how a change in wind speed from 4 m/s to 12 m/s (26.8 mph) causes the turbine to go from 5% of its rated output to 100%. The third region is the maximum power area, where the turbine maintains its rated output in the face of increasing wind speeds through various methods involving pitching the blades or stall control. All generation stops at speeds above 25 m/s (56 mph), known as the cut-out speed, to protect the turbine rotor and structural components.[10]

On average, over the course of a year, individual turbines do not generate any electricity for roughly 20% of the time, almost always due to lack of wind rather than excessive wind speeds.[11] For an individual turbine or wind farm, a weather pattern moving across the area can often result in wind output ranging from zero to maximum output on any given day. When geographically dispersed across the British Isles as a whole wind farms can act more like an aggregated power system, so the issue of variability of any one turbine becomes less of an issue because the reliability of the resource as a whole follows a probabilistic distribution.[2,12] The accuracy of forecasts for wind speed and power output is obviously important in this situation, but the TSO must also be able to assess the likelihood that it will need to call upon dispatchable capacity at times of insufficient wind generation and require curtailing of wind power output at times of excess generation. Thus, the TSO must know the degree of uncertainty (or forecast error) and be able to apply it meaningfully to daily operations so as to maintain an appropriate level of backup plant.

There are many different models used to forecast wind speeds and wind power outputs – it is important to note these are two related, but different, parameters that are being forecast.[13] These models are usually grouped into either statistical methods that rely on large amounts of historical data, physical models that forecast the wind speed at a given time from meteorological data and

Figure 5.1 Indicative power curve of a typical modern wind turbine



known atmospheric dynamics, or hybrid methods that combine various aspects of these.[14] These models are typically 'benchmarked' to assess their performance against a known reference model. Most of these benchmark models involve the 'persistence model', which, at heart, is based on the simple premise that the future wind speed will be the same as the current wind speed.[13] Although this sounds obvious, the persistence model and its derivations perform well for wind speed forecasts over very short-term forecast horizons (the next few minutes) and short-term forecast horizons (up to two hours). However, accuracy very quickly drops off past this horizon, and more advanced alternatives employing statistical and physical approaches can be seen to perform better. This is important to the grid TSO, who must run normal operation reserve, commit units to day-ahead generation schedules, and coordinate when units can be taken offline for planned maintenance.[14]

The normal operation reserve is of particular importance, because this is where the TSO must consider the trade-off between the cost of maintaining the reserve and the risk of there being insufficient reserve to cover loss of load.[15] To run a power system with an acceptable risk threshold that satisfies cost constraints with reliability concerns is why the TSO must understand the degree of uncertainty. Normal operation reserve covers both instantaneous regulating reserve and secondary operating reserve.[16] The former is concerned with sudden disturbances that require instant response (within thirty seconds) to correct system frequency and excessive load fluctuations. Operating reserve is used to make up shortfall due to unforseen load (i.e. higher than forecast demand) or a mismatch between forecast wind power and actual output. Given that the response of regulating reserve is instantaneous, operating reserve is generally required to activate over a period of ten minutes and gradually replace the regulating reserve. Some units within the operating reserve are 'spinning', meaning they are connected to the transmission grid already and can ramp up immediately; other units are 'non-spinning' and require several minutes to warm up before connecting.

The forecast error is defined as the difference between the forecast value and actual measured value, and many different standard statistical evaluations can be applied to the forecast error to assess the quality of a model's predictions.[14] In this way, forecast error can be treated as a probabilistic problem that can be made to fit a normal distribution, which is extremely useful for random naturally occurring variables.[15] For example, it can be calculated that a grid with 10 GW of installed wind capacity must be able to cope with a potential mismatch of 1.103 GW in every half-hour period (see Box 5.1).[17] It is important to note that without the wind capacity, the same grid would face a potential mismatch of 1.02 GW in every half-hour period, so the presence of 10 GW of wind has necessitated an 8% increase in existing reserve capacity. As the time horizon moves past the very short-term to the short-term (from minutes to several hours) there is a drop in forecast accuracy.[14] In the above example, the SD for the wind power forecast for a 4-hour window is 0.93 GW.17 This means a potential mismatch of 2.97 GW in any 4-hour window. Since operating reserve can cover both immediate response (via spinning reserve) and replace regulatory reserve over the short-term horizon (non-spinning reserve) the half hour and 4-hour time windows are generally considered appropriate when accounting for uncertainty in operating reserve requirements.

Box 5.1

As an illustration, one study looked at the effect of 10 GW installed wind capacity on the UK grid by calculating the load uncertainty and wind power output uncertainty as two random variables that both follow a normal distribution.[17] With existing conventional plant it is accepted that load forecast over a half-hour (0.5 h) window will be subject to a 0.34 GW standard deviation (SD), but with 10 GW installed wind capacity there is also a 0.14 GW SD over the same half-hour period. Adding these independent forecast errors together gives a combined SD of 0.368 GW (to add these SD values take the square root of $[0.34^2 + 0.14^2]$, i.e. $\sqrt{.1352} = 0.368$). Because we are following a random variable that follows normal distribution, if the operating reserve is equal to three standard deviations of the overall forecast error that will cover 99.74% of possible mismatches: for the system containing 10 GW of wind capacity that is $3 \times 0.368 = 1.103$ GW.

Forecasting is a continuous, reiterative process, so TSOs can update their data at multiple times. In addition to addressing immediate operational needs through forecast techniques, various statistical models can be combined to improve forecasts for day-ahead and longer advance periods.[13,14] Whilst reiterative short-term forecasting can cope with smoothing out immediate mismatches in power output and demand, forecasts that look further ahead enable the TSO to strategically plan long-term reserves for periods that cover days instead of hours.[18] Long-term reserve allows the system to gradually replace regulatory reserve if additional power is still required for more than four or five hours, such as times when a weather front may result in an absence of wind for an extended period covering days. It is important to remember that reserve capacity is an existing need, even with conventional power generation.[19] Much of the long-term reserve needed to accommodate wind power availibility can be provided by existing plant, so no new capacity is required.

The above example illustrates two important principles related to wind power. They can both be summed up with the phrase 'megawatt for megawatt'. The first is that, contrary to popular belief, the variable output of wind power does not entail installing backup generators to run on a 'megawatt for megawatt' basis. As we saw above, 10 GW of installed wind capacity requires roughly 3 GW (2.97 GW) of operating reserve to manage potential mismatches in demand and output. However, the inherent uncertainty of wind means that when it achieves around 10% penetration on the grid[‡] its capacity credit peaks. At this point, the ability of wind power to replace conventional generating capacity peaks at near wind's average energy output. Output depends on the capacity factor of wind farms,[§] which is around 30%.[2] This means the capacity credit for wind peaks at roughly 0.3, and this reduces as installed capacity exceeds 10% of the total grid's capacity.[17] So, by the same token, installed wind capacity cannot substitute conventional plant capacity on a 'megawatt for megawatt' basis. For example, a simplistic way to understand capacity credit is to assume 10 GW is 10% of the total installed capacity of a power system: the capacity credit of 0.3 for 10 GW of installed wind means only 3 GW of conventional fossil fuel capacity is permanently withdrawn. But, remember this is installed capacity, not what is being generated at any one time. By displacing conventional power output (i.e., the actual electricity generated, not the installed capacity) wind can make significant savings in carbon emissions, since fossil fuels are only consumed in those periods when wind is not available.

Operating with increased wind capacity

The explosive growth of utility-scale wind power is a relatively recent phenomenon that has taken place mostly in the 21st century, whilst many features of the existing grid and power management systems are designed to follow the demands of conventional thermal generation that have remained, in principle, much the same for over 70 years.[14] As the existing grid systems are updated over time, conventional generation will be able to operate with more flexibility and can be integrated with 'smart' load management, i.e., power demand and output can be more effectively controlled to match wind power availbility.[18]

The relatively low capacity credit of wind in comparison with conventional thermal stations has generated some controversy in the past. Conventional plant must be kept to allow for periods when there is insufficient wind power output, and the variability of wind also means that regulating and operating reserve must also be on hand to smooth out any effects. When it was still nationalised, the UK grid maintained a 24% 'margin' where the operator worked on the principle that 100% of demand could be met with 76% of generating capacity.[17] There are significant implications for the way in which reserve capacity is maintained with wind in comparison to traditional generating systems. If conventional thermal plants operate more frequently as spinning reserve then they will only run part-loaded for much of the time, making them less efficient and liable to generate more CO_2 emissions per unit electricity generated (although total emissions are likely to be lower overall). Furthermore, conventional plant, such as coal-fired steam and combined cycle gas turbine (CCGT), is designed to run most of the time and are not suited to adjusting their output ('load-cycling') to the degree that may be needed to cope with variable wind output.[20] The physical stress placed on these conventional plant components operating this way will mean they become less reliable and cost more to maintain.[20,21]

The increasing geographical dispersion of wind farms as it becomes more prevalent counteracts some of the variability, because the 'balancing region' is less vulnerable to changes in any one wind farm location and local demand/supply mismatches can be smoothed out.[11] It is also well known that forecast error drops significantly over a wider area, enabling the TSO to accurately commit units for its operating reserve, minimising cost and needless stress on conventional plant.[14,18,22] It is telling that regions with a relatively high penetration of wind coupled with a good wind resource across a nation's territory show a significantly reduced need for additional reserve capacity over what is normally needed.[18] For example, during one year with poor winds in the Republic of Ireland, which shares with the UK the distinction of having one of the best wind resources in Europe, the wind power available on the grid was still more cost-effective than thermal plant.[2] This could hardly be the case if every megawatt of installed capacity had required a megawatt of conventional capacity to cover it. A large part of wind's effectiveness in Ireland was due to geographical smoothing across the balancing area (i.e. Ireland), coupled with the fact that peaks in wind power availability follow peaks in demand. The coincidence of availability and demand is noteworthy, since the UK wind resource also exhibits this property, whereby seasonal and daily demand cycles occur mostly at times of higher winds.[2,11]

The impact on reliability is also not as great as it may appear, since a distributed network of wind farms will not go offline without warning. The need for regulatory

[‡] Note that at the close of 2013, the UK had 7.5 GW onshore and 3.7 GW offshore of installed capacity for wind power (ref.5). This is between 12 and 13 per cent grid penetration.

[§] Because wind does not blow constantly at the same speed, wind turbines do not operate at their full rated capacity all of the time. The capacity factor is the amount of electricity generated in a year as a percentage of the total energy that could be generated if the turbine operated at 100% for the entire year. Note that no power plant operates at 100% of its rated capacity across a year (see Chapter 4 for a more detailed discussion).

reserve under normal operating conditions means that additional reserve does not have to be matched 'megawatt for megawatt' – national power systems can maintain reliability in the face of significant in-feed loss, and thus can cope with fast fluctuations.[23] Large conventional plant places a burden of risk on the grid, because any voltage mismatch that can cause a conventional power station to disconnect from the grid creates an instantaneous 'hole' of considerable size that must be balanced immediately.[19] By constrast, with wind the predictability of an entire wind farm going offline is such that the change in wind power output can be forecast within the TSO's operating window.[3,14] For instance, because of the modular nature of a wind farm made up of multiple turbines, even the presence of extreme variations, as might be found in an advancing weather front, will only cause a stepwise change in output as the front moves across a wind farm, not the sudden drop experienced by conventional plant going offline; hence, the down-ramping of wind is 'softer' than with conventional plant.[23,24] The design of modern wind turbines also means they have 'fault ride-through' capability, meaning they do not trip if the grid voltage suddenly dips. Since most modern turbines are also asynchronous generators connected via converters, it is possible that turbines can be used in a similar fashion to high voltage transmission interconnectors to rapidly recover frequency dips on the grid,[7] thus relieving some of the need for synchronous conventional plant to perform this role.[**]

Rates of national energy consumption, electricity included, are known to be subject to seasonal variations in weather, as well as differences in weather from year to year.[25] Seasonal variations can affect forecast accuracy, notably unstable weather conditions under low pressure. It has been noted that on rare occasions the UK and surrounding areas of the European mainland can experience days of low pressure and low winds in the winter.[17,26] Most months are likely to have a period where low winds are prevalent over the UK for one or two days, although periods longer than this are extremely rare. Nonetheless, this can pose a problem when there is low wind but high electricity demand.[27] The risk of such rare events is largely why wind's ability to substitute for dispatchable power (i.e. wind's low capacity credit).[17,26] However, in the winter months wind speeds typically coincide with periods of high demand, and forecast accuracy is also greater under high pressure fronts and high wind conditions, which is when wind power output is higher and thus likely to cause more disturbance to the grid if out were to be lost in a short space of time.[11,13] As discussed in the introductory section above, it is the controllability rather than the variability that creates a problem for the TSO, which increased forecast accuracy can mitigate.[2] Projected wind capacity for 2020 will be manageable, even during extended lulls when wind is low and demand is high, but by 2030 it is expected that power demand will have increased significantly as fossil fuels for heating and transport are steadily replaced by cleaner electricity.[27] It is vital that strategic planning decisions made today ensure a flexible system is available in the future. The decades-old tradition of monolithic, centralised suppliers of inflexible baseload power will need to be superceded by a diverse, intelligently managed and coordinated power system.

Cost of backup generation

The need to maintain operating reserve specifically to cover variability in wind power output creates an additional cost to the power system. The TSO works to arrive at the best trade-off between risk of loss of load and cost of maintaining a reserve, exactly as was the case before modern wind power became integrated into power systems.[2,15] One should bear in mind that some of these additional costs are simply the result of a shift from one form of power system to another, and that preserving existing infrastructure centred on what is best for conventional generators will save balancing costs, but will continue to incur other external costs in terms of unsustainability and greenhouse gas emissions, not to mention steadily rising fossil fuel prices and price volatility. In addition, the national grid has always required reserve capacity – even though wind may not replace an equivalent capacity of conventional plant, the existence of this plant plus the reserve capacity already in place means that very little new capacity has to be built 'just for wind'.[19] Impending coal-fired plant closures (due to age and more stringent air quality standards), the need to upgrade ageing infrastructure, rising consumer demand, and future plans to improve connectivity with the European electricity market, have all been identified as necessary investments, and a large part of this is independent of any investment that might be required as a result of increasing wind power capacity.[7,28]

The need to capitalise on the benefits of a diversified energy network that incorporates geographically dispersed wind farms will place additional burdens on the UK's transmission network.[3] Paying generators to operate conventional thermal plant under suboptimal regimes will also mean additional costs in constraints payments on the part of the TSO, and operators having to pay more to maintain their plant.[20] It is crucial that conventional operators are not dissuaded from operating in markets with high wind penetration due to increased operating costs. These increased costs for existing

---

[**] Traditional thermal plant relies on a rotating turbine shaft directly connected to a generator. Sudden changes to grid frequency caused by fluctuations in load or generation can be counteracted by the inertia of the rotating shaft itself, and such generators are said to be synchronous. Wind turbines are designed to operate at variable speeds and work through an AC/DC converter, so they are asynchronous. High voltage DC lines are also asynchronous, which is why they are used to connect two differently synchronised networks across long distances.

generating plant are unavoidable, since the national grid will need to transition from the existing model of centralised energy dominated by inflexible baseload power to one where despatchable generation will need to be far more responsive. It should not be forgotten that wind is not meant to be the sole provider of renewable energy – the UK government has repeatedly stated its aim is to pursue a diverse mix of energy sources.[29] Increasing investment in biomass, marine and tidal energy will create further renewable energy resources that have much less volatilty and can substitute for fossil fuel reserve when needed. However, under the present day model of privatised energy markets, the value of low-margin electricity produced by wind should also be acknowledged and conventional generators must to some extent adapt in the face of a changing market that reflects this new form of electricity.[2]

When the requirements for operating reserve capacity for wind power are separated out from the existing reserve requirements, the added cost to the price of electricity can be estimated. Remember that the additional costs are not for installing a new megawatt of reserve capacity for every megawatt of wind, for the reasons discussed earlier. A comprehensive look at the impact of wind penetration based on 25 GW of installed capacity (this would equate to approximately 25% penetration following 2020 projections) resulted in a combined cost for balancing and reinforcing the transmission network of 0.15 p/kWh.[17] That study was published in 2007, at which time the prevailing domestic cost of electricity was around 5–6 p/kWh. These costs therefore represented roughly 3% added to the average domestic electricity bill at that time.

More recently, the National Grid carried out a very detailed analysis of the cost of supporting more than 26 GW of installed wind capacity in the UK by 2021, which gave a more conservative estimate of the likely increase in household bills.[3] Based on 2011 real prices (the year the updated report was published) the estimated cost of operating response necessary for wind would add 0.2 p/kWh to the cost of electricity, going from 2011 costs of 0.21 to 0.41 p/kWh in real terms. This represents an increase of slightly more than 1% of the average domestic electricity bill. One needs to consider this rise in the context of the existing energy system – consider that between 2007 and 2012 household electricity bills rose by 20% (in real terms), and the largest single driver of this increase was the wholesale price of gas.[30]

Conclusion

The projected level of installed capacity of wind power (both onshore and offshore) across the UK will pose a considerable technical challenge. As penetration of wind surpasses 10% of total installed capacity (by 2013 it was roughly 12%) the variable output of wind power means that the transmission system operator (TSO) will be required to compensate for fluctuations on the grid to balance electrical supply with demand and maintain reliability of the power system. However, whilst availability of wind is to some extent uncertain for any one turbine or wind farm, coping with large swings in supply and demand is a problem transmission operators have been familiar with for some time. Operators run reserve capacity as a matter of course to ensure reliability and adequacy of supply. Variability is an inescapable fact of natural wind flows, but variability in itself is not the cause of concern; it is the predictability and controllability that is important to the TSO. With increasingly accurate and sophisticated wind speed and power output forecasts, system operators can effectively cope with regulation responses, changes in system load, and commit units for day-ahead operation and scheduled maintenance. This enables better dispatch of non-wind resources and allows traders to operate more efficiently on the electricity market.

The reduced capacity credit of wind power as its prevalence increases does entail some additional conventional plant to be held in reserve, but at a fraction of the 'megawatt for megawatt' reserve that many of wind power's detractors often claim. This effectively means that wind cannot substitute more than a small proportion of conventional fossil-fuelled plant directly, but neither does it necessitate building new fossil fuel capacity for new wind. Crucially, significant carbon emissions can be avoided by displacing fossil fuel generation, even if the conventional generating units are not replaced altogether. The increased operating reserve that will be required to support increased levels of wind power in the future will exert a burden on the existing conventional plant that is not set up to operate in a reserve capacity. Although there are fuel savings to be made when wind power displaces fossil fuel, the extra physical demands on load-cycling conventional units will lead to extra costs, and it is incumbent on national energy planners to ensure that plant operators are not dissuaded from maintaining capacity for power systems of the future where it is needed. By the same token, investment in other sources of renewable energy that offer predictable and dispatchable generation, such as biomass, tidal or geothermal, would create less volatile capacity that can be used as additional reserve.

Due to their modular nature, wind farms can offer a certain degree of flexibility on a properly integrated power system. Geographic dispersal can mitigate the effects of variability between sites, although it cannot remove it altogether due to the rare occasions where large weather patterns cover the whole of the British Isles. Generally, however, wind patterns across the UK follow seasonal peaks in demand, meaning that periods of average high wind speeds coincide with higher than average demand, mainly in the winter. Even at times when wind power output is high, and therefore loss of generation would create a significant disturbance on the grid, output across each wind farm drops in a stepwise manner, unlike the instantaneous loss of large amounts of output when a large conventional plant fails.

Whilst coping with wind variability does add to the cost of generating electricity, the final effect on domestic bills is relatively minor (a few per cent), especially when considered in the light of large drivers of costs in the last decade attributable to rising prices of natural gas. In a location like the UK, which is endowed with one of Europe's best wind resources, the value of wind is comparable to that of conventional thermal generation. The 'social resource cost' for accommodating the variability of wind power is arguably a measure of the willingness of society to pay for a sustainable and clean source of electricity that will remain the most commercially viable renewable energy application for some time to come.

References

1. Hemingway J, Michaels C. Chapter 5 – Electricity. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 111–54.
2. Boccard N. Economic properties of wind power: A European assessment. Energy Policy. 2010; 38(7):3232–44.
3. National Grid. Operating the Electricity Transmission Networks in 2020 – Update June 2011. National Grid plc; Jun 2011. 110 p.
4. Dagnall S, Prime J. Chapter 6 – Renewable sources of energy. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 155–89.
5. 'Renewable electricity capacity and generation (ET 6.1)', Statistics: Energy trends section 6: renewables, Department of Energy and Climate Change, Excel spreadsheet www.gov.uk/government/uploads/system/uploads/attachment_data/file/323527/et6_1.xls (last updated 26 Jun 2014), accessed 21 Jul 2014.
6. 'Fuel used in electricity generation and electricity supplied (ET 5.1)', Statistics: Energy trends section 5: electricity, Department of Energy and Climate Change, Excel spreadsheet www.gov.uk/government/uploads/system/uploads/attachment_data/file/323524/et5_1.xls (last updated 26 Jun 2014), accessed 29 Jul 2014.
7. National Grid. 2013 Electricity Ten Year Statement. Warwick: National Grid plc; Nov 2013. 230 p.
8. DECC. 2010 UK Greenhouse Gas Emissions, Final Figures. London: Department of Energy & Climate Change; 7 Feb 2012. Statistical release No.4282. Available from: www.decc.gov.uk/en/content/cms/statistics/climate_stats/climate_stats.aspx [Accessed 28 July 2012].
9. DECC. Updated energy and emissions projections 2013. URN 13D/231. London: Department of Energy and Climate Change; Sep 2013. 50 p.
10. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.
11. Sinden G. Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. Energy Policy. 2007; 35(1):112–27.
12. Lange M. On the uncertainty of wind power predictions – analysis of the forecast accuracy and statistical distribution of errors. J Sol Energy Eng. 2005; 127(2):177.
13. Jung J, Broadwater RP. Current status and future advances for wind speed and power forecasting. Renew Sustain Energy Rev. 2014; 31:762–77.
14. Foley AM, Leahy PG, Marvuglia A, McKeogh EJ. Current methods and advances in forecasting of wind power generation. Renew Energy. 2012; 37(1):1–8.
15. Matos MA, Bessa RJ. Setting the operating reserve using probabilistic wind power forecasts. IEEE Trans Power Syst. 2011; 26(2):594–603.
16. Wang L, Gerber A, Liang J, Dong L, Liao X. Wind power forecasting for reduction of system reserve. Paper presented at: IEEE 45th International Universities Power Engineering Conference (UPEC), 31 Aug – 3 Sep 2010, Cardiff, Wales. 1–5.
17. Strbac G, Shakoor A, Black M, Pudjianto D, Bopp T. Impact of wind generation on the operation and development of the UK electricity systems. Elect Power Syst Res. 2007; 77(9):1214–27.
18. Purvins A, Zubaryeva A, Llorente M, Tzimas E, Mercier A. Challenges and options for a large wind power uptake by the European electricity system. Appl Energy. 2011; 88(5):1461–9.
19. Milborrow D. Quantifying the impacts of wind variability. PI Civil Eng - Energy. 2009; 162(3):105–11.
20. Kubik ML, Coker PJ, Hunt C. The role of conventional generation in managing variability. Energy Policy. 2012; 50:253–61.
21. Meibom P, Weber C, Barth R, Brand H. Operational costs induced by fluctuating wind power production in Germany and Scandinavia. IET Renew Power Gener. 2009; 3(1):75.
22. Ortega-Vazquez MA, Kirschen DS. Assessing the impact of wind power generation on operating costs. IEEE Trans Smart Grid. 2010; 1(3):295–301.
23. Banakar H, Luo C, Ooi BT. Impacts of wind power minute-to-minute variations on power system operation. IEEE Trans Power Syst. 2008; 23(1):150–60.
24. This is a statement made by National Grid to the Scottish Parliament: "[A] coal or gas-fired plant [–] or a nuclear plant — poses us an operational challenge in that its output can suddenly drop off all at once, whereas the output from wind farms tends to come off more slowly; wind farms have a number of turbines, so they do not cause that issue. [. . .] Nuclear and fossil-fuelled plants provide some challenges, while wind farms provide others." Economy, Energy and Tourism Committee, 17th Meeting 2012, Session 4. Edinburgh: Scottish Parliamentary Corporate Body; May 2012. Col. 1542.
25. MacLeay I, Annut A. Chapter 1 – Energy. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 11–40.
26. Oswald J, Raine M, Ashraf-Ball H. Will British weather provide reliable electricity? Energy Policy. 2008; 36(8):3212–25.
27. RAE. Wind Energy: Implications of large-scale deployment on the GB electricity system. London: Royal Academy of Engineering; Apr 2014. 72 p.
28. National Audit Office. Infrastructure investment: the impact on consumer bills. HC 812-I. London: The Stationery Office; 7 Nov 2014. 47 p.
29. DECC. UK renewable energy roadmap: 2013 update. URN 13D/259. London: Department of Energy & Climate Change; Nov 2013. 76 p.
30. DECC. Estimated impacts of energy and climate change policies on energy prices and bills 2012. URN 12D/390. London: Department of Energy & Climate Change; Mar 2013. 96 p.

Chapter 6

Offshore wind turbines

Summary

The UK is currently a world leader in terms of offshore wind capacity installed, and ambitious developments that are underway will cement this leadership role for some time to come. This impressive performance is a result of strong policy signals set by government, together with a fortuitous convergence of major energy company and non-governmental organisation support. Wind resources offshore are generally superior to those onshore, being more consistent and possessing higher average speeds. The harsher conditions at sea, however, make the construction, operation and maintenance of offshore wind farms particularly challenging, especially given lack of experience with the scale of installations currently planned. These and other factors, such as the infrastructure required to connect to the power system on the mainland, means offshore wind is still expensive by comparison to other commercially viable renewables, such as onshore wind and solar. In addition, there will be impacts on the marine environment that must be accounted for through strategies of avoidance, mitigation or offsetting. Care should be taken to favour more comprehensive avoidance or mitigation strategies during planning and development, rather than relying too much on perceived environmental offsets that may occur post-construction. In their haste to expand and develop, major actors like planning authorities and energy companies must also avoid bypassing important stakeholder interests, such as the fishing industry and coastal communities. Decarbonisation of the energy sector necessitates that the UK's wind resource is effectively utilised, so it is important that similar mistakes made in the past during the onshore 'windrush' are not repeated offshore, otherwise public support may quickly wane. Offshore wind is crucial to the government's renewable energy targets, and offers a valuable opportunity for the UK to expand its capacity to produce domestic, sustainable energy long into the future.

What is this based on?

By the end of 2013, the UK had a total installed capacity for offshore wind power of 3,696 MW (3.7 gigawatts, GW), and is the global leader in offshore wind deployment. The UK's dominance in this particular form of renewable energy is likely to continue for some time, thanks to ambitious plans to install as much as 16 GW in UK waters by 2020 and as much as 39 GW by 2030.[1] Offshore wind is crucial to the government's renewable energy targets and is seen by energy companies as a sector with considerable growth potential. The wind resource in open waters is generally superior in comparison to land-based sites, with higher average wind speeds and less wind shear.* Developers and planners alike are drawn by the advantage offshore installations offer in terms of a lower visual impact, and thus the lack of attendant planning issues and public resistance that have often beset onshore wind developments in the UK.[2]

Despite these perceived advantages, offshore wind remains the most expensive commercially viable form of renewable electricity,[3] and the challenges of operating in adverse conditions at sea are considerable for an industry that has only moderate experience with installations on the scale of those planned. The UK has possessed the largest offshore wind fleet since it surpassed Denmark in 2008, at which point the UK's total offshore capacity was just 590 MW – now it is more than six times as large and is set to increase again by another four times in the period 2014–20.[1] Such a large expansion in any industry will present problems, and the demands of building and operating equipment and infrastructure relating to wind turbines in the middle of the sea are something the wind sector is still learning to do. This is important to remember, because 'learning-by-doing' in any industry is typically a balance between growth rate and the time required for experience to feed back in the learning process.[4] For instance, early UK offshore developments have seen higher than expected component failure rates and significantly lower operational availability than projected. As reliability issues are identified and corrected through evolving industry practice this will improve availability and therefore lower maintenance costs and raise revenue.[5] As the volume of offshore development rapidly increases, this will also lead to more specialised designs and materials that better meet the demands of open water operations, rather than relying on adapting preexisting onshore technology.[5]

---

* Less wind shear means less difference between wind speed at different heights, so a more consistent and higher wind speed is typically found at a lower height above the sea surface than above land – the result is that the rotor hub for an offshore turbine does not have to be built as high to achieve the same power ratings as found onshore.

Furthermore, the accelerated expansion of offshore wind has come at a time when the cost of all energy infrastructure projects has risen, largely due to wholesale prices rises for commodities (such as steel) and energy in response to global market forces.[6,7] A fast-expanding industry will also lead to bottlenecks in supply, as manufacturers find their order books are full and there is a delay before the capacity of the supply chain can adjust to increased demand. This is something that has particularly affected the wind power sector, both on and off shore.[7,8]

One other aspect of rapid growth is that offshore developments may outstrip our knowledge of environmental impacts. There is the potential for significant impacts on marine flora and fauna both above and below the water at the site of offshore wind farms; it should be noted that in some cases there are site-specific positive benefits, but these, like the negative impacts, are not well understood at present and may be overstated. There is frequently too little emphasis placed on assessing the cost of these impacts, with developers overly reliant on the 'offset' in terms of alternative environmental benefits that may not always be equivalent.[9] One of the wider environmental benefits is, of course, the delivery of low-carbon electricity that reduces fossil fuel consumption in the energy sector.

The open waters surrounding the UK are also not free from other vested interests, such as the fishing industry and coastal communities, not to mention environmental groups. These will present potentially thorny issues that will require a careful balancing act by planners and policymakers to ensure that the best interests of the environment are served, whether that means decarbonisation of the economy or protecting particularly sensitive habitats and seascapes.[2,10] Planners and developers must take heed and not fall into a mode of operation that overlooks the interests of existing stakeholders, or face a potential backlash from the public. Offshore wind offers the UK a way to advance the decarbonisation of its electricity sector considerably, increasing its capacity to produce domestic, sustainable energy on a long-term basis. Careful strategic planning and paying due diligence to environmental and stakeholder concerns will ensure offshore wind can play a central role in a sustainable future.

What is the current evidence?

Offshore wind will form the cornerstone of Britain's efforts to meet its emissions targets, and will help the government achieve its EU-mandated goal to generate 20% of the country's electricity with renewables by 2020.[2] In all scenarios forecast by the grid operator (National Grid plc.), offshore wind will play a significant role in the UK's energy mix by 2035, making up roughly 50-70% installed wind capacity (i.e. onshore and offshore combined). Given the leading contribution wind power will make to the UK renewable energy sector between now and 2035, offshore wind alone may account for anywhere from one-quarter to two-thirds of the UK's total renewable capacity – in a 'gone green' scenario that is driven by offshore expansion, offshore wind could be almost 40% of the UK's total generating capacity for all forms of energy.[11]

Based on offshore wind projects that are operational, under construction, consented and in planning, the expansion of the UK's capacity should ensure it remains the leading country in offshore wind deployment for some years to come.[2] However, concerns over capital costs and operation and maintenance remain, and it is no secret that offshore wind remains the most expensive form of commercially viable renewable electricity available.[3,4] This is reflected in the renewable subsidy mechanisms currently available (see chapter 3), with offshore wind receiving more than double the level of support under the Renewables Obligation1 and a 55%–66% higher strike price under the new Contracts for Difference scheme.[12]

Recent global economic trends have seen prices for all energy infrastructure projects rise; given offshore wind is a less established industry this price increase has affected offshore capital costs in particular.[5,7] Current costs are more than £3 million per megawatt (£3m/MW) of installed capacity, compared to just £1.5m/MW in the mid-2000s. This has affected the cost of generation, which has likewise increased, going from an estimated 9.9 p/kWh to 14.9 p/kWh between 2006 and 2010.[7] Two matters of note within this trend are that the cost of major conventional forms of generation rose far more steeply over the same period, with gas-fired and nuclear generation both doubling (to 8 and 9.7 p/kWh, respectively), and that onshore wind experienced one of the lowest price increases of all with a rise of just 33%.[6] Onshore wind has experienced a long-term downward trend in generation costs since the mid-1990s, largely due to policies that have supported onshore wind development and deployment that bridged the gap between its cost and that of established fossil fuel technologies.[13] By contrast, the general upward trend and historical volatility of fossil fuel energy prices means that gas and coal-fired generation are unlikely to return to their low pre-2007 prices, and the increased internalising of carbon costs (e.g. through carbon taxes or mandated carbon capture storage technology) will only push prices higher.[14]

The offshore industry is currently experiencing several major supply chain constraints, since the sharp increase in demand as the UK implements its ambitious plans up to 2020 has led to a shortage of new turbines and turbine components, as well as limited port facilities and installation vessels required (many of which are also used by the offshore oil and gas industry).[5] These 'growing pains' are typical of any industry that is undergoing such rapid growth, and learning-by-doing is expected to play an important part in lessening these issues. There is a risk that supply chain constraints may persist due to competition for vessels and other specialised resources with other offshore industries and offshore wind developments elsewhere in Europe.[6] Existing UK projects have shown that offshore wind developments can be profitable for their owners, but this is very sensitive to capital costs; hence, construction delays for future projects could easily cause an offshore wind farm to become economically unviable.[15]

Even with these challenges, there are several factors that make it reasonably certain that prices for offshore wind will fall. The large-scale projects commissioned in UK waters to be built over the next decade will boost supply chain confidence and increase competition, helping improve manufacturing and operating efficiencies, economies of scale, and standardisation as the industry converges on optimal designs for turbines and foundations.[6] This industry learning and a lessening of supply chain constraints will cause capital costs to drop significantly in the first decade, and even further by 2030 (possibly by as much as 30%).[8,16] Generating costs will also decrease, perhaps dropping fast enough to reach 10 p/kWh by the year 2020.[6]

Thus, despite current high prices, offshore wind is likely to become less expensive as today's subsidies support industry expansion and the technology becomes more cost-competitive. Indeed, offshore wind is likely to be more competitive than nuclear power,[†] even in European countries that have greater experience with running a nuclear fleet.[17,18] Under the new Contracts for Difference, which will have completely replace the UK's existing renewable energy subsidy scheme by 2017, new offshore wind will receive support in the form of a feed-in tariff that will degress (gradually reduce year-on-year). This reflects the assumption that a maturing offshore sector will become more cost-effective thanks to the stimulus received by present-day subsidies that allows the industry to rapidly expand.[12]

Although overall costs for offshore wind will probably decrease from their current high point, the costs are unlikely to compare favourably with onshore wind for several decades at least.[5] As the UK's offshore wind resources are exploited to their full, this will entail constructing wind farms further out to sea. Much like onshore wind, the lifetime costs associated with offshore wind are skewed towards the upfront construction and the capital needed to finance this.[7,16] There are notable differences in construction needs, however, since conditions are far more challenging when constructing out at sea (e.g. the requirement for specialised vessels, as mentioned above) and physical requirements to support the turbines mean larger foundations and more connector cables to feed electricity back to the shore. These factors can raise construction and connection costs significantly.[8,16] As may be expected for a relatively young industry, operation and maintenance costs for the UK's existing offshore wind farms have also been higher than expected due to equipment failure, one of the main reasons why capacity factors for these installations have been lower than the European average (see chapter 4). Component failure can be a serious problem for an offshore turbine operator, because the difficulty in effecting repairs out at sea can result in lengthy downtimes for the turbine in question and therefore lost revenue. There is a great deal of research in progress to improve remote condition monitoring of offshore turbines, which will result in significantly improved availability thanks to better maintenance scheduling to head off serious faults before they occur.[19]

As of 2013, most of the UK's existing complement of offshore wind farms can be found clustered along the east coast of England between Kent and Lincolnshire, in the Irish Sea, and a few sites situated off the Scottish coastline.[20] The distance from shore is typically from 5 to 17 km (about 3–10 miles), but there are some that are closer in and others more than 20 km (12.4 miles) out. One compelling argument for siting wind farms offshore is that they will be subject to fewer objections from the public, which has been identified as a major impediment to the expansion of the UK's onshore wind capacity during the 1990s and 2000s.[2,21] But this is very much a misconception, as evidenced by conflicts between planners and public during some of the UK's own offshore developments.[22] Studies conducted in various countries in Europe and the Americas have demonstrated that coastal residents often perceive offshore wind farms as a negative development, largely based on the visual impact.[23]

Residents and frequent users of coastal areas are typically more sensitive to the visual impact of an offshore development, especially if it is perceived to jeopardise the recreational potential of the area; respondents usually express the view that installations should be sited further out to sea.[24] This is by no means an isolated case for wind power, although it is the most familiar offshore technology. Neither is visual impact the sole reason for local resistance, although it does tend to be the dominant issue. Public concerns have been raised against various forms of offshore renewable energy development (e.g. wave power and tidal barrages) and common reasons that are raised include noise disturbance, ecological impacts, threats to tourism, employment opportunities, community harmony and general anti-developer sentiment.[25]

[†] Comparative costs are discussed in Chapter 3. For a discussion of the escalating costs of nuclear power and the reasons behind this trend, see Chapter 8.

There are also some 'marine specific' issues that are a cause for concern, in particular the view that the open sea is an unspoilt place where man-made structures do not belong; this objection to human-engineered structures contrasting with a primarily natural setting lies at the heart of many opposition movements to renewable energy developments, especially wind turbines (see chapter 9, 'Wind turbines and property prices').[25] These conflicts can often reveal complex and even contradictory views. For instance, many coastal communities have strong links to the fishing industry, an endeavor that in modern times frequently comes under scrutiny for overexploiting the marine environment. The ecological benefits that no-fishing zones (or 'no take' zones) around offshore wind farms has been identified as one issue that may bring the wants of local economic groups (i.e. fishing communities) into conflict with environmental groups.[2]

A long-contested offshore development in the USA revealed ambivalence on the part of anti-wind residents towards long-standing industrial structures, even in cases where these have a demonstrable effect on people's health and environment.[26] An in-depth analysis of survey data from across many different countries relating attitudes to existing offshore wind farms suggests that respondents with more experience visiting or viewing turbines were more positive about them, in contrast to those who lived further away from wind farms and had limited experience. Interestingly, the same study demonstrated that offshore wind farms with a greater number of turbines evoked more positive support than those with fewer turbines, and this was independent of the size and height of the turbines themselves, i.e. independent of visual impact.[27] It is clear that residents are quite capable of analysing the benefits and costs of a wind farm installation, and will arrive at a more nuanced view than simply acceptance or rejection.

Whilst it is clear that developers and planners cannot assume moving wind farms offshore will circumvent public opposition, there is some evidence that installations further from shore are perceived as having less of an impact.[24] Even without this pressure, the continued expansion of the UK's offshore industry means that larger and more ambitious wind farms are to be built in the coming decades. In many cases, these will be a considerable distance out to sea, for example, a planned development at Dogger Bank in the North Sea will be 200 km (124 miles) from shore with water depths of up to 63 m (over 200 feet).[8] The impact offshore developments like this will have on marine ecology are not completely understood. It is possible, however, to anticipate effects turbines might have by learning from observations made for other human-made structures, like oil platforms and shipwrecks.[28] For instance, the large foundations required by offshore wind turbines can create new habitats in remote seabeds by providing a substrate for marine organisms such as anemones, barnacles and worm species (collectively known as benthic species). This colonisation can attract other marine species further up the food chain, including crabs and lobsters and fish that thrive on prey found in sea floor sediments, as well as other fish that in turn prey on those.[28,29] Large wind farms will have no-fishing zones (also termed 'no-take' zones) enforced due to the hazards presented by the turbines structures themselves to fishing trawlers and their nets. Although no-take zones can be viewed in a negative light with respect to commercial fishing and the communities that it supports, from an environmental perspective no-take areas can provide havens for fish species and other organisms, and may even serve to extend protected regions in cases where turbines are situated on the edge of an existing conservation area.[2,30]

It is important to remember, however, that ecological changes wrought by offshore installations are certainly not uniformly positive. The construction phase is notably detrimental, driving away many native species of fish, mammals and birds due to increased seagoing traffic on the surface (vessels associated with construction), sea floor dredging to prepare the site, and, especially so, the noise produced during pile driving and related activities as the foundations are put in place.[9] These are arguably short-lived disruptions that only last during construction, but it is of more concern when one considers that it may be a decade or more before numbers of certain species return to their original levels.[9,31]

Changes to the seabed may preclude certain species from recolonising at all, because the concrete foundations do not offer the same complex nooks and crannies that are favoured by some benthic species.[9,29] It is true that offshore installations do appear to attract increased numbers of some species at the top of the food chain, for example, grey seals in the North Sea have been observed to track between turbines at operating offshore wind farms. Whilst this may be viewed as a positive sign, it is still not clear whether such phenomena will be beneficial to ecological communities, since pressure on prey species may be greater if predators can more easily locate them where they are concentrated around wind farms.[32]

This highlights the uncertain nature of long-term impacts on marine ecology, and this is something that the wind industry must ensure remains at the heart of planning and development when considering offshore installations. Despite the dramatic increase in knowledge that has accompanied scientific surveys associated with offshore wind developments over the last decade,[33] it is clear that many measures touted by developers as 'biodiversity offsets' are neither calculated benefits (i.e. they are consequences of the development, but were not designed in advance by developers with conservation in mind) nor are they equivalent in terms of the ecological benefits that may be provided.[9] Thanks to the vast amount of data accumulated from the offshore oil industry over the decades, the need for an environmental impact assessment (EIA) is well understood, but many EIAs have been noted to make much of potential positive benefits at the same time as underplaying negative impacts.[9] There is certainly a great deal of momentum behind the UK's offshore wind industry at present, and the underlying reasons with respect to the wider issues of climate change are compelling, but care should be taken not to give so much weight to these initiatives that important biodiversity conservation goals suffer as a result.[2,9] Striking this balance is no trivial matter – for example, decarbonisation of the energy sector can help reduce the acidification of oceans that is happening due to CO_2 emissions, hence overall biodiversity is improved at the same time as local marine species are reduced. The environmental problem is complex, but it is certainly possible to apply sophisticated methods that best model offshore wind farm developments to maximise the exploitation of clean energy whilst maintaining, possibly even benefiting, marine conservation.[30,33,34]

Conclusions

The UK's offshore wind industry is poised to enter what is likely to be a defining age. Although offshore wind has experienced rising prices since the mid-2000s, this is largely due to wider macroeconomic trends that have similarly affected all forms of energy, and there are good reasons to project falling costs over the coming decades as the industry matures and expands. This optimism should be tempered with the realisation that offshore wind will not be as cheap as onshore wind for several decades, but the sheer scale of the wind resource in British territorial waters means that offshore wind power is quite capable of making one of the largest contributions in terms of decarbonising the UK's energy sector up to 2030 and beyond.

Whilst offshore developments are not immune from similar public opposition movements that have been experienced with onshore wind, there is greater scope for locating large installations far enough out to sea that visual disamenities can be reduced or avoided altogether. The danger with pursuing this policy is that other stakeholder interests may be overlooked or dismissed, such as concerns over the environmental impact of wind farm construction on marine ecology, and commercial interests relating to fishing zones and shipping lanes that may adversely affect certain communities which rely on them.

The planning process for offshore developments in UK waters is somewhat unique, in that the Crown Estates exercises ultimate control over the sea floor and decides where offshore developments are permitted. The Crown Estates is following a pragmatic policy that weighs the merits of any development on a case-by-case basis, which confers a flexibility on the UK's wind industry that is likely to foster its expansion and maintain the nation's status as the global leader in offshore wind. However, planned and future developments are likely to require a delicate balancing act between the conflicting demands of wider environmental goals (reducing national carbon emissions) and the localised concerns that may arise should a specific development negatively affect marine ecosystems and those communities which rely on them.

There are certainly benefits that can accrue from exploiting offshore wind, in terms of both climate change mitigation and local biodiversity conservation efforts. Despite this, developers too often overstate biodiversity benefits in relation to the negative ecological effects, and it is up to the wind industry and policymakers to be clear with the public about the trade-offs that are necessary to pursue climate change and marine conservation aims at the same time. It is important that the government, through the Crown Estate, continues to act as a responsible landlord.

The current UK offshore wind programme has been described as enjoying 'a heady confluence of positive pressures in its favour'.[2] These auspicious circumstances will almost certainly translate to sustained and rapid growth for the UK's offshore wind industry. At the same time, it is hoped that the steady accumulation of scientific knowledge relating to the environmental impact on marine ecology will continue to inform the industry. Further to this, stakeholder engagement is crucial to ensure that the UK's offshore programme continues to enjoy the legitimate support of enviromental organisations and the general public. With these provisos in mind, offshore wind has the potential to deliver a significant portion of the UK's electricity demand in a low-carbon and sustainable manner.

References

1. DECC. UK renewable energy roadmap: 2013 update. URN 13D/259. London: Department of Energy & Climate Change; 5 Nov 2013. 78 p.
2. Toke D. The UK offshore wind power programme: A sea-change in UK energy policy? Energy Policy. 2011; 39(2):526–34.
3. IEA. Medium-term market report 2014: market analysis and forecasts to 2020. Executive Summary. Paris: International Energy Agency; Aug 2014. 20 p.
4. Neuhoff K. Learning by doing with constrained growth rates: an application to energy technology policy. Energy J. 2008; 29(Special Issue 2):165–82.
5. Greenacre P, Gross R, Heptonstall P. Great expectations: the cost of offshore wind in UK waters – understanding the past and projecting the future. London: UK Energy Research Centre; Sep 2010. 124 p.
6. Heptonstall P, Gross R, Greenacre P, Cockerill T. The cost of offshore wind: Understanding the past and projecting the future. Energy Policy. 2012; 41:815–21.
7. Mott MacDonald. UK electricity generation costs update. Brighton: Mott MacDonald; Jun 2010. 100 p.
8. Green R, Vasilakos N. The economics of offshore wind. Energy Policy. 2011; 39(2):496–502.
9. Vaissière A-C, Levrel H, Pioch S, Carlier A. Biodiversity offsets for offshore wind farm projects: The current situation in Europe. Mar Policy. 2014; 48:172–83.
10. Wolsink M. Near-shore wind power—protected seascapes, environmentalists' attitudes, and the technocratic planning perspective. Land Use Policy. 2010; 27(2):195–203.
11. National Grid. 2013 Electricity Ten Year Statement. Warwick: National Grid plc; Nov 2013. 230 p.
12. DECC. Contract for Difference: Final allocation framework for the October 2014 allocation round. URN 14D/328. London: Department of Energy & Climate Change; 1 Sep 2014. 56 p.
13. Badcock J, Lenzen M. Subsidies for electricity-generating technologies: A review. Energy Policy. 2010; 38(9):5038–5047.
14. DECC. Estimated impacts of energy and climate change policies on energy prices and bills. URN 10D/719. London: Department of Energy & Climate Change; 1 Nov 2011. 81 p.
15. Weaver T. Financial appraisal of operational offshore wind energy projects. Renew Sustain Energy Rev. 2012; 16(7):5110–20.
16. ARUP. Review of the generation costs and deployment potential of renewable electricity technologies in the UK: Study Report. No. REP001. London: Ove Arup & Partners Ltd; Oct 2011. 30–51.
17. Harris G, Heptonstall P, Gross R, Handley D. Cost estimates for nuclear power in the UK. Energy Policy. 2013; 62:431–442.
18. Boccard N. The cost of nuclear electricity: France after Fukushima. Energy Policy. 2014; 66:450–461.
19. Yang W, Tavner PJ, Crabtree CJ, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. Wind Energy. 2014; 17(5):673–693.
20. Dagnall S, Prime J. Chapter 6 – Renewable sources of energy. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 155–189.
21. Toke D. Explaining wind power planning outcomes: some findings from a study in England and Wales. Energy Policy. 2005; 33(12):1527–1539.
22. Haggett C. Understanding public responses to offshore wind power. Energy Policy. 2011; 39(2):503–510.
23. Ladenburg J. Stated public preferences for on-land and offshore wind power generation – a review. Wind Energy. 2009; 12(2):171–181.
24. Ladenburg J, Dubgaard A. Preferences of coastal zone user groups regarding the siting of offshore wind farms. Ocean Coast Manage. 2009; 52(5):233–42.
25. Wiersma B, Devine-Wright P. Public engagement with offshore renewable energy: a critical review. WIREs Clim Change. 2014; 5(4):493–507.
26. Firestone J, Kempton W. Public opinion about large offshore wind power: Underlying factors. Energy Policy. 2007; 35(3):1584–98.
27. Ladenburg J, Möller B. Attitude and acceptance of offshore wind farms—The influence of travel time and wind farm attributes. Renew Sustain Energy Rev. 2011; 15(9):4223–35.
28. Hooper T, Austen M. The co-location of offshore windfarms and decapod fisheries in the UK: Constraints and opportunities. Mar Policy. 2014; 43:295–300.
29. Bergström L, Sundqvist F, Bergström U. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. Mar Ecol Prog Ser. 2013; 485:199–210.
30. Punt MJ, Groeneveld RA, van Ierland EC, Stel JH. Spatial planning of offshore wind farms: A windfall to marine environmental protection? Ecol Econ. 2009; 69(1):93–103.
31. Teilmann J, Carstensen J. Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow recovery. Environ Res Lett. 2012; 7(4):045101.
32. Russell DJF, Brasseur SMJM, Thompson D, et al. Marine mammals trace anthropogenic structures at sea. Curr Biol. 2014; 24(14):R638–R639.
33. Bergström L, Kautsky L, Malm T, et al. Effects of offshore wind farms on marine wildlife—a generalized impact assessment. Environ Res Lett. 2014; 9(3):034012.
34. Möller B. Continuous spatial modelling to analyse planning and economic consequences of offshore wind energy. Energy Policy. 2011; 39(2):511–517.

Chapter 7

Wind power and nuclear power

Summary

The UK is invested with some of the best wind resources in Europe, and wind power forms the cornerstone of the government's aim of decarbonising the energy sector and improving energy security. Indeed, without the rapid expansion of installed wind capacity that is projected over the next 20 years it is difficult to see how the UK can meet these objectives. Nuclear power, however, remains under consideration as a form of low-carbon electricity, and it is argued that nuclear avoids the intermittency issues associated with wind by producing steady 'base-load' electricity at a cost at least comparable with onshore wind power. With growing awareness of climate change caused by excessive fossil fuel consumption, combined with the large increase in global electricity use driven by emerging economies, there has been a resurgence of interest in nuclear power in the 21st century, dubbed the 'nuclear renaissance'. Some opponents of wind and other renewables point out that nuclear can potentially supply much of the UK's (and the world's) low-carbon electricity needs, but is this true? With a great deal of support through policy and public financing, nuclear established itself over 50 years ago with promises to produce power 'too cheap to meter'. Since then the industry has been beset with economic woes and several high-profile accidents which threw its shortcomings into stark relief. Despite the industry's recent revitalisation, the latest generation of commercial reactors are proving to be costly and slow to build, and a post-Fukushima world sees safety concerns once more at the forefront.

With already lengthy start-up times, the additional delays that are seemingly inevitable for any new build means nuclear is likely to be irrelevant to any UK plans to cut carbon emissions before 2030. There are also questions being asked about nuclear's environmental credentials, which, while much superior to that of coal from the perspective of carbon emissions, are doubtful when taking into account the logistical chain necessary for extracting and processing uranium, and the construction and eventual decommissioning of the power plant. The latter stage in particular highlights the huge uncertainties surrounding the impact of nuclear power, both financial and environmental. Since private investors have repeatedly shown themselves unwilling to bear these potential costs, nuclear continues to receive substantial public underwriting in the form of subsidies and other financial assistance. The UK's existing nuclear fleet will continue to place a burden on the public purse for most of this century, and even after its first 50 years the industry is still struggling to resolve the unique problem of storage and disposal of hazardous radioactive waste, with the cost and potential health implications to be borne by future generations for many years to come.

What is this based on?

Nuclear power has been used to generate electricity since the 1950s, and purports to be a tried and tested method of power generation. From its heyday in the 1960s and 1970s, the nuclear industry underwent a slump that lasted several decades, precipitated by the high-profile incidents at Three Mile Island and Chernobyl (and other lesser-known incidents). To a large extent this slump came about due to the erosion of public trust as people began to realise that nuclear power carries significant risk despite its ability to provide abundant clean electricity, but by the 1970s growing awareness about radiation hazards had also prompted increasing regulatory standards that were already pushing up the operating costs of existing plant, in addition to making the construction of any new plant a complex and costly business.[1,2] At the start of the 21st century, however, several decades without a repeat of a Chernobyl-like accident had improved public opinion again, and the notable rise in fossil fuel prices coupled with international concern over the inexorable climb of greenhouse gas emissions prompted a resurgence of interest in nuclear power.[1]

The use of nuclear power stations has been hailed in recent years as the most efficient way to produce electricity without relying on traditional fossil fuels, thus creating a relatively 'carbon-free' grid. Whilst not strictly renewable, the potential stockpile of nuclear fuel available for extraction means its supporters describe nuclear power as a viable means to meet the world's energy needs for hundreds of years at least, based on the fraction of physical fuel required by a nuclear plant in comparison by bulk with coal or gas. A typical nuclear reactor will generate the same energy as a coal-fired plant using less than 0.001% of fuel by weight. For example, a 1,000 megawatt (MW) coal station will burn

3.2 million tonnes (Mt) of coal per year, compared with just 24 tonnes of enriched uranium oxide (UO_2) per year for a 1,000 MW nuclear power station (although it should be remembered that this UO_2 comes from 25,000–100,000 tonnes of mined ore).[3] The heat created in a nuclear fission reaction with uranium is used to generate steam which drives the plant turbine to produce electricity; hence, no CO_2 is emitted as a waste product, making nuclear electricity 'on a par' with renewables such as hydro and wind power when considering the operation of a nuclear plant, and nuclear power is certainly a low-carbon source of electricity when compared to fossil fuels.

Although the level of CO_2 emitted by nuclear power compares favourably with renewable energy sources, calculating the emissions can vary by one or two orders of magnitude due to the inherent complexity of the nuclear supply chain, making an accurate comparison very difficult.[4] Indeed, the logistical chain required for extracting and processing uranium can make a significant contribution to overall emissions depending on the fuel enrichment method employed (the older gas diffusion method versus the modern gas centrifuge process) and the existing power system that the process relies on (e.g. a national grid relying largely on coal). Furthermore, uncertain estimates surrounding the quality of uranium ore at the 'front-end' and the impact of decommissioning at the 'back-end' means, for some nuclear power plants, resulting greenhouse gas emissions can approach those of a natural gas-powered plant, many times higher than emissions from wind and other renewables.[5]

Globally, the nuclear power industry has been traditionally beset with problems involving the start-up, operation and decommissioning of nuclear plants, resulting in spiralling costs and threats to public health.[1,6–8] This is true of the UK industry as well, which has a history of poor economic performance, not to mention repeated incidents involving the release of dangerous material, although nothing as severe as the Windscale fire that occurred in 1957.[9,10] Despite decades of experience, the unique problem of storage and disposal of hazardous radioactive waste remains a concern for the nuclear industry, with the cost and potential health implications to be borne by future generations for centuries to come.[11]

Even without the concerns already raised, the long lead time required for construction of a nuclear power plant before it becomes operational means that nuclear power is almost certainly going to be irrelevant to the UK's CO_2 emissions targets prior to 2030. The cost of electricity per unit generated by nuclear power is currently no better than onshore wind power, without taking into account the future costs of cleaning up when a plant is finally decommissioned, and lengthy construction periods means nuclear is even more sensitive to already escalating prices, since so much of the cost of nuclear is in the initial captial required.[6,12] In comparison, the generation of electricity from wind power poses an insignificant threat to public health (see also chapter 12), has seen costs decline over the last few decades, and can be considered a true renewable energy source.[13]

What is the current evidence?

Since the Government's commitment to reducing the UK's carbon emissions, nuclear energy has gone through a turbulent period of initial optimism followed by despondency. Despite being a mature technology with low operating carbon emissions, the question of whether the UK should invest in more nuclear power is dogged by concerns about environmental impact, economic viability, implementation, and safety.

Environmental impact

After Chernobyl, and prior to Fukushima, nuclear energy's role as a central plank of low-carbon energy production was undergoing a resurgence, enjoying greater public support than it had for decades.[1] This had instigated something of a sea-change in UK government policy, which had initially been very conservative about any future role for nuclear power in the early 2000s, to highlighting its potential as a means decarbonise the electricity sector in 2005, to finally being acknowledged in the Electricity Market Reform (EMR) that financial incentives might be put in place to support new build.[14]

The case for specifically incentivising new nuclear development was a difficult one for the government to make, as successive UK adminstrations had pursued a liberalised policy since the late 1980s with regards to the energy market, and had relied on the privatised electricity sector to arrive at its preferred mix of generating technologies, within which framework nuclear had struggled.[9] With the environmental case for reducing carbon emissions becoming more prominent, and, indeed, legally binding, advocates of nuclear power within the main political parties began framing the need for low-carbon electricity in terms of ensuring Britain's energy security and the security of its citizens in the face of destabilising climate change.[15]

The greenhouse gas emissions (measured as 'grammes CO_2 equivalents per kilowatt-hour' or gCO_2eq/kWh) generated by nuclear power are impressively low compared with traditional fossil fuels, and generally perform as well as renewable energy sources such as wind or solar, although some factors of the nuclear life cycle can result in a higher range of values. A comprehensive review of more than a hundred life cycle assessments (LCAs) published for nuclear generation give an average level of emissions of 66 gCO_2eq/kWh

compared to 960 gCO_2eq/kWh for coal and 443 gCO_2eq/kWh for natural gas, although the average emissions are higher than those for true renewable energy sources: e.g. short-rotation forestry wood-fired steam turbines (i.e. biomass generation) of 35 gCO_2eq/kWh; a hydroelectric reservoir emits 10 gCO_2eq/kWh; crystalline solar PV emits 55 gCO_2eq/kWh; and wind turbines* of various configurations (onshore and offshore) has an average of 34 gCO_2eq/kWh.[5,16]

A different group took a similar number of published LCA studies, but also differentiated between technologies in more detail – this is a useful step since there are many different types of nuclear reactor used around the world. More than 80% of reactors operating today use ordinary water as a moderator† and coolant, which is known as light water reactor (LWR) technology. Focusing on LWR nuclear plants, this second study reported average emissions to be 25 gCO_2eq/kWh, compared to 1,000 gCO_2eq/kWh for coal-fired power stations.[17] The same research reported an average of 16 gCO_2eq/kWh for various wind turbine configurations, using more than 100 published LCA estimates.[18]

This group also studied the fuel supply chain for nuclear in detail, something that is rarely examined in LCAs or even reported at all.[17] This is a very important aspect of the nuclear life cycle, since the mining of uranium ore creates a significant environmental impact.[19] Furthermore, advocates of nuclear power as a means to decarbonise the electricity sector project a tripling of the world's nuclear generating capacity, something that will place a strain on uranium resources and require increased mining of lower-grade ores and the discovery of new uranium deposits, leading to greater environmental impacts.[19,20] Looking to the future, if nuclear power capacity increases worldwide the environmental impact due to the front-end operation will only get worse, with greenhouse gas emissions even surpassing 100 gCO_2eq/kWh.[17,21]

This sensitivity to the quality of uranium ore is a significant factor for any expansion of nuclear power, because the long lifespan of a nuclear facility and the amount of capital resources that have to be invested in new build creates a significant degree of technological 'lock in', which makes it more risky as a means of delivering reductions in CO_2 emissions, especially since most new build is likely to rely on reactor designs that are 'once-through' for uranium fuel.[20] This serves as a reminder that nuclear power, although relatively low-carbon during its operation, is ultimately not a renewable source of energy in the same way that wind is. Finally, there are great uncertainties over the back-end stages of mine reclamation, not to mention decommissioning and dismantling of the retired power plant itself, a financially and environmentally costly stage that places liability on future generations.[5,17,19]

Economics and efficacy of implementing new nuclear build

The cost of generating electricity using nuclear power has grown steadily more expensive since the 1970s, and the industry has a notoriously poor record for estimating construction and realisation costs.[1] The enormous complexity of nuclear power stations, non-uniform designs and increasingly stringent safety requirements means that the industry has been unable to capitalise on institutional experience and capacity (so-called 'learning-by-doing') nor on economies of scale. In its heyday of the 1960s and 70s, nuclear build in the United States saw cost overruns of anywhere from 100 to more than 250%.[1] There is an argument that the lull in nuclear's fortunes following Three Mile Island undid any benefits derived from learning-by-doing at that point, but the problem is not just one found in the USA. France is considered the nuclear success story, going from a small number of early gas-cooled reactors in the 1960s to the completion of 58 LWR plants by 2000 that supply almost 80% of the country's electricity, most of these being installed and coming online between 1980 and 1990.[6] This was possible due to a unique institutional setting that permitted centralized decision-making from government, regulatory stability, and dedicated efforts for standardised reactor designs, all realised through a powerful nationalised company, the electric utility ÉDF.‡

However, despite lower operating costs, the expansion of the French nuclear industry has occurred against a backdrop of substantial escalations in the cost of building nuclear facilities. In real terms, the cost of new nuclear build in France grew almost two-and-a-half times§ over the period 1974 to 2000.[6] The two most recent construction projects of advanced third generation (Gen III+) reactors, one of which is in the French commune of Flamanville (the other is on the island of Olkiluoto in Finland), have been bedevilled with safety issues and rising costs since their inception, causing repeated delays and leading to increased risk of electricity shortfalls in France at critical times of the year.[9,22] The cost of these newest facilities – designed and built by leading nuclear companies with arguably more experience over the last 40 years than anyone in the world – has been eye-watering for investors and developers alike: Flamanville-3 has seen a cost escalation

---

[*] The LCA of wind power is discussed in more detail in Chapter 2.

[†] By 'moderating' the fast neutrons in a fission reaction the rate at which these neutrons impact other uranium atoms to create more fission reaction cascades is increased, thus improving the overall fuel efficiency. Ordinary (or 'light') water is commonly used, but some nuclear plants use heavy water (deuterium) or graphite as a moderator instead.

[‡] This is Électricité de France, which operates in the UK under EDF Energy.

[§] This would be three-and-a-half times if the enormously expensive 'N4' reactors are included. The N4 design is an antecedent of the European pressurised reactor (EPR) design. The EPR is one of several advanced third generation (Gen III+) reactors.

of nearly 10% per annum since development began in 2006, whereas Olkiluoto-3 has seen an annual escalation of more than 12% since 2004.[12] The current estimate for the full construction cost of Flamanville will be €8.5 billion, more than double the original price tag, and it is expected to come online in 2016, almost four years overdue.[12,23]

In the UK, there has been no new nuclear capacity introduced since 1995, despite the fact that all but one of the UK's ageing fleet is likely to be retired by the middle of the next decade (several plants will last to 2025, but this will be achieved only by extending them past their original scheduled retirement date).[24,25] A history of escalating costs, regulatory uncertainty and adherence to liberalised market principles in the UK has made private investors wary of spending huge amounts of money on new nuclear build, and nothing has happened to allay these fears given the recent experience at Flamanville and Olkiluoto.[1,9,14]

Although supporters of nuclear energy point out that renewables have received a greater boost from the government under the Renewables Obligations (RO) scheme introduced in 2002, this overlooks the fact that the RO grew out of the Non-Fossil Fuel Obligations (NFFO) that were implemented in the preceding decade as a means to support the nuclear power industry, which was unable to function on the energy market following privatisation in 1989.[26] Due to the private sector's reluctance to take on the risk of lifetime costs of the nuclear-generated electricity industry the state-owned Nuclear Electric received 95% of the funds (roughly £1.2bn per annum) gathered from the NFFO levy on electricity bills. In fairness, most of these costs were needed to run those reactors that were a legacy from Britain's first forays into nuclear development in the 1950s and 60s. The private sector, however, was tasked with a commitment to build four new nuclear plants, but was unwilling to take on even that commercially risky venture.9 In the end, Nuclear Electric oversaw the building of just one new LWR station, Sizewell B, at a cost of £3 billion.

Once Sizewell B opened in 1995, the government felt more confident in the reliability of this new plant together with a collection of older plants,** and embarked on finally privatising the nuclear sector with the formation of British Energy. This new company floated on the stock exchange for £1.7 billion, around half of the cost it took to build Sizewell B, but by 2002 British Energy had collapsed in the face of low electricity wholesale prices (meaning lower revenue streams) that could not compensate for the operating costs of running its fleet.[9] The government stepped in with an aid package that was estimated by the European Commission would total more than £10 billion in cash payments.[27] A later UK government review estimated that the taxpayer, at a minimum, had assumed a liability of £5.3 billion (in 2006 prices).[28]

The first of the new Gen III+ reactors to be introduced to the UK is planned to be Hinkley C, using the same European Pressurized Reactor (EPR) design so bogged down at Flamanville and Olkiluoto. Two EPRs are being built in China as well, although increasing costs of the Gen III+ designs have also raised concerns in China because the lead times are still significant, during which time capital costs keep rising. Construction on China's first EPR began at Taishan in 2009 with an operation date originally set for 2013, but the operational date for the Taishan-1 is now delayed until June 2015.[29]

In the UK, even more uncertainty has surrounded the eventual cost of construction for Hinkley C, with the original budget of £5.6bn in 2008 having ballooned to £18bn. After much wrangling with EDF Energy (the British subsidary of ÉDF) the UK government has offered a 'strike price' of 9.3 p/kWh under the new Contracts for Difference scheme, similar to onshore wind's 9.5 p/kWh but with several important differences (see chapter 3). EDF Energy's strike price will increase with inflation, the government is committing to a 35 year contract for the CfD – renewables are only offered 15 years – and £10bn of Hinkley's construction costs have been underwritten with a government loan guarantee.[64] The longer duration of the CfD reflects the longer payment periods for nuclear, but will expose consumers to greater price uncertainty as the wholesale price of electricity is likely to change substantially over this longer period. Under the current CfD system falls in the price of wholesale electricity are offset by top-up payments, paid for by the government. It is estimated that future top-up payments through the HPC CfD have increased from £6.1bn to £29.7bn since the strike price was agreed in 2013.[64] The government has also committed to a £2bn debt guarantee for Hinkley Point C. If this guarantee is ever called on, it could lead to taxpayer losses.[64]

None of these conditions have been extended to renewables, and onshore wind's strike price will fall to 7.9–8.3p/kWh by 2017. In addition, onshore wind generators must submit competitive bids as part of the process of their CfD allocation.[30] This appears to be in complete contradiction to the government's stated aims in 2011's EMR White paper, which said, 'New nuclear stations should receive no public support unless similar support is available to other low-carbon technologies.'[31] Energy consumers will also bear a larger burden, because the cost of generation from nuclear is likely to continue to rise, and this will be the case in both the UK

**These were the advanced gas-cooled reactors built over the 1960s and 70s. The older Magnox plants (so called because of the alloy used for cladding the uranium fuel rods) were deemed unsaleable and were not included in British Energy's portfolio.

and more experienced markets like France.[12,23] Given typical cost escalations, project overruns and historical capacity factors, it is likely that the cost of nuclear power in the UK will be at least 10 p/kWh but may well exceed even 16 p/kWh, which is higher than the current rate for offshore wind's strike price of 15.5 p/kWh, generally considered to be the most expensive option for renewable energy that is commercially viable.[12] When details of the strike price for Hinkley C initially emerged, there was some criticism that a strike price of 9.25 p/kWh[64] was far too high, allowing EDF Energy to make windfall profits in comparison to cheaper energy generated by other European operators. What seems more likely is that the UK government has actually come closer to the true cost of nuclear expansion.[23]

The hidden financial burden of decommissioning also inhibits investment, involving yet more uncertainty over the fate of spent fuel (see Radioactive Waste below) and the looming spectre of non-operational assets having to be managed for generations.[††] Partly as a result of liabilities incurred by the bankruptcy of British Energy,[28] the 2008 Energy Act mandates operators of nuclear plants to assume liability for clean-up costs through a decommissioning programme that must be fully funded, making it illegal to run a nuclear facility without a government-approved programme in place.[24] The core structure of a nuclear plant becomes increasingly radioactive over its life, and decommissioning costs for a reactor site can be of the same order of magnitude as construction estimates. These costs are considerable, and continue to go up – the Nuclear Decommissioning Authority (NDA) estimated the liability at £73bn in 2007, representing an average increase of 9% every year since government estimates in 2002.[25] Since then the cost has continued to increase with the total estimated at £117bn as of 2016.[32]

In the UK, nuclear operators are required to have insurance to meet claims in the event of an accident. In the case of Hinkley Point C this insurance only covers the first €1.2bn of cost; the UK government (and consequently tax payers) will meet any extra costs over this amount, should they arise.[64] Although there is some merit in the idea that the UK nuclear industry as a whole can make a profit through spin-off technologies involved with commissioning and decommissioning, this contribution is small in comparison with the public cost to manage the legacy of existing UK plant.[33]

It is accepted economic practice to appraise future liabilities of a development by taking the total cash sum needed to pay for the liability and discounting it over the project's lifetime, so expressing it in terms of the amount that should be invested in today's prices so that it earns interest until it is needed – this is the discounted value. This is an intuitive and sensible approach for owners of expensive plants, who must gauge future costs to them and their creditors over several decades. By discounting, the cost to operators of a nuclear facility for decommissioning are minor, making up roughly 2-4% of the cost of generation when set against the facility's entire lifetime.[12,23] However, the periods that apply when considering decommissioning liabilities are in the order of a 100 years from the time the project starts. For instance, the UK's existing nuclear legacy will last into the 22nd century.[32] In this light, one might question the usual assumptions of discounting.

The nuclear industry has a notoriously poor record on cost estimates for upfront processes like construction, but it is being asked to accurately forecast, a century in advance, the cost of back-end processes that have not yet been widely achieved commercially, such as dismantling and cleaning of nuclear sites. In the case of spent fuel disposal, the process has not even begun. The investments must also have a negligible risk of failure at the required rate of interest, something that the recent financial crisis should remind us is certainly not assured. If there is a significant shortfall in funds by the time decommissioning is necessary, future generations will have no choice but to undertake cleaning up and fuel disposal using public resources – there is no option to 'default' on this kind of liability.

One might ask why a 50 year-old energy industry still requires so much public financial backing, even seeing costs go up in a 'negative learning' process as the complexity of nuclear systems increases.[6] It could well be that the inherent properties of nuclear power, being large-scale, inflexible and requiring formidable levels of engineering excellence in construction and operation to ensure safety and efficiency, means that it will remain a hugely expensive and commercially risky venture. In the past, governments could simply dictate energy policy and leave it to nationalised utilities to hash out the details. Nationalised companies could borrow cheaply on government terms and absorb significant losses, confident that costs could ultimately be recovered from the taxpaying consumers beholden to their retail monopolies.[14]

Given the enormous technological and financial resources required, the capital-intensive start-up costs of nuclear power plants and the lengthy lead times before shareholders begin to see returns, it is difficult to see how a genuinely private UK nuclear sector can function in today's liberalised electricity market. This will have a major impact on the UK's attempts to effectively transition to renewable energy sources, because nuclear

---

[††] As part of its £10 billion valuation for the aid package given to British Energy (see p.xx above), the European Commission acknowledged the huge uncertainties of their final cost estimate due to the extremely long time periods involved. The Commission's report stated that British Energy, 'Would not expect to begin dismantling an AGR until at least 85 years after a station has ceased generating, while spent fuel management must continue indefinitely.'

will continue to devour a disproportionate share of financial and political resources at the expense of more viable options in terms of energy efficiency and developing renewables further.[9]

The level of subsidy received by renewables is often criticised (see chapter 3), but the need for subsidies is not unprecedented when one considers that renewable energy technologies are in their infancy compared to nuclear, and that, in its nascent years, nuclear power received enormous subsidies (principally thanks to the weapons potential that came from it.[34]) Since the 1950s, nuclear power has received the bulk of national research and development (R&D) budgets in energy technology. From 1974 to 1992, nuclear received more than 50% of public R&D spending on low-carbon technology in mainly OECD nations; by 2012 that share had fallen to around 30%.[35,36] Although energy research's share of government R&D spending in the OECD nations has fallen from 12% to 4% since the 1980s, nuclear has remained the single largest beneficiary during that time.[35]

Whilst it is difficult to make detailed evaluations of the specific outcomes and returns from energy R&D, studies have shown positive results. For example, the European Union has estimated an internal rate of return of 15% from the period 2010 to 2030 for its R&D investments in its Strategic Energy Technology Plan,[35] although the evidence above suggests this is unlikely to come in the form of cheaper nuclear power.[6] In the United States, the Department of Energy found that its investments between 1978 and 2000, amounting to $17.5bn (in 2012 prices) provided a yield of $41bn; however, this was primarily R&D investments for energy efficiency and fossil energy.[35]

Finally, the 'full' cost of nuclear electricity may be impossible to determine unless the nuclear industry is made to work with full indemnity insurance.[37] Existing and future generations will be saddled with the negative impacts should a nuclear accident occur, but the nuclear industry is able to waive the cost of full-liability insurance cover for critical accidents as such risks are not commercially insurable according to European international treaty.

The only real comprehensive insurance mechanism comes from the Price–Anderson Nuclear Industries Indemnity Act in the USA. Price–Anderson means US operators are paying roughly US$700,000 in annual premiums per reactor, and the insurance pool would cover up to $13bn for any single accident.[23] Thankfully, the largest accident in the USA to date was Three Mile Island in 1979, which resulted in no fatalities and financial impacts to the public were easily covered by the fund. Economically speaking, though, one is reminded of the words of a former commissioner for the Nuclear Regulatory Commission:

> *'The abiding lesson that Three Mile Island taught Wall Street was that a group of NRC-licensed reactor operators, as good as any others, could turn a $2bn asset into a $1bn cleanup job in about 90 minutes.' (Peter Bradford, quoted by Matthew Wald in the New York Times, 2 May 2005.)*

The estimated cost, according to the Japanese Government, of the Fukushima clean-up operation, however, will cost an estimated £142bn over several decades, far exceeding the $13bn provision made under Price–Anderson, which is considered to be by far the most generous payout.[38] Indeed, in Europe, damage cover only extends to €1.4bn (roughly $1.8bn), half of which is met by the operator's insurance and the remainder matched by the relevant government.[23] Japan's laws governing the nuclear industry require operators secure ¥120bn (roughly $1.2bn) in liability coverage. Governments, which means ultimately society's tax money, have to find the resources to make up any shortfall. As discussed above in relation to financing nuclear power, the public has no choice to not pay. This amounts to an implicit subsidy that has given nuclear a substantial economic advantage in avoided costs, and it is unlikely to be removed if nuclear is to remain a central plank of government policy.[37,39]

Safety of nuclear power

As explained above, one reason for the escalating cost of nuclear facilities is the stringent safety requirements.[1] Nuclear power is an unforgiving technology because an accident may result in catastrophic effects that can affect populations and ecosystems over a wide area. In essence, climate change can be argued to have the same widespread impacts as a severe nuclear accident – if not more so – and this has become one central arguments that is driving policies in favour of expanding nuclear power, since nuclear power can provide security to society through its ability to generate low-carbon electricity (although see Environmental Impacts above).[15] Indeed, a recent study suggested that the long-running operation of nuclear power plants over several generations in many industrialised countries has enormously reduced the level of avoidable deaths that would have been caused if coal had been used in its place, since nuclear electricity has mitigated a significant amount of airborne pollutants that would otherwise have been emitted by coal-fired electricity.[40]

Nuclear accidents, like all industrial accidents, are typically caused by human error, either lapses in awareness or miscalculations.[41] In light of this, and following several accidents in the 1950s and 60s, nuclear plant designs over the last 40 years have applied principles of reliability, redundancy and separation of safety systems from the plant process systems.[42] This 'defence-in-depth' is the cornerstone of modern nuclear plant design. However, the fact that nuclear power has developed, through hard-won and sometimes tragic experience, the ethos of making it 'fail safely' underscores the inherent dangers of the technology. This inherent danger and the probabilistic nature of the risk[§§] is a feature common to all industry, but few expose the public to the same level of hazard should systems catastrophically fail. The nuclear industry operates under impressively exacting safety standards, but in many cases safety principles are based on idealised situations and do not take into account the randomness of real events and human fallibility.[7]

Despite high-profile incidents in the past, the nuclear industry safety record is in fact very good, with a worldwide fatality rate expressed as 0.007 deaths per gigawatt of electricity per year (0.007 deaths/GWey) due to accidents – a statistic that is markedly better than coal (5.92; although 90% of this is due to China), oil (0.95) and natural gas (0.12).[43] Even with attributed deaths from Chernobyl, the figure for nuclear is just 0.03 deaths/GWey, although the total number of fatalities that will eventually result from Chernobyl is subject to some debate. Wind power, between 1975 and 2012, has 80 reported fatalities, many of which occurred in the early days of small kilowatt-scale turbines and were due to owners or maintenance staff failing to follow precautions, such as not using fall protection gear or working on turbines that were rotating at the time; one incident was a suicide.

As the wind industry rapidly expanded and began deploying many more megawatt-scale turbines, the rate of fatalities per unit of electricity has declined by three orders of magnitude since the 1980s and now stands are around 0.00003 fatalities per gigawatt-hour.[44] Based on data for the UK and Germany (countries with some of the largest uses of offshore and onshore wind, respectively) the fatality rate for wind is around 0.005 deaths/GWey, although offshore (0.009) is notably more dangerous than onshore (0.002).[43]

It is clear that in terms of fatality risk, both nuclear and wind far outperform fossil fuel electricity generation. Although the risk of fatal accidents is not negligible for wind, its decentralised nature and lack of inherent hazards in the form of dangerous radionuclides strongly limits its catastrophic potential should a major incident occur. A failure of nuclear reactor core containment can have severe consequences in terms of fatalities, many thousands of times greater than wind.[43] The attribution of deaths due to 'latent mortality' with regards to the Chernobyl disaster remains a contentious issue. Most epidemiological studies have focused on thyroid cancer and leukaemia, because the radioisotopes iodine-133 (133I), caesium-134 and caesium-137 (134Cs, 137Cs) were released in large quantities from the reactor core and contributed the most to the dose that surrounding regions were exposed to.[45]

In fact, there is little evidence of leukaemia cases being directly attributable to the Chernobyl disaster, but data for the incidence of thyroid cancer (note: incidence is the number of cases, not the number that result in death) suggest that the radiation leak was responsible for around 4000 cases by 2005, and it is estimated this will rise to 16,000 cases across Europe by 2065.[46] When one considers the additional incident cancers (other than of the thyroid) may be roughly 25,000 over the same period, the figures make for sobering reading. It is important to note, however, that across that same period the population of Europe is expected to suffer from hundreds of millions of cases of cancer from all causes. Indeed, it would be difficult for a normal epidemiological study to register this elevated incidence of cancer against such a large incident background,[46] which underlines the imprecision inherent in trying to account for the true cost of such an event.

The relationship between received dose and disease incidence is complex, and the dose regime that populations surrounding Chernobyl were exposed to is still not known in adequate detail.[47] It is safe to say that some of the more outlandish claims of hundreds of thousands of deaths can be ignored.[45] But each one of those cancer cases from the many thousands that are attributable to Chernobyl, even though a very small fraction of the number of cases expected to occur in the normal course of events, represents a desperate, and sometimes fatal, tragedy for those involved. Even 50 years after the atomic bombing of Japan in the Second World War, data were still being revised in the face of unexpected health detriments to exposed victims, and less than 30 years has passed since Chernobyl.[47]

In the public's opinion, due to the potentially catastrophic nature of a nuclear accident, the nuclear industry (and government) has failed to show that it operates under a reasonable level of safety given the hazards involved. This remains a major factor preventing the acceptance of nuclear-generated electricity as a valid source of low-carbon energy. Communities are questioning the viability of nuclear with regards to what constitutes a 'normal accident' and whether society should embrace the inherent risks in nuclear. Arguably, society has made the same decision before with regards to fossil fuel energy, which clearly comes with significant risks.[8] This doubt is not surprising: the disaster at Fukushima Daiichi caused by the tsunami of 11 March,

---

[§§] That is to say, there may be great uncertainty surrounding the calculation of the exact risk, but that there is risk is evident. It is well known that most people have a limited understanding of risk and how to make decisions accordingly – in particular, we tend to be less concerned over low-probability risks, but, when they eventually occur, we tend to overestimate their likelihood and impact.

2011, was the result of a natural hazard that was supposedly beyond what designers had envisioned, even though the threat seismic activity poses to nuclear facilities is well known.[7] The tsunami completely overwhelmed a sophisticated, multi-layered safety system and left the nation's nuclear industry improvising its response on an hour-by-hour basis. The Fukushima emergency shows that even the most considered 'belt-and-braces' safety system can be undermined by a combination of extreme natural events and human oversight.[***] The effects of the massive radioactive leak as a result of three reactor core meltdowns will be felt for decades to come.[38] Although the amount of radionuclides from Fukushima released to the surrounding area was much lower than what occurred at Chernobyl (it helped that the majority of the material went out to sea), the likely number of excess cancer deaths will be in the region of 500–1000. That this is a relatively low number is in large part thanks to the prompt preventive action taken by Japanese authorities.[48]

There will also be long-term detriments to surrounding environments; effects are already being seen on local species in the 30 km exclusion zone around Fukushima.[49] These results echo what has been found at Chernobyl, where species viability has been compromised by decades of exposure to longer-lived radionuclides.[49,50] Furthermore, field-based ecological assessments have challenged the dose thresholds derived for radioactive elements, with doses received by organisms in the field seemingly having a greater effect than predicted by laboratory models.[51] This ecological data further underscores the uncertainty surrounding the full long-term effects that will result due to chronic exposure of populations to radionuclides accidentally released to the environment.

In the UK, despite promises that things are now much safer, as recently as 2005 the Thermal Oxide Reprocessing Plant (THORP) plant at Sellafield was found to have leaked 83,000 litres of liquid containing 22 tonnes of uranium fuel into a sump for a period of eight months before being discovered; the leak only came to light at the plant because the follow up accountancy system noticed there was missing nuclear material. The contents did not escape into the environment since they were caught in the secondary containment tank, but the inspector's report made it clear that the plant operated under an 'alarm-tolerant culture', at one point stating:

> *'The HSE investigation team found that there were significant operational problems with the management of a vast number of alarms in THORP, resulting in important alarms being missed.' (See ref.10: M. Weightman, HSE report, 2007, 13, para 67.)*

In the USA, the Government Accountability Office (GAO) issues regular reports on the country's Nuclear Regulatory Commission (NRC). A review of plant performance from 2001 to 2005 noted 98 incidences of a plant's failure to comply with NRC regulations and industry standards such that it had an effect on overall plant safety (out of more than 4000 incidences).[52] It should be stressed that most of these 98 cases were of low-to-moderate risk, but 12 were deemed to be significant. In all, 75% of the US's operating nuclear plants were placed on additional oversight by the NRC in that five-year period due to data reported for individual indicators that were outside of NRC's acceptable performance category. Whilst only a fraction of a percent of all data reported (30,000 reports in total) this still represents more than 150 incidences.

In Europe, the delays with the Olkiluoto plant are also caused primarily by safety concerns of the Finnish regulatory authority (STUK), although there was also some public disquiet among independent parties over why it took STUK so long to discover non-compliant components.[53] Other designs for new Gen III+ reactors also have lingering safety concerns (and no operational experience, since none have been finished).[1] This has led to delays over construction in China at Sanmen (a different site to Taishan and incorporating a different reactor); although construction is proceeding much more smoothly than European projects, Sanmen-1 is still not in operation more than three years after its scheduled start date of August 2013.[†††] It is expected to be in commercial operation by the end of 2017.[65]

The same reactor design, the AP1000, is awaiting approval from the UK's Office for Nuclear Regulation (ONR). In 2011 the ONR issued a report listing 51 issues with the design that must be resolved before the AP1000 can be approved for use in the UK.[54] No resolution has been pursued since, although NuGeneration (owned by Toshiba, the parent company that owns the AP1000 design) is planning to build three AP1000 reactors next to the existing Sellafield site. The ONR states that, 'The 51 issues requiring resolution span 13 of the GDA assessment areas, and are technically challenging. Therefore we expect the completion of GDA for the AP1000 reactor design to take a number of years.'[55]

It is commendable that the nuclear industry acknowledges that it should operate with exceedingly high safety standards, but the desirability of relying on a source of power that must 'fail safely' or else risk dire consequences should surely be questioned. From an economic point of view, if nothing else, the inherent risk means that a large, capital-intense facility like a nuclear

---

[***] Questions were raised during the aftermath of the crisis when the operator admitted to multiple inspection failures just weeks before the disaster (see Tabuchi, Onishi and Belson, New York Times, 21 March, 2011; A1, A6).

[†††] See 'First concrete at Sanmen,' World Nuclear News, 20 Apr, 2009, www.world-nuclear-news.org/NN_First_concrete_at_Sanmen_2004091.html

plant, on the very small chance that they do fail, will fail spectacularly, and will require enormous amounts of time, money and resources to repair.[8]

Radioactive waste

The problem of radioactive waste impinges on both human safety and the environment and represents a major technological challenge.[11] Nuclear waste from nuclear power plants is in the form of spent nuclear fuel or what remains after that spent nuclear fuel is reprocessed. Spent fuel can be reprocessed by converting it to a mixed-oxide fuel (MOX) that is a mixture of uranium and plutonium oxides. Reprocessing spent fuel to MOX is carried in the UK at the THORP facility (although no operating UK reactor uses it) and reprocessing and MOX usage is a central feature contributing to the efficiency of France's nuclear fleet.[56,57] It can increase energy recovery of the original fuel by up to 30%, reducing the demand for natural uranium in fresh fuel.[20] Mixing plutonium fissile material with uranium to produce MOX for subsequent re-use in a reactor is also a useful way to reduce stockpiles of weapons-grade plutonium, something that is carefully balanced in the French system so that no spare inventory remains (in the civil programme at least – France does possess a nuclear arsenal).[57] By contrast, the UK possesses the largest stockpile of plutonium in the world, partly because the UK reprocessed spent fuel on behalf of other nations, but to a large extent because of decisions taken in the early days of Britain's nuclear programme to stockpile it for weapons use and for a potential future fleet of fast-breeder reactors that subsequently never got off the ground.[58]

The spent nuclear fuel and waste streams from reprocessed spent fuel are known as high-level waste (HLW) and are highly radioactive.[42] The main radioactive content in HLW is from spent nuclear fuel (>99%)[11] that contains a mixture of fission products, mainly caesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) both have a half-life ($t_{½}$) of roughly 30 years. Various decay products of fissile material in the fuel give rise to longer-lived products, such as americium-241 (^{241}Am, $t_{½}$ of 430 years), americium-243 (^{243}Am, $t_{½}$ of 7,400 years), plutonium-239 (^{239}Pu, $t_{½}$ of 24,000 years) and technetium-99 (^{99}Tc, $t_{½}$ of 213,000 years). Those listed here are some of the most problematic due to their radioactivity and movement through biological and geological systems, but it is by no means a comprehensive list. In reactor core meltdowns the most important radioisotopes are those that are most volatile and easily dispersed into the environment and have a short t½ so radiological exposure is particularly acute. In Fukushima, the main radioisotopes included 131I, 137Cs and xenon-133 (^{133}Xe).[38] Note most of the products listed above in HLW move more slowly through environments and are not as easily dispersed.

The problem inherent with fissile products in spent nuclear fuel is that the HLW produced has a very lengthy radiological toxicity and so must be isolated and contained for a sufficient period such that it no longer poses a threat to human health and the environment if exposed.[11] In fact, the majority of radioactive waste from a nuclear plant is low-level or intermediate-level waste and can be safely stored for several decades to allow any contaminants to decay, after which point it can be disposed of reasonably safely.[42] The remaining HLW is more problematic, since short-term storage is a troublesome issue itself. For instance, the UK's Nuclear Decommissioning Authority is finding that many of the decommissioned sites around the country contain a mixture of toxic and radioactive materials that generate a great deal of heat and require careful handling and storage to minimise the danger (a costly and hazardous exercise).[25]

The UK's high-level waste is predicted to be 478,000 m^3 by the 22nd century (equivalent to filling the Albert Hall five times over).[59] This waste is highly toxic and must be made safe: it is generally solidified in borosilicate glass, a process called 'vitrification' that is mainly carried out at Sellafield.[25] The government has agreed to take on liability for disposing spent fuel and intermediate level waste from Hinkley Point C.[64] What to do with this waste after that is still moot, and one that government and the industry have not been able to resolve completely. Spent nuclear fuel in storage at nuclear facilities, not to mention the plutonium stockpile, also represent a considerable hazard in the event of a malicious attack designed to release large amounts of radioactive material into the surrounding area.[58] The French authorities admitted to a recent spate of drones flying over several nuclear facilities on October 2014, with no clues as to who is operating the aircraft.[‡‡‡]

The preferred recommendation of the UK government is for a geological repository, and this has been reiterated by the Committee on Radioactive Waste Management (CoRWM) as the best available approach when compared to the risks of other management schemes.[60] As they have done previously, CoRWM has taken pains to point out that the position adopted on the issue is presented to the public in terms that are too simplistic and optimistic, and have cautioned that the uncertainties over geological screening at the depths associated with a nuclear repository should not be underplayed when dealing with communities.[60] The only area in England to date (the Scottish Parliament has ruled out a geological repository) that had progressed to site assessment stage was west Cumbria, but a local

---

[‡‡‡] See A. Neslen, 'Three arrests fail to staunch mystery of drones flying over French nuclear plants,' Guardian, 6 Nov, 2014, www.theguardian.com/environment/2014/nov/06/arrests-myster-drones-flying-french-nuclear-plants

county council voted to stop the process in January 2013, ending a three-year consultation process. No other regional authority has expressed an interest in hosting a repository.[61]

After two decades of extensive research by various countries, only two identified sites have been able to progress, one in Finland (at Olkiluoto) and the other in Sweden (Forsmark).[11] The most well known case study, that of the Yucca Mountain repository in the USA, suffered a setback in 2011 when the Department of Energy (DOE) and the NRC withdrew from the licensing process following many years of public opposition from Nevada residents. The Yucca Mountain site was considered one of the most comprehensive evaluations performed for a geological repository, and the withdrawal decision by the government agencies caused a great deal of recrimination. Because of the large amounts of nuclear waste accumulating at American nuclear facilities, many operators are in the process of suing the federal government for the closure of the Yucca licensing process, since there is now no agency to take this decades' worth of waste from them and it must still be managed. These legal actions are likely to cost the American taxpayer tens of billions of dollars over the coming decades.[62] It appears material hazards and financial burdens continue to define nuclear power.

Conclusions

Nuclear electricity offers significant reductions in greenhouse gas emissions in comparison to fossil fuels, with savings almost comparable to many renewable sources of energy. Given the long-term effects of elevated CO^2 levels in the atmosphere and the continuing environmental detriments created by fossil fuel extraction and combustion, there is a pressing need to decarbonise the energy sector. In terms of modern low-carbon generation technolgies, nuclear power has been established the longest, with a record of producing electricity stretching back to the mid-1950s. Indeed, a recent study suggests that the long-running operation of nuclear power plants over several generations in many industrialised countries has enormously reduced the level of avoidable deaths that would have been caused if coal had been used in its place.

Considering this, expanding nuclear power would seem poised to play an important role in the future of low-carbon energy and climate change mitigation, and comparisons are often drawn suggesting that wind power is not needed as nuclear power could be expanded to serve the same needs. But investment in nuclear energy represents an enormous commitment, with any meaningful expansion of the UK's nuclear capacity likely to come from the public purse. The benefits of such a policy are by no means clear, but what is certain is that the legacy of such a policy would place a financial and environmental burden on future generations that is difficult to predict. Nuclear power's operating characteristics will also tie the UK to the old-style model of a heavily centralised power system that makes it far more difficult to integrate renewable sources of electricity, because baseload nuclear power cannot adapt to the operational demands of a grid that contains a significant proportion of generators relying on wind and solar. Nuclear only contributes to the electricity energy needs of the UK – it cannot meet the demand for transport or heating which are dominated by fossil fuels. The UK's electricity production consumes roughly one-third of the nation's primary energy supply, mostly in the form of fossil fuels (about 75%).[§§§] At most, this is a theoretical maximum of 27% of the UK's total fossil fuel demand that can be replaced. Much the same can be argued for wind power (and other renewables), but wind does not have the same safety and environmental problems, and can be removed more cheaply and quickly if a better solution presents itself.

The salutary lesson to be taken from nuclear's difficult first 60 years is that cleaner, low-carbon generation is key to improving societal well-being, and an ideal solution would be if this can be achieved by combining energy efficiency with sustainable sources of energy that do not give rise to the myriad safety concerns that nuclear does. Evidence suggests that any benefits accrued from low-carbon nuclear electricity comes at a considerable financial cost, and the trend of the last five decades is that these costs will continue to go up, not down. In contrast, support for burgeoning wind and solar industries has seen prices tumble, whilst nuclear has been blighted by safety issues, unfortunate accidents and financial uncertainty.

Even the new generation of reactors have failed to prove themselves financially viable, although they do display an impressive range of safety features that the industry hopes will signal that nuclear power is finally 'turning the corner'. Unfortunately, the history of the current generation of reactors, most recently the disaster at Fukushima, has shown that it may be impossible to adequately design for events beyond the realm of regular expectations. Though the risk of failure itself may be very slim, nuclear remains a technology with considerable catastrophic potential. Whilst modern energy systems do provide a bounty of benefits, energy accidents degrade human health and welfare, and destroy natural environments. The effects are particularly far-reaching when one examines the whole energy supply chain of fossil fuels and also the long legacy of nuclear power.

[§§§] I. MacLeay and A. Annut, 2013, 'Chapter 1 – Energy,' Digest of United Kingdom Energy Statistics 2013, (London: The Stationery Office/TSO), 11–40.

Clearly, every benefit yielded comes at a cost. This is inescapable given how integrated energy infrastructure is in modern society. If society wishes to maintain its current level of energy consumption and continue to rely on conventional, large, centralised power systems running on fossil fuels and nuclear then it will have to embrace these risks to a certain extent. But if society is to transition successfully to a low-carbon future, the options must be assessed in terms of their desirability to society instead of from a reductionist and technocratic perspective. Nuclear power certainly delivers an abundance of low-carbon electricity at present, but its ability to sustain this over the next century is questionable if its global capacity is to expand sufficiently to make a meaningful impact on carbon emissions. Meanwhile, its ability to deliver electricity cheaply appears to be receding ever further, and it is difficult to see how imposing large amounts of inflexible baseload power will contribute to the diversified renewable energy sector the UK is trying to achieve. Coupled with the inherent risks arising from the complex and unforgiving nature of the technology, the better option would seem to be investing resources in alternatives. In the words of one commentator:

> *'While nuclear power is still a looming presence in our energy policy, it will continue to consume a grossly disproportionate share of the resources and political attention. How else can the dismal quality of the UK housing stock and the poor rate of exploitation of the UK's enviable renewable resources be explained?' S. Thomas, Energy Policy, 2010, vol.38, 4908.*

The industry in the UK has not shown that it has learnt from mistakes of the past, and seems poorly placed to compete in the privatised electricity market of today. The flexible, modular approach that wind power and other renewables offer means that technology and policy can be fine-tuned or redirected as the situation requires, without entrenching UK energy sector in a costly and potentially risky enterprise that would draw on resources for years to come and saddle future generations with intractable problems they did not ask for. Time is running out before CO_2 levels in the atmosphere reach a limit that will make it difficult to recover from, but this threat should not be tackled by exchanging one hazard for another.

References

1. Kessides IN. The future of the nuclear industry reconsidered: Risks, uncertainties, and continued promise. Energy Policy. 2012; 48:185–208.
2. O'Connor M, van den Hove S. Prospects for public participation on nuclear risks and policy options: innovations in governance practices for sustainable development in the European Union. J Hazard Mater. 2001; 86(1):77–99.
3. WNA. Energy for the World – Why Uranium? [Online]. London: World Nuclear Association; c.2014 [last updated Dec 2012]. Available at: www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Energy-for-the-World---Why-Uranium-/ [last accessed 29 Oct 2014].
4. Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sustain Energy Rev. 2013; 28:555–65.
5. Sovacool BK. Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy. 2008; 36(8):2950–63.
6. Grubler A. The costs of the French nuclear scale-up: A case of negative learning by doing. Energy Policy. 2010; 38(9):5174–88.
7. Möller N, Wikman-Svahn P. Black elephants and black swans of nuclear safety. Ethics Policy Environ. 2011; 14(3):273–8.
8. Sovacool BK. The costs of failure: A preliminary assessment of major energy accidents, 1907–2007. Energy Policy. 2008; 36(5):1802–20.
9. Thomas S. Competitive energy markets and nuclear power: Can we have both, do we want either? Energy Policy. 2010; 38(9):4903–8.
10. Weightman, M. Report of the investigation into the leak of dissolver product liquor at the Thermal Oxide Reprocessing Plant (THORP), Sellafield, notified to HSE on 20 April 2005. Report by HM Chief Inspector of Nuclear Installations (M.W.). Health and Safety Executive; Feb 2007. 28 p.
11. Birkholzer J, Houseworth J, Tsang C-F. Geologic disposal of high-level radioactive waste: status, key issues, and trends. Annu Rev Environ Resour. 2012; 37(1):79–106.
12. Harris G, Heptonstall P, Gross R, Handley D. Cost estimates for nuclear power in the UK. Energy Policy. 2013; 62:431–42.
13. Badcock J, Lenzen M. Subsidies for electricity-generating technologies: A review. Energy Policy. 2010; 38(9):5038–47.
14. Toke D. Climate change and the nuclear securitisation of UK energy policy. Environ Politics. 2013; 22(4):553–70.
15. Toke D, Vezirgiannidou S-E. The relationship between climate change and energy security: key issues and conclusions. Environ Politics. 2013; 22(4):537–52.
16. Nugent D, Sovacool BK. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy. 2014; 65:229–44.
17. Warner ES, Heath GA. Life cycle greenhouse gas emissions of nuclear electricity generation: systematic review and harmonization. J Ind Ecol. 2012; 16(Suppl 1):S73–S92.
18. Dolan SL, Heath GA. Life cycle greenhouse gas emissions of utility-scale wind power: systematic review and harmonization. J Ind Ecol. 2012; 16(Suppl 1):S136–S154.
19. Mudd GM, Diesendorf M. Sustainability of uranium mining and milling: Toward quantifying resources and eco-efficiency. Environ Sci Technol. 2008; 42(7):2624–30.
20. Englert M, Krall L, Ewing RC. Is nuclear fission a sustainable source of energy? MRS Bull. 2012; 37(04):417–24.
21. Lenzen M. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. Energy Convers Manag. 2008; 49(8):2178–99.
22. RTÉ. Generation adequacy report on the electricity supply–demand balance in France: Update 2010. Paris-La Défense: Réseau de Transport d Électricité; Jul 2010. Available from: www.rte-france.com (last accessed 17 Dec 2010).
23. Boccard N. The cost of nuclear electricity: France after Fukushima. Energy Policy. 2014; 66:450–61.
24. IEA. Energy Policies of IEA Countries: United Kingdom 2012 Review. Paris: International Energy Agency/Organisation for Economic Co-operation and Development; 2012. 180 p.
25. National Audit Office. Taking forward decommissioning: the Nuclear Decommissioning Authority. HC 238 2007-2008. London: The Stationery Office/TSO; 2008. 53 p.

26. Mitchell C. The England and Wales non-fossil fuel obligation: history and lessons. Ann Rev Energy Environ. 2000; 25(1):285–312.
27. European Commission. Commission decision of 22 September 2004 on the State aid which the United Kingdom is planning to implement for British Energy plc. (2005/407/EC). OJ. 06.06.2005; L142: 26–80.
28. House of Commons, Committee of Public Accounts. The Restructuring of British Energy: Forty–third Report of Session 2006–07. HC 892. London: The Stationery Office/TSO; 19 Jul 2007. 43 p.
29. World Nuclear News [Online] First Taishen EPR completes cold tests. [Last accessed: 24 Jan 2017] Available from: www.world-nuclear-news.org/NN-First-Taishan-EPR-completes-cold-tests-0102164.html
30. DECC. Contract for Difference: Final allocation framework for the October 2014 allocation round. URN 14D/328. London: Department of Energy & Climate Change; 1 Sep 2014. 56 p.
31. DECC. Planning our electric future: a White Paper for secure, affordable and low-carbon electricity. (Cm8099). London: The Stationery Office/TSO; Jul 2011. 8, para 10.
32. Nuclear Decomissioning Authority [online] Nuclear Provision: the cost of cleaning up Britain's historical nuclear sites. Updated 1 September 2016. [Last accessed: 24 January 2017] Available from: www.gov.uk/government/publications/nuclear-provision-explaining-the-cost-of-cleaning-up-britains-nuclear-legacy/nuclear-provision-explaining-the-cost-of-cleaning-up-britains-nuclear-legacy
33. Sherry AH, Howarth PJA, Kearns P, Waterman N. A review of the UK's nuclear R&D capability. Report prepared by the Dalton Nuclear Institute, National Nuclear Laboratory and Battelle. Swindon, UK: The Technology Strategy Board; 2009. 76 p.
34. Goldberg M. Federal energy subsidies: not all technologies are created equal. Report No. 11. Washington, DC: Renewable Energy Policy Project; Jul 2000. 18 p.
35. IEA. Policies to promote technology innovation. In: Energy Technology Perspectives 2012: Pathways to a clean energy system. Paris: International Energy Agency; 2012. 108–133.
36. IEA. Policies to accelerate a low-carbon technology transition. In: Energy Technology Perspectives 2010: Scenarios and strategies to 2050. Paris: International Energy Agency; 2010. 476.
37. Laes E, Meskens G, van der Sluijs JP. On the contribution of external cost calculations to energy system governance: The case of a potential large-scale nuclear accident. Energy Policy. 2011; 39(9):5664–73.
38. BBC [online] Japan Fukushima nuclear plant 'clean up costs double' Updated 28 November 2016 [Last accessed: 24 January 2017] Available from: www.bbc.co.uk/news/world-asia-38131248
39. Faure MG, Fiore K. An economic analysis of the nuclear liability subsidy. Pace Environ Law Rev. 2009; 26(2):419–77.
40. Kharecha PA, Hansen JE. Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. Environ Sci Technol. 2013; 47(9):4889–95.
41. Rasmussen J. Risk management in a dynamic society: a modelling problem. Saf Sci. 1997; 27(2–3):183–213.
42. OECD, NEA. Nuclear Energy Today. 2nd ed. Paris: OECD Publishing; Sep 2013. 123 p.
43. Burgherr P, Hirschberg S. Comparative risk assessment of severe accidents in the energy sector. Energy Policy. [In press] 2014; doi:10.1016/j.enpol.2014.01.035.
44. Gipe P. 'A Summary of Fatal Accidents in Wind Energy,' wind-works.org, Excel spreadsheet, www.wind-works.org/cms/fileadmin/user_upload/Files/DeathsDatabase.xls (last updated 7 Dec, 2012), accessed 11 Nov, 2014.
45. Smith JT, Beresford NA. Chernobyl: catastrophe and consequences. Chichester: Praxis Publishing Ltd (in association with Springer); 2005. 310 p.
46. Cardis E, Krewski D, Boniol M, et al. Estimates of the cancer burden in Europe from radioactive fallout from the Chernobyl accident. Int J Cancer. 2006; 119(6):1224–35.
47. Baverstock K, Williams D. The Chernobyl accident 20 years on: an assessment of the health consequences and the international response. Ciência & Saúde Coletiva. 2007; 12(3):689–98.
48. Evangeliou N, Balkanski Y, Cozic A, Møller AP. Global and local cancer risks after the Fukushima Nuclear Power Plant accident as seen from Chernobyl: A modeling study for radiocaesium (134Cs & 137Cs). Environ Int. 2014; 64:17–27.
49. Møller AP, Nishiumi I, Suzuki H, Ueda K, Mousseau TA. Differences in effects of radiation on abundance of animals in Fukushima and Chernobyl. Ecol Indic. 2013; 24:75–81.
50. Mousseau TA, Møller AP. Genetic and ecological studies of animals in Chernobyl and Fukushima. J Hered. 2014; 105(5):704–9.
51. Garnier-Laplace J, Geras'kin S, Della-Vedova C, et al. Are radiosensitivity data derived from natural field conditions consistent with data from controlled exposures? A case study of Chernobyl wildlife chronically exposed to low dose rates. J Environ Radioact. 2013; 121:12–21.
52. GAO. Nuclear Regulatory Commission: Oversight of Nuclear Power Plant Safety Has Improved, but Refinements Are Needed. GAO-06-1029. Washington, DC: US Government Accountability Office; Sep 2006. 79 p.
53. STUK. Management of safety requirements in subcontracting during the Olkiluoto 3 nuclear power plant construction phase. Investigation Report 1/06. Helsinki: Radiation and Nuclear Safety Authority; 10 Jul 2006. [translated 1 Sep 2006].
54. ONR. Summary of the detailed design assessment of the Westinghouse Electric Company LLC AP1000® nuclear reactor (Step 4 of the Generic Design Assessment process). ONR-GDA-SR-11-002. London: Office for Nuclear Regulation; Dec 2011. 85 p.
55. ONR. Generic Design Assessment: Progress report for the period January 2014 to March 2014. TRIM 2014/184570. London: Office for Nuclear Regulation; 2014. 5, para 33.
56. Stamford L, Azapagic A. Sustainability indicators for the assessment of nuclear power. Energy. 2011; 36(10):6037–57.
57. Poinssot C, Bourg S, Ouvrier N, et al. Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles. Energy. 2014; 69:199–211.
58. Beach H, Crossland I, Cowley R, Harris J, Watson C. Report of the Working Group on the Management of Separated Plutonium in the UK. London: British Pugwash; 2009. 60 p.
59. CoRWM. Managing our radioactive waste safely: CoRWM's recommendations to Government. CoRWM Doc 700. London: Committee on Radioactive Waste Management; Jul 2006. 192 p.
60. CoRWM. Tenth Annual Report 2013–14. CoRWM doc 3157. London: Committee on Radioactive Waste Management; Jul 2014. 78 p.
61. CoRWM. Ninth Annual Report 2012–13. CoRWM doc 3107. London: Committee on Radioactive Waste Management; Jun 2013. 55 p.
62. GAO. Spent Nuclear Fuel: Accumulating Quantities at Commercial Reactors Present Storage and Other Challenges. GAO-12-797. Washington, DC: US Government Accountability Office; Sep 2012. 66 p.
63. EDF Energy [Online] Hinkley Point C project cost. Updated May 12 2016. [Last accessed 24 January 2017] Available from: www.edfenergy.com/energy/nuclear-new-build-projects/hinkley-point-c/news-views/cost-clarification
64. National Audit Office [online]. Nuclear Power in the UK. 2016. [Last accessed 16 Jan 2017] Available from: www.nao.org.uk/wp-content/uploads/2016/07/Nuclear-power-in-the-UK.pdf
65. World Nuclear News [online] Integrated Head package in place at Sanmen. Updated 14 March 2016. [Last accessed 24 January 2017] Available from: http://www.world-nuclear-news.org/nn-integrated-head-package-in-place-at-sanmen-1-1403164.html

Chapter 8

Public acceptance and community engagement

Summary

Attitudes toward wind power are fundamentally different from attitudes toward wind farms, a divergence that has created what is sometimes called the 'social gap'. Despite the broad public support for renewable energy (wind included), the development of wind farm projects is often met with stiff opposition at a local level. Although some opposition is based on misconceptions about wind power in general, local resistance to wind farms is a complex interconnection between a position of acting 'for the greater good' and negativity toward what can be seen as an unwelcome imposition on the visual landscape to which residents have a strong emotional attachment.

The pejorative term 'nimby' (from 'not in my back yard') has regularly been levelled at residents when negative opinions about planned wind farms have been raised. This term is inaccurate, unfair and has no explanatory value, serving only to increase antagonism if it achieves anything at all. Understanding the issues involved, namely what lies behind the concerns and preconceptions of residents, is crucial if a community is to accept and even welcome the installation of a wind farm nearby.

What is this based on?

The UK government has committed itself to a long-term plan to restructure the nation's energy economy to be low-carbon, sustainable and more secure.[1] An unprecedented level of renewable energy introduced into the UK's energy infrastructure will have profound effects on the social and geographical matrix of the country, with direct effects on residents across many localities.[2] A key contributing factor to the relatively slow uptake of renewable energy in the UK has been the failure of projects to gain planning permission in a streamlined and timely manner.[1] Although wind has frequently been seen as the main focus of public opprobrium, projects in Europe and North America involving geothermal, tidal energy and biomass have also met with opposition.[3,4]

Even though public opinion is generally in favour of renewable energy, including wind power, local resistance to renewable energy projects is not uncommon, and this is reflected in the high proportion of failed planning applications for wind turbines across the UK.[3,5]

There is no simple explanation for this apparent contradiction between the high level of support for wind energy nationally and low approval rate for wind power projects locally, which has been described as the 'social gap'.[6] This phenomenon is rooted in the complex mix of views, values and emotions held by people within a community that relate to procedural justice, distributive fairness and a sense of place; and in the tensions that inevitably arise when national, long-term policies driven by central government come into conflict with the locally relevant objectives of affected residents.[7–9] Despite this, there is compelling evidence that most residents who come into contact with wind turbines on a regular basis do not find their presence objectionable.[10] Provided the benefits to both the community and wider society are properly explained and taken on board, most people display a surprisingly unselfish view of the need for such installations and close correlation is found between local community perspectives on wind farm developments and public support for clean energy as a whole.[5,7] It is a salient fact that renewable energy, of which wind power is the most prominent and familiar technology, is routinely viewed as desirable by the public, and is far more acceptable than nuclear power even when framed in terms of nuclear's low-carbon attributes.[11]

A hallmark of modern democratic society is the engagement of its citizens in all aspects of society planning, and the ethos of public participation has become the cornerstone of environmental planning in particular.[12] Ensuring a collaborative process throughout any renewable energy project is important to improve the quality and durability of any decision reached.[7,10,13] Engaging residents within an affected locality with any renewable energy project reaffirms the democratic process, allowing citizens to participate in decisions that affect them on a personal, community and society level.[14] It also fosters collective learning, increasing the awareness, acceptance and furthering the advocacy of renewable energy in both local and national settings.[2,13]

What is the evidence?

The need for public participation

Wind power is going to be instrumental in the UK achieving its renewable targets for 2020.[15] In the UK, however, deployment of renewable energy technologies, wind power especially, has never enjoyed the kind of widespread activism and grassroots support seen in other European countries.[3,16] In addition, forms of local ownership and municipal leadership that are common to many nations, particularly the Germanic and Scandinavian regions that lead the way in renewables deployment, have historically never played a part in national energy planning in the UK.[17,18] Recent policy changes by the UK government that have ended subsidies for onshore wind and solar photovoltaic (PV) power, introduced new planning requirements that require pre-allocated sites for wind development, and opened an ongoing consultation on reducing feed-in tariff rates for renewables, also present major obstacles.[19–22] These decisions have caused great consternation within environmental groups and the renewable energy industry,[23] with warnings that investor confidence in UK renewable technologies is 'being shattered.'[24]

One of the key factors identified as necessary for the UK to meet its renewable energy targets is the support of local communities; conversely, failure of renewable energy projects to achieve planning permission in a streamlined and timely manner is identified as one of the major obstacles.[3–5] The problem lies not just with objections to wind power, although the highly visible nature of wind turbines and its commercial readiness means wind power historically has generated most of the headlines and provided material for a great deal of academic research on the matter of public opposition.[9] Although there remains broad public support for renewable energy projects, uncertainty over viability, sustainability, procedural justice, provision of benefits, and local environmental impacts means that renewable energy projects are frequently opposed by local residents during planning and development.[2,25–27] It is important to note that, contrary to initial assumptions by the industry, renewable technologies located offshore are also subject to opposition by local communities.[8,28]

The long-term, diffuse and uncertain nature of climate change impacts can also play a role, where one group of stakeholders may perceive the risks and urgency of action to mitigate emissions differently from another group.[29] There is a danger that local resistance is dismissed as simply the public being unaware of the risks associated with climate change, but this is typically not true.[30] This can be thought of as a form of the 'information deficit' model, whereby public opposition to wind farms and similar developments is underpinned by ignorance of the 'real' or 'correct' facts.1[0,30] This model has long be considered deficient as a means of explaining social conflicts relating to scientific issues.[31] The fact that this model lives on in the ethos of many institutions, both political, scientific and technological, is problematic.[32] This can be seen in the way in which opponents of renewable energy developments have historically been viewed.

The problem of local resistance to renewable energy projects is frequently obfuscated and made even more contentious by the label of 'nimby' (from 'not in my back yard'). For a long time, the social gap phenomenon was simply dismissed as a manifestation of nimby behaviour, which was – and still is – applied as a pejorative that makes little attempt to understand the underlying issues that drive residents to either oppose renewable energy projects or, at best, offer only qualified support for them.[6,10] In fact, local opposition is typically based on detailed knowledge of the area, and a good understanding of the proposed renewable energy development itself, and associated issues of sustainability and environmental impacts.[8]

The public may be in favour of renewable energy technologies, including wind, but this enthusiasm is discriminating and support can be qualified.[5] Although many sociologists over the past several decades have done a great deal to discredit the nimby hypothesis, it persists in the minds of policy makers, planners, developers and the media, even if the accusation of 'nimby' is no longer made explicitly.[30,33] This can be partly attributed to the institutional tenacity of the information deficit model.[32]

As we shall see, the reaction of local communities to renewable energy projects is a product of many factors which centre on the requirement for public participation to be included in any energy project. There is no one 'correct' method of public participation, and it can be performed as an ongoing fluid process to assess the degree to which residents wish to exercise their right to express their objectives and values in the context of their community and on a wider national (or even global) scale.[4,12,25] The challenge is to engage local residents and the wider community using a framework that acknowledges the values of all actors involved in such a complex issue.[34–36] In many instances, empowering communities by ceding power to them in the decision-making process enables greater collective (or social) learning, improves the social and environmental outcomes of any decisions made, and creates an informed citizenry that can better approach problems affecting people on local and national scales.[10,12–14] Crucially, this social learning frequently leads to a deeper understanding and realisation of the issues associated with energy provision in a modern society, especially with regards to renewable energy.[7,13,37]

Understanding the public's views on wind power

Rethinking nimby-ism

Since the early citizen advocacy movements of the 1960s and '70s public participation has been seen as a cornerstone of environmental policy and decision-making.[12] Several countries in Europe that far exceed the UK in terms of renewables penetration in the national infrastructure have a long history of engaging in a public participation process, one which stresses the need for collaborative discourse and cooperative decision-making, in particular for localised energy projects.[3,16–18,38] In contrast, energy infrastructure in the UK has grown out of a top-down (technical–managerial) model whereby development is centrally planned and organised, or entirely led by private entities with little stakeholder involvement, least of all ordinary citizens.[6,12,38] Since 2000 the concept of public participation has moved to the centre of the renewable energy debate in the UK, illustrated by the government's increasing emphasis on 'community' (discussed below), but it is still commonplace for planners and developers of renewable energy projects to face opposition from residents and local authorities.[5,10,39] More than any other renewable energy source, wind power is highly visible, and many opposition movements that protest against the development of wind turbines are born out of aesthetic concerns.[9] However, this is not to say arguments simply boil down to locals not liking turbines 'spoiling their view'. To use such a reductive argument to characterise community members views on wind power is inaccurate and attempts to ostracise those who are exercising their democratic rights.[33] It is important for developers, policy-makers and community advocates to understand what motivates residents to oppose or support wind power in their locality.[5,7,10]

First of all, what is implied by the term nimby? It is best defined as the dichotomy between the public good and an individual's attempt to maximise their own utility.[7] This is to say, obtaining energy from renewable sources is for the public good; and local opposition to the building of a specific renewable energy installation is the manifestation of the individuals' desire to minimise the impact on them personally. However, studies on community views relating to the installation of wind farms reveal that opposition – whilst instigated largely by the announcement of an impending local development – is not driven by local considerations alone, but by the perceived gap in understanding how wind power will benefit society as a whole.[5,7–9,27] As with any infrastructure development, there can be a disparity between the global benefits in adopting wind power generally and the impact of wind turbines on a specific locality.[8,27,40] The impacts, whether real or speculative, are keenly felt by locals, who may be concerned for the immediate effects on landscape, environment and safety, but too often the benefits and revenue are seen to be externalized, 'leaking' away to non-local agents.[41] Finding a 'true' nimby resident is rare, and it is typically the case that democratic and open engagement with communities reveals a range of nuanced and qualified support for wind turbines, although some communities may conclude that a development is not suitable for them.[5,7,9] Labelling opposition as 'nimby-ism' serves no explanatory purpose, and ignores the fact that people may conceptualise their views of renewable energy technologies in many different ways that encompass uncertainty, apathy, and other qualified viewpoints, rather than outright support or opposition.[5,42]

Clearly, there is a need to address the concerns of local communities during the planning process, where the community is engaged from the start so that residents can fully explore what the development means to them in the context of both local effects at the site and the wider issues of national energy and climate change policy.[10,36,39] Indeed, the new planning regulations requiring wind projects to have pre-allocated sites in a local policy framework or neighbourhood plan[20] can be viewed as a means to engage in truly participatory local planning for wind power, where regional communities can explore opportunities for wind developments across a given area rather than presenting a single option that has been pre-selected by a developer.

In light of jettisoning the nimby hypothesis, the legitimate site-specific concerns that residents might have must be addressed. There will always be issues that are unique to any one locality, but a number of features common to wind farm developments have been found in cases from the UK, Europe and North America where significant public opposition exists. It is instructive to look at these and identify the wider issues they signify.

Perception of landscape affects 'place protective' behaviour

Aesthetic value and how wind turbines change the uses and perceptions of a landscape is an issue that lies at the heart of most controversies surrounding wind power developments.[9] Such a value-laden area of discourse presents a particularly challenging dilemma that resists easy technical fixes. The social, cultural and psychological nature of the issue means that complaints differ significantly across time, place, land tenure, history and culture. The notion of 'place-protective' behaviour is a recent and compelling narrative that seeks to explain the emotional connection of residents to a locality and how it forms part of their identity.[4]

The concept of 'landscape' itself is fluid and hard to assign any defined meaning. Commentators have sought to explain aesthetic experience of landscape in terms of both 'multisensory engagement' and 'cognitive understanding' of its nature, potentially leading to preferences for landscapes where there appears to be a 'functional fit' between human interventions and the natural environment.[43] This sense of landscape also extends to the seascape, which is frequently, and erroneously, considered to be free from the conflicts seen with onshore installations.[8] Offshore wind power is not exempt, receiving resistance from otherwise environmentally minded groups who protest turbines and other infrastructure developments that are proposed to be built out at sea.[28,44,45] For many residents, the inherent characteristics of wind power technology, especially its visual aspect, threaten the way people at wind sites have become accustomed to living.[9] To exploit wind at a site necessitates the building of wind turbines – there is no way around this fact. Efforts by wind developers to address the root cause of local opposition to wind farms too often ends up with them stressing the 'greater good' but seemingly offering nothing but detrimental effects on the landscape. By disregarding residents' sense of place attachment, in the process presenting any provision of direct benefits in the language of inducements or compensation, then the public will unsurprisingly see any wind farm development as an imposition to be borne.[4,10] The wind industry's attempts to sidestep this public backlash has been to point out that wind power,[46]

> *'…produces no toxic waste, no radiation, no acid rain, no greenhouse gases, no thermal discharges, and no irreversible landscape changes. Though correct on all counts, there was still nothing the industry could do or say that would make the turbines invisible, and this left the most glaring infraction of wind power unresolved.'* Pasqualetti (2001, p.694.)

This highlights that the place of wind power in the landscape will always be a challenge for advocates and developers. The reaction of locals to wind farm developments is difficult to predict, but it is worth remembering that there is plenty of evidence that shows wind turbines are also often viewed as a welcome addition, increasingly appearing as backdrops in film and TV, photographs and paintings, and even being described as beautiful and calming.[9,47–51] People's connection to landscapes can encompass the fact that the land can provide important resources, clean, renewable energy being one of them.

Crucially, opposition to wind turbines is, much like supportive views, subject to qualification. Some residents may oppose a wind farm being built in a certain type of landscape, wherever that may be. In this case, support for wind power is qualified by the need to demonstrate that the technology will not adversely affect important natural environments. This is a very different motivation to that of a 'place-protector', who may resist any development in a specific landscape to which they hold deep psychological affinity for, even though they may hold a more moderate view of non-local developments in similar landscapes.[5] It can be difficult to identify these differing motivations and value judgements within a community. Indeed, acknowledging that there is no homogeneous 'community of place' that developers can address is a necessary part of public engagement strategy. In reality, the situation is more typically represented by dynamic 'communities of interest' that do not always align and can shift during the lifetime of a development.[39,52] This relates to the next theme, concerning issues surrounding ownership of the development and locals' relationship with the developers and wind power advocates, both external and internal.

Ownership and distributive fairness

It is an oft-repeated maxim that the UK has little history of the alternative energy activism and cooperative ownership models so prominent in several European countries, such as Denmark and Germany.[6,16] Some have argued that, in fact, community owned renewable energy projects were not precluded in Britain, and successful locally owned wind farms have been possible even with economic and planning barriers.53 Since the early 2000s, national and local government departments have stressed the importance of community funded renewable projects to the future of a 'low-carbon' UK.[39] Both UK and devolved administrations have invested in financial support schemes, e.g. the Rural and Urban Community Energy Funds in England, CARES in Scotland and Ynni'r Fro in Wales, and there has been substantive policy support in the form of the UK's first Community Energy Strategy.[54] Despite these good intentions, UK energy infrastructure has remained locked in to a centralised system of large corporate owners advancing renewable energy technologies in response to a government-mandated national energy strategy.[55]
In the UK, lack of community involvement is regarded as a contributing factor to the continuing difficulties wind farms face during planning applications. Historically, where local residents and authorities are often the motivating force behind wind farm developments, direct involvement in the planning process and a stake in the economic benefits that result leads to greater acceptance and deployment of renewable energy technologies, and better outcomes for the communities involved.[3,10,47,56]

The interpretation of how 'community' takes a central role in renewable energy projects in the UK has taken on many forms, including public sector partnerships, social enterprises and locally-owned cooperatives.[13,17] In many ways, the openness and malleability of the term 'community' in the context of renewable energy planning has given flexibility and space for more innovation, allowing different projects to flourish under conditions appropriate to the local situation.[13,37,38]

However, this uncertainty has also meant that issues arise over inclusiveness and distributive fairness, especially as the scale of benefits to be obtained from a wind farm increases.[39,52] Conflict may also stem from compensatory benefits offered by corporate-owned wind farms.[26] For example, in west Texas, where wind power is almost universally viewed by communities as a welcome development that has brought economic revitalisation, there are still profound disagreements over distributive fairness. There is a sense that not everyone in the community benefits equally, and that many of the more impoverished residents find themselves even worse off and further marginalised.[48]

A striking example of resistance to offshore wind off the coast of Redcar in Teesside, also shows that existing industrial development does not automatically lead to public acceptance for further development.[8] The general view is that,

> *'...the difference between the wind farm and the petrochemical factories is that these industries form the economic heartland of the area, and (unlike the wind farm) provide jobs and income for local people.'* Haggett (2011, p.506) [emphasis added]

Opposition to wind power developments have also been noted in other proposed developments in 'industrial' dockland environments,[57] These places may not be considered unspoiled landscapes, but, nevertheless, residents clearly feel that the existence of industrial developments is no reason to add more development.58

Local versus national and global impacts

The history of renewable energy deployment in the UK since the 1990s has shown that residents are quick to voice concerns over perceived local impacts, particularly environmental.[8,9,25,44] Indeed, an environmentally conscious citizen, who might well be mindful of the wider issues pertaining to climate change, can hardly be expected to endorse a local wind farm if they believe it will be detrimental to the local environment. Note that the information deficit model would fail to explain this form of opposition.[5,30]

Too often, it is assumed that renewable energy technologies are viewed by the public as implicitly good or beneficial. The views of residents will be shaped largely by societal and cultural norms, and it is no surprise these will not automatically fall into line with the institutional opinions that have dispassionately weighed the benefits and risks of a large-scale renewable energy development.[10,59] When these external institutions are introducing unfamiliar technology that some communities may feel intrudes on a special landscape, it stretches the community's credulity to simply accept these changes without questioning them.[8,28,32] Increasingly, a more environmentally-aware public is also more interested in the issues surrounding large-scale implementation of renewable energy and land use impacts, and are unwilling to accept assurances on face value.[25,44] This is a clear demonstration of the fallacy of the nimby label, which is predicated on the rationale that an uninformed citizenship is simply dismissing local developments out of hand.[4–7] It shows that developers must actively seek to rid themselves of this view that the public is an 'ever present danger'.[10]

Local environmental concerns often obscure an important misconception surrounding many wind power developments. In contrast to the commonly held view that opposition arguments are driven by local concerns and supportive arguments are driven by national or global concerns, many communities make the decision to accept wind power because it addresses local needs.[36,39,47,48] Economic revitalisation and the ability to demonstrate that a community is dynamic, innovative and welcoming to high-tech industry are fundamental to many renewable energy planning decisions made at the local municipal and community level.[16,36,41,48,60] Because of the degree of automation in wind turbines, reinvestment of revenues from wind power generation is the key to making a development serve the community in an equitable manner, rather than relying on economic benefits from associated operations, such as construction and servicing.[41,48]

When positive impacts are made inclusive, with reinvestment into social schemes with well-defined objectives, a wind farm development can improve social sustainability and provide benefits to struggling communities. Revenue fed back into local social services, i.e., education, healthcare and residential care, and into non-core industries, e.g., community businesses, agriculture and fishing, can help maintain the local labour force and increases the economic activity of the regional population.[41] As mentioned above, however, assessment of and engagement with a community must be transparent and inclusive. With growing revenue streams fed by wind farm developers back into communities there is increasing conflict over how 'affected communities' should be defined.[39,52,61] The corollary is how these funds should therefore be managed and governed, given the possible wider application of community in this context.[52] For place-based reinvestment, it is vital to use local participation when planning disbursement of funds, and to fully understand the limits and appropriateness of any financial measures proposed. Distributive fairness and the motives of developers remain central concerns for locals. The approach of developers must not be to frame disbursement of funds as compensatory or an inducement, but to incorporate financial mechanisms early on in planning as a genuine means to provide economic benefits to a community.[26,41,52,62] Social and economic growth, after all, should be seen as a natural extension of a community's closer engagement with modern decentralised energy technologies and industry.

The final facet of the local vs national issue is that it is commonly the case that communities place great store in opinions of local news and campaign organisations, whereas developers and central government receive little confidence. Indeed, while educating and placing responsibility on individuals in the areas of microgeneration and saving energy in the home and transport system has been a central pillar of the UK government's climate change policy, there has been a failure to link this 'bottom-up' approach with the national strategy regarding large-scale energy generation infrastructure.[10,55,63]

Thus, at the domestic level, citizens are treated as active, willing participants who are asked to voluntarily adopt a 'range of new, unfamiliar, and rather expensive technologies'; whereas when it comes to large-scale generation projects communities are considered 'hosts' and public engagement is simply to 'secure public acceptance of developer-led projects.'[10] Here again is another demonstration of the tensions that are caused by conflict between local and national priorities.[12,64] The UK general public consistently show greater level of trust in local pressure groups and environmental non-governmental organisations (NGOs).[25,26,44] NGOs may even hold favourable views regarding renewable energy in support of national interests, but find themselves in opposition at the level of a local branch.[25] Efforts to speed planning procedures in an attempt to meet national targets for renewable energy only serve to further erode the public's trust in a centralised government or nationally-based private developer. When battle lines are drawn between local and national agencies, then an 'us and them' or 'progressive vs. conservative' character is established, circumventing the participatory discourse that is supposed to give citizens a chance to air their views.[14,27]

Such rigid stances will lead to a failure of many developments to gain planning permission and, perhaps worse, make the public mistrustful of renewable energy generally. Ensuring public participation helps build trust with local organisations, who frequently convey information to residents in their role as trusted sources, helping mediate social learning and acceptance of change to their place of attachment.[4,35,65]

Procedural justice, exploration of values and public participation

People are aware of environmental impacts, both local and global; they understand that landscapes may be mutable, and adapt to prevailing social and technological trends; and it is obvious to many that development of renewable energy should bring with it benefits, but may also bring disadvantages if not appropriately planned and delivered. Engagement, discourse and participation from the beginning of any renewable energy project should be one of the key aims of planners and developers, so allowing communities to explore and voice their values and interest in the context of the UK's evolving energy infrastructure.[2,10,13,14,35] There are several ways in which public engagement can be approached, and these are discussed below. What is highlighted here is the very real problem that exists in the UK, where centralised, top-down planning imperatives are forced on a dissenting public in the face of the participatory process, which leads to increased hostility to or defiance of the measures implemented.

The centralised, top-down model means that the public generally has only a limited understanding of how the energy they consume is sourced and delivered to them. This has the effect of creating 'significant spatial and psychological distance between energy generation and use'.[38] This disconnect between the provision of energy services and the externalities associated with this process is of great importance; for public participation to be valid it must first create the opportunity for learning.[6,14] Engaging residents in the weighing and analytical process that forms part of any complex project, such as a modern wind farm, frequently results in a greater appreciation of the difficulties faced by developers and policy-makers; it builds trust, and highlights in the public's mind the challenges and objectives involved when implementing an overall renewables strategy at local and national scales.[7,10,13,66]

This is not the same as a public consultation where residents are presented with a didactic process designed to lead them to the 'right' choice. Rather, consultation should engage members within a framework where stakeholders in a local community can assess the advantages and disadvantages of a project based on environmental and social impacts resulting from the siting of renewable energy developments, then being able to express opinions in a way that reflects the residents' own values.[2,4,25,66]

The issue of procedural justice is an exacting one for renewable energy developers, whether they are an external corporation or community-led group of local activists. For one, deciding how wide to extend the notion of 'affected community' is difficult, and not getting it right the first time can quickly heighten tensions between resident groups.[39,52,61] Many private developers are reluctant to involve community groups, seeing community partners as constraining and adding to the complexity of any development.[55] On the other hand, the ill-defined nature of 'community' with regards to renewable energy in the UK means that, if a development is labelled as a community project, when members of the wider community feel they are excluded from the key planning decisions and receive little direct benefit from an installation in their locality, then this will increase the scope for resentment and objections.[13,39,61] Although local residents may have many similar overlapping concerns as other stakeholders, there can be fundamental differences in the way they perceive benefits derived from a wind farm, particularly if they believe most of the benefits will accrue to distant consumers or groups of shareholders rather than to the affected community.[8,13,26,41,66]

Transparency and trust are key to any engagement with the public. In many cases, it will be apparent that some decisions have been made, or at least the options limited, during planning and development. It is essential that residents are not 'managed' in an attempt to have them acquiesce to something already decided.[12,67] As has been touched on above, national climate change mitigation strategies are driven by predetermined aims, which frequently are in conflict with residents' short-term objectives. How then to accommodate dissenting voices and ensure all residents are given the opportunity to meaningfully explore what the development means to them and have their say? The danger here is that developments described as involving public *engagement* are increasingly treated as synonymous with public *participation*.[10,67]

Standard methods of engagement are not synonymous with true participation – often the flow of information is only from sponsor to locals, with no dialogue and certainly no formulating of new opinions (most evident in the 'decide-announce-defend' approach to community engagement). In many cases, developers simply desire a one-way communication of ideas versus a more participatory process.[30] This inevitably leads to tensions or outright conflict.[10]

Pursuing public engagement for purely instrumental objectives, i.e., to achieve what the developer wants, fosters the belief in the public as unknowledgeable, uneducated and unwilling to engage with renewable energy technologies at all, which is damaging and quite incorrect. In the end, communities become sceptical of developers' motives, which too frequently hardens into the belief that 'developers do not engage with objectors to listen to and address their concerns, but rather to find ways of overcoming or managing local opposition.'[67] These objections are important, because public engagement has no legitimacy if it is simply there to lend credibility to a decision already made. Nothing will alienate communities and turn public opinion away from renewable energy developments faster than paying lip service to the idea that their opinion matters. As Arnstein[68] points out in her seminal 1969 paper on citizen participation:

> *'There is a critical difference between going through the empty ritual of participation and having the real power needed to affect the outcome of the process […]* ***Participation without redistribution of power is an empty and frustrating process for the powerless.'***
> Arnstein (1969, p.216) [emphasis added].

Degrees of public participation

Typologies of participation (that is, the range of participatory mechanisms that are employed when implementing environmental developments) have often been treated as a hierarchal *ladder of citizen participation*.[68] Based on the reasoning that some types of public participation are more appropriate than others depending on the circumstance, the ladder of participation was revised to the non-linear wheel of participation (see Figure 8.1).[34,69] This is an important consideration that helps agencies avoid following a 'one size fits all' approach to public and stakeholder participation. Broadly, participatory mechanisms can be categorised as:[12]

- **passive participation,** characterised by a more didactic approach whereby the public receives information on decisions that have already been made;
- **consultative,** where the public is given some opportunity to deliberate on a (generally quite limited) range of predetermined options;
- **interactive participation,** in which case the public is more deeply involved in analysis of problems and formulating solutions;
- **self-mobilization,** where the public takes initiative independently of external agencies.

These mechanisms are not rigidly delineated and there may be elements of all types found in any one locality where a renewable energy development takes place. It is interesting to note that surveys carried out in UK communities suggest the public does not automatically gravitate to the most all-inclusive mechanism (interactive or self-mobilisation in the list above) as one might assume.[70,71] Although there is desire to give communities more control over projects that directly affect them, many residents appreciate the benefits that expert leadership by external agencies can bring to help develop, build, coordinate and operate renewable energy facilities.[37,38,55,71]

The willingness of citizen stakeholders to adopt appropriate forms of participation (rather than demanding total control) is a timely reminder that developers can only gain from public participation.[4] It is also a demonstration of the importance of ventures taken on by social enterprises.[17,37] Such schemes typically involve residents and consumers as stakeholders in a project. This facilitates acceptance and installs an important social element into the mix, such as putting in place strategies for reinvestment of revenue, helping target fuel poverty, involving local contractors where possible, and encouraging rural economic development.[17,37,41,62] On mainland Europe such ventures are often coordinated and pushed forwards by municipal administrations, so guaranteeing an additional element of local governance.[16,60]

Conclusion

One key obstacle to achieving a lower-carbon energy supply system in the UK is the high proportion of renewable energy projects that fail to progress past the planning stage in the face of local opposition. The widespread implementation of renewable energy infrastructure since the 1990s across has shown that opposition is not limited to wind turbines alone, with bioenergy facilities, geothermal projects and offshore structures also facing public opprobrium. The increasing integration of these types of distributed energy projects differs from the dominant centralised model of traditional fossil fuel generation, and it has highlighted the tension that exists between national interests and local opinion.

This 'social gap' between acknowledging the benefits of wind power (and other renewable energy technologies) whilst objecting to any such development on a local level has in the past been dismissed as nimby-ism. This fails to address the complex interactions between a community's societal and cultural norms and their link with place attachment, and the nimby 'myth' has been justifiably discredited. It is increasingly recognised by sociologists that 'the public' reacts in ways that can be difficult to predict, based upon interlocking value judgements and a keen sense of both potential advantages and disadvantages relating to renewable energy infrastructure. The information deficit model, which holds that the public possess 'incorrect knowledge' and has a tendency to make emotive rather than rational decisions, is slow to lose its grip on the institutional culture of planners and developers. However, whilst the value of fully engaging residents through models of public participation is slowly being taken on board by the wind industry, there is still a tendency to take public engagement to mean public participation. There are many forms of participatory mechanisms that can be applied to renewable energy projects, but the key issue is that communities are empowered to explore values important to them and assess possible configurations of renewable energy provision. This collaborative discourse between affected communities and developers allows informed citizens to take control of their energy infrastructure at an appropriate level.

In the UK a top-down (technical–managerial) approach has driven much of the country's renewable energy development so far, creating a democratic deficit that is often filled by vociferous opposition groups. Involving communities in the decision-making and planning process fosters cooperative discourse rather than open-ended conflict, and creates a better understanding of the wider issues involved in energy policy and the environment. In addition, an informed and motivated community with a real investment in a wind power development will be well-equipped to integrate renewable technologies effectively in a manner that reduces social inequity. Communities take pride in their history of development, with local technologies and industries often a source of pride. Clearly, there is space for wind power developers and local supporters to find common ground with residents concerned about the impact of wind turbines in their vicinity. Rather than instigating confrontation and compromising on an uneasy truce, it should be possible to avoid drawing battle lines at all.

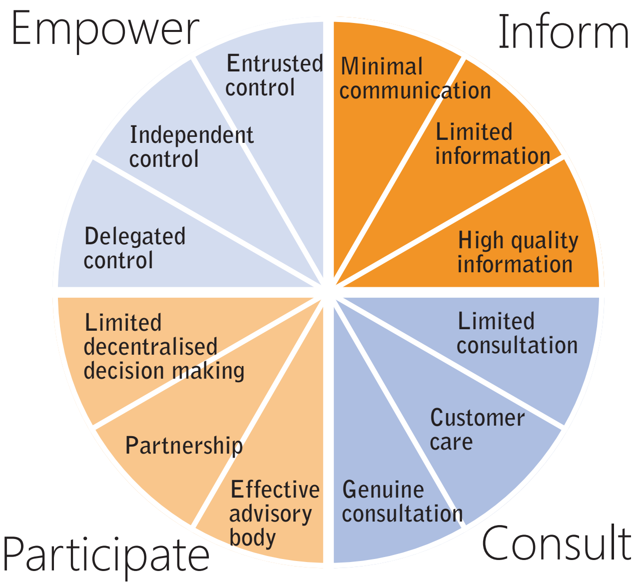


Figure 8.1 An abridged version of the wheel of participation, adapted from the original in Davidson (1998). Through a collaborative process, communities, planners and other stakeholders, collectively decide on the quadrant that should best define the project. This helps to attain the appropriate level of community involvement with the full participation of residents in this decision.

References

1. DECC (Department of Energy & Climate Change). *The UK Low Carbon Transition Plan: National Strategy for Climate Change.* URN 09D/716. London: The Stationery Office/TSO; Jul 2009. 230 p.
2. Walker G, Cass N. Carbon reduction,"the public"and renewable energy: engaging with socio-technical configurations. Area. 2007; 39(4):458–69.
3. Toke D, Breukers S, Wolsink M. Wind power deployment outcomes: How can we account for the differences? Renew Sustain Energy Rev. 2008; 12(4):1129–47.
4. Devine-Wright P. Rethinking NIMBYism: The role of place attachment and place identity in explaining place-protective action. J Community Appl Soc Psychol. 2009; 19(6):426–41.
5. Bell D, Gray T, Haggett C, Swaffield J. Re-visiting the "social gap": public opinion and relations of power in the local politics of wind energy. Environ Politics. 2013; 22(1):115–35.
6. Bell D, Gray T, Haggett C. The "social gap" in wind farm siting decisions: explanations and policy responses. Environ Politics. 2005; 14(4):460–77.
7. Wolsink M. Wind power implementation. The nature of public attitudes: equity and fairness instead of 'backyard motives'. Renew Sustain Energy Rev. 2007; 11:1188–207.
8. Haggett C. Understanding public responses to offshore wind power. Energy Policy. 2011; 39(2):503–10.
9. Pasqualetti MJ. The misdirected opposition to wind power. In: Szarka J, Cowell R, Ellis G, Strachan PA, Warren C, editors. *Learning from Wind Power.* Basingstoke: Palgrave Macmillan; 2012. 133–52.
10. Devine-Wright P. Public engagement with large-scale renewable energy technologies: breaking the cycle of NIMBYism. Wiley Interdiscip Rev Clim Chang. 2011; 2(1):19–26.
11. Corner A, Venables D, Spence A, Poortinga W, Demski C, Pidgeon N. Nuclear power, climate change and energy security: Exploring British public attitudes. Energy Policy. 2011; 39(9):4823–33.
12. Few R, Brown K, Tompkins EL. Public participation and climate change adaptation: avoiding the illusion of inclusion. Clim Policy. 2007; 7(1):46–59.
13. Walker G, Devine-Wright P. Community renewable energy: What should it mean? Energy Policy. 2008; 36(2):497–500.
14. Webler T, Kastenholz H, Renn O. Public participation in impact assessment: a social learning perspective. Environ Impact Assess Rev. 1995; 15(5):443–63.
15. National Grid. *2013 Electricity Ten Year Statement.* Warwick: National Grid plc; Nov 2013. 230 p.
16. Schreuer A, Weismeier-Sammer D. Energy cooperatives and local ownership in the field of renewable energy technologies: a literature review. RICC, 4. Vienna: WU Vienna University of Economics and Business; Oct 2010 Oct. 46 p.
17. Kelly S, Pollitt MG. The local dimension of energy. In: Jamasb T, Pollitt MG, editors. *The future of electricity demand: customers, citizens, and loads.* Cambridge University Press; 2011. 249–79.
18. Nolden C. Governing community energy—Feed-in tariffs and the development of community wind energy schemes in the United Kingdom and Germany. Energy Policy. 2013; 63:543–52.
19. *House of Commons Hansard Debates* 22 July 2015. Onshore Wind Subsidies. 597(20) c.617. [Online]. UK Parliament. Available from: www.publications.parliament.uk/pa/cm201516/cmhansrd/cm150622/debtext/150622-0001.htm#1506227000002
20. *House of Commons Hansard Debates* 18 Jun 2015. Communities and local government: local planning. 597(19) c.9WS. [Online]. UK Parliament. Available from: www.publications.parliament.uk/pa/cm201516/cmhansrd/cm150618/wmstext/150618m0001.htm#15061882000007
21. Ibid. Energy and climate change: onshore wind subsidies. 597(19) c.9WS–10WS.
22. DECC. Consultation on a review of the Feed-in Tariffs scheme. URN 15D/435. London: Department of Energy & Climate Change; 27 Aug 2015. 61 p.
23. For example, see: Murray, 'Government confirms it will halt onshore wind subsidy scheme a year early', Business Green, 18 June, 2015; 'RenewableUK comment on climate change speech by Energy Secretary', RenewableUK, 24 July, 2015; Vaughan, 'Green groups express "major concern" over Tory policies in letter to Cameron', Guardian, 31 July, 2015.
24. House of Lords Hansard Debates 22 July 2015. Energy Bill Second Reading. 764(37) c.1122. [Online]. UK Parliament. Available from: www.publications.parliament.uk/pa/ld201516/ldhansrd/text/150722-0001.htm#column_1122
25. Upham P. Applying environmental-behaviour concepts to renewable energy siting controversy: Reflections on a longitudinal bioenergy case study. Energy Policy. 2009; 37(11):4273–83.
26. Cass N, Walker G, Devine-Wright P. Good neighbours, public relations and bribes: The politics and perceptions of community benefit provision in renewable energy development in the UK. J Environ Policy Plan. 2010; 12(3):255–75.
27. Ellis G, Barry J, Robinson C. Many ways to say "no", different ways to say "yes": Applying Q-Methodology to understand public acceptance of wind farm proposals. J Environ Planning Manag. 2007; 50(4):517–51.
28. Wiersma B, Devine-Wright P. Public engagement with offshore renewable energy: a critical review. Wiley Interdiscip Rev Clim Chang. 2014; 5(4):493–507.
29. Kunreuther H, Gupta S, Bosetti V, et al. Integrated risk and uncertainty assessment of climate change response policies. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al. (editors). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press: 2014. 151–206.
30. Burningham K, Barnett J, Walker G. An array of deficits: Unpacking NIMBY discourses in wind energy developers' conceptualizations of their local opponents. Soc Nat Resour. 2015; 28(3):246–60.
31. Nisbet MC, Scheufele DA. What's next for science communication? Promising directions and lingering distractions. Am J Bot. 2009; 96(10):1767–78.
32. Wynne B. Public engagement as a means of restoring public trust in science – hitting the notes, but missing the music? Community Genet. 2006; 9(3):211–20.
33. Wolsink M. Undesired reinforcement of harmful "self-evident truths" concerning the implementation of wind power. Energy Policy. 2012; 48:83–7.
34. Reed MS. Stakeholder participation for environmental management: A literature review. Biol Conserv. 2008; 141(10):2417–31.
35. Bidwell D. The role of values in public beliefs and attitudes towards commercial wind energy. Energy Policy. 2013; 58:189–99.
36. Rygg BJ. Wind power—An assault on local landscapes or an opportunity for modernization? Energy Policy. 2012; 48:167–75.
37. Van der Horst D. Social enterprise and renewable energy: emerging initiatives and communities of practice. Soc Enterp J. 2008; 4(3):171–85.
38. Walker G, Hunter S, Devine-Wright P, Evans B, Fay H. Harnessing community energies: explaining and evaluating community-based localism in renewable energy policy in the UK. Glob Environ Politics. 2007; 7(2):64–82.
39. Walker G, Devine-Wright P, Hunter S, High H, Evans B. Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy. Energy Policy. 2010; 38(6):2655–63.
40. Firestone J, Kempton W. Public opinion about large offshore wind power: Underlying factors. Energy Policy. 2007; 35(3):1584–98.
41. Okkonen L, Lehtonen O. Socio-economic impacts of community wind power projects in Northern Scotland. Renew Energy. 2016; 85:826–33.

42. Batel S, Devine-Wright P, Tangeland T. Social acceptance of low carbon energy and associated infrastructures: A critical discussion. Energy Policy. 2013; 58:1–5.
43. Selman P, Swanwick C. On the meaning of natural beauty in landscape legislation. Landscape Res. 2010; 35(1):3–26.
44. Wolsink M. Near-shore wind power—Protected seascapes, environmentalists' attitudes, and the technocratic planning perspective. Land Use Policy. 2010; 27(2):195–203.
45. Bailey I, West J, Whitehead I. Out of sight but not out of mind? Public perceptions of wave energy. J Environ Policy Plan. 2011; 13(2):139–57.
46. Pasqualetti MJ. Wind energy landscapes: Society and technology in the California desert. Soc Nat Resour. 2001; 14(8):689–99.
47. Warren CR, McFadyen M. Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. Land Use Policy. 2010; 27(2):204–13.
48. Brannstrom C, Jepson W, Persons N. Social perspectives on wind-power development in west Texas. Ann Assoc Am Geogr. 2011; 101(4):839–51.
49. Eltham DC, Harrison GP, Allen SJ. Change in public attitudes towards a Cornish wind farm: Implications for planning. Energy Policy. 2008; 36(1):23–33.
50. Aitchison C. Tourism impact of wind farms. [Online]. Submitted to Renewables Inquiry Scottish Government; 2012 (last accessed 11 Aug 2015). 22 p. Available from: http://www.research.ed.ac.uk/portal/files/4647070/Aitchison_C_WindFarms_2012.pdf
51. Braunholtz S, MORI Scotland. Public attitudes to windfarms: a survey of local residents in Scotland. On behalf of Scottish Executive Social Research. Edinburgh: Stationery Office; 2003. 37 p.
52. Bristow G, Cowell R, Munday M. Windfalls for whom? The evolving notion of "community" in community benefit provisions from wind farms. Geoforum. 2012; 43(6):1108–20.
53. Toke D. Renewable financial support systems and cost-effectiveness. J Clean Prod. 2007; 15(3):280–7.
54. DECC. Community Energy Strategy: Full Report. URN 14D/019. London: Department of Energy & Climate Change; 27 Jan 2014. 107 p.
55. Strachan PA, Cowell R, Ellis G, Sherry-Brennan F, Toke D. Promoting community renewable energy in a corporate energy world: Promoting community renewable energy in the UK. Sust Dev. 2015; 23(2):96–109.
56. Viardot E. The role of cooperatives in overcoming the barriers to adoption of renewable energy. Energy Policy. 2013; 63:756–64.
57. Toke D. Explaining wind power planning outcomes: some findings from a study in England and Wales. Energy Policy. 2005; 33(12):1527–39.
58. Jones CR, Orr BJ, Eiser JR. When is enough, enough? Identifying predictors of capacity estimates for onshore wind-power development in a region of the UK. Energy Policy. 2011; 39(8):4563–77.
59. Kasperson RE, Ram BJ. The public acceptance of new energy technologies. Daedalus. 2013; 142(1):90–6.
60. Hoppe T, Graf A, Warbroek B, Lammers I, Lepping I. Local governments supporting local energy initiatives: lessons from the best practices of Saerbeck (Germany) and Lochem (The Netherlands). Sustainability. 2015; 7(2):1900–31.
61. Simcock N. Exploring how stakeholders in two community wind projects use a "those affected" principle to evaluate the fairness of each project's spatial boundary. Local Environment. 2014; 19(3):241–58.
62. Munday M, Bristow G, Cowell R. Wind farms in rural areas: How far do community benefits from wind farms represent a local economic development opportunity? J Rural Stud. 2011; 27(1):1–12.
63. Akcura E, Haney AB, Jamasb T, Reiner DM. From citizen to consumer: energy policy and public attitudes in the UK. In: Jamasb T, Pollitt MG, editors. The future of electricity demand: customers, citizens, and loads. Cambridge University Press; 2011. 231–48.
64. Smith J, Blake J, Grove-White R, Kashefi E, Madden S, Percy S. Social learning and sustainable communities: An interim assessment of research into sustainable communities projects in the UK. Local Environ. 1999; 4(2):195–207.
65. Owens S, Driffill L. How to change attitudes and behaviours in the context of energy. Energy Policy. 2008; 36(12):4412–8.
66. Stagl S. Multicriteria evaluation and public participation: the case of UK energy policy. Land Use Policy. 2006; 23(1):53–62.
67. Aitken M. Why we still don't understand the social aspects of wind power: A critique of key assumptions within the literature. Energy Policy. 2010; 38(4):1834–41.
68. Arnstein SR. A ladder of citizen participation. J Am Inst Planners. 1969; 35(4):216–24.
69. Davidson S. Spinning the wheel of empowerment. Planning. Apr 1998; No.1262:14-15.
70. Rogers JC, Simmons EA, Convery I, Weatherall A. Public perceptions of opportunities for community-based renewable energy projects. Energy Policy. 2008; 36(11):4217–26.
71. Watson J, Devine-Wright P. Centralization, decentralization and the scales in between: what role might they play in the UK energy system? In: Jamasb T, Pollitt MG, editors. The future of electricity demand: customers, citizens, and loads. Cambridge University Press; 2011. 280–97.

Chapter 9

Wind turbines and property prices

Summary

As the number of proposals for wind farms across the UK increases, detractors fear that nearby residents will see their property values drop. Given the negative press that wind turbines often receive in the mainstream media, it is not surprising that this becomes a concern for local residents during the planning and development of a wind farm. In fact, a great deal of research in the UK and abroad shows that there is no devaluation in property prices nearby once a wind farm is operating. A single large-scale study suggests some effect relating to turbine visibility, but lack of detailed analysis of changes over time and assumptions relating to the actual visibility used in this single study may go some way to explain these contradictory findings. Fears over property value losses frequently manifest as 'anticipation stigma', which has been found to exist during the planning and construction of wind farms, often bearing little relation to the actual community opinion or local property markets. It is no great surprise that opponents of wind farms are quick to seize on this sensitive issue, but the evidence overwhelmingly supports the view that wind turbines do not cause house prices in the surrounding area to fall.

What is this based on?

This is a common objection raised against the siting of onshore wind farms. As property is the single largest financial and emotional investment a person is likely to make, residents' concerns are legitimate and understandable. The premise seems obvious: why would someone be willing to pay as much for a property (especially when situated in a rural area) that has wind turbines in view, when compared with a property that does not? Peoples' direct experience of wind farms remains relatively rare and the uncertainty a new development brings can lead residents to anticipate detrimental local impacts that will result in reduced property values. As of 2014, there are several updated and comprehensive studies on the effects of wind turbine developments and housing prices that have been released, mostly using data from North America and Great Britain. As wind farm developments become more and more common, the level of data open to analysis will continue to increase. For the studies published so far, the vast majority of evidence shows that the proximity of wind turbines in an area does not have any negative impact on surrounding house prices, although there are a small handful of exceptions that suggest there is indeed some adverse effect on prices that is attributable to turbines being visible to properties within several kilometres.

The largest and most robust studies that failed to find any link between lower property values and the presence of wind turbines have frequently taken the different stages of wind farm development into consideration: prior to construction, during construction, after construction once turbines are operating, and some even going back to the period before any announcement of a possible wind farm development was made. This has been beneficial in terms of revealing certain trends associated with wind farm developments and the response in the local housing market, and may help explain some of the reasons behind the few studies that do suggest a reduction in property prices.

What is current evidence?

Since the first UK commercial wind farm began operation in Delabole, Cornwall in 1991, wind turbines have become an increasingly common feature of the landscape across the UK.[1] This reflects the trend in several European countries that are leading exponents of wind energy (e.g., Germany and Spain), and also in the United States, where the rapid expansion of wind farms is continuing across many states.[2] The continued growth the wind industry since the 1990s means that there is an increasing number of areas that have an established history of wind farm development, and this has facilitated several large-scale studies in Great Britain and North America that look at the effect the presence of wind turbines have on house prices over time. As noted by several later researchers, many of the earliest studies were contradictory and contained several limitations: over-reliance on survey results instead of historical transaction data; the inclusion of confounding data that were not arms-length sales;* treating turbines as being visible from all properties in the radius area studied;

---

* House sales may not be 'arms-length' sales when the parties are not independent of each other or on an equal footing, e.g. in transactions between family members, a sale resulting from a divorce, or the break up of an estate. These types of sale are likely to result in unreliable price indicators.

assuming visibility impacts are the same regardless of proximity; and general lack of statistical rigour, including not properly isolating other amenities and disamenities that may affect property value, known as the hedonic pricing method.[3,4]

One research group, sponsored by the Royal Institute of Chartered Surveyors (RICS), who looked at 919 transactions in the period 2000–2005 near two wind farms in Cornwall, used an analysis that incorporated a hedonic approach to allow for other factors that may influence house prices (e.g. waterfront views) The initial data from these areas showed no linear correlation between the proximity of a wind farm on house prices for properties within 6.4 km (4 miles), and the authors stated that non-linear effects were likely attributable to other variables not analysed in their regression analysis.[4] The same researchers focused on a smaller group of houses (199) that were situated within 1.6 km (1 mile) of one of the Cornish wind farms, and analysed in more detail the effect of turbine visbility from the properties, including which side of the house the turbines could be seen from. In this sample, the authors discovered both positive and negative effects on house price in relation to turbine visibility; for example, a rear-facing view of turbines had a slight negative effect overall, in contrast to a positive effect for side- and front-facing views of the turbines, but terraced houses with rear-facing views of the turbines also displayed a slight positive effect on property value. The authors again concluded there was no direct relationship between turbine visibility and property values within 1.6 km of a wind farm.[5]

The first truly large-scale statistical analyses, encompassing transaction data from multiple states in the USA and using the hedonic pricing method, were carried out by a research group at the Lawrence Berkeley National Laboratory.[3] The authors have included data relating to different stages of wind farm development, grouped as ‘pre-announcement’, ‘post-announcement pre-construction’ and ‘post-construction’.[6] The sales data stretched back to 1996, several years before any of the earliest wind farms were announced, and the authors applied several multiple hedonic models, as well as analysing repeat sales and testing to see if volume of sales in an area were affected.[3,6] The first report looked at 7,459 arms-length house sales up to 2008 and found no measurable relationship between house prices and distance or visibility of wind turbines.[3]

The second study was able obtain a larger data set, compiling 51,276 transactions involving properties across nine states that surround 67 different wind farms in total, and as the sales data spanned 1996–2012 there were significant numbers of sales from prior to any announcement and well after the wind turbines became operational.[6] Again, there was no statistical evidence to show that wind turbines affected house prices.[†]

Finally, in a collaborative study, the Berkeley group looked at another very large data set of 122,198 transactions in the densely populated state of Massachusetts, with properties concentrated in more urban areas that surrounded a total of 26 wind facilities.[‡] Following their analyses similar to before, the authors concluded:[7]

> *“The results of this study do not support the claim that wind turbines affect nearby home prices. Although the study found the effects on home prices from a variety of negative features (such as electricity transmission lines, landfills, prisons and major roads) and positive features (such as open space and beaches) that accorded with previous studies, the study found no net effects due to the arrival of turbines in the sample’s communities. Weak evidence suggests that the announcement of the wind facilities had an adverse impact on home prices, but those effects were no longer apparent after turbine construction and eventual operation commenced.” (p.36)*

An analysis by a different group of 48,554 transactions in the state of Rhode Island, looking at an area similarly urbanised to the Massachusetts study that contained wind facilities of a comparable or smaller scale (half of the sites had turbines in the 100–275 kW range), also found no statistically significant impact of turbines on property values.[8] As with the earlier Berkeley group studies, the data for Massachusetts and Rhode Island covered a period of more than a decade, with a substantial number of sales and repeats sales from before any announcement of a development to several years after the turbines became operational.[7,8]

Two major studies based in England and Wales were officially published in 2014. Although a draft version of the report from the LSE’s Spatial Economics Research Centre (SERC) was released in 2013, the final revised version was only published in April 2014.[9] This report obtained a very large dataset from England and Wales postcodes where either wind turbines were already operational or became operational at some point. Sales data were from the period between 2000 and the first quarter of 2012, covering more than 125,000 transactions in rural postcodes within 4 km (2.5 miles) of turbines, of which 36,000 of these were within 2 km (1.25 miles) of turbines. In all, the author incorporated data up to 14 km (8.7 miles) from wind farms, which encompassed 148 wind facilities in all, with a median of

[†] This second study from the Berkeley group was also published online in July 2014 (prior to print publication) in the peer-reviewed Journal of Real Estate Finance and Economics.

[‡] These 26 sites consisted of between one and three turbines, except for one ten-turbine wind farm; the nameplate capacity of the turbines was mostly in the 1.5–2 MW range, with the lowest being 0.6 MW found at six of the sites.

6 turbines per wind farm (the average was skewed by a handful of very large offshore farms), and a total of more than 1,700,000 property sales over the 12-year period. The author approximated whether the turbines would be visible by using information about the elevation and aspect of the houses in question, and used this as a basis to measure the 'visibility coefficient' by comparing houses within the same postcodes that have turbines in view with those that do not. Although cases were removed when the potential visibility was highly ambiguous, landscape features such as trees and buildings were not taken into account when assessing visibility. In summary, this study suggested that wind farms 1–10 turbines in size cause a 5% reduction in prices for properties within 2 km from which turbines are visible, with this impact falling to 1.5% by 4 km distance and becoming insignificant thereafter. When the very largest wind farms were also included, the average price reduction caused by visible turbines within 2 km was between 5 and 6 per cent, falling to just below 2% by 4 km; there is a very small effect (less than 1%) at distances up to 14 km.[9]

In contrast, a different study published in March 2014 that took site-specific data from England and Wales came to quite the opposite conclusion.[10] This study looked at transaction data over a lengthy period, from 1995 to mid-2013, and analysed trends between rural house prices for properties within 5 km (3.1 miles) of wind turbines compared with average trends for comparable properties across the county, a total database of over 1,043,000 transactions. In total, 82,223 sales occurred that involved houses within 5 km of a wind farm, across seven different sites that included both small (2–6 turbines) and large facilities (two wind farms had 26 turbines each). Tracking the county averages and comparing them with the 82,223 sales that took place within 5 km of a wind farm showed that the presence of a wind farm had no effect on house prices.[10] In one case, prices were reduced slightly in the phase following planning permission being awarded for six turbines, but these quickly recovered during construction of the wind farm and comfortably outperformed the county average. Two other sites saw prices within the 5 km radius actually outperform the county averages, and transaction data for the other sites all closely tracked the county averages.

A further econometric analysis within the same study was designed to separate out variables affecting house prices to see the effects that a wind farm may have had during either public planning, construction or operation of the turbines.[10] The study authors removed smaller datasets for two of wind farms[§] because the transaction data within 5 km was too limited in terms of distribution of property types or number of sales to be statistically valid – this excluded 2,854 sales from the total used for the econometric analysis. Regression analysis of the remaining 79,369 transactions across five wind farms demonstrated that price trends closely tracked the county averages for all of the sites, and were clearly driven by factors operating across the county-wide market. The fall in prices across all properties following the 2008 financial crisis was particularly evident, but the presence of wind turbines had no effect on this trend; in fact, the analysis revealed a small but statistically significant positive effect (1%–2%) on property prices for dwellings within the 5 km radius of a wind farm across both the construction phase and following operation of the turbines.[10]

One United States study of significant size (11,331 transactions within 16 km) purportedly revealed that turbines may negatively affect property values, although it was not nearly as robust as the SERC study mentioned earlier.[11] The authors show that in two adjacent New York counties there was a significant reduction in house prices caused by nearby wind farms (based on 210 transactions within 5 km), although in the third, non-adjacent county studied there was a slight positive effect (from 250 transactions in the same size radius). Data from the two negatively affected counties consisted mostly of post-announcement pre-construction sales, with the turbines only becoming operational for a very short period before the study ended. The county that showed a slight positive effect had more data covering both pre-construction and post-construction periods because the wind farms in question became operational several years earlier. Furthermore, due to the way the authors incorporated the distance variable into their model (using an inverse distance effect), they extrapolated the negative effects to within a very close distance of the turbines, despite the fact that they only had 10 transactions within half a mile of any of the turbines studied.[11] This makes it difficult to warrant the conclusions of this study as statistically valid.[6]

Tracing property prices in relation to the development phase of a nearby wind farm can be important. What many hedonic price model studies have shown is an 'anticipation stigma', whereby the perceived negative impact of wind turbines being constructed nearby causes a transitory drop in house prices, which quickly reverses when these negative affects fail to materialise post-construction.[3,4,6,7,12] This anticipatory effect was also illustrated by community responses to early wind farm developments in the UK. In 2003 the Scottish Executive commissioned a landmark survey to assess the impact of wind farms on nearby residents, using ten major sites across the region.[13] The survey design was carefully planned and extensive in scope, and took into account how close to the wind farms residents lived, encompassing the surrounding 20 km of each site. Overall, only 7% of those questioned said their local

---

[§] This included one of the larger wind farms comprising 26 turbines.

wind farm had had a negative impact on the area; this is compared to 20% who said the impact was positive, and 73% who felt it had no impact either way.

Perhaps most surprisingly of all, respondents in the Scottish survey who lived closest to the wind farm (<5 km) and could see the turbines most often made up the highest proportion of those who responded positively. Those respondents who were already living in their house prior to the wind farm being built were asked about house prices. Some 7% of them said that they had anticipated that house prices would be reduced by the wind farm; when asked about the actual effect, the number who said house prices had fallen dropped to just 2%.[13]

In many cases, the stigma is reinforced by the opinions of estate agents when planning for wind farms begins, but this viewpoint is found to be misguided when post-construction data is available.[4,14,15] It is accepted that predictions by estate agents are found to be inaccurate (negative predictions in particular often being significantly inflated) when compared with actual transaction data and the views of the buyers themselves.[3–5,14,15] Furthermore, the actions of groups inherently opposed to the construction of wind turbines can distort popular perceptions of how a community integrates a new installation. The RICS-sponsored research on early wind farm developments in Cornwall found that 95% of objections raised during the planning stage originated from non-locals.[4]

Failing to account for the trends in property values at all times before, during and after wind farm development can obscure drivers of house prices that are independent of the presence of wind farms. It is clear from the most robust studies that incorporate this detail that lower house prices are not related to wind farms, often being lower than the surrounding average before plans to site a wind farm are even announced.[6–8,10,12] Due to the anticipation stigma effect, house prices may drop temporarily before construction begins, at a time when the influence of residents' own uncertainty is particularly acute, often compounded by negative reactions from outside sources and a tendency for estate agents to treat future wind farms as a disamenity.[3–5,12,14] This has been found to recover relatively quickly when construction is complete and the sites are operating.[3,4,12,13]

The largest studies that show a negative effect due to turbine proximity or visibility, such as the report from the LSE's SERC, do not account for the whole timeline and therefore much of the data does not reveal price trends prior to any planning announcement.[9,11] In addition, the LSE study does not account for house price trends within the postcode areas that received wind farms, but has to rely on broader regional trends, which makes it difficult to control for the effect of wind farms in this instance.[9]

For the majority of large-scale studies, which show wind farms have no effect, the data show no change in sales activity in areas that receive wind farms, and repeat sales data that is available suggest no drop in prices between pre-announcement and post-construction for houses with nearby wind farms.[3,7,8] The England and Wales study from SERC also reported a remarkably consistent sales volume for all sites pre- and post-operation of wind farms,[9] although it is difficult to know if pre-operation sales covered the pre-announcement or just pre-construction phases. The SERC report did discount the variable of lower-quality housing after analysing postcode data within a 4 km radius. The large U.S. studies, however, analysed property prices within less than 1 km of wind farms, where turbines could reasonably be expected to be visible from all properties. These analyses showed both consistently lower property values prior to any announcement of a wind farm, and did not show any effect of the wind turbines following construction, even though the samples were large enough to catch an effect of the size reported in the SERC report.[7,8]

Lack of detailed data relating to timing in the SERC study, in contrast to the different construction and operation phases described in the Berkely group reports, can obscure the real effect of variables other than wind turbines themselves.[6,7] First, it is impossible to see the impact of any parallel trends in house prices that existed already and were unrelated to wind turbines. Second, lack of data on how prices track over the course of a wind farm's development also fails to account for any anticipation effects. For instance, homeowners who are convinced they must move as soon as news of a wind farm development is made public can skew results based on the limited sales data from a handful of postcodes close to the turbines, because such owners are more likely to accept a lower price to ensure they can move. Thus, this drives the downwards trend in house prices observed near wind turbine sites, but does not capture the temporary nature of this trend. Other studies based in the UK have, indeed, shown that house prices can rebound and even exceed the overall regional trends in property values.[6,10,12,13]

Conclusion

The amenity and disamenity effect of any infrastructure development must be seriously considered, and wind turbines are no exception. Residential property is the single largest financial investment most people will make in their lifetime, and it is justifiable that owners are concerned by changes that may negatively affect property values. The anxiety over house price trends caused by many different factors can be compounded by the uncertainty introduced whenever a major development such as a wind farm takes place near a community. The novelty and high visibility of commercial-scale wind farms makes them an obvious conduit for residents' concerns, but also one for misinformation. Despite anti-wind protests insisting that wind turbines will lower property values in the surrounding area, an increasingly large body of evidence from several major UK and American studies shows that this is not the case. In many cases, detailed analysis over the different phases has revealed that an 'anticipation stigma' commonly manifests in a short-lived drop in values close to proposed wind farms, but prices quickly recover following construction and operation, and may even outperform regional averages. Fears stoked by pressure groups and mistaken preconceptions by estate agents add to residents' own worries, and it is not surprising that this can translate into a temporary dip in house prices at a time when the real impact of a such a development can only be imagined.

One major study released by the London School of Economics (LSE) used England and Wales postcode sales data to demonstrate a possible effect driven largely by the visibility of nearby wind farms. The study draws on a very large dataset, but the maximum price reduction effect stated (roughly 5% if within 2 km) is large enough that it should have been caught by several other large-scale studies, but the majority of these studies have failed to show any significant effect.

Therefore, it is difficult to say why this one study contradicts the other major studies, although it is possible that the lack of any detailed analysis of pre-planning data versus the post-operation phase of the wind farms may introduce confounding factors. This means any pre-existing trends in property prices, or short term trends driven by anticipation stigma, may not be properly accounted for.

However, it is possible that lack of timeline data may actually obscure the negative impact of wind farms on house prices. For instance, the LSE's report (mentioned above) only takes account of operational turbines, i.e. not those that are partially constructed. If the construction phase does cause house prices to be lowered, then this might affect overall house price trends, as we seen in the anticipation stigma. In the case of the LSE's report, this would lead to an underestimate of the effects of wind farm developments, since the downward trend in house prices attributed to completed wind farms would not appear to be as dramatic, thanks to prices already being lower as a result of the negative impact of wind farm construction. However, this can only be speculated, because the existing LSE study does not account for house price trends within the postcode areas that received wind farms, but has to rely on broader regional trends. This makes it hard to control for confounding factors that are affecting house price trends generally.

A different study using site-specific data from England and Wales, but one that accessed a similarly large number of transactions as the previous report, assessed a longer time period both before and after wind farms were planned and built. This study demonstrated that the state of the regional (county) housing market was the main driver of house prices between 1995 and 2013, and this remained the case during and after wind farm construction. Property values within 5 km of a wind facility were not reduced at all by the presence of turbines, in fact, in some cases, the proximity of a wind farm had a small positive effect on property values.

Given the importance property value holds with a large proportion of the population, controversy over the effects of wind turbine proximity on house prices is unlikely to diminish in the near future. In sporadic cases, it is entirely possible that the presence of a commercial wind turbine may act to reduce a particular amenity associated with a property, and such a tiny fraction is unlikely to be revealed in anything but the most exhaustive statistical analysis. However, the balance of evidence clearly shows that wind turbines have no long-term effect on house prices in surrounding areas. Fears that prices may be reduced are largely driven by uncertainty surrounding local changes to an area coupled with activism by anti-wind groups, often instigated by remote actors rather than local residents. Within this milieu, it is not surprising that some temporary price reductions can occur, typically in the early stages of planning and construction. The experience of operating wind farms is that long-term effects are generally neutral or even slightly positive.

References

1. Dagnall S, Prime J. Chapter 6 – Renewable sources of energy. In: Digest of United Kingdom Energy Statistics 2013. London: The Stationery Office/TSO; 2013. 155–89.
2. REN21. Renewables 2013 Global Status Report. Paris: REN21 Secretariat; 2013. 49–52.
3. Hoen B, Wiser R, Cappers P, Thayer M, Sethi G. The impact of wind power projects on residential property values in the United States: A multi-site hedonic analysis. Report No. LBNL-2829E. Berkeley: Ernest Orlando Lawrence Berkeley National Laboratory; Dec 2009. 164 p.
4. Sims S, Dent P. Property stigma: wind farms are just the latest fashion. J Property Invest Finance. 2007; 25(6):626–51.
5. Sims S, Dent P, Oskrochi GR. Modelling the impact of wind farms on house prices in the UK. Int J Strateg Prop Manag. 2008; 12(4):251–69.
6. Hoen B, Brown JP, Jackson T, Wiser R, Thayer M, Cappers P. A spatial hedonic analysis of the effects of wind energy facilities on surrounding property values in the United States. Report No. LBNL-6362E. Berkeley: Lawrence Berkeley National Laboratory; Aug 2013. 58 p.
7. Atkinson-Palombo C, Hoen B. Relationship between wind turbines and residential property values in Massachusetts. Report No.: LBNL-6371E. Joint report of University of Connecticut and Lawrence Berkely National Laboratory; Jan 2014. 47 p.
8. Lang C, Opaluch JJ, Sfinarolakis G. The windy city: Property value impacts of wind turbines in an urban setting. Energy Econ. 2014; 44:413–21.
9. Gibbons S. Gone with the wind: valuing the visual impacts of wind turbines through house prices. SERCDP0159. London: Spatial Economics Research Centre, LSE; Apr 2014. 49 p.
10. CEBR and RenewableUK. The effect of wind farms on house prices. Collaborative report between Centre for Economics and Business Research and RenewableUK; Mar 2014. 66 p.
11. Heintzelman MD, Tuttle CM. Values in the wind: a hedonic analysis of wind power facilities. Land Econ. 2012; 88(3):571–88.
12. Hinman JL. [Master's thesis] Wind farm proximity and property values: A pooled hedonic regression analysis of property values in central Illinois. Department of Economics, Illinois State University; May 2010. 143 p. [Last accessed 19 Aug 2014]. Available from: http://renewableenergy.illinoisstate.edu/wind/pubs.shtml.
13. Braunholtz S. Public attitudes to windfarms: a survey of local residents in Scotland. Edinburgh: MORI Scotland; 2003. [Last accessed 24 Nov 2010]. Available from: www.scotland.gov.uk/publications/2003/08/18049/25579.
14. Khatri M. Impact of wind farms on the value of residential property and agricultural land: a RICS survey. London: Royal Institute of Chartered Surveyors; 2004. 11 p. [Archived 28 Jan 2006]. Available from: https://web.archive.org/web/20060128125726/http://www.rics.org/NR/rdonlyres/66225A93-840F-49F2-8820-0EBCCC29E8A4/0/Windfarmsfinalreport.pdf.
15. Sims S, Dent P. High-voltage overhead power lines and property values: A residential study in the UK. Urban Stud. 2005; 42(4):665–94.

Chapter 10

Siting wind farms on ecologically sensitive land

Summary

Although many environmental drivers, both natural and man-made, have historically had more far-reaching impacts on sensitive environments than wind farms are likely to, the addition of any intensive renewable energy development on such land creates an additional pressure. Therefore, it is necessary to consider these impacts in the context of vulnerable habitats, especially so for wind power since by its nature many of the most viable wind resource sites in the British Isles coincide with areas of unique ecological and cultural value. Nowhere is this more evident than the upland fens and bogs that are characterised by peaty soils, which not only support habitats of international importance due to their rarity across Europe, but also sequester significant quantities of carbon in the soil itself. In all cases, the strategic importance of renewable energy developments must be weighed against the potential stress such developments can place on sensitive or overburdened ecosystems.

Existing windfarms in upland areas, particularly in Scotland and Ireland, have shed some light on how good practices can ameliorate the negative effects that infrastructure and turbine construction can have on upland habitats. In some cases, windfarm developments can be successfully combined with peatland reclamation due to the requirement that commercial conifer stands are cleared in the proximity of turbines, although these associated forestry operations can themselves have short-term effects on ecosystem function, such as streamwater nutrient flows. In addition, disruption of upland habitats can exclude some bird populations during wind turbine construction. Despite evidence that some species numbers recover post-construction, this is not the case for several species of waders; thus, careful site assessment is needed to ensure important species are not permanently displaced.

What is this based on?

As with any infrastructure development, wind farms require the construction of site facilities and associated transport structures to enable the connection, maintenance and operation of turbines so that they can supply electricity to the national power system. Because of the nature of the wind resource across the British and Irish Isles, many of the best sites for wind farms fall within areas of peatland.[1,2] Upland areas have higher average wind speeds and thus offer the best returns in terms of renewable electricity and financial reward. The negative perception of local wind farm developments, which has been particularly strong in the UK in comparison with many other European countries where community ownership is more common, also means that developers are often keen to site turbines further away from the more settled lowland areas.[3,4] These same upland areas, however, are characterised by high rainfall, high water tables and low agricultural productivity; consequently, a large proportion of the UK's upland areas are covered by heather-dominated moorland, fens and bogs.[5]

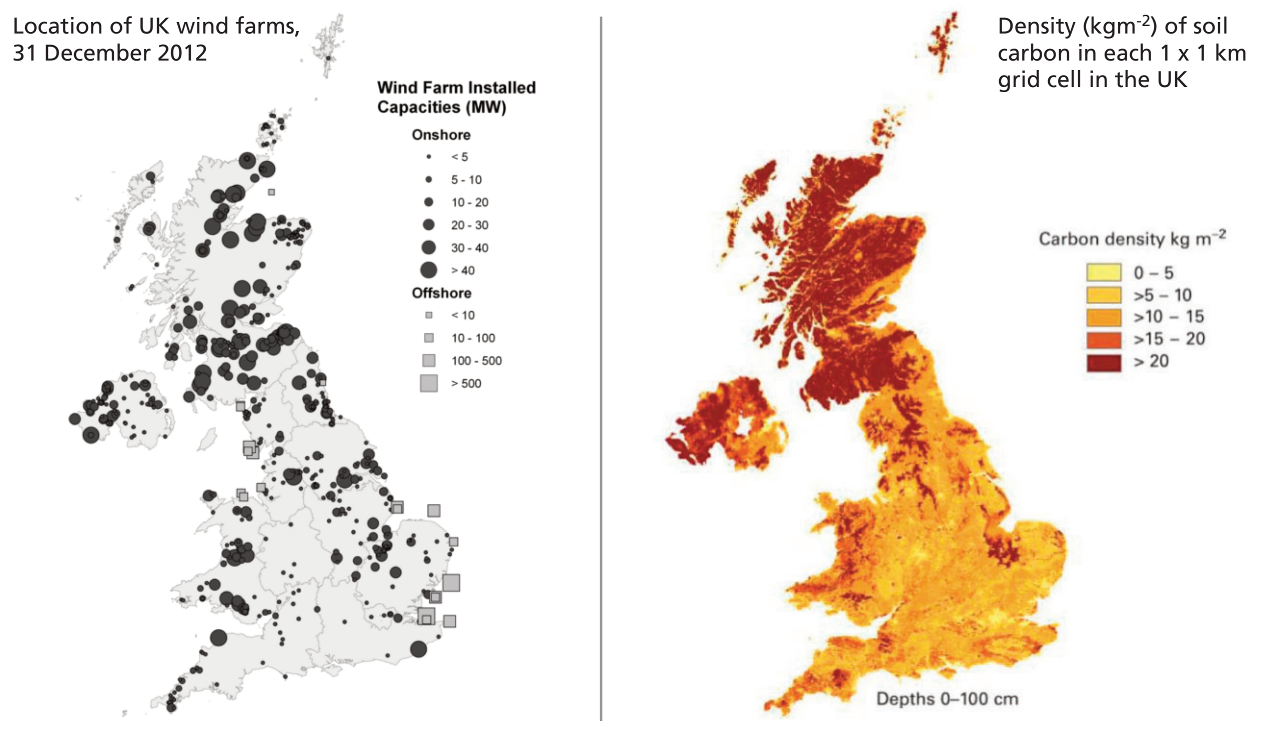
Due to their disappearance across many areas of Europe, upland habitats in Britain and Ireland are of international importance, particularly the fens and bogs.[1,5] The wet conditions and cool temperatures that are prevalent allows the formation of peaty soils, which are very high in organic content and act as a major carbon 'sink'. The flux of carbon in habitats with peaty soils is generally in the direction of sequestering carbon in the soil fraction, rather than releasing carbon (in the form of CO_2) back into the atmosphere, so these peatland areas represent an important resource with regards to mitigating carbon emissions.[5] Indeed, such is the density of carbon in peaty soils that Scotland alone, where there is a preponderance of upland habitats, holds nearly half of all the UK's soil carbon,* even though Scotland makes up less than one-third of the UK's total land area.[6] A significant proportion of the UK's major existing and planned wind farms are sited in upland areas (see Figure 11.1).[7]

Although most existing wind farms are sited on the fringes of core habitats, growing numbers of these developments means that there will be increasing pressure on sensitive ecological areas in the UK, in particular those dominated by moorland, fens and bogs.[5] At the end of 2013, Scotland contained 61% of the UK's total installed onshore wind capacity, which illustrates the general trend for wind farms to be within

---

* The actual figure for Scotland is 48%. For comparison, England accounts for 38% of the UK's total soil carbon, even though it makes up more than half (54%) of the UK's land area.

Figure 10.1 The preponderance of wind farms situated in upland areas that coincide with peaty, high-carbon soils. (Maps from ref. 6 and 7, with permission.)



Location of UK wind farms, 31 December 2012

Density (kgm^{-2}) of soil carbon in each 1 x 1 km grid cell in the UK

potentially sensitive and important habitat areas.[8] With careful planning and attention to restorative works following construction, it is possible to minimise the negative impact of wind developments on sensitive habitats whilst benefiting from the positive contribution made by the supply of renewable electricity. However, failure to follow good practices in areas with carbon-dense soils (mainly peat, but woodland areas too) can negate much of the carbon emission savings, resulting in only small reductions at the cost of disrupting important ecosystems.[2]

What is the current evidence?

Experience with extensive wind farm developments on peatland areas in Scotland and Ireland has hastened a range of guidelines and legislation to inform developers during the construction period, and also restorative work that must be undertaken afterwards.[1,9] In particular, a notable landslide in a blanket bog area in Ireland in 2003 following the installation of a 60 MW wind farm led to the formulation of extensive guidelines to monitor and mitigate 'peat slide'.[1] In the UK, this led the Scottish Executive to establish clear guidelines and requirements for any energy-related development in peatland areas.[10] These requirements include surveying to reveal deep peat soils where developments should be avoided altogether.

The major impact on upland areas is soil disturbance caused by construction of the turbines themselves and also related forestry operations.[9] For peaty soils, these disturbances can significantly affect streamwater chemistry, meaning that the flow of nutrients and organic compounds (the latter primarily made up of carbon), is perturbed in the local catchment area.[11] For peaty soils, with their ability to sequester large amounts of carbon thanks to the prevailing temperate and wet conditions, the increasing flow of organic matter out of the area can be a problem if this leads to excessive export of stored carbon.[2]

The forestry operations are carried out for several purposes. In addition to the trees cleared to site the turbines themselves, sometimes it is necessary to clear an area to reduce turbulence and improve wind flow to maximise the output of the wind farm. Furthermore, trees can be harvested around the area of a wind farm as part of a habitat management plan, often carried out to increase the area of blanket bog to compensate for vegetation lost to the turbine siting and provide alternative foraging grounds for native wildlife.[12] It should be remembered that the major cause of habitat loss in UK upland areas in the post-war years is due to more intensive grazing of marginal lands, commercial forestry plantations and the deposition of airborne pollutants.[†] [5,13] As such, restoration of traditional peat

---

[†] In addition to acidification caused by airborne pollutants, which has declined since the 1980s, major disruption to upland habitats is caused by active nitrogen compounds being deposited at relatively high levels, creating imbalances in the nutrient cycle that adversely affect native plant species in sensitive ecosystems like upland heaths and bogs. This nitrogen deposition is an ongoing problem.

bogs is a priority for the UK Biodiversity Action Plan, and also benefits the national climate change mitigation strategy by increasing soil carbon storage; thus, habitat management plans can be considered an enhancement in some cases, not just a compensatory measure.[5,12]

Several major wind farms in Scotland can be found situated in upland areas of mixed commercial forestry plantations and bog habitats. Several of these sites have been the subject of extensive surveys since the planning stage, resulting in, for example, decisions to reroute access roads across peat areas that were already degraded due to forestry instead of disturbing pristine undrained soils.[12] However, disturbances are inevitable, and existing developments have provided useful demonstrations in how wind farm developments can temporarily alter habitats in sensitive areas at all stages, including post-construction. It has revealed the importance of monitoring nutrient flows out of the catchment area before and after development, and the importance of accurately tracing the source of nutrients, such as whether they are from fractions of differing ages stored in the soil, or from excess atmospheric deposition.[11]

It is also clear that associated forestry operations are a major cause for the increases in the level of carbon and phosphorous export observed in streamwaters of a wind farm development, although the same study also found that access tracks and their associated features (e.g. settlement ponds and ditch blocking) could, conversely, reduce the export of organic matter.[9] One feature of forestry clearfelling and habitat restoration that requires careful balancing is the use of 'brash mulching' to protect the exposed peaty soils after trees are harvested; even though this helps speed up the process of bog restoration, this technique can significantly increase nutrient run-off into surrounding waters (brash is the leftover residue from felled trees that is not suitable for the timber trade, like small stems and conifer leaves, and it has a high nutrient content). Solutions may involve the phased application of brash mulching to even out the flow of nutrients into streamwater, removing some of the excess brash material and using it for biomass energy, or immediate seeding of cleared areas with fast-growing grass species.[9]

For any renewable energy project, calculating the carbon emissions created by developing a previously undeveloped area, especially where the soil is carbon-dense, and setting these against the carbon emissions saved through the generation of renewable electricity is paramount.[2] There are many nuances to this, such as accounting for the natural flux of carbon emissions from peatlands – for example, undrained peat soils will effectively sequester CO_2 but they do emit higher levels of CH_4 (methane, another greenhouse gas) than drained soils. A very comprehensive lifecycle assessment of a large Scottish wind farm development suggests that best practices can mean carbon emissions from development can be as little as 9% of the emissions saved (i.e. savings are still significant); without proper management of the site the emissions savings may be reduced by as much as 34%; and if the site selection is poor in combination with minimal habitat management and restoration, then the carbon savings may be cancelled out almost entirely.[2] The key to best practice is careful site selection to avoid excessive drainage of undisturbed peatland, combined with prompt and carefully managed habitat restoration to mitigate disturbances caused by turbine construction and access roads.

One final consideration is the impact a development may have on wildlife.[‡] Several species of birds of conservation importance are located in upland habitats, although major developments for wind farms tend to fall outside those areas where bird populations are most sensitive.[14] Monitoring of bird populations during and after construction of wind turbines has shown that many species are not seriously affected overall, with the most acute disruption occurring during the construction phase.[15,16] However, although many displaced bird populations do return to the vicinity of developed areas once construction is over, numbers may take a some time to reach pre-construction levels. Furthermore, some species, such as snipe and curlew, show a strong aversion to wind turbines and do not repopulate in developed areas.[16] It is vital that steps are taken to prevent further displacement of particularly vulnerable species.

Conclusion

Any construction works or installation that encroaches on the natural or semi-natural landscape must be subject to an Environmental Impact Assessment (EIA), as prescribed by EU law.[17] The upland areas of the UK, which are typically further from settled areas, less agriculturally productive and more exposed, offer the best wind resources in the country. These same conditions are also largely responsible for the formation and maintenance of upland heaths, fens and bogs containing peaty soils – the rarity of these across Europe means that such habitats in the British Isles are of special conservation importance. Due to the ability of peaty soils to store large amounts of carbon and act as a carbon sink, UK peatlands also represent an important strategic resource in relation to climate change mitigation. Thus, although the principles of the EIA and good practices apply to any site where a wind farm is to be developed, the UK upland areas are of particular consequence as they are where key climate change and conservation interests converge.

[‡] The effect of wind farms on wildlife is discussed in further detail in Chapter 12.

Given their nutrient-dense soils and high water tables, disturbances to undrained peatland habitats represent the biggest potential for ecological impact when constructing wind farms. The EIA can identify where siting is appropriate and what measures can be taken to minimise or mitigate these impacts. In many instances, peatland that has already been degraded by commercial forestry or intensive grazing can be used with minimal adverse effects, and careful habitat management planning can even improve the status of valuable bog habitats due to the requirements for commercial forest clearing. Once construction is complete, the resulting 'footprint' of an operating wind turbine array is relatively small in relation to the total area encompassed by the wind farm, although developers should take into account the impact of drainage and the potential to fragment pristine habitat areas. In addition, the impact on important avian species is expected to be minimal based on evidence from existing and planned wind farm sites, but there are a few individual species of waders that appear to be vulnerable to disruption. Measures such as mobile screening, no-go areas and prohibiting construction activities during breeding seasons may go some way towards mitigating the impact on these species, although more observations are necessary to confirm whether these will be effective.

References

1. Renou-Wilson F, Farrell CA. Peatland vulnerability to energy-related developments from climate change policy in Ireland: the case of wind farms. Mires Peat. 2009; 4:Art. 8.
2. Nayak DR, Miller D, Nolan A, Smith P, Smith JU. Calculating carbon budgets of wind farms on Scottish peatland. Mires Peat. 2010; 4:Art. 9.
3. Toke D. Explaining wind power planning outcomes: some findings from a study in England and Wales. Energy Policy. 2005; 33(12):1527–39.
4. Toke D, Breukers S, Wolsink M. Wind power deployment outcomes: How can we account for the differences? Renew Sustain Energy Rev. 2008; 12(4):1129–47.
5. Van der Wal R, Bonn A, Monteith D, et al. Mountains, moorlands and heaths. In: *The UK National Ecosystem Assessment Technical Report.* Cambridge: UK National Ecosystem Assessment, UNEP-WCMC; 2011. 105–60.
6. Bradley RI, Milne R, Bell J, Lilly A, Jordan C, Higgins A. A soil carbon and land use database for the United Kingdom. Soil Use Manag. 2005; 21(4):363–9.
7. Dagnall S, Prime J. Chapter 6 – Renewable sources of energy. In: *Digest of United Kingdom Energy Statistics 2013.* London: The Stationery Office/TSO; 2013. 155–89.
8. 'Renewable electricity capacity and generation (ET 6.1)', *Statistics: Energy trends section 6: renewables,* Department of Energy and Climate Change, Excel spreadsheet www.gov.uk/government/uploads/system/uploads/attachment_data/file/323527/et6_1.xls (last updated 26 Jun 2014), accessed 21 Jul 2014.
9. Murray HS. Assessing the impact of windfarm-related disturbance on streamwater carbon, phosphorus and nitrogen dynamics: A case study of the Whitelee catchments. PhD thesis. University of Glasgow; 2012 [last accessed 20 Aug 2014]. Available from: http://theses.gla.ac.uk/3343.
10. Scottish Executive. *Peat landslide hazard and risk assessments: best practice guide for proposed electricity generation developments.* Edinburgh: Scottish Executive; 2007. 72 p.
11. Waldron S, Flowers H, Arlaud C, Bryant C, McFarlane S. The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance, a stoichiometric perspective. Biogeosciences. 2009; 6(3):363–74.
12. SNH. *Good practice during wind farm construction.* 2nd edition. Joint publication by Scottish Renewables, Scottish Natural Heritage, Scottish Environment, Protection Agency, Forestry Commission Scotland, Historic Scotland; 2013. 86 p.
13. RoTAP. *Review of Transboundary Air Pollution: Acidification, Eutrophication, Ground Level Ozone and Heavy Metals in the UK.* Penicuik, Midlothian: Centre for Ecology & Hydrology; Jun 2012. 316 p.
14. Bright JA, Langston RHW, Pearce-Higgins JW, Bullman R, Evans R, Gardner S. Spatial overlap of wind farms on peatland with sensitive areas for birds. Mires Peat. 2008; 4:Art. 7.
15. Douglas DJT, Bellamy PE, Pearce-Higgins JW. Changes in the abundance and distribution of upland breeding birds at an operational wind farm. Bird Study. 2011; 58(1):37–43.
16. Pearce-Higgins JW, Stephen L, Douse A, Langston RHW. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. J Appl Ecol. 2012; 49(2):386–94.
17. European Parliament and the Council of the European Union. (2012) Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. Off J; 55: L26/1.

Chapter 11

What effect do wind turbines have on wildlife?

Summary

Reports of excessive avian mortality present in some of the first large-scale wind farms built in the 1980s, which particularly affected some protected and endangered bird of prey species, have cemented a long-standing misconception that most wind turbines will inevitably cause disproportionate harm to bird populations in the vicinity. In fact, wind turbines kill far fewer birds than other human activities. Birds colliding with building windows and the predations of domestic and feral cats are the leading causes of avian mortality due to human activity, and both far exceed anything caused by wind turbines. In terms of emissions and pollutants and the wider impacts these can have on wildlife, wind is also a significantly more benign source of electricity when compared to conventional forms of power generation.

Of more concern is the issue of bat fatalities, which may have a proportionally larger and more damaging effect due to the slow rate at which bats reproduce. The foraging and migratory patterns of bats are not well understood, although more data is being amassed across sites in Europe and America. Although it is thought that the unexpectedly high mortality at some sites may be accounted for by altered behaviour during seasonal migrations, there is the possibility that bats may be affected when following normal foraging patterns too. Thus, the matter is still subject to a significant degree of uncertainty, and there is an urgent need to acquire more data and incorporate what existing – albeit limited – knowledge of bat movements there is into the decision process when siting wind farms and placing individual turbines. There have been encouraging signs that some mitigation methods may be able to significantly reduce bat mortality rates, but these are so far unproven on a large scale.

Very little is known about the effects of wind turbines on non-volant animals (i.e. animals that do not fly), with only a limited number of studies on certain terrestrial species. Most evidence suggests that wind turbines have no discernable effect on the behaviour and population levels of the animals studied, which includes elk, reindeer, ground squirrels and tortoises. Although not as apparently pressing an issue as is the case for bats, there is clearly much scope for research to be done on terrestrial species as the number of operational wind farms continues to increase. In addition, it has been noted that many wind farm operators remain reluctant to openly share data on wildlife mortality, which harms research and may ultimately lead to flawed policy planning.

What is this based on?

Avian mortality due to all sorts of human activity (anthropogenic causes) has been well-documented for many decades, and is an ongoing area of research.[1–8] Some of the first large-scale wind farms built in the 1980s had a number of attributes that, it was soon realised, were causing a worryingly high number of avian fatalities due to birds colliding with operating turbines.[9] As well as some design features, the placement of these wind farms across habitats used by ecologically sensitive bird of prey (raptor) populations compounded the problem, resulting in particularly deleterious effect on some protected populations of rare species.[10] These instructive incidents took place in major wind developments built in several regions of Spain and in the US state of California.

Since the 1980s, changes in turbine design, size and siting procedures have reduced the extent of damage to avian wildlife by wind farms built subsequently, but the mistakes of earlier projects have created a deeply rooted misconception that most wind farms will inevitably cause disproportionate harm to bird populations in the vicinity. In fact, this is demonstrably not the case, with data suggesting that wind turbines kill far fewer birds than other human activities.[11] However, the impact on avian mortality should not be trivialised. As will be discussed subsequently, impacts can be disproportionate for certain species, and there are limitations to the existing data. Hence, ongoing concerns are not entirely unjustified.

The significant impact wind turbines can have on bat populations was first appreciated when reports emerged from the USA of a small number of wind farms in the Appalachian Mountains where surprisingly large numbers of bat carcasses had been found.[12,13] Although these particular instances seemed out of the ordinary, since other wind farms in the USA had reported much lower levels of bat mortality, the fact that bat population growth is relatively slow means they have a limited ability to recover from excess deaths.[14] This concern prompted more research into bat deaths at wind farm sites, and similar problems were also found at sites across Europe.[15] Deaths occur between many different species of bat, some populations of which are more sensitive to population decline than others.

Unlike the case of avian deaths, there is as yet no clear link between the general characteristics of wind farm sites, e.g. topography, and bat mortality caused by wind turbines. Why some species are affected at one site and different species are affected at another site is also not clear, although migratory patterns are likely to play an important role.[14,16] The evolution of wind turbine design and siting has not had the same effect of reducing mortality for bats as it has for birds.[17] The relative lack of data on bat behaviour also means that mitigation methods are not yet proven, although there are promising results from a few trials.

Not surprisingly, *volant* species (animals able to fly or glide) have been the focus of research with regards to the effect wind turbines have on wildlife. Comparably, the published research on the impact of wind turbines on *non-volant* species (animals that cannot fly) is sparse.[18] Pilot studies on terrestrial species, such as reindeer and caribou, suggest wind turbines do not have any meaningful impact on these populations. As discussed later on in this chapter, there is some limited evidence that wind turbine installations may affect prey–predator relationships both on land and in the sea, although in several cases the impact may have a beneficial effect on some species.

Limitations of existing data

Although several large-scale studies appear to be converging on roughly comparable estimates for avian deaths attributable to wind turbines[1,3] there remains a great deal of uncertainty within each data set, which often contain biases or wide-ranging estimates as a result.[1,2] Inconsistencies are evident when different data sets are compared, which is compounded by a lack of clarity in the way avian deaths at wind farm sites are often reported by the industry.[2,3] There are issues with the way areas are searched for evidence of bird fatalities, such as monitoring periods that are too short or fail to account for seasonal variability, difficulties inherent in finding carcasses in the first place, inappropriate intervals between routine carcass searches, and search radii that are too small.[2,1,19,20] We can ‘unpack’ some of these limitations, which helps illustrate the complexities inherent in assessing environmental impacts.

Not accounting for seasonal variability is an important consideration when monitoring wildlife impacts, especially for avian or bat species that are migratory. Monitoring periods are often too short (sometimes just six to eight weeks in a year) to account for interannual changes in population number. Although the timing of these monitoring periods are usually based on seasonal periods predicted to have high mortality, these short windows can have the effect of underestimating year-round mortality. Not only are significant fatalities missed in outside periods, but shorter search period means that fewer carcasses are found, which skews data when extrapolated.[2] To more effectively estimate year-round mortality, data should be collected in all seasons. For migratory populations, data should be collected throughout the whole migration period, rather than transecting the study population at one point during the migratory period.[19]

One ubiquitous limitation is low searcher-detection rate, which is a constant problem for any environmental impact study that relies on monitoring carcasses (bird, bat or otherwise), although there are statistical models to account for this; these models, however, require the application of appropriate search intervals.[2,20] For instance, a carcass missed by a searcher on a first pass may very likely be taken by scavengers within three days, so too long an interval between passes during any particular monitoring period will underestimate fatalities. Carcasses that have been dismembered by contact with turbine blades are harder to detect, as are carcasses that have been missed on the first pass and subsequently decomposed (if not taken by a scavenger already). A one-day interval between searcher passes may introduce a very slight positive bias into fatality rates, because, for example, dead birds killed by something other than the wind turbines are also more likely to be detected and may be included in the total for turbine-related fatalities.

Conversely, search intervals of seven days or more introduce a strong negative bias as many carcasses will be missed due to decomposition and removal by scavengers.[2] As mentioned already, these effects can be modelled to some degree, but search intervals must be appropriate and be consistently applied and clearly reported.[1,3,20] All of this also underlines the need to increase the chance of finding a carcass in the first place as much as possible. This can be accomplished, for example, by ensuring intervals between searches are not too long, or improving detection probability through the use of dogs, a method that has seen notable success when applied to studies of bat mortality at wind farms.[2,20,21]

Another example of the limitations of existing data for wind farms is that the search radius as a factor of turbine height may be routinely underestimated. For example, initial monitoring of problem sites in California typically used a maximum search radius of 50 metres when recording avian fatalities due to collisions with turbines, but subsequent research suggests this radius could be set as high as 125 metres.[2] That said, whilst there is general agreement that search radii being too small introduces a negative bias in reported mortality rates, it is also the case that background mortality (i.e., bird carcasses found in the search area that were not killed by the turbines) introduces a positive bias – this positive bias will increase as the search radius gets bigger, leading to an overestimate of avian deaths being attributed to wind turbines.[1]

Other errors arise due to lack of pre-impact population data, biases in extrapolated results that can positively or negatively skew estimates, and insufficient data to properly extrapolate site-specific figures to obtain meaningful estimates of the population impact on a regional, national and continent-wide scale.[11,19] These limitations apply equally, if not more so, to data obtained for bat fatalities. It is essential to understand that these limitations in the data exist, but it is also important to note that such limitations exist for all types of environmental impact assessments of this kind. As will be pointed out several times throughout this chapter, turbine-related mortality data for birds and bats is comparatively well-documented when measured against other human structures, such as conventional power plants, residential and commercial buildings, or road networks. Thus, whilst rates of avian and bat mortality are not to be dismissed, it is increasingly clear that wind power poses much less of a threat to wildlife than many existing human activities, even before taking into account any benefits of climate change mitigation.

What is the current evidence?

Impact on bird populations

At one of Spain's oldest wind farm developments in the Navarre region, the mortality rate for griffon vultures, a vulnerable species, was found to be exceptionally high; and in southern Spain similar results were seen for griffon vultures at several wind farm facilities in the mountains of the Campo de Gibraltar region.[4,10] The particular arrangement of turbines along ridges used by migrating raptors to gain height in the absence of thermals was thought to contribute to the high rate of fatalities, as little difference was seen between turbines of older and newer designs. Although relatively small in terms of generating capacity, several other European wind farms were also found to be responsible for excess mortality in sensitive breeding populations of seabirds (Zeebrugge, Belgium) and white-tailed eagles (Smøla, Norway).[4,22]

In the Altamont Pass Wind Resource Area (APWRA) in California, the first wind farm developments had turbines sited with very little consideration for the indigenous raptor populations, causing an excessive rate of mortality in six raptor species.[9] This effect is not observed to such a degree in similar wind farms sited elsewhere in the USA leading to the conclusion that poor planning and outmoded turbine design is largely responsible.[23] This is supported by evidence from APWRA sites that have been 'repowered', i.e. a smaller number of larger, modern monopole turbines have replaced older designs, which subsequently saw a significant decline in mortality rate.[24]

Whilst research is still ongoing, there is already a great deal of data available on the overall effects of wind turbines on bird populations. As with data on anthropogenic causes of avian mortality in general, much of this information collected is site-specific and requires a great deal of assimilation to enable an ecosystem-wide view of the effects of wind power on birds. There are also limitations due to inter-annual variability – mortality studies typically take place for short periods (a few months) based on seasonal periods predicted to have high mortality, but this has the effect of underestimating year-round mortality. It is possible that significant fatalities are missed in outside periods, and shorter search periods means fewer carcasses are found, which skews data when extrapolated.[2] The effects from these spatially restricted studies are often extrapolated to effects on regional populations and thence to national populations, even though the uncertainties are considerable when attempting to match up population trends across so many different scales.[19]

Similarly, studies rarely (if ever) incorporate mortality estimates specifically into the local populations that are directly affected. Instead, local mortality rates are frequently compared with total national or continent-wide populations.[1] Even though low mortality compared to total population would indicate there is not a problem, this approach tends to underestimate other considerations, such as the carrying capacity of the area affected locally and how the impact of developments can adversely affect species richness and population density in that area.[19] For some species, obtaining species-specific data may be crucial for the effective implementation of measures designed to conserve rare or vulnerable populations.[25] It is important not to overlook these issues of geographical scale. The population of a species within a particular region needs to remain viable, because the gradual cumulative fragmentation of bird populations may eventually pose a significant threat to the more vulnerable or less adaptive species.[26,27]

As the phenomenon of bird collisions with wind turbines becomes more widespread, as is inevitable if more turbines are built, then extrapolating local observations and small data sets to national scales is complex and comes with many caveats. Effects are immediately apparent when a 'headline' species (e.g. the griffon vulture and white-tailed eagle) are relatively confined to

a particular landscape or habitat, but when attempting to infer the impact of wind power on more widespread species (mostly songbirds and other small, perching birds, known collectively as passerines) it is important to account for estimates comparing different spatial scales. However, extrapolation of data is still necessary if we are to estimate the wider impact of human developments on species, and has long proved useful in many ecological impact studies.[11] It should also be noted that this principle applies to all infrastructure impact studies, of which wind turbines are just a small part. Indeed, many existing facilities, such as those involved with fuel extraction and conventional power generation, may end up being superseded by wind power, which is itself less harmful on the whole (see following).

Because avian mortality from various human activities, or anthropogenic sources, has been continually assessed for decades, it is worthwhile summarising the data (see Figure 11.1). This shows that the contribution made by wind turbines to avian mortality is negligible when compared to overall mortality from anthropogenic sources. Figures collected across Europe and North America consistently show that bird deaths caused by collisions with wind turbines are insignificant when compared to overall avian mortality due to human activity.

Collisions with built infrastructure other than wind turbines

It has long been known that buildings are one of the most significant causes of avian mortality, responsible for billions of bird deaths worldwide.[4,28] This is thought to be largely due to windows, which birds seem poorly equipped to detect, and so fatalities are a given wherever birds and windows are found in proximity.[29] Contrary to what is commonly supposed, large, high-rise buildings contribute very little to this death toll; instead, residential dwellings and small commercial buildings of just two or three storeys are responsible for almost all bird deaths involving building collisions.[8] Collisions with and electrocution by power transmission lines is another significant cause of bird deaths, as are collisions with road traffic.[4,28,30,31] Communication towers are a smaller, but still very significant, contributor to mortality, with some very tall towers seemingly responsible for incidents where large numbers of birds are killed at one time.[19,32]

Predation by cats

More recent studies that have monitored the behaviour of free-ranging domestic cats and how many small animals and birds are taken by both owned and stray cats roaming their territory. Because they are fed by their owners, numbers of cats can reach very high densities in some areas, far higher than a habitat could support for any naturally occurring predator.[5] Most studies of the predation rate of cats in countries where cat ownership is popular (e.g. the UK, Australia, New Zealand, Canada and the USA) suggest that for many species of birds, the predation level is likely to cause long-term population decline.[33,34] In urban areas, it is likely that the effects on local bird populations are underestimated because studies are unable to assess a bird species' true abundance due to the fact that these areas have already long been subject to cat predation.[33] Urban areas can act as a 'sink' for some species, drawing in birds from surrounding semi-rural areas to compensate for higher overall numbers lost to cats in the urban habitat.[35]

Efforts to better understand the level of avian mortality due to domestic cats has revealed a truly astonishing death toll.* Based on there being nine million cats in Britain, it is estimated around 25–29 million birds are killed each year by free-ranging cats (more recent estimates suggest Britain now has 10 million domestic cats).[33,36] Studies of avian mortality in North America have estimated around 135 million birds are killed each year by domestic cats in Canada, and a staggering 2,400 million (or 2.4 billion) are killed each year in the contiguous United States. Over two-thirds of this is caused by un-owned cats (i.e. feral or stray cats), but even so the median estimated mortality in Canada and the USA caused by owned domestic cats totals roughly 799 million birds each year.[6,30]

Collisions with wind turbines

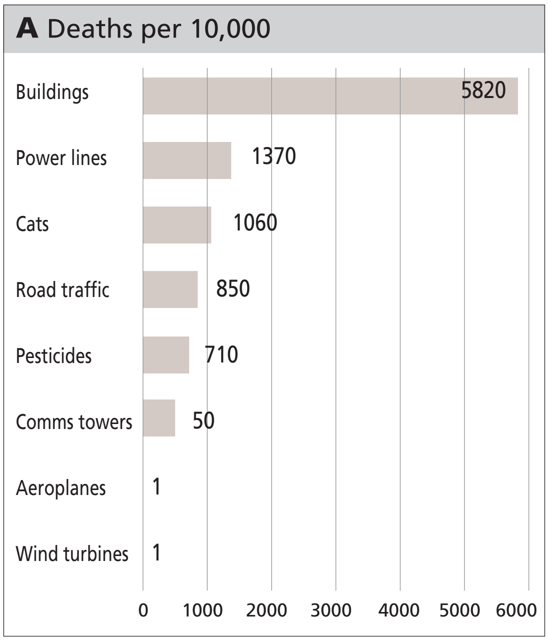
Following concerns over the impact on important raptor species due to poorly sited wind farms in the Navarre and Altamont regions, there have been a relatively large amount of data generated on the estimated avian mortality caused by wind turbines. Analysis of these findings has increasingly taken into account some of the deficiencies known to be inherent in mortality estimation surveys (discussed above, see p80). Consequently, more recent mortality estimates for the contiguous United States has considered a mean projected estimate of 234,000 bird deaths each year due to collisions with wind turbines (estimates ranged from 140,000 to 328,000).[3]

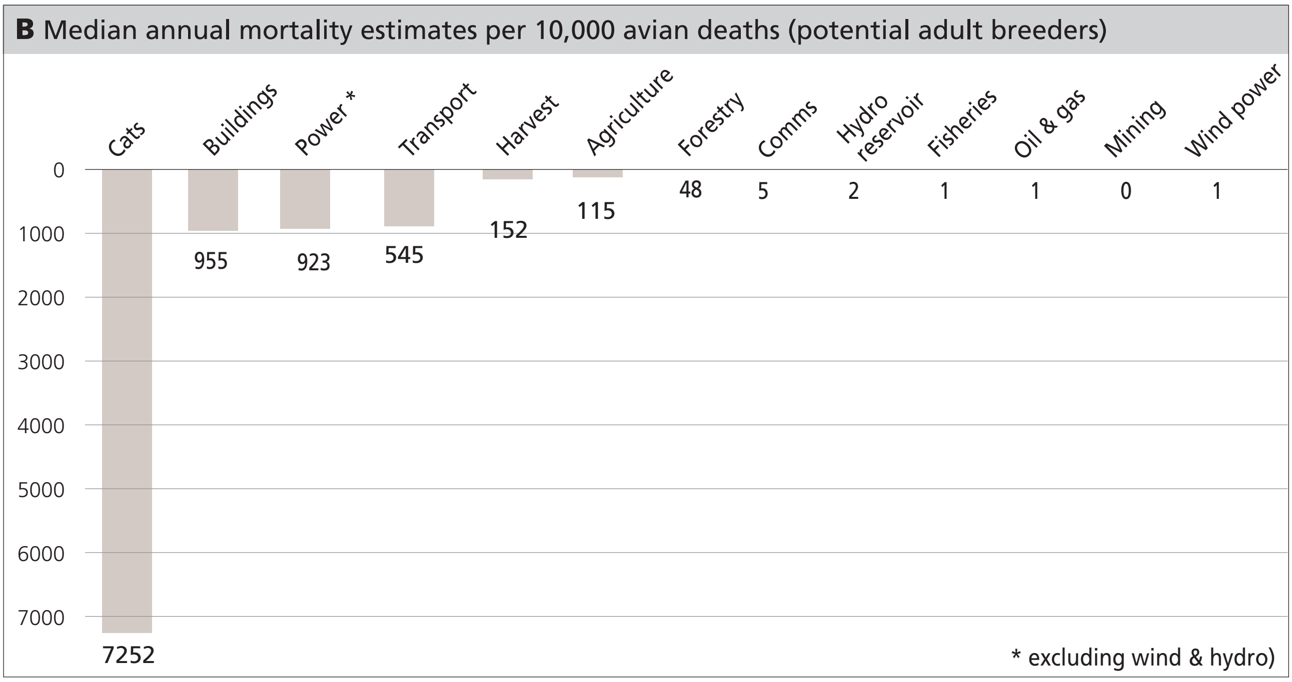
This estimate, the authors noted, was higher than previous estimates of around 20,000–40,000 bird deaths,[28] but a similar study that applied more stringent criteria to likely underestimations suggested the number of bird deaths in the USA caused by wind turbines could be as high as 573,000.[2] Other studies have looked at the effect on different species, such as passerines. The median annual mortality rate of passerines due to wind turbine collisions across Canada and the USA is estimated to be between 134,000 and 230,000 birds,

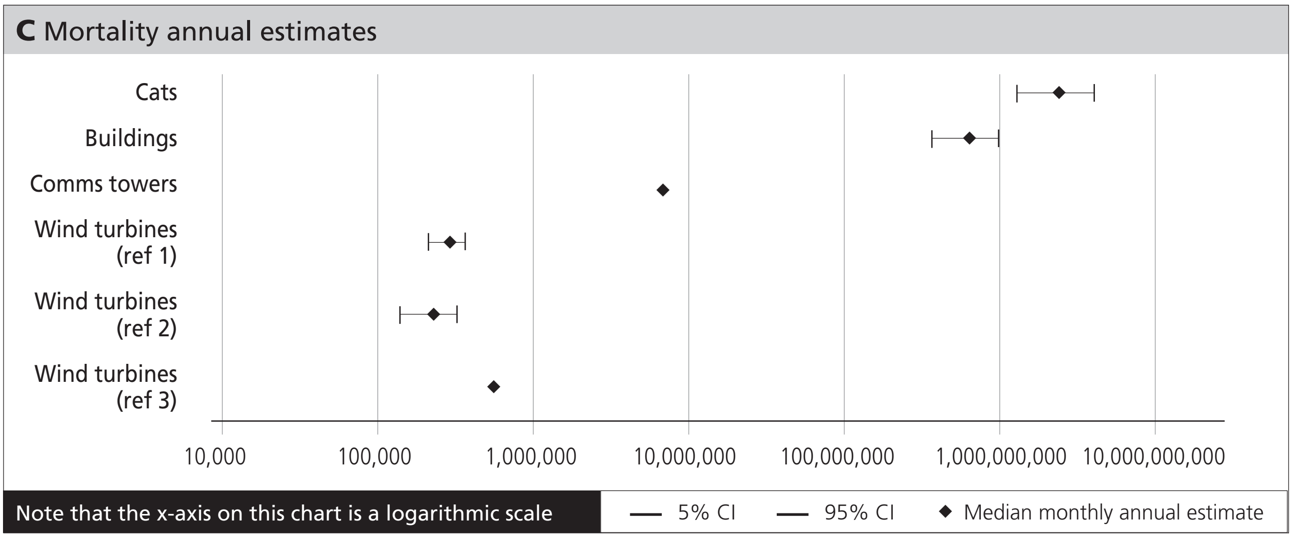
---

* Note that the discussion here only addresses birds killed by cats. Domestic cats are also responsible for killing even greater numbers of small animals, including mammals, reptiles and amphibians.

Figure 11.1 Data from eight separate studies carried out over the past 12 years on estimated annual avian mortality due to human activity, based on data from North America. Panels A (data from ref.28, 2002) and B (data from ref.30, 2013) show bird deaths attributable to each cause per 10,000 fatalities that occur. While the 2002 study determined that collisions with buildings were the leading cause of bird deaths from human activity, the later study demonstrated predation by domestic cats to be a more significant factor. In both cases, wind power contributes 0.01% of total avian mortality. Panel C shows total median estimated annual avian mortality values from 6 different studies – note that the x-axis is a logarithmic scale. Values in C were taken from refs. 1–3 (which studied avian deaths caused by wind power) and 6–8 (which studied avian deaths from other causes), and, where values were stated in the study, confidence intervals are also shown. A similar trend can be seen across all data sets, showing wind turbines account for only a tiny fraction of total bird deaths. The two most recent studies (refs. 6 and 30 [both 2013]) reveal domestic cats are by far the single largest cause of birds killed due to human activity, contributing many thousands of times the number of bird deaths that are attributed to wind turbines.







which accounts for 63% of all types of bird killed by wind turbines. Diurnal raptors (birds of prey active during the daytime) and upland game birds were the next two major groups, accounting for another 8% of fatalities in each case (i.e. 16% in total).[1] The authors used these figures to give an estimate of 214,000–368,000 total fatalities each year for all bird species caused by collisions with wind turbines, which overlaps the higher-end estimate of 328,000 for the contiguous United States mentioned above.[1,3]

These estimates show that avian deaths caused by wind power contribute a fraction of one per cent to all bird deaths caused by human activity. Figure 11.1 shows different sets of data for annual mortality estimates due to various human activities from studies based on large, nationwide data sets in North America. The studies for wind power covered roughly 9%–15% of total wind farm installed capacity in the USA (between 2012 and 2013). Relative to other sectors of industry and types of infrastructure, the wind industry has been unusually closely-studied with regards to avian mortality and has comparatively reliable data as a result when considering extrapolating figures for wind energy nationwide.[1,2,7,32,37] This may have important ramifications when attempting to compare wind energy impacts with other infrastructure, as discussed further below.

Deaths caused by non-renewable energy production

Since wind farms are being introduced as a means to reduce carbon dioxide emissions, a more meaningful way to analyse avian mortality would be to compare wind power with non-renewable energy sources. The studies discussed above rarely present bird deaths in this way (if at all), although several may quote estimates of birds killed per turbine or per megawatt of installed capacity. Whilst simply comparing total deaths to other forms of infrastructure can be useful in terms of placing anthropogenic causes of bird deaths in context, making comparisons specifically between energy sources is necessary to more fully comprehend the true costs and benefits involved in producing electricity.[38] The peer-reviewed literature does not appear to contain any studies that set out to compare electricity sources and avian mortality on a watt-by-watt basis, except for Sovacool's preliminary study in 2009,[39] revised in 2012.[38] The author applies limited data from examples of coal, nuclear and wind power plants to estimate that existing fossil fuels cause 15 times the number of bird deaths for every gigawatt-hour (GWh) produced: 5.18 deaths/GWh for fossil fuels, 0.42/GWh for nuclear, and 0.27/GWh for wind power.

What can we make of these estimates? Of note, especially with regards to the preceding discussion of various mortality estimates, data on bird deaths used by Sovacool can be considered conservative, as it relies on older studies.[28,38] An approximate estimate of avian mortality per GWh might be obtained from more recent studies, on the basis of total installed capacity for the contiguous United States[†] combined with the average capacity factor of wind turbines (taken as 33% – see ref.11 in Chapter 4). In these instances, high-end estimates of avian mortality per GWh are more than ten times the number quoted by Sovacool (2.0–3.6 deaths/GWh versus 0.27/GWh quoted above), still lower than fossil fuels, but the gap has narrowed.[1,2]

However, one must also bear in mind that systematic studies which attempt to gauge avian mortality due to conventional power generators are rare – nothing like the detailed analysis of bird deaths performed for wind farms has been done for conventional power plants. The simple fact is that wind farms have been subjected to far greater scrutiny. Whilst directly comparing collision rates between structures such as wind turbines and conventional power stations allows an easy comparison, it is much harder to account for the many *negative externalities* of conventional electricity generation – acid rain and its damage to fisheries and crops, water degradation and excessive consumption, particle pollution, radioactive waste and abandoned uranium mines and mills, and the cumulative environmental damage to ecosystems and biodiversity through species loss and habitat destruction.[40,41]

Studies frequently cite the average number of collisions per individual turbine. Data from many different regions of North America suggest a annual collision rate of 9 birds/turbine.[1–3,37] Again, a rough inference can be made from this with regards to the UK. A high estimate of 20 GW installed onshore wind capacity is a feasible scenario set by the National Grid.[42] As of 2014, the average size of a turbine in the UK is 2.5 MW, although that is rapidly moving closer to 3.0 MW.43 Keeping the current average size, 20 GW of installed capacity is equivalent to 8,000 2.5 MW turbines, which would likely result in an estimated 71,000 birds killed due to collisions with operating turbines. Making a similar assumption as to annual electricity generation that was used above, this would be 1.23 bird deaths/GWh. The above figures are significant, although it is clear that even 71,000 bird deaths pales in comparison to the 25–29 million killed each year by domestic cats in the UK. What *can* be stated with certainty is that no form of electricity supply is completely benign.

There are some concerns that habitat loss poses greater threat to bird species than collisions.[27] However, the footprint of wind turbines is comparatively small, allowing other activities, such as farming, to take place

---

[†] Erickson (ref.(1)) took total installed capacity to be 63 GW, Smallwood (ref.(2)) stated 52 GW.

around wind farms, and being much smaller in area than, say, national road networks.[37,44] Studies of large wind farms suggests the construction phase is the main driver of population decline, with populations returning or stabilising once turbines are operating.[45–47] Despite this, care should be taken that wind farms are not sited or laid out in such a way as to cause barriers to migratory species.[4,47]

Impact on bat populations

Bat fatalities were known at wind farms in the USA as part of earlier studies on bird mortality,[48] but the phenomenon received more attention from conservation researchers when a surge in bat deaths was recorded at several wind farms in the Appalachian Mountain region between 2002 and 2005.[23] In particular, a small installation in Tennessee and a much larger wind farm in West Virginia both reported a worryingly high fatality rate ranging between roughly 20 and 50 bats per turbine.[12,13] Although some of the US studies suggested no endangered bat species were being harmed,[13] and that other wind farms reported much lower numbers of bat deaths,[49] the few cases of large fatality rates being reported were alarming given that bats are long-lived and slow to reproduce, thus having a limited capacity to recover from any abrupt decline in population.[14]

The problem also quickly became apparent in Europe. Between 2003 and 2014, there were over 6,400 bat carcasses discovered at wind power facilities across Europe where mortality was attributed to the presence of wind turbines – this represents 27 affected bat species.[15] Some species on the European mainland are known to migrate notable distances, but data on UK migratory patterns is currently scarce.50 However, studies on bat deaths involving wind turbines across Europe have not revealed any clear difference between migratory and non-migratory bat species, which is in contrast to the findings in North America, where sites with unusually numbers of bat fatalities are associated with migratory populations.[51–53]

Although several nesting populations in the UK are showing positive growth trends,[54] this is likely to be due to bat conservation measures that have been introduced since the 1990s, and prior to this bat populations had steadily declined due to human activity. In addition, 13 of the 17 nesting species in the UK are known to be at the edge of their European ranges, which means the UK populations for these species tend to be rarer, smaller in number and exhibit negligible growth rates.[55,56] This can be problematic when assessing wind power schemes and similar infrastructure projects, because an impact assessment often relies on the assumption that wildlife losses can be mitigated to the degree that they do not affect the wider population; but, if bat populations in certain areas are already vulnerable, any significant reduction in numbers may have severe consequences.[57] The discovery that bat fatalities can occur in large numbers around some wind farms was initially surprising, since bats are known to be excellent at avoiding moving objects using their ability to navigate by echolocation. Researchers put forward many hypotheses to try and explain what might be contributing to these fatalities.[17,58] One factor that has quickly become apparent as multi-megawatt wind turbines become the norm is the speed at which a rotating blade tip moves. Speeds in excess of 160 mph are not uncommon, and this is simply too fast for bats in the proximity to detect and avoid in time.[53] As well as striking the turbines blades directly, there is increasing evidence that dramatic changes in air pressure around the moving blade edges induces barotrauma,[‡] which causes fatal internal haemorrhaging.[53,59]

There are likely other factors that contribute to the number of bats killed by wind turbines. Like similar data for birds, estimates of bat fatalities based on carcass discovery is subject to uncertainty. Even so, enough is known to see some patterns that set bat fatalities apart from bird fatalities: bat carcasses are typically found much closer to the base of wind turbines, bat fatalities are not observed next to non-rotating (i.e. non-operating) turbines, and bat mortality is negligible around other prominent structures.[49,58]

The lack of bat deaths caused by other prominent structures is very different from recorded bird deaths caused by collisions, since, as discussed above, considerable avian mortality arises from birds colliding with structures such as buildings, communication towers, power lines, cooling towers and wire fences.[4,7,8,30] Thus, aside from random collisions being on account of the simple fact that bats are present at a wind farm site, data suggests there are additional factors that attract bats to rotating turbines in the first place, or that coincide with migratory and foraging behaviours, all of which combine to cause excess mortality.[14,17] These uncertainties mean predicting potential impacts during the planning phase can be challenging.

Mitigating avian and bat mortality

The reasons for birds colliding with wind turbines are now much better understood since the early days of wind power in California and northern Spain. For instance, vulnerable populations of raptors are known to follow ridgelines and steep slopes, which is why wind farms sited at Navarre and the APWRA have seen excessive mortality for species such as vultures and other

---

[‡] Barotrauma results from the sudden increase in outside air pressure relative to the pressure within a bat's internal air spaces caused by the passing pressure wave at the turbine blade's leading edge. This difference in pressure can cause vulnerable tissues, such as the lungs, to rupture.

birds of prey.[22] Understanding how landscape features may cause birds to follow particular flight patterns is a key part in mitigating the impact of wind farms before they are even built. Knowledge of foraging areas for resident birds and flight paths of migratory species is also crucial. However, it is a fact that many preconstruction estimates of avian mortality have been found to be unreliable, typically due to planners failing to consider site-specific risks and variations between turbines within a single installation.[3]

Poorly sited wind farms across important topographical features and existing flight paths can cause long-term impacts. For instance, upgrading of turbines to larger, tubular designs in the APWRA has led to reduced avian mortality,[24] but the same pattern has not been observed in the Navarre region where similar 'repowering' has taken place. The experience in Navarre demonstrates that, in some cases, avian mortality does not necessarily correlate with turbine structure itself, merely the presence of wind turbines along a particular topographical bottleneck.[10] This can result in misleading predictions for mortality estimates when developments are first installed or upgraded.[60] Similarly, the expansion of wind power into novel environments also needs to be approached with care, since knowledge concerning the behaviour of resident avian species may be insufficient. For example, a recent study of gannet populations off the coast of Scotland that used 3D monitoring demonstrated foraging birds routinely flying at heights (up to 27m), which would bring them into conflict with the blades of offshore wind turbines.[61] This is contrary to previous radar data that suggested they flew no higher than 12 meters.

For bat mortality, this situation is more complicated. There is no clear link between topography and fatality rates between wind farms, although placement of individual turbines possibly has a significant effect given that some turbines are responsible for disproportionate levels of bat deaths. However, one key aspect is likely to be the identification of 'movement corridors' for bat species that move between sites for hibernation or breeding at certain times of the year.[14] Identifying potential impacts during the planning phase may be difficult when population movements are uncertain, unless there are clearly evident circumstances where impacts are likely to occur, e.g. near an important roost, or where it can be easily predicted that impacts will not occur, such as hostile, windy and cold sites where bats are unlikely to be found.[57]

Behavioural patterns are important, as we have seen with example of gannets off the Scottish coast. This applies to all avian species, including passerines, e.g. the behaviour of larks at certain times of the year may contribute to higher mortality rates due to male birds flying higher than normal (up to 250 m) whilst courtship singing.[1] Movements in flocks can also affect behaviour. There may be limitations to some collision prediction models, which do not take into account social interactions when birds fly in groups.[62] As well as seasons, common behaviours are intimately associated with the physical habitat – as one author noted, raptors 'do not move over the area at random, but follow main wind currents, which are affected by topography'.[60] That said, it is known that some populations show avoidance behaviour, which results in a level of bird collisions that are not a cause for concern.[47] However, this phenomenon is species- and site-specific, and so requires good knowledge derived from careful monitoring of proposed sites using recognised experts in bat behaviour.

These factors are equally important for predicting the impact of wind farm developments on bat populations.[57] Foraging bats will routinely adhere to movement corridors in their local habitat. For example, wind turbines near wooded areas may involve the construction of access roads and the creation of clearings around the turbine bases. This can significantly affect the use of these areas by individual species of bats, which reduces the usefulness of preconstruction behavioural studies when applied to the landscape after a wind farm has been built.[63] The reasons for foraging bats straying near to, or being attracted to, wind turbines are known to vary between species, and there is currently little consensus on how common patterns of behaviour can be predicted.[14,57]

For avoiding unnecessary bird deaths, the best course of action at the planning stage is to take into account strategic needs across a wide area, so as to optimise the placement of wind turbines to meet energy needs and minimise new connective infrastructure at the same time as avoiding sensitive populations.[52,64] This can make use of existing detailed sensitivity mapping of habitats, populations and flight paths available for some regions, such as areas of Scotland[65], although these should not take the place of a local environmental impact assessment.[22] In the European Union all wind energy developments that are likely to have a significant impact on environment should be subjected to an environmental impact assessment (EIA).[§] As mentioned above, repowering of existing wind farms can reduce total bird deaths, although there may be some trade-off necessary to protect local bat populations.

Changes to the site characteristics and operation of individual wind farms and turbines are possible that can also mitigate bird deaths. It is known that the use of constant (steady-burn) lighting at wind farms and similar facilities (e.g. communication towers) can contribute to excessive bird fatalities, especially in areas prone to

---

[§] Article 2 of Directive 85/337/EEC.

inclement weather.[7,32] Flashing lights, which are mandated by civil aviation authorities, do not appear to have the same effect. Individual turbines can also be limited at certain times of the day during sensitive periods, such as the known presence of migratory flocks, or returning foragers at certain times of day.[22] The area around the base of wind turbines can also be made less attractive to potential prey, such as rodent species that raptors typically hunt.[66] Finally, identifying individual turbines that cause the majority of fatalities can enable repositioning of the offending turbine or changes to its daily operation, which can be achieved quite easily through remote systems control.[22,66]

Mitigating excessive and potentially damaging levels of bat mortality may prove more challenging than for birds. There are possibly several confounding factors that lead to bat deaths at wind farm sites, since it is possible that as well as collisions, the incidence of barotrauma may mean some bat kills are missed because the animals have time to fly away before dying from their injury.[14] Of some concern is the finding that the increased height of modern turbines contributes to fatalities in migratory bat populations.[17] There are theories that this effect is caused by the habit of migrating bats to fly higher than their usual foraging routine, and that some bats may not use echolocation when following migration paths.[58] Although this may have implications for newer wind farms and the repowering of existing wind farms with larger turbines, it should be noted that migratory bats seem to be of particular concern in North America rather than Europe,[51,52] and the increase in generating capacity from larger turbines can greatly reduce the number of deaths per megawatt.[14]

A positive development is the finding that ‘feathering’ turbines, whereby the turbine’s cut-in point is at a slightly higher wind speed, can significantly reduce bat fatalities.[67] Further evidence for slightly higher cut-in speeds is encouraging, especially for turbines that rotate at low wind speeds even though no power, or a negligible amount of power, is being generated.[14] Because bats do not forage in winds over a certain speed, the prevailing wind speed can be a strong predictor of bat activity, which makes feathering a useful mitigation method, and it results in only a few percentage points in lost electricity generation over the course of a year.[47,67]

However, reducing wind power output may not be feasible for older, existing wind farms, so alternative mitigation measures need to be found. Measures might include changing turbine colour to reduce insects congregating around turbines; using electromagnetic signals from small radar sets to reduce number of bats foraging around turbines (not migratory bats); and using ultrasound bursts to interfere with echolocation and discourage bats from feeding around turbines.[68,69] However, none of these methods have been tested at working wind farms to assess their effectiveness, and only feathering remains proven to be a successful mitigation measure.[14,57,70]

Impacts on non-volant wildlife

Most studies on non-volant wildlife in relation to wind farms have been prompted by known effects of oil and gas operations on terrestrial mammals in remote areas.[18] For wind farms, published research is relatively sparse, relating to populations of wild elk in North America and semi-domestic reindeer in Norway.[71,72] In a similar fashion to the development of avian monitoring on wind farms, studies of infrastructure impacts on terrestrial wildlife are carried out after construction, and there are few before-and-after impact studies.

Initial studies on the effect of wild elk in response to wind farms were prompted by evidence that oil wells built in Alaska caused changes to caribou foraging habits, and by evidence that roads and tourist facilities in Norway reduced local population density for caribou.[18,71] However, a study of Rocky Mountain elk in Oklahoma demonstrated that foraging and normal ranges were completely unaffected by wind farm development, either during or after construction.[71] Similarly, behaviour of semi-domestic reindeer was unaffected by the presence of wind turbines, with no behavioural aversion evident.[72]

Other preliminary studies suggest that, in some circumstances, the presence of wind farms can actually reduce predation, e.g. tortoise populations in California had a slight but significant increase in survival where a large wind farm had been developed.[18] Though seemingly a positive outcome, there is no evidence that the wind farm in question was planned with any regard for the local tortoise population. In the absence of further data, there is no guarantee that such an outcome would be seen at other wind farm sites with similar resident wildlife.[73] A study of ground squirrels in proximity to wind turbines within the APWRA showed that squirrels living in burrows close to wind turbines exhibited a greater degree of vigilance that was thought to compensate for the noise from the turbines.

With respect to colony size and predator abundance, there appeared to be no difference between squirrel colonies close to or far away from the wind turbines.[18,52] Similarly, marine species have been seen to increasingly congregate or forage in proximity to offshore wind farms. This applies to species of fish that are avoiding predators or using turbine pilings as potential breeding spots, or to predator species themselves, such as seals navigating between turbines.[74–76] Other impacts on marine environments are discussed in chapter 6, ‘Offshore wind turbines’.

Conclusion

Burgeoning utility-scale wind farms in the 1980s were often poorly sited, resulting in excessive fatalities for some important bird of prey species. Since then, the impact of wind farms on avian mortality has been the subject of a great deal of study, arguably to an extent not seen for any other form of infrastructure, many of these far more prevalent in modern societies. It is an accepted fact that wind turbines contribute to bird and bat deaths. In the context of all avian fatalities, however, the number of birds killed by collisions with wind turbines represents an insignificant fraction of the total number attributable human activity. It is no secret that wind turbines kill birds, and wind farms in the UK are subject to an Environmental Impact Assessment, which must take into account any sensitive bird populations, including migratory species. The planning regulations and advisory guidelines ensure bird populations in areas affected are studied to best predict the influence a proposed wind farm might have, and planning permission should be refused if the perceived detrimental effects are unacceptable or cannot be sufficiently mitigated.

Of more concern is the issue of bat fatalities, which may occur on a proportionally larger scale, and are potentially more damaging to some of the species involved. The foraging and migratory patterns of bats are not well understood, although more data is being amassed across sites in Europe and America. Although it is thought that the unexpectedly high mortality at some sites may be accounted for by altered behaviour during seasonal migrations, there is the possibility that bats may be affected when following normal foraging patterns too. One key difference between recorded bird and bat deaths is that bats appear to be particularly susceptible to wind turbines, as bats are not found to be killed as a result of contact with other structures, unlike the case for birds.

Co-ordinating the needs of both local and migratory bird and bat populations presents a challenge to the wind energy industry, and one that will have to be tackled on a site-by-site basis. The natural development of the commercial wind sector that has brought about turbines with taller, tubular designs that have slower rotating blades has mitigated bird fatalities to some extent, although there is a risk this may actually increase the threat to vulnerable bat populations. The accumulation of useful data since the 1980s, with regards to birds, has helped generate the information needed to correctly plan future sites for wind farms. It seems reasonable to assume that the impact of any wind farm can be significantly reduced through careful siting in response to data gathered on seasonal density in feeding and nesting areas, and on flight paths. Meticulous collection of information can aid flexibility when developing sites for wind energy, using 'micro-siting' so as not to disrupt flight paths.

Despite the positive developments with regards to reducing bird mortality, there is still a need for wind farm operators to perform more comprehensive monitoring, and ensure that more data is collected both before and after a wind farm is built. Routine monitoring of wind farms is often not rigorous enough in its approach, and many mortality studies rely on separate detection trials that themselves introduce forms of bias. Detection trials should be an integral part of routine monitoring – this would improve the raw data and carcass detection probabilities, which would reduce the need for post-hoc adjusting of data.

It is important that wind farms are developed with the possible threat to bat populations kept in mind, and where bat deaths are known to occur at existing wind farms mitigation measures need to be implemented as a precaution until such are effects are found to not have an impact on the viability of the population. Research has shown that curtailing wind turbine operation at lower wind speeds can significantly reduce bat deaths with minimal loss of power generation, but this remains to be tested on a large scale. The effectiveness of other mitigation methods is so far unproven. There is considerable variation in bat fatality rates between wind farms in different regions and continents, and it is also the case that individual turbines may be responsible for the majority of fatalities at a given wind farm, which suggests that it may be feasible to mitigate the impact on bats through micro-siting and making adjustments to the operating profile of specific turbines.

To date, little is known about the effect wind farms may have on other wildlife. The limited evidence suggests terrestrial animals are largely unaffected. There have been recent studies to suggest that patterns of foraging and predation by marine animals may be altered by the presence of offshore wind turbines, although there is evidence that such effects are not necessarily detrimental (see also chapter 6).

An assessment of current data shows that wind turbines kill few birds individually, but perhaps of greater importance is how estimates of total avian deaths due to wind energy compare to other sources of mortality. It has been clearly established that buildings – particularly residential and low-rise structures – communication towers, road traffic, transmission lines and agriculture result in far greater numbers of bird deaths each year, yet these latter causes of bird mortality have received comparatively little notice in the public sphere. Domestic cats, allowed to range freely, are by far the single largest cause of bird mortality, being responsible for many hundreds, if not thousands, of times more bird deaths than wind turbines. Comparing these data with that accumulated from wind farms suggests more consideration should be given to other anthropogenic sources of mortality that have to date received comparatively little attention from planners, regulatory authorities and (crucially) the media.

Wind farms are clearly delineated infrastructure developments that can be carefully planned to incorporate strategies for the avoidance, mitigation and offset of bird fatalities. Many other sources of avian mortality require much more complex approaches to governance. The issue is one of a tragedy of the commons. For instance, the difficulty with the bird–window collision issue are the building managers, housing developers and millions of homeowners who choose to build or retain regular windows with no regard for their impact on bird populations, despite it being shown, for example, that retrofitting UV-reflective film to offending windows can make them a visible barrier to birds but not to humans. The same goes for cat ownership, where there exists a profound disconnect between most cat owners' perception of the problem and the data that demonstrates cats are a persistent and serious threat to many avian populations. Each of these groups is responsible for a tiny slice of the cumulative problem. Solutions exist to help avoid these issues, but in the absence of public opprobrium or legislative pressure none of them are likely to be implemented. In this regard, the improvements made in the wind energy sector with regards to avian mortality shows that it can lead by example, by continuing to evolve its planning and operational methods in light of emerging data, thus delivering on its promise to be a clean and environmentally benign form of electricity.

References

1. Erickson WP, Wolfe MM, Bay KJ, Johnson DH, Gehring JL. A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. Brigham RM, editor. PLoS ONE. 2014 Sep 15;9(9):e107491.
2. Smallwood KS. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Soc B. 2013 Mar;37(1):19–33.
3. Loss SR, Will T, Marra PP. Estimates of bird collision mortality at wind facilities in the contiguous United States. Biol Conserv. 2013 Dec;168:201–9.
4. Drewitt AL, Langston RHW. Collision effects of wind-power generators and other obstacles on birds. Ann NY Acad Sci. 2008 Jun;1134(1):233–66.
5. McDonald JL, Maclean M, Evans MR, Hodgson DJ. Reconciling actual and perceived rates of predation by domestic cats. Ecol Evol. 2015 Jul;5(14):2745–53.
6. Loss SR, Will T, Marra PP. The impact of free-ranging domestic cats on wildlife of the United States. Nature Commun. 2013 Jan 29;4:1396.
7. Longcore T, Rich C, Mineau P, MacDonald B, Bert DG, Sullivan LM, et al. An estimate of avian mortality at communication towers in the United States and Canada. Krkosek M, editor. PLoS ONE. 2012 Apr 25;7(4):e34025.
8. Loss SR, Will T, Loss SS, Marra PP. Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability. Condor Ornithol Appl. 2014 Feb;116(1):8–23.
9. Smallwood KS, Thelander C. Bird mortality in the Altamont Pass Wind Resource Area, California. J Wildl Manag. 2008 Jan;72(1):215–23.
10. Barrios L, Rodríguez A. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines: Bird mortality at wind power plants. J Appl Ecol. 2004 Feb 12;41(1):72–81.
11. Machtans CS, Thogmartin WE. Understanding the value of imperfect science from national estimates of bird mortality from window collisions. Condor. 2014 Feb;116(1):3–7.
12. Kerns J, Kerlinger P. A study of bird and bat collision fatalities at the Mountaineer Wind Energy Center, Tucker County, West Virginia: Annual Report for 2003 [Internet]. Cape May Point, N.J.: Reported prepared by Curry & Kerlinger, LLC for FPL Energy and Mountaineer Wind Energy Center Technical Review Committee; 2004 Feb [cited 2011 Jan 26] p. 39. Available from: www.wvhighlands.org/Birds/MountaineerFinalAvianRpt-%203-15-04PKJK.pdf
13. Nicholson CP, Tankersley, Jr. RD, Fiedler JK, Nicholas NS. Assessment and prediction of bird and bat mortality at wind energy facilities in the Southeastern United States [Internet]. Knoxville: Tennessee Valley Authority; 2005 [cited 2011 Jan 26] p. 65. Available from: www.tva.gov/environment/bmw_report/bird_bat_mortality.pdf
14. Arnett EB, Baerwald EF. Impacts of Wind Energy Development on Bats: Implications for Conservation. In: Adams RA, Pedersen SC, editors. Bat Evolution, Ecology, and Conservation [Internet]. New York, NY: Springer New York; 2013 [cited 2015 Sep 24]. p. 435–56. Available from: http://link.springer.com/10.1007/978-1-4614-7397-8_21
15. EUROBATS. Report of the IWG on Wind Turbines and Bat Populations. 20th Meeting of the Advisory Committee, Budva, Montenegro, 23–25 March 2015 [Internet]. UNEP/EUROBATS Secretariat; 2015 [cited 2015 Sep 28] p. 28. Report No.: Doc.EUROBATS.AC20.5. Available from: www.eurobats.org/official_documents/advisory_committee/20th_meeting_advisory_committee
16. Cryan PM. Wind turbines as landscape impediments to the migratory connectivity of bats. Environ Law. 2011;41(2):355–70.
17. Cryan PM, Barclay RMR. Causes of bat fatalities at wind turbines: hypotheses and predictions. J Mammal. 2009;90(6):1330–40.
18. Lovich JE, Ennen JR. Assessing the state of knowledge of utility-scale wind energy development and operation on non-volant

terrestrial and marine wildlife. Appl Energy. 2013 Mar;103:52–60.

19. Loss SR, Will T, Marra PP. Direct human-caused mortality of birds: improving quantification of magnitude and assessment of population impact. Front Ecol Environ. 2012 Sep;10(7):357–64.
20. Bernardino J, Bispo R, Costa H, Mascarenhas M. Estimating bird and bat fatality at wind farms: a practical overview of estimators, their assumptions and limitations. New Zeal J Zool. 2013 Mar;40(1):63–74.
21. Mathews F, Swindells M, Goodhead R, August TA, Hardman P, Linton DM, et al. Effectiveness of search dogs compared with human observers in locating bat carcasses at wind-turbine sites: A blinded randomized trial. Wildlife Soc B. 2013 Mar;37(1):34–40.
22. Marques AT, Batalha H, Rodrigues S, Costa H, Pereira MJR, Fonseca C, et al. Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. Biol Conserv. 2014 Nov;179:40–52.
23. GAO. Wind Power: Impacts on Wildlife and Government Responsibilities for Regulating Development and Protecting Wildlife [Internet]. Washington, D.C.: U.S. Government Accountability Office; 2005 Sep [cited 2011 Jan 26] p. 64. Report No.: GAO-05-906. Available from: www.gao.gov/products/GAO-05-906
24. Smallwood KS, Karas B. Avian and bat fatality rates at old-generation and repowered wind turbines in California. J Wildl Manag. 2009 Sep;73(7):1062–71.
25. Longcore T, Rich C, Mineau P, MacDonald B, Bert DG, Sullivan LM, et al. Avian mortality at communication towers in the United States and Canada: which species, how many, and where? Biol Conserv. 2013 Feb;158:410–9.
26. Langston RHW. Birds and wind projects across the pond: A UK perspective. Wildlife Soc B. 2013 Mar;37(1):5–18.
27. Kuvlesky WP, Brennan LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC. Wind energy development and wildlife conservation: Challenges and opportunities. J Wildl Manag. 2007 Nov;71(8):2487–98.
28. Erickson WP, Johnson GD, Young DP. Summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions. In: Ralph CJ, Rich TD, editors. Bird Conservation Implementation and Integration in the Americas: Proceedings of the Third International Partners in Flight Conference 2002 March 20-24; Asilomar, Calif, Vol2 [Internet]. Albany, Calif.: U.S. Dept of Agriculture, Forest Service; 2005 [cited 2010 Nov 12]. p. 1029–42. (General Technical Report; vol. 2). Available from: www.fs.fed.us/psw/publications/documents/psw_gtr191/
29. Klem D. Landscape, legal, and biodiversity threats that windows pose to birds: A review of an important conservation issue. Land. 2014 Mar 24;3(1):351–61.
30. Calvert AM, Bishop CA, Elliot RD, Krebs EA, Kydd TM, Machtans CS, et al. A synthesis of human-related avian mortality in Canada. Avian Conserv Ecol [Internet]. 2013 [cited 2014 Aug 27];8(2). Available from: http://www.ace-eco.org/vol8/iss2/art11/
31. Erritzoe J, Mazgajski TD, Rejt . Bird casualties on European roads — a review. Acta Ornithol. 2003 Dec;38(2):77–93.
32. Kerlinger P, Gehring JL, Erickson WP, Curry R, Jain A, Guarnaccia J. Night migrant fatalities and obstruction lighting at wind turbines in North America. Wilson J Ornithol. 2010 Dec;122(4):744–54.
33. Thomas RL, Fellowes MDE, Baker PJ. Spatio-temporal variation in predation by urban domestic cats (Felis catus) and the acceptability of possible management actions in the UK. Hayward M, editor. PLoS ONE. 2012 Nov 16;7(11):e49369.
34. Baker PJ, Molony SE, Stone E, Cuthill IC, Harris S. Cats about town: is predation by free-ranging pet cats Felis catus likely to affect urban bird populations? Ibis. 2008 Aug 21;150:86–99.
35. van Heezik Y, Smyth A, Adams A, Gordon J. Do domestic cats impose an unsustainable harvest on urban bird populations? Biol Conserv. 2010 Jan;143(1):121–30.
36. Woods M, Mcdonald RA, Harris S. Predation of wildlife by domestic cats Felis catus in Great Britain. Mammal Rev. 2003 Jun;33(2):174–88.
37. Zimmerling JR, Pomeroy AC, d'Entremont MV, Francis CM. Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments. Avian Conserv Ecol [Internet]. 2013 [cited 2016 Feb 11];8(2). Available from: www.ace-eco.org/vol8/iss2/art10/
38. Sovacool BK. The avian benefits of wind energy: A 2009 update. Renew Energy. 2013 Jan;49:19–24.
39. Sovacool BK. Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. Energy Policy. 2009 Jun;37(6):2241–8.
40. National Research Council (U.S.). Hidden costs of energy: unpriced consequences of energy production and use. Washington, D.C: National Academies Press; 2010. 473 p.
41. Epstein PR, Buonocore JJ, Eckerle K, Hendryx M, Stout III BM, Heinberg R, et al. Full cost accounting for the life cycle of coal. Ann NY Acad Sci. 2011 Feb;1219(1):73–98.
42. National Grid. 2013 Electricity Ten Year Statement [Internet]. Warwick: National Grid plc; 2013 Nov [cited 2014 Jul 29] p. 230. (Electricity Ten Year Statement). Available from: www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Electricity-Ten-Year-Statement/
43. DECC. Digest of UK Energy Statistics 2014. London: Stationery Office; 2014. 270 p. (A National Statistics Publication).
44. Howard DC, Wadsworth RA, Whitaker JW, Hughes N, Bunce RGH. The impact of sustainable energy production on land use in Britain through to 2050. Land Use Policy. 2009 Dec;26:S284–92.
45. Pearce-Higgins JW, Stephen L, Douse A, Langston RHW. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. J Appl Ecol. 2012 Apr;49(2):386–94.
46. Astiaso Garcia D, Canavero G, Ardenghi F, Zambon M. Analysis of wind farm effects on the surrounding environment: Assessing population trends of breeding passerines. Renew Energy. 2015 Aug;80:190–6.
47. Schuster E, Bulling L, Köppel J. Consolidating the state of knowledge: A synoptical review of wind energy's wildlife effects. Environmental Management. 2015 Aug;56(2):300–31.
48. Johnson GD, Perlik MK, Erickson WP, Strickland MD. Bat activity, composition, and collision mortality at a large wind plant in Minnesota. Wildlife Soc B. 2004 Dec 1;32(4):1278–88.
49. Arnett EB, Brown WK, Erickson WP, Fiedler JK, Hamilton BL, Henry TH, et al. Patterns of bat fatalities at wind energy facilities in North America. J Wildl Manag. 2008 Jan;72(1):61–78.
50. Jones G, Cooper-Bohannon R, Barlow K, Parsons K. Scoping and method development report: Determining the potential ecological impact of wind turbines on bat populations in Britain. Phase 1 Report prepared by Report by University of Bristol and Bat Conservation Trust commissioned by Defra [Internet]. Department for Environment, Food and Rural Affairs; 2009 May [cited 2015 Oct 9] p. 150. Report No.: WC0742. Available from: http://randd.defra.gov.uk
51. Rydell J, Bach L, Dubourg-Savage M-J, Green M, Rodrigues L, Hedenström A. Bat mortality at wind turbines in northwestern Europe. Acta Chiropterol. 2010 Dec;12(2):261–74.
52. Northrup JM, Wittemyer G. Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation. Regan H, editor. Ecol Lett. 2013 Jan;16(1):112–25.
53. Grodsky SM, Behr MJ, Gendler A, Drake D, Dieterle BD, Rudd RJ, et al. Investigating the causes of death for wind turbine-associated bat fatalities. J Mammal. 2011 Oct 14;92(5):917–25.
54. DEFRA. UK Biodiversity Indicators 2015 [Internet]. London: Department for Environment, Food and Rural Affairs; 2016 Jan [cited 2016 Feb 5] p. 59. Report No.: PB14348. Available from: www.gov.uk/government/statistics/biodiversity-indicators-for-the-uk
55. DEFRA, EUROBATS. Report on the implementation of the Agreement in the United Kingdom [Internet]. UNEP/EUROBATS Secretariat; 2014 Jul [cited 2015 Sep 28] p. 30. Report No.: Inf.EUROBATS.MoP7.43. Available from: www.eurobats.org/about_eurobats/parties_and_range_states/united_kingdom
56. Dietz C, Nill D, Helversen O von. Bats of Britain, Europe and Northwest Africa. London: A & C Black; 2009.
57. Peste F, Paula A, da Silva LP, Bernardino J, Pereira P, Mascarenhas M, et al. How to mitigate impacts of wind farms

on bats? A review of potential conservation measures in the European context. Environ Impact Assess Rev. 2015 Feb;51:10–22.

58. Kunz TH, Arnett EB, Erickson WP, Hoar AR, Johnson GD, Larkin RP, et al. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Front Ecol Environ. 2007 Aug;5(6):315–24.
59. Baerwald EF, D'Amours GH, Klug BJ, Barclay RMR. Barotrauma is a significant cause of bat fatalities at wind turbines. Curr Biol. 2008 Aug;18(16):R695–6.
60. Ferrer M, de Lucas M, Janss GFE, Casado E, Muñoz AR, Bechard MJ, et al. Weak relationship between risk assessment studies and recorded mortality in wind farms. J Appl Ecol. 2012 Feb;49(1):38–46.
61. Cleasby IR, Wakefield ED, Bearhop S, Bodey TW, Votier SC, Hamer KC. Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms. Österblom H, editor. J Appl Ecol. 2015 Sep;Article first published online: 28 SEP 2015:n/a – n/a.
62. Croft S, Budgey R, Pitchford JW, Wood AJ. The influence of group size and social interactions on collision risk with obstacles. Ecol Complex. 2013 Dec;16:77–82.
63. EUROBATS. Progress Report of the IWG on Wind Turbines and Bat Populations. 18th Meeting of the Advisory Committee, Sofia, Bulgaria, 15–17 April 2013 [Internet]. UNEP/EUROBATS Secretariat; 2013 [cited 2015 Sep 28] p. 30. Report No.: Doc.EUROBATS.AC18.6. Available from: www.eurobats.org/official_documents/advisory_committee/18th_meeting_advisory_committee
64. European Commission, Directorate-General for the Environment. Wind energy developments and Natura 2000 guidance document. [Internet]. Luxembourg: Publications Office of the European Union; 2010 [cited 2016 Feb 12]. 116 p. Available from: http://dx.publications.europa.eu/10.2779/98894
65. Bright JA, Langston RHW, Pearce-Higgins JW, Bullman R, Evans R, Gardner S. Spatial overlap of wind farms on peatland with sensitive areas for birds. Mires Peat. 2008;4:Art. 7.
66. May R, Reitan O, Bevanger K, Lorentsen S-H, Nygård T. Mitigating wind-turbine induced avian mortality: Sensory, aerodynamic and cognitive constraints and options. Renew Sustain Energy Rev. 2015 Feb;42:170–81.
67. Arnett EB, Huso MM, Schirmacher MR, Hayes JP. Altering turbine speed reduces bat mortality at wind-energy facilities. Front Ecol Environ. 2011 May;9(4):209–14.
68. Nicholls B, Racey PA. The Aversive Effect of Electromagnetic Radiation on Foraging Bats—A Possible Means of Discouraging Bats from Approaching Wind Turbines. Arlettaz R, editor. PLoS ONE. 2009 Jul 16;4(7):e6246.
69. Arnett EB, Hein CD, Schirmacher MR, Huso MMP, Szewczak JM. Evaluating the Effectiveness of an Ultrasonic Acoustic Deterrent for Reducing Bat Fatalities at Wind Turbines. Russo D, editor. PLoS ONE. 2013 Jun 19;8(6):e65794.
70. EUROBATS. Resolution 7.5. Wind Turbines and Bat Populations. 7th Session of the Meeting of the Parties, Brussels, Belgium, 15–17 September 2014 [Internet]. UNEP/EUROBATS Secretariat; 2014 [cited 2015 Sep 28] p. 3. Report No.: EUROBATS.MoP7.Record.Annex8. Available from: http://www.eurobats.org/official_documents/meeting_of_parties/7th_session_meeting_parties#3
71. Walter WD, Leslie DM Jr, Jenks JA. Response of Rocky Mountain elk (Cervus elaphus) to wind-power development. Am Midland Nat. 2006 Oct 1;156(2):363–75.
72. Flydal K, Eftestøl S, Reimers E, Colman JE. Effects of wind turbines on area use and behaviour of semi-domestic reindeer in enclosures. Rangifer [Internet]. 2004 Apr 18 [cited 2014 Aug 28];24(2). Available from: http://septentrio.uit.no/index.php/rangifer/article/view/301
73. Agha M, Lovich JE, Ennen JR, Augustine B, Arundel TR, Murphy MO, et al. Turbines and terrestrial vertebrates: Variation in tortoise survivorship between a wind energy facility and an adjacent undisturbed wildland area in the desert southwest (USA). Environmental Management. 2015 Aug;56(2):332–41.
74. Bergström L, Sundqvist F, Bergström U. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. Mar Ecol Prog Ser. 2013 Jun 27;485:199–210.
75. Hooper T, Austen M. The co-location of offshore windfarms and decapod fisheries in the UK: Constraints and opportunities. Mar Policy. 2014 Jan;43:295–300.
76. Russell DJF, Brasseur SMJM, Thompson D, Hastie GD, Janik VM, Aarts G, et al. Marine mammals trace anthropogenic structures at sea. Curr Biol. 2014 Jul;24(14):R638–9.

Chapter 12

Wind turbines and safety

Summary

All sources of energy supply, wind power included, can present a hazard to human health: fuel extraction and transport; construction and maintenance of plant and distribution networks associated with energy production; and the operation of such facilities; present a risk to human health, both to industry workers and, in rare instances, the public. In the energy industry, fatalities are measured in such a way as to show the cost/benefit for the energy produced, i.e. deaths per unit of energy generated. Wind energy enjoys one of the lowest fatality rates per GWy of any energy source, considerably lower than that for fossil fuels.

However, there is no escaping the fact that deaths occur due to the installation and use of wind turbines. These are overwhelmingly related to industry workers, although there are rare incidences of members of the public being killed: as with any industry, wind energy must strive to minimise or eliminate any fatalities where possible. However, when appraising wind energy, it must be remembered that wind continues to provide one of the safest forms of electricity generation available, without the additional environmental burdens that can impinge on public health, such as pollution or hazardous by-products.

What is this based on?

Despite having no operational requirement for large sources of fuel to be extracted (as with fossil fuels) or dangerous reactions to be controlled (as with nuclear reactors),* wind turbines create hazards of their own. In terms of newly installed capacity, the wind industry has been dominated by megawatt-scale turbines since the mid-2000s, and a significant proportion of these are 2 to 3 megawatts (MW) or more.[1] A typical commercial 2–3 MW turbine will have a hub height anywhere from 65 to 100 m (215–330 ft) with blades exceeding 45 m or even 50 m (148–164 ft) in length.[1,2]

The risks of working on such high structures are readily apparent, not to mention the potential hazards created when transporting the component parts. Between 1975 and 2012, worldwide reported figures reveal 65 industry workers have been killed whilst involved in the manufacture, installation, maintenance or removal of turbines.[3] In addition, there have also been five members of the public reported killed in accidents involving large utility-scale turbines between 2000 and 2012, which includes a parachutist in Germany, a crop duster pilot in the US, traffic accidents in both the UK and Ireland involving turbine transports, and a snowmobile driver in Canada who was killed when he struck a fence surrounding a wind farm construction site.[3]

The growth of wind power worldwide has been extraordinarily rapid, and this is likely to continue. Although Europe is beginning to fall behind China and the USA in terms of overall wind capacity, the UK looks set to remain a leading exponent of offshore wind power for some years to come.[4] This steady expansion means that the number of people employed in some aspect of wind power development is constantly growing. The USA wind industry provides jobs for roughly 73,000 workers; in Europe, the number of jobs supported by the wind industry is 192,000, with the industry itself claiming this could grow to 446,000 by 2020.[1,5] Such large numbers of people working in what is essentially the manufacture and operation of complex machinery results in obvious occupational safety hazards that have been known to similar industries for many years. Indeed, activities such as servicing generators and gearboxes, erecting tall structures and manufacturing specialist materials are common to many industries, but wind power is unique in that it often requires many of these activities to be performed in tough and unforgiving environments located in remote, windy areas. Furthermore, a maintenance worker may find themselves having to work at considerable heights either exposed on the outside of a turbine or confined within the small space of the nacelle alongside the generating apparatus.[5]

A new workforce in a relatively new industry will introduce new hazards and require the concerted application of new training and operating procedures. The wind industry has introduced many design and workplace practices that have helped mitigate risks and make the routine, but dangerous, tasks associated with construction and maintenance safer.[6] However, accidents in the rapidly expanding offshore industry have shown that the industry must be more proactive in addressing the hazards that come with any burgeoning industry.[7]

---

* The energy and material used to build wind turbines is discussed in Chapter 2.

As pieces of heavy machinery, wind turbines can pose several hazards for workers and members of the public *in situ* if something goes wrong. Turbines can catch fire, or a structural component can fail.[8] Published reports dealing with the failure of structural components tend to group these incidents into categories relating to the three main parts of a wind turbine; the blades, the rotor and nacelle, and the tower.[2] Failure of the blade itself can result in 'blade throw', whereby a blade or piece of a blade becomes detached and is thrown clear of the turbine. Failure of the nacelle or rotor can be severe enough to cause the rotor hub and blades to fall to the ground; and mechanical and electrical machinery housed in the nacelle can catch fire. Failure of the tower typically results in the whole turbine collapsing, presenting an obvious hazard to any persons within the fall radius.

Related to blade throw, and a reported problem in areas prone to hard winters with prolonged icy conditions (e.g., Alpine regions, Scandinavia and Canada), is the occurrence of 'ice throw' – as the name implies, ice accreted on the blade edge can come loose and slingshot through the air in chunks of varying sizes. Blade throw and ice throw are of particular concern, as the distances travelled by blade parts or large pieces of ice can be considerable.[9,10] There are concerns that research into blade throw in particular is hampered by the confidential nature of field data collected, born largely of the manufacturers' anxiety over releasing performance data that is proprietary and potentially alarming to the public.[2]

Since 2006, the UK trade body, RenewableUK, has been relatively proactive in encouraging industry members to submit data to a confidential database, though this information is only made available to other industry members.[2,5] Although understandable, this sensitivity by the industry makes it difficult for hazards to be openly reported and addressed. The most comprehensive dataset that collates incidents of blade throw is derived from Danish and German sources covering approximately 7500 turbines that operated between 1990 and 2001.[†] This reported a blade tip or part of a blade from a small (300 kW) turbine being thrown 500 metres, by far the furthest distance given out of the seven total incidents observed in the period.[9]

Perhaps partly due to the industry's attitude of secrecy, the issue of blade throw is further complicated by reports that are difficult to corroborate. For example, a 1993 incident where a large part of a blade was thrown almost 500 metres is regularly cited as indicative of the large distances involved in blade throw events, although the Danish–German report above would suggest this is a highly unlikely and extreme event. This quoted distance should be treated with some scepticism: the mechanical failure in question was caused by a storm affecting an installation of turbines (each 300 kW) and is referred to on a prominent anti-wind website.[‡] Although the website carries a citation from an industry publication, the 'over 400m' distance is not mentioned anywhere in this reference cited,[§] nor is it mentioned in any related articles (in fact, no distances are mentioned at all). The website citation includes the fact that, 'An independent witness estimated the blade piece to weigh 1 tonne and travel almost 500m,' but fails to mention any source for this additional statement. A report commissioned by the Health and Safety Executive notes that:

> *'Wind turbine data compiled by pressure groups may be unreliable and is often only partially complete. In these cases failure databases are often based upon estimates from eyewitness testimony or un-validated reports, rather than accurate measurement of distances. Throws are often not distinguished between full blade throw and fragments, and fragment sizes are typically not given.'* Robinson et al. (2013, p.1).

What is the evidence?

Modern society derives its energy needs from a mixture of fossil fuels, nuclear and renewables, each with a cost to society through impacts on the environment or directly on human health.[12] In the dry language of economics these are termed 'negative externalities'; that is to say, they are the costs and burdens society is faced with due to an economic activity, in this case energy production. For instance, one cost that can be measured is the impact energy demand has on the safety of workers involved in energy supply chains, from initial mineral extraction (such as mining or oil drilling), to the manufacture of generating facilities (like building a power plant or erecting wind turbines), to the operations needed to ensure delivery of energy to the end consumer (such as transport of fuel and parts, or ongoing operations and maintenance). A key statistic in this regard is fatalities in energy supply expressed in such a way as to show the cost/benefit ratio to society for the energy produced, i.e. deaths per unit energy generated. This is usually given as deaths per gigawatt year (GW_y). The salient fact is that with all the above methods of delivering energy there is injury and loss of life involved.[13,14] It is generally accepted that society strives to minimise these as much as possible, but such social costs remain a grim reality.

[†] Rademakers and Braam, 'Analysis of risk-involved incidents of wind turbines', Guide for Risk-Based Zoning of Wind Turbines, [Original in Dutch], Energy Research Centre of the Netherlands, 2005. [English translation by Hopmans and van Dam, published in Larwood et al., 2006 (see ref. 9).]

[‡] 'Wind turbine accident compilation' [Online], Caithness Windfarm Information Forum, 2011 (accessed 18/05/16). Available: www.caithnesswindfarms.co.uk/fullaccidents.pdf.

[§] 'Storm takes its toll on turbines', Windpower Monthly, 1 Jan, 1994 (accessed 18/05/16). Available: www.windpowermonthly.com/news/953141/Storm-takes-its-toll-turbines.

There has been a considerable amount of data collected on the safety of conventional energy industries and hydroelectricity.[15–17] Increasingly, renewable energy technologies are being included as their contribution to global electricity and heat supply grows.[18,19] Taking figures from the start of the commercial wind energy industry in 1975 up to the end of 2012, there have been 80 recorded fatalities, of which seven were members of the public.[3] Many of these fatalities occurred in the early days of small kilowatt-scale turbines and were due to owners or maintenance staff failing to follow precautions, such as not using fall protection gear or working on turbines that were rotating at the time; one incident was a suicide. Two deaths include a child in Canada playing around a small residential turbine under repair, and a teenager in the USA who died after climbing a 50 kw turbine as part of a prank. As the wind industry rapidly expanded and began deploying many more megawatt-scale turbines, the rate of fatalities per unit of electricity has declined by three orders of magnitude since the 1980s.[3] This is including the five fatalities involving members of the public that were described at the beginning of this chapter. Based on data for the UK and Germany (countries with some of the largest uses of offshore and onshore wind, respectively) the fatality rate for wind is around 0.005 deaths/GW_y, although offshore wind (0.009 deaths/GW_y) is notably more dangerous than onshore (0.002 deaths/GW_y).[19]

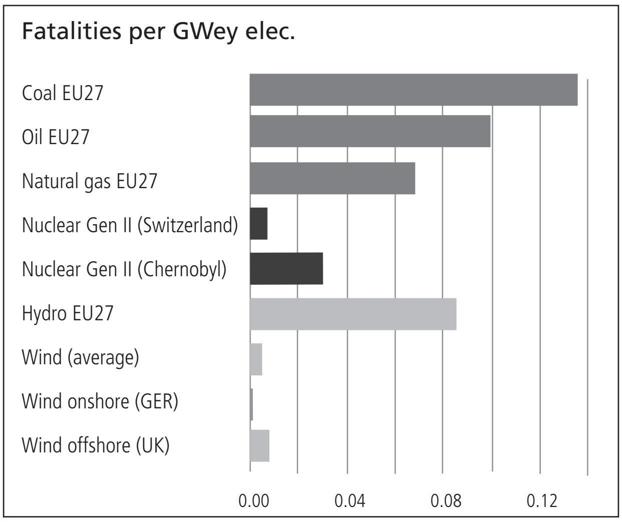
Conventional fossil fuel industries have higher rates of severe accidents resulting in fatalities, especially when global figures are taken into account. However, staying within the EU27 nations, fatality rates range from 0.068 deaths/GWy for natural gas, to 0.100 deaths/GW_y for oil and 0.140 deaths/GW_y for coal.(19) The notable outlier is nuclear power, with worldwide figures of just 0.007 deaths/GWy due to accidents, although this figure excludes the core meltdown event at Chernobyl.** It should be remembered that the hazards associated with nuclear energy are much greater in the event that something does go wrong,[20] with 'latent mortality' and associated societal costs difficult to quantify.[13,21] Data on fatality rates are illustrated in Figure 12.1 below.

It is clear that maintaining an energy supply carries a human cost, but the superior safety profile of wind energy is evident. Going back to the UK's electricity generation over five years, from 2009 to 2013 natural gas and coal were used to deliver 146 GW_y of electricity at a supposed rate of 14 fatalities, if taking the average accident risk calculated for the EU27 countries.[11,19] An equivalent supply generated by wind power would, on average, result in one death, if rounded up to the nearest whole number.

But what of nuclear? It is, indeed, an impressively safe industry when the above figures are analysed. Some recommend that the estimated fatality rate for modern 'Generation III' nuclear reactors slated for use in OECD nations should be several orders of magnitude lower (as of 2016, Gen III reactors have yet to come into use).[16,19] The risk is low, but the hazard that nuclear power plants pose should something go wrong is considerable. Such risks are not limited to nuclear power. As an example, the catastrophic effects of the Banqiao Dam disaster, a single incident that killed 26,000 people in 1975 when the resulting flood wiped out a 300 square-mile area, has distorted the safety profile of hydroelectricity. Across the EU27 countries, hydroelectricity has a fatality rate of 0.085 deaths/GW_y (see Figure 12.1); across non-OECD nations the fatality rate is roughly 10 times higher at 0.954 deaths/GW_y. When the Banqiao disaster is included the non-OECD fatality rate is higher still, reaching 7.03 deaths/GWy, more than 80 times the fatality rate for Europe.[15,19]

Finally, additional negative externalities exist that are not adequately captured by the data above, which simply focus on immediate fatalities. The decentralised nature of wind power limits the degree to which even extreme failure can result in catastrophic effects.[19] As well as

Figure 12.1 Number of fatalities per gigawatt-year electricity (GWy) for major fossil fuel, nuclear, hydro and wind power energy supply chains. Figures based on Burgherr and Hirschberg (2014).[19] Data for fossil fuels and hydropower are derived from a database covering 1970–2008 that only includes severe accidents involving five or more fatalities; figures shown relate to the EU27 countries. Fatality rate for illustrative Swiss 'Gen II' nuclear reactors is calculated by probabilistic safety assessment. Note the separate figure for Chernobyl, which was an early Gen II reactor design known as RMBK. Wind power fatality rates are based on expert assessment and surveys of publicly available data (e.g., ref. 3) updated for 2000–2012;[16] figures shown are based on Germany and the UK, which offer most comprehensive data for onshore and offshore, respectively.



** The issue of nuclear safety remains controversial and figures prominently in any debate surrounding the use of nuclear power as a means to mitigate anthropogenic climate change. Chapter 7 looks at some of these arguments in more detail.

being a comparatively safe form of electricity generation, wind power does not create air pollution or radioactive emissions, and has a significantly lower carbon footprint than any conventional thermal power source.[22–24]

Risks to wind industry workers

Although these 'global' figures show that wind power has a comparatively low societal impact in relation to the energy it provides, the rapid expansion of the wind industry means that there is a risk more accidents will occur as a larger workforce and increasing numbers of the public come into contact with turbines. The wind industry has adopted design standards that improve safety for personnel, especially as turbines have grown in size.[6,25] Design features include basic precautions to mitigate harm to on-site workers, such as guard shields on moving parts and the provision of multiple attachments for safety harnesses for maintenance crews working in the nacelle itself; and equipping towers with fall arresters and rest platforms at regular intervals (usually a maximum of 9 metres apart) for workers ascending and descending.

Turbines with a hub height of more than 60 metres are now required to have personnel lifts, although it should be pointed out that having lifts installed can present other risks relating to electrical and fire incidents, as well as possibly impeding quick access for emergency rescue services.[††] Less obvious features, but vitally important to the safety of crews working on turbines, are emergency stop buttons located at key points where maintenance personnel work; systems that isolate the turbine to give the on-site workers full control to avoid having the turbine restarted by remote control; mechanisms that allow crew members to immobilise the rotor and yaw assembly; and alternative routes of egress from the nacelle should an emergency escape be necessary.[5,6]

Many industrial accidents are caused by operator error, a fact acknowledged by the BS EN ISO 12100:2010 *Safety of Machinery* industry standards, which go so far as to list situations that are foreseeable based on experience of and studies on human behaviour.[26] These include behaviour caused by loss of concentration, carelessness, or taking the 'line of least resistance'; there is also reflex behaviour that occurs when equipment malfunctions or fails, or an emergency incident takes place. Although never completely avoidable in any industrial setting, it is incumbent upon the wind industry to incorporate predictable behaviours into their design and operational ethos. One cause of unintended behaviour is where operators are under pressure to 'keep the machine running in all circumstances'.[26] As wind power expands into ever more inhospitable environments, notably offshore installations far out to sea, there is the possibility that there will be 'conflicting objectives of safety and efficiency'.[7] Large offshore wind developments will be a challenging arena for a relatively young industry. Maintenance procedures that would normally be routine for personnel servicing onshore wind farms can present new hazards when transferred to hostile conditions on an offshore wind farm. Transferring personnel by boat or helicopter onto the turbine can itself be dangerous, and workers may find themselves stranded at the turbine for longer than planned if weather conditions deteriorate.[5] There is a need to implement industry-wide training standards, and the offshore wind industry can certainly benefit from the experience gained by marine operators and the offshore oil and gas industry.[5,7]

Risks to the general public

The hazard to the general public that garners most attention is the risk of blade throw. Although information on this phenomenon is not generally available outside of the industry, there has been enough data collected and released to accept that a throw event in the instance of blade failure has a probability of 0.00026 (a probability of 1.0 means an event is certain to happen).[9,27]

At this point it is useful to remind ourselves what 'failure' means in this context. A failure is reported for a wind turbine subassembly or component when it results in loss of power generation, it does not automatically denote that a component has completely broken, come free, collapsed, or some other dramatic event.[2] Thus, when reviewing all instances of blade 'failure' during the many hundreds of thousands of operational hours that wind turbines have been running, it is important to remember that this does not mean a blade or blade fragment was thrown from the turbine.

When a blade or blade fragment is thrown, then there is a risk of it striking a person or structure and causing injury or death. A similar risk exists in the case of ice throw. There have been many studies on rates of blade throw and modelling the probability of impact on the ground.[2,9,27–29] Smaller blade fragments fly further, although it is important to note that for modern 2–3 MW turbines, even a 'small' fragment can be several metres long.[28] The main factor that determines the extent a thrown fragment might travel is the release velocity.[9,27] Although this may seem obvious, one important fact to remember is that larger turbines may have slower blade tip speeds.[‡‡] This has important

---

[††] This is noted by the UK trade body: 'H&S Guidelines: Lifts in Wind Turbines', RenewableUK [Online], 1 Feb, 2011, p.2 (Available from www.renewableuk.com/en/publications/index.cfm/Lifts-in-Wind-Turbines).

[‡‡] Blade tip speed, or more precisely, the ratio of blade tip speed to wind speed, is an important parameter with regards to the maximum power coefficient of a rotating blade. Optimum performance does not mean achieving the fastest possible tip speed, hence, higher rated turbines with longer blades may operate with slower tip speeds than lower-rated turbines with shorter blades.

implications for setting safe setback distances in case of blade throw, since many guidelines simply rely on a multiple of the turbine's blade radius or hub height, which typically fall in line with a turbine's power rating.[9] However, a 1.5 MW turbine with blade radius of 35 metres may well throw a fragment further than a 3.0 MW turbine with blade radius 45 metres.[27)] When determining setback distances based on acceptable risk, therefore, it is likely that setbacks based on arbitrary multiples of blade radius or hub height are inaccurate. In this context, 'acceptable risk' is typically a thrown fragment exceeding the setback distance once per year for 20,000 turbines, i.e. 20,000:1 odds, or a probability of 0.00005. Note these are the odds of an incidence of blade throw resulting in the setback distance being exceeded, not the odds that blade throw occurs at all.

What happens in the unlikely event that blade throw does occur? In this circumstance, one must take into consideration that the calculated risk is conditional, because it is predicated on the blade throw having occurred, which, as mentioned before, is generally accepted to have a probability of 0.00026. What this means is that the risk of fatality from being struck by blade throw must take into account the failure rate that leads to this event. A recent Health and Safety Excecutive report determined that the risk posed to a member of the public standing within 160 metres of a 2.3 MW turbine (a common size rating for onshore utility wind farms in the UK) is equivalent to a holidaymaker taking two flights per year.[2] In other words, the risk was very low, significantly lower than societal risks associated with activities such as travelling by car, regularly commuting by train, or even working in the service sector.

Some form of failure is not unexpected in such a complex piece of industrial machinery – for comparison, a normal car engine is designed to operate for about 5,000 hours, whereas offshore wind turbines are designed to operate for 70,080 hours.[5] Although component failure rates were higher than expected in the early days of the 1990s, the wind industry has steadily achieved improvements in reliability of components, and is now on a par with the reliability expected of industrial gas turbines.[30]

Reliability is an obvious concern for wind turbine operators. Not only is any downtime costly, but the more complex the repairs then the more likely workers are to be exposed to occupational hazards.[5] Surprisingly, given the focus they receive from the industry, gearbox assemblies are not the main source of component failure, but electrical systems, rotor, converter and generator subassemblies have suffered from a higher than expected number of faults over the decades, even by the standards of a relatively new industry.[31] Although reliability continues to improve, the move from onshore to offshore means that what may be an acceptable maintenance schedule on dry land could become prohibitively costly and dangerous at sea. Consequently, developing remote sensory systems that monitor the condition of the various wind turbine subassemblies, including icing of blades, is a key part of the wind industry's attempt to implement preventive maintenance standards.[32,33]

Returning to the theme of the wind industry's disinclination to share, it has been noted that costly subassembly failures in the earliest UK offshore (Round 1) wind farms may have been mitigated to some degree if the industry as a whole were more open to exchanging information and knowledge with other operators, contractors and researchers.[34] There are signs that this may be changing with the start of the UK's 'Round 3' tranche of offshore wind farms, with trade groups like RenewableUK initiating network events with members to galvanise the offshore industry, and efforts by government departments, such as the Technology Strategy Board, to facilitate knowledge sharing.[35]

Conclusions

As with other features of modern life (e.g. travel by air, rail or car), society makes the decision to accept certain risks in exchange for the benefits that this development brings. Measuring one against the other is of paramount importance, as is a continual effort to minimise the risks along with any detrimental outcomes. This also implies that we should regularly re-evaluate the costs and benefits, so that we can be sure that what was once an acceptable cost is still the case and meets the increasing standards of safety expected in modern society.

Great care should be exercised when attempting to show wind-generated electricity is a completely benign source of energy. There have been at least 80 recorded fatalities involving wind power since 1975 – while this is very low by the standards of the energy industry, the fact that lives are lost should not be ignored.

Analysing these statistics again reveals that the mortality rate per unit electricity generated has dropped three orders of magnitude since the first commercial expansion of the wind industry in the 1980s. However, wind turbines continue to suffer reliability issues, which may have serious ramifications for the wind industry's rapidly expanding workforce, especially in the case of the still nascent offshore industry. The increasing penetration of wind power in national energy infrastructure will pose more potential hazards to workers and the public. For instance, the problem of blade throw has been around for some time, and efforts by to downplay this issue can only be detrimental to the reputation of the industry given the risk is, in reality, much smaller than most societal risks.

Much has been learnt in the last two decades as the wind energy industry has grown: more rigorous safety standards are being implemented in turbine design, and more studies into issues such as blade throw enable risks to be adequately modelled and incorporated into planning. Although it could, and should, tackle some issues more openly, overall the wind energy industry has one of the best safety records of any energy industry, and has seen fatality rates decrease in the face of a rapidly expanding capacity. Wind continues to offer a clean, safe form of electricity supply, with considerably less cost and risk to society than either fossil fuels or nuclear energy.

References

1. Wiser R, Bolinger M. 2014 Wind Technologies Market Report. DOE/GO-102015-4702. Oak Ridge, Tenn.: U.S. Department of Energy; Aug 2015. 81 p.
2. Robinson CME, Paramasivam ES, Taylor EA, Morrison AJT, Sanderson ED. Study and development of a methodology for the estimation of the risk and harm to persons from wind turbines. Report No.: RR968. Health and Safety Executive; 2013. 86 p.
3. Gipe P. Accidents & Safety: A Summary of Fatal Accidents in Wind Energy [Online]. Wind-Works.org. c.2016 [last updated 1 May, 2013]. Available from: www.wind-works.org/cms/
4. REN21. Renewables 2015 Global Status Report. Paris: REN21 Secretariat; 2015. 250 p.
5. EU-OSHA. Occupational safety and health in the wind energy sector. European Risk Observatory Report. TE-RO-13-008-EN-N. Bilbao: European Agency for Safety & Health at Work; 2013. 75 p.
6. Burton T, Jenkins N, Sharpe D, Bossanyi E. Conceptual design of horizontal axis wind turbines. Wind energy handbook. 2nd ed. Chichester: Wiley; 2011. 325–82.
7. Albrechtsen E. Occupational safety management in the offshore wind industry – status and challenges. Energy Procedia. 2012; 24:313–21.
8. Manwell JF, McGowan JG, Rogers AL. Wind energy systems: environmental aspects and impacts. Wind energy explained: theory, design and application. 2nd ed. Chichester: Wiley; 2009. 547–92.
9. Larwood S, van Dam CP, California Wind Energy Collaborative. Permitting setback requirements for wind turbines in California. CEC-500-2005-184. California Energy Commission, Public Interest Energy Research (PIER) Program; Nov 2006. 42 p.
10. LeBlanc MP, Morgan CA, Bossanyi EA, Garrad AD. Recommendations for risk assessments of ice throw and blade failure in Ontario. Report No.: 38079/OR/01. Canadian Wind Energy Association (CanWEA); May 2007. 16 p.
11. Keria M. Chapter 5 – Electricity. In: Digest of United Kingdom Energy Statistics 2014. London: The Stationery Office/TSO; 2014. 113–56.
12. Fischedick M, Schaeffer R, Adedoyin A, et al. Mitigation potential and costs. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 791–864.
13. Hirschberg S, Burgherr P, Spiekerman G, Dones R. Severe accidents in the energy sector: comparative perspective. J Hazard Mater. 2004; 111(1-3):57–65.
14. ExternE. External costs: research results on socio-environmental damages due to electricity and transport. European Commission, Directorate General for Research. Report No.: EUR 20198. Luxembourg: Office for Official Publications of the European Communities; 2003. 24 p.
15. Burgherr P, Hirschberg S. A Comparative Analysis of Accident Risks in Fossil, Hydro, and Nuclear Energy Chains. Hum Ecol Risk Assess Int J. 2008; 14(5):947–73.
16. Burgherr P, Eckle P, Hirschberg S, Cazzoli E. Final Report on Severe Accident Risks including Key Indicators. SECURE Deliverable n° D5.7.2a. Brussels: SECURE project "Security of Energy Considering its Uncertainty, Risk and Economic implications"; 2011. 70 p.
17. Bickel P, Friedrich R, Directorate-General for Research Sustainable Energy Systems, editors. ExternE: Externalities of Energy; Methodology 2005 Update. Luxembourg: European Communities; 2005. 282 p.
18. Sovacool BK. The costs of failure: A preliminary assessment of major energy accidents, 1907–2007. Energy Policy. 2008; 36(5):1802–20.
19. Burgherr P, Hirschberg S. Comparative risk assessment of severe accidents in the energy sector. Energy Policy. 2014; 74:S45–S56.
20. Lelieveld J, Kunkel D, Lawrence MG. Global risk of radioactive fallout after major nuclear reactor accidents. Atmospheric Chem Phys. 2012; 12(9):4245–58.
21. Laes E, Meskens G, van der Sluijs JP. On the contribution of external cost calculations to energy system governance: The case of a potential large-scale nuclear accident. Energy Policy. 2011; 39(9):5664–73.
22. Epstein PR, Buonocore JJ, Eckerle K, Hendryx M, Stout III BM, Heinberg R, et al. Full cost accounting for the life cycle of coal. Ann N Y Acad Sci. 2011; 1219(1):73–98.
23. Nugent D, Sovacool BK. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy. 2014; 65:229–44.
24. Dolan SL, Heath GA. Life cycle greenhouse gas emissions of utility-scale wind power: systematic review and harmonization. J Ind Ecol. 2012; 16:S136–54.
25. BSI. BS EN 50308:2004. Wind turbines — Protective measures — Requirements for design, operation and maintenance. London: British Standards Institution; Sep 2004. 28 p.
26. BSI, CEN (European Committee for Standardization). BS EN ISO 12100:2010. Safety of machinery — general principles of design — risk assessment and risk reduction. London: British Standards Institute; 2011. 77 p.
27. Rogers J, Slegers N, Costello M. A method for defining wind turbine setback standards. Wind Energy. 2012; 15(2):289–303.
28. Slegers N, Rogers J, Costello M, Puga M, Arons P. Modeling the risk of a failed wind turbine blade impacting a power transmission line. Wind Eng. 2009; 33(6):587–606.
29. Carbone G, Afferrante L. A novel probabilistic approach to assess the blade throw hazard of wind turbines. Renew Energy. 2013; 51:474–81.
30. Tavner PJ, Xiang J, Spinato F. Reliability analysis for wind turbines. Wind Energy. 2007; 10(1):1–18.
31. Spinato F, Tavner PJ, van Bussel GJW, Koutoulakos E. Reliability of wind turbine subassemblies. IET Renew Power Gener. 2009; 3(4):387–401.
32. Yang W, Tavner PJ, Crabtree CJ, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. Wind Energy. 2014; 17(5):673–93.
33. Purarjomandlangrudi A, Nourbakhsh G, Esmalifalak M, Tan A. Fault Detection in Wind Turbine: A Systematic Literature Review. Wind Eng. 2013; 37(5):535–48.
34. Weaver T. Financial appraisal of operational offshore wind energy projects. Renew Sustain Energy Rev. 2012; 16(7):5110–20.
35. Kern F, Smith A, Shaw C, Raven R, Verhees B. From laggard to leader: Explaining offshore wind developments in the UK. Energy Policy. 2014; 69:635–46.

Chapter 13

Shadow flicker and epilepsy risk

Summary

At certain angles the blades of a wind turbine will rotate in front of the sun, casting a moving shadow that may be seen by observers in nearby dwellings. When there is a narrow opening, such as a door or window, these moving shadows can be of sufficient contrast to project a flickering effect known as 'shadow flicker'. Despite early fears that wind turbines may cause photo-epileptic seizures, studies have shown that modern wind turbines rotate at a rate well below the threshold that would potentially be of risk for vulnerable persons. Whilst it poses no threat to safety, shadow flicker from turbines may be an annoyance factor for observers who are subjected to it for longer than a certain time. However, due to the geometries involved, shadow flicker is an easily modelled property and can be accounted for during planning and development of a wind farm; indeed, even existing wind turbines that are found to cause an issue can easily implement measures to remove the occurrence of shadow flicker. UK government planning regulations stipulate that the possibility of shadow flicker must be considered during wind farm development, and there are a number of software packages that can model the phenomenon consistently and accurately.

What is this based on?

Wind turbines are tall structures, and present an open disc in the form of rotating blades. Depending on the sun's bearing in relation to observers (this is the sun's azimuth) and the sun's altitude in the sky, wind turbines will cast a shadow over nearby ground – this shadow can be a significant length at certain times of the day and at certain times of the year. An important factor in the case of wind turbines is that the rotating blades will pass in front of the sun's azimuth, giving rise to moving shadows that are particularly noticeable through windows and doors where the contrast between light and shade is most apparent. This shadow flicker effect could certainly present an annoyance to exposed residents, and some critics have predicted (wrongly) that sufferers of photosensitive epilepsy would be prone to seizures as a result.

What is the evidence?

A number of different factors must coincide to result in shadow flicker, and the magnitude of the effect can also vary greatly in response to changing conditions.[1] Crucially, the position of the wind turbine in relation to a constrained opening – a window or door – determines whether the flicker effect will be observed. The height and position of the sun, i.e. its azimuth, must also be such that the rotating blades cast a long enough shadow that falls on the critical area; the wind speed must be enough that the turbine is operating during these periods when such shadows may be cast. Finally, the contrast of light and dark, which will determine the magnitude of the effect, is dependent upon prevailing cloud cover and time of year. Due to the latitude of the UK, only dwellings sitting within 130° either side of north relative to the turbines can be affected (going clockwise, that is 230° to 130° from true north); no long shadows are cast southwards by turbines in northern latitudes.[2]

Research carried out at early wind farm developments in the UK showed that shadow flicker only occurs when the shadow is sufficiently in focus and lasts a certain duration, both properties that diminish rapidly with distance from the rotating blades. This led to the '10× diameter' rule, whereby distances that fall within ten times the rotor diameter can create the right circumstances to give rise to shadow flicker.[3,4] For example, a rotor diameter of 80m will potentially give rise to shadow flicker up to 800m away, if conditions are right. This ratio is used as part of the planning regulation guidelines for the siting of wind turbines in the UK.[2]

Since it is possible to predict this phenomenon it is relatively simple to include an assessment of potential shadow flicker when developing a site for a wind turbine. Even if residences may potentially fall within a shadow flicker area this does not necessarily mean a development should be excluded. There are several relatively simply mitigation measures developers can take, such as 'micrositing' to adjust the position of problem turbines within a wind farm, programming the relevant turbines to stop operation in the brief window of time during which shadow flicker has been predicted to affect certain dwellings, and planting a screen of trees between the turbines and the affected properties to disperse the light.[1]

Although the leading software used as standard in the industry gives consistent results between different programs, the lack of real climatic data that is modelled means the predictions are 'astronomical worst case' scenarios.[1] This is meant in relation to the simplifications of the general model, which treats the sun as a point source of light, presents the turbine rotor face as a solid disc formed from perfectly rectangular blades, and assumes the atmospheric conditions are completely clear. Conditions in reality combine so that shadow flicker is not apparent during many of the times when it is predicted to occur. Sunlight hitting the Earth radiates from the disc of the sun, not a point source; the blades of a turbine are trapezoid, so different parts of the blade will cause different levels of shadowing; and on many days the intensity of sunlight is diminished due to atmospheric scattering and the presence of aerosols like water droplets and particulate matter.[5]

Seasonal variation is also important, since the shadow effect is more far reaching in winter when the sun is lower in the sky, but winter also corresponds with more frequent cloud cover so the light is muted (winter also happens to coincide with higher average wind speeds, when turbines will operate closer to their maximum rating for longer).[1] So, in the UK winter months although the sun is lower in the sky and casts longer shadows, 80% of the time the sunlight is not bright enough to create the necessary contrast for shadow flicker to be apparent;* even in summertime, the sunlight is not bright enough 60% of the time. The sun must also be at the correct bearing in relation to the turbine rotor face to cast a shadow across an exposed dwelling. Due to this combination of sunlight and bearing, these circumstances in reality only occur together for a fraction of the theoretical maximum calculated by the astronomical worst case scenarios: 15% in winter and 30% in summer. All of these variables have led some to suggest that the shut-down strategy of mitigation, a popular solution for wind farm operators, may be overused in many cases because these real-world conditions are not taken into account.[1,5]

Prolonged exposure to shadow flicker of around 60 minutes or more has been documented to cause transient symptoms relating to stress, such as reduced concentration span and elevated heart rate.[6] Whilst generally not harmful due to the temporary nature of the symptoms, a regard to minimise these effects led German planning authorities to stipulate shadow flicker on exposed buildings is limited to a maximum of 30 hours in the course of a year or 30 minutes per day on the worst affected day.[1] Other planning authorities have adopted similar guidelines, such as Northern Ireland and the Republic of Ireland. In rare cases where repeated exposure has occurred, most often due to office building situated near wind farms, simple mitigation measures have been successfully implemented.[1]

It has also been suggested that shadow flicker poses a threat to the small percentage of epileptics who suffer from photosensitive epilepsy, in which seizures are triggered by flashing lights or contrasting patterns of light and dark.[7] In the UK, the National Society for Epilepsy states that 1 in 100 people suffer from epilepsy during their lifetime, and about 5% of this group will have photosensitive epilepsy.[8] Flashing or flickering at frequencies between 3–30 hertz (Hz) are the most common form of photic stimuli known to cause photo-epileptic seizures, and concern regarding wind turbines was due largely to the fact that rotation frequencies in this range are found in small, building-mounted turbines, not the commercial scale turbines found in wind farms. These smaller turbines have the dual problems of greater blade numbers and faster rotation speeds that create flicker above the critical frequency.[9] Commercial turbines with a three blade design – the industry norm – would have to rotate at 60 revolutions per minute (rpm) to generate a flicker effect of 3 Hz or more, but in fact turbines of this kind rotate at much slower speeds and will not pose a threat to photosensitive epilepsy sufferers during operation.[7,10] Speeds of some representative commercial turbines are illustrated in Table 14.1. Even for smaller 'domestic-size' turbines (up to a rating of about 10 kW) that may possess the potential to induce photo-epileptic seizures, typical atmospheric conditions result in a contrast threshold between light and dark that is significantly reduced such that any observed flicker will not have the capacity to induce epileptic seizures at distances greater than 1.2 times the height of the turbine rotor.[10]

There are some concerns that the flicker effect caused by reflected light from turbine blades can be apparent at greater distances than is taken into account by planners. Note that this strobe effect is different from shadow flicker. However, the same principle with regards to frequency of flicker and the exact positioning of an

Table 13.1 Representative commercial-scale wind turbines and typical rotation speeds during operation

Manufacturer	Model	Rating	Typical rpm
General Electric	GE 1.6-100	1.5 MW	10–16
REpower	MM92	2.0 MW	8–15
Siemens	SWT-2.3	2.3 MW	6–16
Vestas	V112-3.0	3.0 MW	6–17

Figures for rotation speed as stated in ref.7. MW, megawatt; rpm, revolutions per minute

---

* As light is increasingly scattered by atmospheric conditions it creates a more even ambient light through diffuse radiation; hence, the 'beam' effect of direct sunlight that creates the sharpest constrast shadows is mitigated. On days with complete cloud cover, for instance, the result is muted light levels with no shadows cast.

observer with relation to the turbine are applicable, even though reflected light can affect areas not reached by shadow.[9] Government guidelines advise developers to minimise the specular properties of turbine blades to avoid light reflecting off the blades unduly; indeed minimising reflectiveness of the blades is something the industry has been carrying out for several decades already, and it is typically no longer an issue.[1,2,11]

Conclusion

Shadow flicker from the rotating blades of a wind turbine is a known, quantifiable effect. Large commercial turbines can potentially create a flicker effect at frequencies below 2 Hz, safely below the threshold that can cause photo-epileptic seizures, and there is no evidence that the operating characteristics of commercial wind turbines can induce seizures in the vulnerable population of epilepsy sufferers. If endured continuously for prolonged periods, the annoyance factor of shadow flicker can lead to temporary stress-related symptoms in observers, but planning guidelines and mitigation measures can ensure this situation does not occur.

Due to the precipitating factors, which involve turbine position in relation to the solar azimuth and sun's altitude above the horizon relative to an observer, this phenomenon can be accurately modelled and predicted. In practice, shadow flicker occurs within narrow spatio-temporal limits. This means that even if it is predicted to affect certain dwellings, shadow flicker is only apparent when the intensity of sunlight and angle of the blades to an observer combine with the sun's position in the sky to create a noticeable effect – this is effectively for short periods in any single day affecting those particular dwellings that are vulnerable during such periods.

The predictability and infrequency makes shadow flicker an eminently manageable problem: it can be curtailed by the introduction of various mitigation measures, among them re-siting of individual turbines, creating screening features such as treelines (or using existing ones), and programming the turbines to cease operation for the short time during which offices or dwellings are affected.

References

1. Parsons Brinckerhoff Ltd. Update of UK shadow flicker evidence base. London: Department of Energy & Climate Change; Mar 2011. 59 p.
2. Ove Arup and Partners. Planning for renewable energy: a companion guide to PPS22. London: Office of the Deputy Prime Minister; 2004. 184 p.
3. Clarke AD. A case of shadow flicker/flashing: assessment and solution. Milton Keynes: Open University; 1991.
4. Taylor D, Rand M. Planning for wind energy in Dyfed. Report by Energy and Environment Research Unit, EERU 065. Milton Keynes: Open University; 1991.
5. Freund H-D. [In German]. Influences of the opaqueness of the atmosphere, the extension of the sun and the rotor blade profile on the shadow impact of wind turbines. DEWI Magazin Nr. 20. Feb 2002;43–51.
6. Ellenbogen JM, Grace S, Heiger-Bernays W; On behalf of MassDEP and MDPH. Wind Turbine Health Impact Study: Report of Independent Expert Panel. Massachusetts Department of Environmental Protection and Massachusetts Department of Public Health; Jan 2012. 164 p.
7. Knopper LD, Ollson CA, McCallum LC, et al. Wind turbines and human health. Front Public Health. 2014; 2:Article 63.
8. Photosensitive epilepsy [Online]. Epilepsy Society. Updated Sep 2013. [Last accessed 8 Sep 2014]. Available from: www.epilepsysociety.org.uk/photosensitive-epilepsy.
9. Harding G, Harding P, Wilkins A. Wind turbines, flicker, and photosensitive epilepsy: Characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them. Epilepsia. 2008; 49(6):1095–8.
10. Smedley ARD, Webb AR, Wilkins AJ. Potential of wind turbines to elicit seizures under various meteorological conditions. Epilepsia. 2010; 51(7):1146–51.
11. McAulay I. The influence of colour on the aesthetics of wind turbine generators. ETSU Report W/14/00533/00/00. London: Department of Trade and Industry; 1999.

Chapter 14

Wind turbines and noise

Summary

Wind turbines rely on mechanical operations to generate electricity. The movement of the blades through the air inevitably creates noise, and the increasing size of medium-to-large turbines (typically 2.3–3.6 MW rating, standing 65–105m tall) has prompted concern that they will generate an unacceptable level of noise for nearby residents. In the UK, this phenomenon has been studied by a government working group, and detailed guidelines form part of UK planning regulations to prevent undue noise pollution. These, coupled with the quieter design of modern turbines, mean that the noise levels generated by wind farms are comparable to outdoor background noise. Studies have found topography and changing wind patterns at night can accentuate this noise in specific locations, but understanding this process means it can be correctly assessed during planning to ensure that properties that might be prone to these effects are not affected.

People may hear the same noise, but experience quite different impressions of it. Excepting those instances where nuisance noise can clearly and objectively be demonstrated, controversies over wind turbine noise reveal the shortcomings of the planning process. Evidence suggests that some residents negatively perceive wind turbine noise and suffer annoyance due to the technocratic and opaque way in which many wind farms are developed in Britain, and are rightly aggrieved when their concerns are dismissed by developers who are then accused of hiding behind what some observers increasingly see as inadequate, arbitrary and out-of-date guidelines. This brings the legitimacy of wind power into question, shaping perceptions of future developments and increasing the likelihood that more residents will consider that they have suffered loss of amenity. Lessons from Europe, in particular Germany, suggest that early participation, and local ownership, or favouring social enterprises, are far more successful ways to implement wind power. Experience has shown that residents' negative perceptions of noise are reduced when communities are actively engaged in the planning process and enjoy some direct financial benefit from wind farms, rather than ignoring concerns, presenting last-minute 'consultations' and doggedly adhering to prescriptive and inflexible noise limits as a defence when challenged.

What is this based on?

Any large device that has moving parts will create some noise, and wind turbines of any size are no exception. The sounds generated by wind turbines are either mechanical or aerodynamic. Modern turbine designs have resulted in progressively quieter mechanical operation, to the extent that mechanical noise will not exceed aerodynamic noise under normal operation.[1] The aerodynamic sounds are caused by the turbine blades moving through the air as the wind is blowing, and are usually classed as tonal, low-frequency, broadband and impulsive.

These sounds are the result of changes in wind speed experienced by the blades at different heights as they go through a complete revolution, the blades interacting with atmospheric turbulence, and the deflection of air due to the blade aerofoil itself (the aerofoil, or airfoil, is the cross-section of the blade, which determines how air passes around the blade and aerodynamic force is generated).[1,2]

Table 14.1, below, demonstrates the levels of noise commonly associated with utility-scale turbines (1.0–3.6 MW), with typical noise output ranging between 97 and 107 dB(A).[3]

Table 14.1. Sound power level for Vestas V90-3.0MW (80m Hub)

U_sm/s	4	5	6	7	8	9
Lw dB(A)	97.9	100.9	104.2	106.1	107.0	106.9

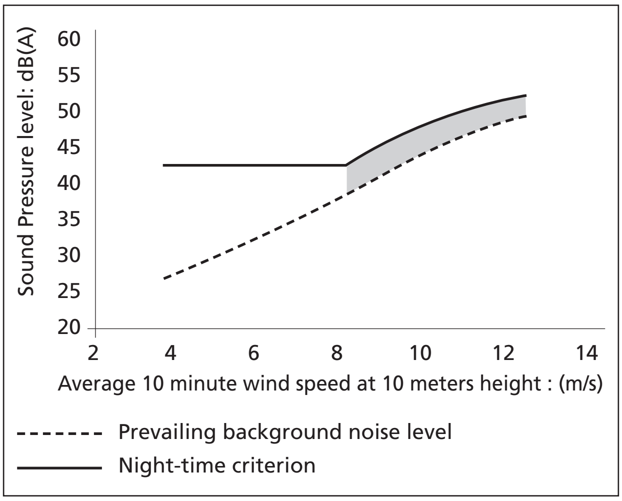
U_sm/s is the wind speed in m/sec at a standardised anemometer height of 10m. Lw is sound power level re 10^{-12} watts

It is apparent from this that wind turbines cannot be sited too close to residential dwellings. The World Health Organization (WHO) has stated that excessive 'community noise', defined as noise from traffic, industries, construction works, and the urban environment, can create a host of adverse effects on human health.[4] Noise levels encountered in everyday situations are given in Table 14.2. Note that noise levels are measured using an 'A-weighting' that emphasises those frequencies to which the human ear is most sensitive, hence sound pressure levels are given in dB(A) (decibels with A-weighting). The A-weighting helps ensure measured sound levels are close to the perceived sound levels of the human subject. The dynamic range of human hearing is discussed in more depth in the section on low-frequency sounds (section 15).

As the wind energy sector began to expand in the early 1990s, UK planning authorities recognised that guidelines were needed that adequately cover the use of increasingly large, utility-scale wind turbines. In 1996, the Energy Technology Support Unit (ETSU) set up a Noise Working Group to carry out research on behalf of the government so that the lower limits for noise emissions from wind farms could be defined. The recommendations were published as ETSU-R-97 and then incorporated into national planning guidelines the following year.[5,6]

These guidelines provide a general rule that day and night noise levels should be a maximum of 5 dB(A) above ambient background noise. For example, if background noise levels are 50 dB(A), then the permitted noise level due to a wind farm is 55 dB(A). However, there is also a fixed *lower* threshold for background ambient noise, below which developers do not have to adhere to the +5dB(A) rule. These thresholds are 35–40 dB(A) for daytime noise levels and and 43 dB(A) nighttime noise levels.[5] What this means is that, should a particular location have a nighttime background noise measurement of 25dB(A), the noise from the wind farm is not limited at 30dB(A) (which is 25 +5 dB(A)), but would actually be acceptable under ETSU-R-97 as high as 43dB(A) (the fixed lower threshold for night-time noise). (see Figure 14.1).

Figure 14.1 Graphical representation of ETSU recommended noise limits for night time.



The ETSU-R-97 report is still in use today. Despite this longevity, ETSU-R-97 has been the subject of criticism for some time.7 To begin with, the authors of the report themselves aired the view that the report should be revised after two years. Twenty years on, no revision has been forthcoming. Given how much the average wind turbine has increased in size since the 1990s, this is quite surprising. It is especially puzzling in light of the fact that wind turbine noise continues to be reported as an annoyance factor for a significant minority of residents living near wind farms.[8–10]

Table 14.2 Indicative noise levels for situations commonly experienced in normal life.

Source	Noise level in dB(A)
Jet aircraft at 150m	105
Pneumatic drill at 150m	95
Truck at 30mph at 100m	65
Busy general office	60
Car at 40mph at 100m	55
Wind farm at 350m	**35-45**
Rural night-time background	20-40
Quiet bedroom	20

(Threshold of pain = 140 dB(A))

The way in which wind turbine noise is compared against background noise levels has also been criticised.[7] The ETSU-R-97 report took much of its inspiration from the widely used British Standards, BS4142 ('Method for rating industrial noise…').*[11] This set of standards stipulated that measurements of background noise be representative of the period, and include the quietest part of said period. However, on this point ETSU-R-97 departed from BS4142 by recommending sound pressure level measurements that do not include the quietest period and are averaged across the entire period (see p.60 of ref. 5, 'the LA90 descriptor is also being proposed for the turbine noise').[5] The upshot of this decision is that, when compared with good practice laid out in BS4142, actual wind turbine noise may effectively be 7 dB(A) above background levels, rather than 5 dB(A), but still fall within the permitted limits proposed by ETSU-R-97.

Perhaps most contentious of all is that ETSU-R-97 permits higher noise levels at night than during the day – the only guidelines on noise to do so anywhere in the world.[7,12] At certain sites, wind turbine noise was found to be unexpectedly loud at night time, and it is now known that meteorological conditions that occur more commonly at night contribute to the apparent loudness.[2,13] Thus, noise emissions from wind turbines can be problematic even when planning guidelines are adhered to. A recent good practice guide, published by the Institute of Acoustics, on how to apply ETSU-R-97 to

---

* In 1996, this standard was BS4142:1990, which was superseded in 1997 by BS4142:1997 'Method for rating industrial noise affecting mixed residential and industrial areas'. The current standard is BS4142:2014.

wind farm proposals incorporates the effect of meteorological conditions on sound propagation.[14] The central tenets of the ETSU report, however, remain unchanged.

Although ETSU-R-97 guidance has some shortcomings, it is important to note that the evidence of a direct link between wind turbine noise, annoyance and sleep disturbance continues to be conflicting.[9] One crucial aspect, and one that ETSU makes no allowance for, is the non-acoustic element of noise disturbance, that is, the meaning that humans attach to perceived sounds.[7] Despite evidence that particular acoustic characteristics of turbines are more intrusive than previously thought, especially the phenomenom of 'amplitude modulation',[15,16] studies also show that context plays a role in self-reported disturbance and even in objectively measured sleep patterns.[17–20] Negative attitudes towards wind turbines can be a strong predictor of annoyance, independent of the actual sound levels experienced. Awareness of the source of the noise, and also the benefit that an individual receives personally from a wind farm, can have a significant effect.[8,17,20–23]

What is considered noise can be highly subjective and may largely depend on the attitudes of the person receiving the sound. National planners and wind energy developers have been reluctant to concede that non-acoustic factors can add layers of meaning to a sound, which may be why noise from the same wind farm can seemingly be both 'undetectable' and 'unbearable' to different residents.[7] Unfortunately, this has also nurtured the belief that wind turbine noise is somehow uniquely damaging, giving rise to various health scares that have little basis in fact. [24,25] Pernicious myths like 'wind turbine syndrome' (see chapter 15) do a disservice to those individuals experiencing ordinary, but intrusive, noise from wind turbines.

What is the current evidence?

Aerodynamic noise

Thanks to improvements in gearbox design and machining, the use of anti-vibration mountings and couplings to limit structure-borne noise, and other features such as acoustic damping of the nacelle and liquid cooling of the generator, mechanical noise generated by modern wind turbines is minimal.[2,26] Although the original turbine blade designs sought to optimise aerodynamics using knowledge from aeronautics, which meant little attention was paid to sound, blade design has since been refined to be aerodynamically designed for maximum energy generation and minimum noise.[1,27]

As we have seen, aerodynamic noise from wind turbine blades can still be significant, and research into quieter designs is still ongoing, especially given increasing noise constraints as wind power continues to expand. Already, blade manufacture is often adapted to suit a particular wind farm, and researchers are looking at low-computational methods that can allow design to be improved on a site-by-site basis, with optimal trade-off between annual power production and noise.[28] This demonstrates that it is possible to mitigate aerodynamic noise, which, as will be discussed below, is especially important at low wind speeds when background noise is diminished but wind turbines are still capable of operating; the most efficient generation still occurs at higher wind speeds when background noise masks wind turbine noise.[29]

The aerodynamic noise generated by wind turbines during operation takes a variety of forms, usually classed as tonal, low-frequency, broadband and impulsive.[1,2] Tonal sounds typically arise from mechanical parts (e.g. gears meshing) and are also a notable feature of blade aerofoils in small kilowatt turbines, but tonal sounds are not an issue for utility-scale turbines used on wind farms.[26] There is a great deal of misunderstanding and misinformation on the nature and impact of low-frequency sound, which, along with 'infrasound', is blamed as the cause of a multitude of health complaints. This is discussed in detail in chapter 15, which concludes that there is simply no evidence for these health complaints. As mentioned above, the persistence of these 'myths' is an unhelpful distraction from the real problem of wind turbine noise.[24]

Amplitude modulation – swishing and thumping

It is acknowledged that the problem of wind turbine noise lies with the broadband and impulsive emissions caused by the rotating blades. This is because these sounds are subject to amplitude modulation.[1]

Broadband sound – so called because the sounds cover a wide range of frequencies anywhere from 18 to 2,000 Hz – is generated by the front of the blade (the leading edge) pushing through turbulent air and by the back of the blade (the trailing edge) interacting with turbulent air that has just passed across either side of the blade itself. The key feature here is that sound waves generated by the force of these interactions are pushed along in the direction that the blade is travelling. This gives the sound an unusual directivity.[26] A listener on the ground will hear this broadband sound most clearly each time a blade passes a certain position whereby the sound is 'pushed', or projected, in their direction. Thus, to this listener, the sound rises and fades in a rhythmic fashion, i.e. the amplitude modulates up and down.[30]

This rhythmic amplitude modulation is generally described onomatopoeically as a 'swish', 'swoosh' or 'whistle'. The 'swish' is the characteristic sound of wind turbines, and can be an annoyance factor if especially audible, which might happen in rural or semi-rural areas.[8,21] In particular, there appears to be a threshold of around 40 dB(A) at an affected residence where the sound is prominent (though not necessarily annoying, since context affects this).[31,32] Of more concern is the phenomenon at times of high activity of a 'thumping' noise (sometimes described as a roar or rumble), which is experienced as a more intrusive sound.[13,21] The cause of the 'thump' has been a matter of some debate, but it is now thought to be the sound generated by the trailing edge of the blade that is reinforced at times by local atmospheric conditions.[26] Since the thumping sound varies rhythmically in a similar fashion to the swishing sound, it too is a form of amplitude modulation.[1] What makes thumping a concern is that the conditions that cause it are not well understood, so it is more difficult to predict and mitigate; the amplitude modulation can be relatively large, more than 6 dB rather than the usual 1–2 dB for swish; and there is an increased low-frequency component that contributes to the unusual and insistent nature of the sound in the ears of the listener.[13,21,26,30]

Both the Institute of Acoustics and the main industry body for wind power (RenewableUK) are investigating further the incidence of impulsive amplitude modulation. At the end of 2013, RenewableUK released findings[†] that suggest 'transient stall' of the blades may be a cause of thumping, and may occur independently of atmospheric conditions.[33] Since the onset of stall can be minimized by adjustments to blade pitch (and possibly changes to blade design), this recent research suggests that it is possible to reduce the risk of amplitude modulation that results in thumping.

In addition, and what is a welcome move considering the existing guidance under ETSU-R-97 has remained unchanged since 1997, RenewableUK put forward a proposal for a penalty scheme to account for amplitude modulation.[‡] This proposal builds on RenewableUK's research programme to develop a robust metric to describe the level of amplitude modulation (essentially, the 'depth' of modulation, i.e. how much the modulation causes noise levels to go up and down above the level of background noise), and how that might relate to annoyance levels.[33] Once modulation depth is at a level that is likely to induce annoyance, a 'penalty' of 3–5 dB(A) is added on a sliding scale to the measured turbine noise level, meaning that measured noise levels from the turbine must be this much lower to compensate for the intrusive nature of the 'thump'.

The Institute of Acoustics, which did not incorporate amplitude modulation in its 2013 good practice guide, released a statement in 2014 saying it is carrying out its own investigations to provide guidance on how to rate amplitude modulation when applying ETSU-R-97 to wind farm developments. The Institute has not officially endorsed RenewableUK's penalty scheme.[34] The Institute is yet to release its official guidance (as of early 2016), but is assessing various methods that can be used to effectively monitor and rate amplitude modulation.[35]

Limitations of noise guidelines

Despite recent moves on the part of the wind industry to address the issue of problematic noise from turbines due to amplitude modulation, existing guidelines are still based on ETSU-R-97, which, it has been noted, has several shortcomings.

Wind speed

A 2011 report into the way ETSU had been applied to noise assessments for wind farm developments highlighted the variable nature of these assessments when submitted to planning authorities.[36] Prior to 2009, slightly more than half of assessments reviewed were found to inconsistently account for meteorological conditions (e.g. temperature, humidity, barrier attenuation) when predicting noise levels. In particular, the phenomenon of wind shear was not addressed.

Wind shear is the variation in wind speed with height from ground level; apart from some rare circumstances, wind speed increases with height. This relates to one of the fundamental problems when assessing wind turbine noise, that is, wind turbines only generate noise when rotating, which only occurs when the wind is blowing, itself a source of noise.[37] This is why assessments of wind turbine noise use background noise levels plotted against different wind speeds.

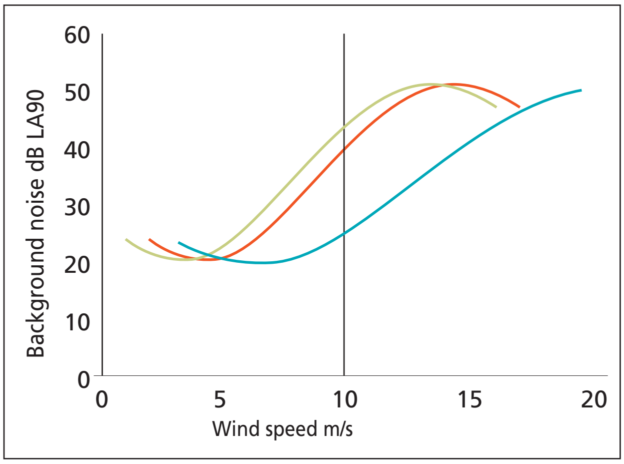
Let us remind ourselves how wind speed affects turbine operation. Megawatt-rated wind turbines do not spin the moment there is a breeze – instead, wind turbine output follows a power curve (see Figure 5.1 in chapter 5) that is dependent on the wind speed at the turbine's hub (in metres per second, m/s). The *cut-in speed*, is typically 3–4 m/s (roughly 7–9 mph), at which point the turbine can extract useful energy from the wind; below 3 m/s the turbine does not operate. Once the cut-in speed is reached, power output and wind speed are related through a cubic relationship, which means a small change in wind speed can result in a large change in power output. At 7 m/s (15.7 mph) wind speed, a turbine will be generating roughly 40%–50% of its maximum rated output. By the time wind speed is up to 12 m/s (26.8 mph), the turbine will be operating at 100% of its rated output. For the protection of structural

---

[†] See references in [34]. Findings summarized in: D. Fiumicelli, 'Summary of research into amplitude modulation of aerodynamic noise from wind turbines', Temple (London; 13 December, 2013).

[‡] See in [34]: 'Template Planning Condition on Amplitude Modulation: Noise Guidance Notes', RenewableUK (London; 16 December 2013).

Figure 14.2 This is an idealised graph showing how wind speed measurements at different heights can affect the derived background noise level.[§] The three best-fit lines use the same noise data plotted against: measured 10 m wind speed (blue line), standardised 10 m wind speed (red), and measured hub height wind speed (green). Note when wind speed at hub height reaches 10 m/s, background noise L_{A90} is still below 30 dB. The standardised wind speed, however, suggests background L_{A90} is almost 40 dB. Under these conditions, the turbine is likely to be operating at 80%–90% capacity.



and electrical components, a wind turbine will cut out when wind speeds reach about 25 m/s, or 56 mph.[38]

Following ETSU-R-97, Institute of Acoustics guidance recommends the area being assessed for wind turbine noise should include at least the area predicted to exceed 35 dB L_{A90} (more on the use of L_{A90} below) at wind speeds up to 10 m/s (22 mph) due to sound generated from all existing and proposed turbines.[14] One should note that wind speed in this measurement is usually derived from turbine's electrical output and power curve, and it is the adjusted wind speed at a reference height of 10 metres, which typically incorporates a factor relating to ground conditions. Using a reference height enables useful comparisons between assessments and is standard practice when measuring wind turbine noise.[2] The problem is that using standardised readings in this way shifts the background noise level in relation to wind speed, so that background noise appears to be higher than it actually is in relation to the wind speed at hub height. This is easier to visualise graphically, as seen in Figure 14.2.

At hub height wind speeds that correspond to significant operational output (recall turbines go from roughly 50% capacity to 100% between 7 and 12 m/s wind speed) there is a disparity between the derived background noise levels. When hub height wind speed is 10 m/s, the standardised wind speed readings suggests a background noise level approximately 10 dB(A) higher than what may actually be the case, which would underestimate how audible wind turbine sounds are in the context of background noise levels. This is one factor that can lead to misleading assessments of the impact of wind turbine noise when using ETSU-R-97.[37]

Background noise

Contrary to Germany, the Netherlands and Denmark, which set limits on the maximum sound pressure level permitted when turbines are operating, ETSU-R-97 guidelines follow the logic that a maximum permitted +5 dB increase be allowed on top of background LA90, as well as including a fixed lower limit, which we have previously seen can lead to permitted levels of wind turbine noise that are considerably more than 5dB(A) above background levels. (see Figure 14.1). And, as we have just seen, the risk of underestimating background noise levels to start with makes the UK guidelines prone to allowing a much greater disparity between wind turbine noise levels and background noise levels. Permitting a fixed minimum limit at night-time that is higher than daytime can also result in notable incongruences[7] – one might have a situation where a wind farm in an area close to a major road will operate at or near the 43 dB(A) level but be comfortably within 5 dB of the background noise level, whereas a similar development in a very quiet rural area may see the same operational noise limit be 10 dB or more above the background level of noise (quiet rural areas frequently have background levels around 25–30 dBA). Clearly, the impact of the latter development is significant, but ETSU-R-97 would see them as the same.

Use of L_{A90} is itself questionable. Industrial noise assessments use two types of metrics when monitoring environmental noise impacts, the equivalent continuous noise level (Leq) and the noise level that is exceeded 90% of the time (L_{90}). Since noise assessments use A-weighting, these metrics are notated as LAeq and L_{A90}.

The L_{Aeq} is useful for continuous sound levels that fluctuate over a given period. An L_{Aeq} measurement is the average of sound pressure levels over a period of interest, presented in decibels (technically, this makes the L_{Aeq} a logarithmic average because decibels are a logarithmic scale, but this does not change the basic principle). For example, monitoring night-time noise levels at a location may see measurements as low as 25 dB(A) at the quietest moments, but levels as high as 60 or 70 dB(A) when there is passing traffic (or, for that matter, when it is very windy). The LAeq over this period shows the average noise level a listener is subjected to. The WHO note that 24-hour exposure to 70 dB LAeq

[§] Although presented as an idealised graph, this is based on a plot of real data found in: R. Bowdler, 'ETSU-R-97. An alternative view', www.dickbowdler.co.uk/content/publications/ETSU-R-97_-_The_Alternative_-_Incl_figures.pdf, c. 2016 Dick Bowdler.

will not cause hearing impairment,4 and daily occupational exposure is limited by UK law to 85 dB(A).**

The L_{A90} is commonly used for background noise levels, notably in BS4142.[39] For example, a reading of 30 dB L_{A90} for a 10 minute period (L_{A90},10min) means that noise levels are 30 dB(A) or above for 9 of those 10 minutes (not necessarily 9 consecutive minutes). In industrial noise assessments, background noise levels are L_{A90} (usually L_{A90},15min for night-time readings) and the source noise (i.e. the equipment or premises that is creating the noise impact) is rated as L_{Aeq}. The rated source L_{Aeq} is then compared to the background L_{A90}. The BS4142:2014 advises that, *'depending on the context'*, a difference of 10 dB(A) indicates 'a significant adverse impact', 5 dB(A) 'an adverse impact', and between 0 and 5 dB(A) is 'less likely' to have an adverse impact. Despite citing BS4142 as a useful model for assessing noise impact, ETSU-R-97 applied the L_{A90} to the 'source' noise, in other words, wind turbine noise is measured using L_{A90} and compared directly to background L_{A90}.[5] The issue here is that the difference between L_{A90} and LAeq is about 2 dB.[2] In effect, when wind turbine noise is 5 dB L_{A90} above background levels as per ETSU-R-97, the LAeq is 7 dB above background according to BS4142, which indicates 'an adverse impact'. Furthermore, the ETSU-R-97 night-time minimum limit of 43 dB(A) is the L_{A90}, meaning the continuous noise level permitted at night averaged over an eight hour period could be 45 dB(A) even when background levels are only around 30 dB L_{Aeq} (28 dB L_{A90}).

Compounded by misleadingly high background noise levels in some cases (as explained above), is it any wonder that some residents complain of noise disturbance even when the conditions of ETSU-R-97 have been met?[7,24] People's perception of intrusive noise is often based on what can be heard at quietest times, not what is heard on average.

Amplitude modulation

The same 2011 report that highlighted inconsistencies in noise assessments submitted to planning authorities also revealed that around 37% of assessments had not addressed amplitude modulation at all.[36] This is not surprising, as ETSU-R-97 does not address amplitude modulation either (it does include tonal sounds).[5,14] As discussed already, RenewableUK released its own guidance on the issue in December of 2013.[33] The Institute of Acoustics is carrying out its own research prior to releasing official guidance. Whilst the RenewableUK guidance is a much needed and transparent process, there is some evidence that the analysis method suggested by RenewableUK leads to an underestimation of the effect.[35] In addition, there is still a reliance on L_{A90} as a measure of wind turbine noise when applying the amplitude modulation 'penalty', the limitations of which have been discussed in the preceding section. Although not official guidance, the Institute of Acoustics has recommended that RenewableUK's method of characterising amplitude modulation could be improved by filtering noise recordings (a band-pass filter) to account for the lower frequencies inherent in the thumping sound.[35]

When the peculiar characteristics of wind turbine noise were becoming known, it was hypothesised that meteorological conditions and the topography could be a major contributing factor for the unexpectedly high noise emissions, especially at night.[13] In particular, a meteorological condition known as a temperature inversion can result in relatively low noise exposure close to the turbine (within 200 metres), called a 'shadow zone', but higher noise levels further out from the shadow zone. Wind speed can have a similar effect, especially when wind shear is more pronounced.[2] Furthermore, cross-winds have been found to increase the depth of amplitude modulation, so that even if sound levels from a wind farm are lower overall the more pronounced swish caused by cross-winds makes the sound more recognisable.[30] These contributing factors, such as wind shear are addressed in the recent guidance from the Institute of Acoustics, in addition to RenewableUK's own efforts to tackle amplitude modulation.

Unfortunately, the prescriptive nature of ETSU-R-97 means that some noise complaints relating to wind farm developments from the 1990s and 2000s have been dismissed, simply because the ETSU guidelines were met. This has meant that the small number of residents with a genuine grievance who have pointed out wind turbine noise may be annoying and intrusive have not had their concerns adequately addressed.[7,24] This has led to increasing opposition to new renewable energy developments, with residents no longer trusting the intentions of developers or the government's renewable energy strategy, and gifting opposition groups a ready supply of controversial talking points.[40–42] This brings us to what is perhaps the most important part of the debate over wind turbine noise: the meaning that neighbours of wind farms attach to what they can hear.

Psychology – the 'meaning' of wind farm noise

For all that has been discussed up to this point, there is one important element still remaining. It is a simple fact that many residents do not like wind turbines intruding in their local environment. Although this fact is simple enough, what gives rise to it is a very complex interaction between value judgements that are informed by psychological and social cues. The context of a wind

---

** Control of Noise at Work Regulations 2005.

farm development within a community – its politics, its perceived 'winners' and 'losers' – is as vital a part of the annoyance factor (or lack thereof) as any objective measure of sound levels. These issues are discussed in detail in chapter 8, 'Public acceptance and community engagement', but here we will relate some of the issues specific to reports of annoyance, noise disturbance and wind turbines.

Complaints about wind turbine noise are not new.[43] The discovery that a small but significant proportion of residents find audible emissions annoying and intrusive was initially surprising, as levels of noise were found to be within accepted limits for ambient background noise.[15,44] Effects such as amplitude modulation are now better understood, and help explain some of the initial theories that perhaps the characteristics of aerodynamic noise from wind turbines may be perceived differently depending on the sensitivity of individual residents.[45] After visual impact, noise is most frequently cited as the reason for complaints by nearby residents relating to wind farms, and a feature common to most studies into intrusive noise is that negative attitudes toward the siting of wind farms plays a large part in any individual subject's response to noise.[8,15,19]

Familiarity with and proximity to wind turbines can elicit more of a response if the context, i.e. the perceived intrusion, is negative.[22,46] Likewise, familiarity combined with positive attitude towards wind turbines has a significant effect on how wind farms are viewed.[8,21,47–50] Context and individual attitudes is key, something that even the BS4142 acknowledges with respect to industrial noise.[39] When assessing the impact of a wind farm, planners and developers must consider both visual and auditory aspects of wind turbines in relation to residents' experience of quiet areas. Where existing developments may have engendered negative attitudes already, further developments may be met with greater opposition.[51] Given the characteristics of wind turbine noise, although objectively measured sound levels may show that levels are not excessive compared with other environmental sources of noise, it is likely that perceptually relevant information will be a strong influence.[52]

Therefore, an unsympathetic approach to wind farm developments, especially where complaints of noise have been dismissed in the past, introduces a new problem for wind power that goes beyond the objective level of noise to a situation where noise from wind turbines, *when identified as such,* has a lower annoyance threshold for certain people. Awareness of the source is a relevant aspect for noise perception. Studies suggest that when wind turbine noise is unidentified it is perceived no differently from road traffic noise, which is interesting in light of data from early surveys where wind turbines were singled out as annoying despite traffic noise being at comparable levels.[13,15,46] This 'acoustical recognition factor' has been experimentally demonstrated for wind turbine sounds. It is clear that subjective experience is likely to become more relevant with the recognition of wind turbine noise.[46,53]

A person's evaluation of the sound is affected by the social process between themselves and the operator of the source.[54] Researchers into the peculiar noise characteristics of wind turbines and their effect on annoyance and disturbance have pointed out that if residents feel disconnected from decisions made by local government, or are generally unhappy with changes to their community space, then they are much more likely to be affected once a wind farm is installed. Residents who enjoy a personal benefit from a neighbouring wind farm (e.g. direct payments or community improvements from revenue) do not experience the same feelings of annoyance despite being exposed to the same level of noise.[8,20,21] Wind turbine noise shows a clear association with self-reported incidences of annoyance, but the link between annoyance and exposure to wind turbine noise is not linear, and frequently breaks down when other factors – such as economic benefit – are analysed.

In this context, although studies show annoyance and stress are correlated with subjects reporting they are disturbed by turbine noise, it is not clear if annoyance with wind turbine noise is a result of stress or vice versa. A poor experience with wind developers during the planning phase of a wind farm can lead a stressed individual to appraise wind turbine noise as a threat to their psychological well-being and be annoyed by it, regardless of objective sound levels.[20,31]

It is possible to find that sleep disturbance is highly correlated to annoyance, but sleep disturbance is not correlated to turbine noise level, even though annoyance alone is correlated to wind turbine noise.[20] Similarly, measuring quality-of-life indicators through questionnaire surveys of residents living anywhere from 7 miles away to within 250 metres of a wind farm fails to show any direct relationship between between quality-of-life effects and exposure to wind turbine noise.[18]

A recent pilot study across several different wind farms in Canada used objective measurements of sleep disturbance along with self-reported questionnaires, and did not show any relationship between sleep disturbances (including diagnosed sleep disorders) and exposure to wind turbine noise up to 46 dB(A).[17] Findings such as these may explain the contextual relationship between wind turbine noise and annoyance. Negative expectations can affect how wind turbine noise is perceived by individuals.[46,55] The converse may also be true: inducing positive expectations can mitigate or reduce levels of annoyance, even in noise-sensitive subjects.[50,56]

The provision of benefits can be a tricky area. Even well-intentioned developers may be caught out by locals' ambivalence towards the nature of benefits, which can easily be perceived as a form of bribery.[40] In the UK, most benefits are the result of bilateral negotiations between developers and affected communities once a proposal is announced, which speaks volumes about the UK's lack of tradition in alternative energy for grassroots movements, local co-ownership and early participation in infrastructure projects that characterises much of the discourse between planners and communities in countries like Germany.[57–60] Local authorities can be valuable intermediaries in the negotiation process, but the historically top-down approach that has sought to impose few limits on wind power developments, led inevitably by large power companies, means that the dictates of central planning too often trump the efforts of local planning authorities.[42,57,61,62] This may change with the introduction in June 2015 of a planning requirement that wind developments can only be brought forward where there is an allocated site in a local or neighbourhood plan[††]. Such allocated sites can be reasonably broad and, if used well, this provision could allow for better and earlier local engagement about the need for (and appropriateness of) potential wind developments in a given area, well before any developers are involved in promoting individual sites for specific turbines. However, since little technical or site specific noise analysis will need to be done in order to allocate a site, there still remains opportunity for conflict to arise over perceived noise issues once a specific site for a wind farm project is progressed.

Finally, one important point should be borne in mind: wind turbines are often situated in rural areas, what the EU Noise Directive classes as 'quiet area in open country'.[‡‡] This means the effect of wind turbine noise is more likely to cause annoyance that is disproportionate to their impact on ambient sound levels.[22] Noise assessments must take into account the 'psycho-acoustical factors' that can affect whether the sound is pleasant or unpleasant, which is particularly germane to the type of landscape where wind farms are frequently sited.[63] Surveys of residents show that wind turbine noise levels and annoyance are more strongly linked in quiet areas.[20] Although wind turbines were far from the most prevalent cause of sleep disturbance in the Canadian study, there was a link between wind turbine noise of 35 dB(A) or more and residents self-reporting that wind turbines were the cause of their disturbed sleep.[17] It should be noted that the researchers found background night-time sound levels were lowest in areas where wind turbine noise exposure was highest (40–46 dBA), so it is plausible that once awake, residents were more aware of wind turbine noise.

In instances where annoyance or disturbance is caused by wind turbine noise, some of these may well be the result of shortcomings in planning guidelines. For some residents, the manner in which wind farm developments are carried out, with perceptions of secretive planning in the early stages and last-minute consultations once plans have already been laid, means that disillusioned residents who may be able to hear the wind turbines operating will experience the noise as annoying, even if levels are comfortably within guidelines. This should not be understated – annoyance caused by a sound that is deemed inappropriate or to represent an imposition is still intrusive to the sufferer.

The Institute of Acoustics take the position that:

> *'A significant aspect of the consultation should be whether [noise] surveys are required, and if they are, agreement on the number and position of background noise level measurement locations should be sought. Such agreement will benefit all parties, as background noise level measurements can be an area of considerable debate, and targeting resources at this early stage in the development process should provide dividends in the future by reducing the likelihood of protracted arguments and potentially the need for additional background noise level measurements'* (See ref.14, p.38).

Conclusion

Renewables are essential for the move toward low-carbon energy sources and public attitudes on the whole are strongly in favour of their implementation. However, there is a striking divergence between overall support and more local opposition to the installation of renewable technologies (see chapter 8, 'Public acceptance and community engagement'). An increasing number of installations will see an increasing number of challenges from concerned residents unless the causes of negative opinion are understood. In spite of continual improvements made to turbine design, there is a significant body of evidence showing that the characteristics of noise emissions from wind turbines can affect a small proportion of the communities that are exposed. Initially, complaints were typically met with assurances by wind farm developers that guidelines were in place and that the sited turbines complied (with a few exceptions). However, the guidelines in place, set by the ETSU-R-97 report, are problematic, as they do not

---

[††] www.publications.parliament.uk/pa/cm201516/cmhansrd/cm150618/wmstext/150618m0001.htm (Accessed 19/05/16)

[‡‡] EU Directive 2002/49/EC relating to the assessment and management of environmental noise, OJ, L189, 18.07.2002, p.14.

always take adequate account of the aerodynamic noise characteristic of wind turbines. More troubling is the application of noise limits in ETSU-R-97, which are quite unlike any other national guidelines and can result in a significant disparity between background noise levels and wind turbine noise. The issue is further complicated by the fact that background noise levels are affected by wind speed, which is also directly related to the operational noise level of the turbines themselves.

Accordingly, the issue of noise should be treated with due consideration, and guidelines must be strictly adhered to, or efforts made to revise them if necessary. Although some steps have been taken to ensure the practice of noise assessments for wind turbines is more rigorously and consistently applied, critics point out that the existing UK planning guidelines, enshrined by ETSU-R-97, are inadequate to safeguard residents' acoustical amenity. There is some justification for this when current planning regulations continue to refer to a working group report released in 1996; indeed, the original authors themselves stated that ETSU-R-97 should be updated in a timely manner as new evidence emerges and wind power technology advanced. Despite its shortcomings, the ETSU report clearly adheres to the principle that sound pressure levels, not distance, should determine the minimum setback from nearby dwellings:

> *The difference in noise emissions between different types of machine, the increase in scale of turbines and wind farms seen today and topographical effects described...all dictate that separation distances of 350–400 metres cannot be relied upon to give adequate protection to neighbours of wind farms' (*See ref.5, p.46).

There is arguably a need for overhauling the ETSU guidelines rather than attempting to reconcile its shortcomings by issuing usage guidance. Where ETSU-R-97 departs from the BS4142 standard – such as the use of metrics that may underestimate the noise impact of turbines relative to background levels, or applying a fixed minimum permitted noise level that is higher at night-time than daytime – it has created a situation where wind farms may be compliant but still cause unnecessary annoyance to some neighbouring dwellings.

It is important to note that the literature on the small but significant number of residents who are continually disturbed by perceived noise from wind farms reveals that self-reported annoyance or disturbance is frequently not directly related to the respondents' exposure to wind turbine noise. Visibility plays a significant part in exacerbating disturbance due to sound, with affected respondents frequently already unhappy that their local setting has been marred by the introduction of wind farms, and the overall perception of intrusive sound is intimately associated with the feeling that the visible structures have been forced on the landscape without any say from them.

Civic planning ought to reduce conflict and lead to more positive consent decisions. Alienated residents – those not involved in decision making, with no direct economic benefit, without a knowledge of how wind energy operates and suspicious of wind farms thrust upon them – will ultimately perceive any wind farm development negatively, regardless of public support in general.

What has worsened the situation is the reaction of many residents who are ambivalent to or outright oppose wind farms to assume harm where there is none. Controversies over wind turbine noise has given rise to various myths surrounding the nature of the sound from wind farms, in many cases setting negative expectations that are self-fulfilling. The 'nocebo effect' where sufferers continue to hear noise that is not detectable or not generated at all (i.e. activity has ceased) has been documented in similar instances of industrial noise. Dismissing complainants by resorting to tactics such as pointing to compliance with (possibly inadequate) guidelines is damaging to genuine cases where noise is a problem, and jeopardises future renewable developments. Accusations of nimbyism are unhelpful and irrelevant: it is up to the wind energy industry and its supporters to be honest about any noise concerns local residents might have, and to work with them to minimise these affects within the framework of the planning regulations (designed for exactly this purpose).

Human beings give meaning to sound. It is evident that residents who feel wind developments are forced upon their local setting will judge any subsequent noise accordingly. Trust in the developer and development process must be earned. It is cogent that clearly realised benefits for residents, such as direct financial benefit and a better understanding of how wind power contributes to a low-carbon economy, can also significantly mitigate this negative bias.

References

1. Renzo T. Sources of wind turbine noise and sound propagation. Acoust Aust. 2012; 40(1):20–7.
2. Burton A, Jenkins N, Sharpe D, Bossanyi E. Wind turbine installations and wind farms. In: Wind energy handbook. 2nd ed. Chichester, West Sussex: Wiley; 2011. 525–64.
3. Vestas. V90-3.0 MW® at a Glance [Internet]. 2014. [Accessed 27 Jan 2016.] Available from: www.vestas.com/en/products_and_services/turbines/v90-3_0_mw
4. WHO. Burden of disease from environmental noise: Quantification of healthy life years lost in Europe. Theakston F, editor. Copenhagen: World Health Organization, Regional Office for Europe; 2011. 106 p.
5. ETSU. The assessment and rating of noise from wind farms. ETSU-R-97. Final Report of the Working Group on Noise from Wind Turbines. URN 96/1192. Department of Trade and Industry; Sep 1996. 153 p.
6. Ove Arup and Partners. Planning for renewable energy: a companion guide to PPS22. London: Office of the Deputy Prime Minister; 2004. 184 p.
7. Haggett C. The social experience of noise from wind farms. In: Szarka J, Cowell R, Ellis G, Strachan PA, Warren C, editors. Learning from Wind Power. Basingstoke: Palgrave Macmillan; 2012. 153–73.
8. Janssen SA, Vos H, Eisses AR, Pedersen E. A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. J Acoust Soc Am. 2011; 130(6):3746.
9. Schmidt JH, Klokker M. Health effects related to wind turbine noise exposure: A systematic review. Tong S, editor. PLoS ONE. 2014; 9(12):e114183.
10. Onakpoya IJ, O'Sullivan J, Thompson MJ, Heneghan CJ. The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies. Environ Int. 2015; 82:1–9.
11. BSI. BS 4142:1997. Method for rating industrial noise affecting mixed residential and industrial areas. London: British Standards Institute; 1997. 16 p.
12. Berger RG, Ashtiani P, Ollson CA, Whitfield Aslund M, McCallum LC, Leventhall G, et al. Health-based audible noise guidelines account for infrasound and low-frequency noise produced by wind turbines. Front Public Health. 2015; 3:Article 31.
13. van den Berg GP. Effects of the wind profile at night on wind turbine sound. J Sound Vib. 2004; 277(4-5):955–70.
14. IOA. A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise. St. Albans, Herts.: Institute of Acoustics; May 2013. 38 p.
15. Pedersen E, Persson Waye K. Perception and annoyance due to wind turbine noise—a dose–response relationship. J Acoust Soc Am. 2004; 116(6):3460–70.
16. Møller H, Pedersen CS. Low-frequency noise from large wind turbines. J Acoust Soc Am. 2011; 129(6):3727–44.
17. Michaud DS, Feder K, Keith SE, Voicescu SA, Marro L, Than J, et al. Effects of wind turbine noise on self-reported and objective measures of sleep. Sleep. 2016; 39(1):97–109.
18. Feder K, Michaud DS, Keith SE, Voicescu SA, Marro L, Than J, et al. An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines. Environ Res. 2015 Oct; 142:227–38.
19. Pedersen E, Hallberg L-M, Waye KP. Living in the vicinity of wind turbines — A grounded theory study. Qual Res Psychol. 2007; 4(1-2):49–63.
20. Bakker RH, Pedersen E, van den Berg GP, Stewart RE, Lok W, Bouma J. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Sci Total Environ. 2012; 425:42–51.
21. Pedersen E, van den Berg F, Bakker R, Bouma J. Response to noise from modern wind farms in The Netherlands. J Acoust Soc Am. 2009; 126(2):634–43.
22. Maffei L, Iachini T, Masullo M, Aletta F, Sorrentino F, Senese V, et al. The effects of vision-related aspects on noise perception of wind turbines in quiet areas. Int J Environ Res Public Health. 2013; 10(5):1681–97.
23. Chapman S, St. George A, Waller K, Cakic V. The pattern of complaints about Australian wind farms does not match the establishment and distribution of turbines: Support for the psychogenic, 'communicated disease' hypothesis. Convertino M, editor. PLoS ONE. 2013; 8(10):e76584.
24. Bowdler R. Why turbine noise annoys. In: Fourth International Meeting on Wind Turbine Noise, Rome, Italy, 12-14 April, 2011. 9 p.
25. McCunney RJ, Mundt KA, Colby WD, Dobie R, Kaliski K, Blais M. Wind turbines and health: a critical review of the scientific literature. J Occup Environ Med. 2014; 56(11):e108–30.
26. Doolan CJ, Moreau DJ, Brooks LA. Wind turbine noise mechanisms and some concepts for its control. Acoust Aust. 2012; 40(1):7–13.
27. Shen WZ, Hrgovan I, Okulov V, Zhu WJ, Madsen J. Design of low noise wind turbine blades using Betz and Joukowski concepts. J Phys Conference Ser. 2014; 524:012131.
28. Rodrigues SS, Marta AC. On addressing noise constraints in the design of wind turbine blades. Struct Multidiscip Optim. 2014; 50(3):489–503.
29. Burton A, Jenkins N, Sharpe D, Bossanyi E. Conceptual design of horizontal axis wind turbines. In: Wind energy handbook. 2nd ed. Chichester, West Sussex: Wiley; 2011. 325–82.
30. Oerlemans, Schepers. Prediction of wind turbine noise and validation against experiment. Int J Aeroacoust. 2009; 8(6):555–84.
31. Pedersen E. Health aspects associated with wind turbine noise—Results from three field studies. Noise Control Eng J. 2011; 59(1):47–53.
32. Pawlaczyk-Łuszczyńska M, Dudarewicz A, Zaborowski K, Zamojska-Daniszewska M, Waszkowska M. Evaluation of annoyance from the wind turbine noise: A pilot study. Int J Occup Med Environ Health. 2014; 27(3):364–88.
33. RenewableUK. Industry Statement on other amplitude modulation [Internet]. RenewableUK. 2013. [Accessed 3 Feb 2016.] Available from: www.renewableuk.com/en/renewable-energy/communities-and-energy/industry-statement-on-OAM/
34. IOA. Institute of Acoustics Statement in respect of Wind Farm Noise Assessment. Institute of Acoustics; 2014.
35. IOA Noise Working Group (Wind Turbine Noise), Amplitude Modulation Working Group. Discussion Document: Methods for Rating Amplitude Modulation in Wind Turbine Noise [Internet]. Institute of Acoustics; 2015. [Accessed 2 Mar 2016.] Available from: www.ioa.org.uk/publications/wind-turbine-noise
36. Hayes McKenzie. Analysis of how noise impacts are considered in the determination of wind farm planning applications. Report No.: 2293/R1. Salisbury: Hayes McKenzie Partnership Ltd; Apr 2011. 49 p.
37. Bowdler R. What is the real background noise? In: Second International Meeting on Wind Turbine Noise, Lyon, France, September 20–21, 2007. 18 p.
38. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.
39. BSI. BS 4142:2014. Methods for rating and assessing industrial and commercial sound. London: British Standards Institute; 2014. 76 p.
40. Cass N, Walker G, Devine-Wright P. Good neighbours, public relations and bribes: The politics and perceptions of community benefit provision in renewable energy development in the UK. J Environ Policy Plan. 2010; 12(3):255–75.
41. Devine-Wright P. Public engagement with large-scale renewable energy technologies: breaking the cycle of NIMBYism. Wiley Interdiscip Rev Clim Chang. 2011; 2(1):19–26.
42. van der Horst D, Toke D. Exploring the landscape of wind farm developments; local area characteristics and planning process outcomes in rural England. Land Use Policy. 2010; 27(2):214–21.

43. Wolsink M, Sprengers M, Keuper A, Pedersen TH, Westra CA. Annoyance from wind turbine noise on sixteen sites in three countries. European Community Wind Energy Conference, Lübeck-Travemünde, Germany, March 8-12, 1993: 273–6.
44. Pedersen E, Persson Waye K. Wind turbine noise, annoyance and self-reported health and well-being in different living environments. Occup Environ Med. 2007; 64(7):480–6.
45. Waye KP, Öhrström E. Psycho-acoustic characters of relevance for annoyance of wind turbine noise. J Sound Vib. 2002; 250(1):65–73.
46. Van Renterghem T, Bockstael A, De Weirt V, Botteldooren D. Annoyance, detection and recognition of wind turbine noise. Sci Total Environ. 2013; 456-457:333–45.
47. Johansson M, Laike T. Intention to respond to local wind turbines: the role of attitudes and visual perception. Wind Energy. 2007; 10(5):435–51.
48. Ladenburg J, Möller B. Attitude and acceptance of offshore wind farms—The influence of travel time and wind farm attributes. Renew Sustain Energy Rev. 2011; 15(9):4223–35.
49. Ladenburg J, Termansen M, Hasler B. Assessing acceptability of two onshore wind power development schemes: A test of viewshed effects and the cumulative effects of wind turbines. Energy. 2013; 54:45–54.
50. Crichton F, Dodd G, Schmid G, Petrie KJ. Framing sound: Using expectations to reduce environmental noise annoyance. Environ Res. 2015; 142:609–14.
51. Power S, Cowell R. Wind power and spatial planning in the UK. In: Szarka J, Cowell R, Ellis G, Strachan PA, Warren C, editors. Learning from Wind Power. Basingstoke: Palgrave Macmillan; 2012. 61–84.
52. Gygi B, Kidd GR, Watson CS. Similarity and categorization of environmental sounds. Percept Psychophys. 2007; 69(6):839–55.
53. Maffei L, Masullo M, Gabriele M, Votsi N-E, Pantis J, Senese V. Auditory recognition of familiar and unfamiliar subjects with wind turbine noise. Int J Environ Res Public Health. 2015; 12(4):4306–20.
54. Maris E, Stallen PJ, Vermunt R, Steensma H. Evaluating noise in social context: The effect of procedural unfairness on noise annoyance judgments. J Acoust Soc Am. 2007; 122(6):3483–94.
55. Crichton F, Dodd G, Schmid G, Gamble G, Petrie KJ. Can expectations produce symptoms from infrasound associated with wind turbines? Health Psychol. 2014; 33(4):360–4.
56. Crichton F, Petrie KJ. Health complaints and wind turbines: The efficacy of explaining the nocebo response to reduce symptom reporting. Environ Res. 2015; 140:449–55.
57. Toke D, Breukers S, Wolsink M. Wind power deployment outcomes: How can we account for the differences? Renew Sustain Energy Rev. 2008; 12(4):1129–47.
58. Nolden C. Governing community energy—Feed-in tariffs and the development of community wind energy schemes in the United Kingdom and Germany. Energy Policy. 2013; 63:543–52.
59. Strachan PA, Cowell R, Ellis G, Sherry-Brennan F, Toke D. Promoting community renewable energy in a corporate energy world: Promoting community renewable energy in the UK. Sust Dev. 2015; 23(2):96–109.
60. Hoppe T, Graf A, Warbroek B, Lammers I, Lepping I. Local governments supporting local energy initiatives: lessons from the best practices of Saerbeck (Germany) and Lochem (The Netherlands). Sustainability. 2015; 7(2):1900–31.
61. Wolsink M, Breukers S. Contrasting the core beliefs regarding the effective implementation of wind power. An international study of stakeholder perspectives. J Environ Planning Manag. 2010; 53(5):535–58.
62. Ellis G, Barry J, Robinson C. Many ways to say ‘no’, different ways to say ‘yes’: Applying Q-Methodology to understand public acceptance of wind farm proposals. J Environ Planning Manag. 2007; 50(4):517–51.
63. Baker D. Application of noise guidance to the assessment of industrial noise with character on residential dwellings in the UK. Appl Acoust. 2015; 93:88–96.

Chapter 15

Infrasound, 'wind turbine syndrome' and other health concerns

Summary

Within the last decade, the development of wind farms around the world has been accompanied by a profusion of health concerns that have been the cause of much contention between advocates and opponents of wind power. The longest-running, and perhaps most contentious of all, is the subject of low-frequency noise normally considered inaudible to the human ear, commonly known as infrasound. The role of infrasound as a hidden causative agent behind 'wind turbine syndrome' – the reported ill-health suffered by some individuals living near wind farms – has garnered significant support, but this movement has been based largely on the promotion of a small group of self-publicising researchers and anti-wind protest groups.

The theory that infrasound from wind turbines might be causing real, physiological effects on nearby residents has so far failed to produce any empirical evidence or, indeed, even a plausible mechanism. The persistence of 'wind turbine syndrome' as a reason for rejecting wind farm developments seems to be more closely linked to the expectation of negative health effects from proposed and existing wind power facilities, an expectation that has been driven by largely unfounded reports from media and campaign groups about potential health impacts. This has entrenched the idea of wind turbines as one more modern malaise that contributes to a variety of non-specific health problems. This has parallels with other modern health worries, such as concerns over the presence of electromagnetic fields, where there is a common pattern of sufferers' symptoms and associated psychological distress being attributable to the 'nocebo' effect rather than any physical stimulus.

Since the latter half of the 2000s, claims about the potential health impacts of wind turbines have surfaced more frequently due to the continuing coverage that 'wind turbine syndrome' receives, despite consensus in the peer-reviewed literature that there is no evidence such a thing exists. The repeated propagation of baseless claims obscures the much-better understood issues surrounding environmental noise generated by wind turbines that is audible. The continued distraction also hinders treatment for the small number of individuals who genuinely suffer from anxiety, stress and attendant health problems brought on by the perceived existence of negative environmental agents with no discernible physical cause.

What is this based on?

With the rapid proliferation of utility-scale wind power since the 1990s, there has been controversy over the potential health impacts of modern, large wind turbines. This has led to repeated calls to investigate evidence that the operation of wind turbines leads to impaired health in those living close by, despite evidence demonstrating that the vast majority of claims are unfounded.[1–3] Early opposition groups objecting to the installation of wind farms frequently highlighted the risk of harm to bird and bat populations, or the risks posed by shadow flicker and the level of audible noise emitted by rotating turbines. (These issues are addressed in their own chapters elsewhere in this guide – see chapters 11, 13 and 14). Since the early 2000s, infrasound (low-frequency noise below 20 Hz) and electromagnetic fields from wind turbines have been touted as having 'hidden effects', with concerns about infrasound in particular culminating in the invention of 'wind turbine syndrome', which posits that a variety of non-specific health effects can be attributed directly to the operation of wind turbines. [3–6] Added to this is the more recent emergence of suggestions that there is a link between wind turbines and autism. This chapter will address these three issues.

In 2009, drawing on a series of case studies from 10 families with a total of 37 subjects, Nina Pierpont (a paediatrician in New York state) attributed the following symptoms to low frequency sound emissions from wind turbines: sleep disturbance, headache, tinnitus, other ear and hearing sensations, balance and equilibrium disturbances, anxiety, nausea, irritability, energy loss, motivation loss, memory and concentration disturbances. The author of this case series grouped these symptoms together under the umbrella of 'wind turbine syndrome'. These findings have been self-published in a book marketed by the author.[7] Although Pierpont's publication gained immediate popularity with anti-wind groups, the attribution of health problems to the existence of nearby wind turbines had started to gain traction in opposition movements several years earlier, around 2002 and 2003.[4] While these early reports mentioned specific concerns such as shadow flicker, many other serious but non-specific symptoms came to light, such as increased stress, sleep disturbance and need for prescription medicines.[8] A similar report by a UK doctor was released in 2007 (although it is credited as being work that began in 2003), which suggested that the myriad symptoms reported by residents were due to the 'complexity' of the noise and vibration generated by wind turbines.[9] A group of researchers studying technicians and aircraft crews subjected to loud industrial noise – far in excess of what a wind turbine produces and with very prolonged exposure – coined the term 'vibroacoustic disease',[10] although this condition was never recognized by any other group despite several decades of research.[†] [6,11] Despite the absence of any demonstrated link between vibroacoustic disease and noise emissions from wind turbines, the same vibroacoustic disease researchers lent their backing to the idea that low-frequency noise emitted by wind turbines caused a host of health problems.[11,12] This announcement helped sanction within anti-wind groups the concept that low-frequency noise, especially subaudible infrasound, was the causative agent of various non-specific health issues reported by respondents living near to wind farms, even though evidence has shown that personal attitudes to wind turbines is a better predictor of these symptoms than any objectively measured infrasound.[2,5,13]

In a similar fashion to the infrasound theory, a focus on health impacts due to electromagnetic fields produced by wind turbines has led in recent years to an increase in negative reporting, raising the expectation that health impacts will occur once a wind farm is operational.[14,15] This has been seized upon by anti-wind groups, and has translated into greater anxiety over wind farm proposals and an increase in health issues being cited as a reason for organised opposition.[4,14,16] It has been shown that these negative expectations manifest as a 'nocebo' effect. Rather like a placebo has a positive effect on a person's condition despite there being no physical agent present that might produce such an outcome, a nocebo can induce a psychological or psychosomatic effect that is detrimental to a person's health. The reporting of non-specific health problems attributed to electromagnetic fields has been shown to be independent of actual exposure, but greatly influenced by negative reporting, a phenomenon also seen in controlled studies where subjects are exposed infrasound from wind turbines.[17,18]

More recently, the refusal of planning permission for a wind farm near to the home of autistic twins has led to the emergence of concerns that wind farms can cause or exacerbate the symptoms of autistic spectrum disorders.

What is current evidence?

Low-frequency noise and infrasound

Sound propagates as a pressure wave through vibrations in the air. The energy intensity, or amplitude, of the pressure wave emitted is measured in decibels (dB), which is a useful measure of how humans perceive the loudness of a sound. The dB scale is a logarithmic scale, such that an increase from 0 dB to 10 dB is a 10-times increase in energy intensity, from 0 dB to 20 dB is a 100-times increase in loudness, and so on. Note, however, that a person with normal hearing would consider an increase from 10 dB to 20 dB to be 'twice as loud' even though the energy intensity has increased tenfold. The number of vibrations per unit time – the frequency – is given in Hertz (Hz). The range of frequencies at which sound is audible to the human ear is enormous, between 20 and 20,000 Hz, but the human ear is most sensitive to frequencies between 1,500 and 4,000 Hz, where even very soft sounds (0 dB or thereabouts) are discernible.

Sound at frequencies 20–250 Hz is classed as low-frequency noise. Below the 20 Hz threshold is *infrasound* – low frequency sound outside the normal range of human hearing. However, this definition is more to do with practicality and convention; hearing is a continuous process that does not simply terminate at 20 Hz.(19,20) It is accepted that frequencies below 20 Hz are indeed audible, with subjects hearing frequencies as low as 4 Hz in a sound chamber and 1.5 Hz through headphones.[19,21] Thus, the concept of 'infrasound' as a sharp delineation between what can and cannot be heard is not correct. It has been suggested that is reasonable to consider audible low-frequency noise to extend as low as 5 Hz.[19)]

What is important to note is that these frequencies only become audible, that is, detectable by the sensory structures of the inner ear and transmitted to the auditory cortex in the brain, at high sound pressure levels (e.g. 79 dB for 20 Hz, 107 dB for 4 Hz).[6,22] Studies that expose subjects to infrasound at very high sound pressure levels (120 dB or more) have shown that the auditory cortex is the only region that processes the incoming sound, and infrasound at subaudible levels (90 dB or less) does not stimulate this area of the brain.[23] This supports earlier work showing that sound pressure waves are detected by the cochlear across the low-frequency and infrasound range.[24] In other words, low-frequency noise and infrasound is received by the inner ear and processed by the brain in the same way as sounds in higher frequency ranges, but the lower the frequency the louder the sound must be to be perceptible.

[†] Henning von Gierke, a noted researcher in the field of noise and health, remarked that vibroacoustic disease 'remains an unproven theory belonging to a small group of authors and has not found acceptance in the medical literature.' Von Gierke H, Mohler SR. Aviat. Space Environ. Med. 2002;73(8):828–9.

Although the sound pressure level required for auditory perception becomes very high as the frequency decreases, a small percentage of the population have a lower hearing threshold for low-frequency noise, with the most sensitive 10th percentile possessing a threshold of more than 6 dB compared to the median.[25] Furthermore, despite loss of sensitivity to higher frequencies with increasing age, it has been observed that hearing thresholds in the low-frequency noise and infrasound range may be a few decibels lower for some 50–60 year-olds compared with young adults.[6]

The effects of noise on human health and activities have been studied for many decades. Work on the effects of low-frequency noise largely began with the Apollo space programme, which focused on the need to ensure physiological harm was avoided when workers were routinely exposed to very loud environments.[19] In less extreme circumstances, environmental noise in modern society originates primarily from traffic (road, rail and air), industrial workplaces and the urban environment.[26] Unfortunately, due to the misrepresentation of some early research, combined with common misconceptions about the audibility of low-frequency noise (mentioned above), the term 'infrasound' quickly entered the public consciousness as an entity associated with various scare stories about hidden, or silent, health impacts.[‡] This prompted complaints of low-frequency noise and lurid Cold War myths of the power of infrasonic weapons.[19] Investigation of complaints involving low-frequency noise having a detrimental effect on sufferers inevitably fails to objectively detect levels of noise – the source remains mysterious, even if the psychological distress is very real.[25,27] It is conjectured that non-acoustic sources may be responsible for sufferers' symptoms, and failure to isolate the cause of distress leads complainants to blame a more tangible source, such as low-frequency noise or infrasound from gas pipelines, boiler rooms, or, in recent years, wind turbines.[6,19] In some cases, electromagnetic waves are blamed, and the presence of electromagnetic fields are themselves frequently attributed with causing many of the same non-specific health effects as infrasound.[6,28] These are considered later in this chapter.

Infrasound, and low-frequency noise in general, is increasingly cited as a particular property of wind turbine sound that makes them uniquely capable of causing health disorders.[5] With this argument arising more and more in cases opposing wind farm development, there have been an increasing number of studies on the noise generated by wind turbines. As already discussed, it is possible for infrasound to be audible if the sound pressure level is high enough. Indeed, infrasound can very quickly reach annoying or distressing levels when it passes into the audible threshold;[21] but, all studies of infrasound produced by wind turbines show that levels are significantly below audible unless the listener were located less than 100 metres from the nearest turbine.[3,5,13,19,20,29–34]

Overall, the case for 'wind turbine syndrome' as put forward by Pierpont and propogated by groups opposing wind farms presents very weak evidence for anything akin to a definable syndrome. Following several years of campaigning after a wind farm was proposed next to her town in Malone, New York state, Dr. Pierpont asked for respondents who already believed they were suffering symptoms caused by nearby wind turbines. This self-selection bias makes it difficult to identify a causative agent. Many of the subjects suffered from pre-existing conditions including: mental health disorders, persistent migraines, continuous tinnitus and motion sensitivity, and several had a history of significant exposure to loud noise in the workplace. Similar reports, which abound in popular online literature but are absent from peer-reviewed publications, exhibit many of the same methodological flaws.[4,13]

There is some conjecture that 'sensitised' residents may have lower than normal hearing thresholds, which is theoretically possible.[25] However, such individuals are rare in the population, and, in instances where complaints about infrasound have been investigated, it is normal to find that there is little difference between the low frequency thresholds of those who complain of low-frequency noise and those who do not.[6]

One group of authors published a review in 2010 putting forward the hypothesis that certain specialised hair cells within the inner ear may respond to infrasound.[35] Within the inner ear, *inner hair cells* suspended in fluid in the cochlea transduce mechanical fluid movement (originating from vibrations of the ear drum due to sound waves) to the auditory cortex of the brain via nerve signals. These inner hair cells are responsible for almost all of the auditory capability of human hearing, i.e. sounds generally above 20 Hz, but are mostly insensitive to infrasonic frequencies. The inner ear also possesses *outer hair cells*, which are more numerous than inner hair cells, but are serviced by only a fraction of the sensory nerves that connect to the inner hair cells. Instead, outer hair cells are largely innervated by nerves carrying messages *from* the brain rather than *to* the brain. The outer hair cells respond to very loud volumes by 'dampening' the vibrations within the cochlea (this protects inner hair cells from being damaged), and by helping 'tune' the response of inner hair cells so that sounds can be better distinguished when signals reach the auditory cortex.[36] Based on animal models, the authors of the 2010 review suggested that the mechanical movement of outer hair

---

[‡] For example, see headlines as quoted in ref.6: 'The silent sound menaces drivers', Daily Mirror, 19 October, 1969; 'Danger in unheard car sounds', Observer, 21 April, 1974; 'The silent killer all around us', London Evening News, 25 May, 1974.

cells is more sensitive to infrasound, inferring that some physiological effect can be elicited by infrasound at levels below normal auditory perception.[35] The authors propose that these effects are only likely to appear in susceptible subjects, meaning people who suffer from rare conditions affecting the inner ear. Whilst not entirely implausible, no evidence has been seen that movement of outer hair cells in this way results in signals being transmitted to the brain,[5] and it remains a speculative mechanism of action.[§] Where the authors mention infrasonic frequencies measured in the noise spectrum of wind turbines, they quote values taken from distances much closer than would occur in a residential setting, giving the impression that turbine-generated infrasound is close to audible levels when in fact it would be 10 to 20 dB lower.[19,29]

Keeping with the subject of inner ear anatomy, it should be remembered that the inner ear is a poor detector of low frequency sound. It has evolved to insulate the auditory apparatus from much of the internal infrasonic frequencies produced by breathing and the pulsatile pressure waves that result from blood being pumped around the body.[19] The natural environment also contains a number of sources of infrasound, such as wind and other turbulent weather fluctuations, ocean waves and coastal wash. These are typically subaudible, although loud events such as thunderclaps or volcanic eruptions are obviously perceptible. Physical activity, like jogging or running, may temporarily generate infrasound of around 5 Hz at barely audible levels. For example, a child on a swing is subjected to a low frequency of 0.5 Hz at 110 dB.[25] In studies on normal subjects that aimed to produce ill effects from infrasound, the participants had to be subjected to very high levels of sound well within audible range, considerably higher than those produced by wind turbines.[3,21,29,37] At typical setback distances there is little difference between the audibility of natural infrasound versus that generated by wind turbines.[30,31]

Finally, it is often stated that the *weighting* of sound pressure level measurements paints a misleading picture. Because we know the human inner ear is not equally sensitive to all frequencies (see above), sound meters used in observations of environmental noise usually apply what is called *A-weighting*,[22] which accounts for the fact sounds in the mid-range of human hearing will be perceived as being louder for a given sound pressure level. However, given that the noise spectrum from wind turbines is in lower frequencies below 1,000 Hz, it has been argued that using different weightings is more appropriate to ascertain perceptible infrasound and low-

---

[§] The authors say as much in their own paper, 'The fact that some inner ear components (such as the OHC) may respond to infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way.' (Salt and Hullar, 2010, p.19)

Is there a case for 'wind turbine syndrome'?

To understand the refutation of the idea that infrasound causes detrimental effects to the health of residents living near wind turbines, it is useful to break down the hypothesis of 'wind turbine syndrome' into its two main parts.[7]

1. Infrasound at 1–2 Hz from wind turbines propagating through the air directly affects the vestibular system of the ear.

The vestibular apparatus within the inner ear plays an important part in balance and detecting motion, and also works in combination with the visual system to maintain focus when moving. To do this, specialised hair cells are anchored at various points within bony structures of the vestibular apparatus. These hair cells protrude into viscous fluid or gel. The inertia of these fluids are the key to detecting motion. When the rest of the head moves, the fluids lag behind and cause the hair cells to bend. This mechanical movement of the hair cells is transmitted via nerves to the brain, thereby telling the brain the nature of the movement (information about roll, pitch and yaw) and allowing compensatory muscle movements to maintain balance and keep the eyes focused on a target. This balance detection system reveals the original function of the vertebrate ear – the auditory function evolved later, giving rise to the cochlea and other structures involved with hearing, and the neural pathways are 'wired' quite differently.[36]

A recent review put forward the suggestion, based on evidence from animal models, that the mechanical movement of outer hair cells is more sensitive to infrasound, inferring that some physiological effect can be elicited by infrasound at levels below normal auditory perception.[35] The authors propose that these effects are only likely to appear in susceptible subjects, meaning people who suffer from rare conditions affecting the inner ear whose vestibular apparatus is sensitive to changes in pressure. However, no evidence has been seen that movement of outer hair cells in this way results in signals being transmitted to the brain, and it remains a speculative mechanism of action.[5] It should be remembered that within the normal, healthy inner ear the vestibular apparatus and the auditory system are well insulated from each other, the former responding to head movement and not airborne sound waves while the latter responds easily to vibrations in cochlear fluid transmitted via the ear drum.[5,19] Stimulation of the inner ear by low or infrasonic frequencies show that it is the auditory system that transmits signals to the brain.[23] Vestibular disturbances can occur when vibrations are sufficient to stimulate the hair cells of the vestibular apparatus, but this requires levels well above audible threshold, indeed, at levels that could induce trauma (120 dB), which is far above anything frequency noise.[21,29] Two weightings that are commonly used to incorporate this low-frequency portion are *C-* and *G-weighting*. Although there are many studies available that only report A-weighted measurements from wind turbines, when C- and G-weighted measurements are given it is clear that infrasound levels are still well below audibility at distances of 100 metres or more.[5,29–31,34,38] Therefore, it is highly unlikely that exposure to infrasound from wind turbines is responsible for the myriad non-specific health issues normally attributed to it.[3,4,39,40]

Although it as advised that noise measurements taken from wind turbines should always include G-weighted levels, it appears as though the A-weighting continues to reflect human perception of the noise generated.[34] Low-frequency audible noise, i.e. not infrasound, can be a source of annoyance in certain cases (discussed in chapter 14), but it is generally concluded that 'Even close to the turbines, the infrasonic sound pressure level is much below the normal hearing threshold, and infrasound is thus not considered as a problem with turbines of the investigated size and construction [2.3–3.6 MW].'[21]

It increasingly appears that psychological expectations may explain the link between wind turbine exposure and health complaints.[4,18] From the early days of large-scale wind farm development, disruption of the visual aesthetic was typically the single most important factor governing local public support (or lack thereof) for wind turbines (see chapter 8). Increasingly, though, the perceived health effects during the planning phase have become a major concern and a strong indicator of opposition.[14] This nocebo effect may be driven largely by the way opposition groups have perpetuated the link between infrasound from wind turbines and health issues, which has been further propagated by media reports.[4,15,19]

The next section briefly discusses electromagnetic fields. More precise details of 'wind turbine syndrome' and its flaws are discussed in the box, *Is There A Case For 'Wind Turbine Syndrome'?* below.

Electromagnetic fields

The effect of negative media reporting – 'scare stories' – has also been shown to be a significant factor in other reports of non-specific health problems attributed to electromagnetic fields.[17,28] As with infrasound, there is no evidence that exposure to electromagnetic fields generated by wind turbines has an effect on nearby residents. However, there is evidence that increasing public anxiety over media reports about electromagnetic fields has led to concerns being raised at development meetings.[14,16] This seemed to come around the same time as a heightened anxiety about fears that Wi-Fi was

measured from a wind turbine.[5,21] Furthermore, where the author of the 'wind turbine syndrome' case report cited research to support the vestibular disturbance hypothesis, she failed to mention that the study in question used a vibrating device applied directly to the skull behind the ear, not air-conducted noise.[7,41] Subsequently, this misrepresentation was openly criticized in a national newspaper by the lead researcher of that selfsame study.[42] It is not surprising that the hair cells of the vestibular apparatus, being connected to the skull via the bony structure of the inner ear, will respond to vibrations applied directly to the skull, but this says nothing about how airborne infrasound can affect this system.[5,19]

2. Infrasound at the 4–8 Hz range enters the lungs via the mouth and then vibrates the diaphragm, transmitting vibration to the body's internal organs .

Proponents of 'wind turbine syndrome' posit that internal vibration conflicts with auditory and visual signals received by the brain, causing agitation, anxiety, nausea and irritability. The author coins the term 'visceral vibratory vestibular disturbance' (VVVD) to explain this phenomenon.[7]

In addition to the vestibular system mentioned above, the internal organs (generally termed the viscera) can transmit information to the brain based on the body's position and motion. This sense is called proprioception, and is initiated by the balance organs in the inner ear and by 'proprioreceptors' found in the muscles and supporting ligaments; it is also thought to involve contact and vibration receptors in the skin, although these receptors are not sensitive to sound waves at infrasound frequencies. It is the effect of infrasonic vibrations transmitted via the lungs to the diaphragm and thence to the viscera that supposedly forms the basis of VVVD.[7] The natural resonant frequency of the viscera is around 4 Hz, which is infrasonic, but the wavelength at this frequency is so long (85 metres) that the sound pressure behaves as a compression wave of negligible force, acting on the body equally from all points and thus preventing any resonant vibrations in the lungs.[37]

Air within the chest cavity does not have an effect on the resonance of the chest cavity either, so the mechanism of vibrations being conducted to the viscera seems implausible.[6] What is known is that the chest resonates at 50 to 80 Hz, but this is in response to a sound level of 80 dB; similarly, chest and abdominal resonances have been observed by exposing subjects to frequencies between 20 and 50 Hz, but this required very high sound levels exceeding 100 dB. Profoundly deaf subjects can also experience airborne infrasound, but this was a frequency of 16 Hz at 128 dB, showing that the visceral sensation of low-frequency sound requires extremely high noise levels to elicit a 'vibrotactile' response.[5,6,37]

also a possible cause of harm, for example, as found in several incredibly misguided articles concerning 'electropollution'.[**] The parallels between this and the scare headlines about infrasound are apparent.[4,17,43] Questions have been raised about the presence of electromagnetic fields in everyday life since the 1970s.[44] Electric and magnetic fields are close by or surround us for most of our lives in modern society, being emitted whenever a charge exists or a current flows. Evidence thus far has failed to show causal a link between adverse health effects and the exposure of individuals or populations to electromagnetic fields from appliances, residential wiring and power lines.[45]

Concerns over the potential impact of electromagnetic fields generated by wind turbines have prompted a few recent studies, which have shown that electromagnetic fields from operating wind turbines are four orders of magnitude lower than the threshold guidelines.[3]

The first study measured the electromagnetic field propagated by a large wind farm on the edge of the Black Sea in Bulgaria, consisting of 55 wind turbines rated at 3 MW each (i.e. large, utility-scale wind turbines).[46] The authors reported that the electromagnetic fields generated by the operating turbines, measured within three metres of the turbines themselves, were far below EU Council Recommendations for public exposure. The magnetic flux density recorded (magnetic flux is generated when an electric current is flowing) ranged from 0.013 to 0.023 microtesla (μT) near the wind turbines,[46] which compares with the EU recommendations that restrict public exposure to magnetic flux densities of 100 μT.[47] These levels were comparable, if not slightly lower, than levels found in the houses of the nearest village, which is to be expected given the normal magnetic fields found in residential dwellings in Europe.[44]

A more recent study of a smaller wind farm in Ontario reported similar findings to the one in Bulgaria.[16] This involved an installation of 15 wind turbines rated at 1.8 MW each – a common size, although newer turbines tend to be similar to those in the Bulgarian wind farm mentioned above. The authors of the Ontario study also took the opportunity to measure the turbines under three different conditions: when wind speed was high enough to rotate the turbines and generate power for the grid, when wind speed was insufficient to rotate the turbine but the turbine continued to draw power for general maintenance functions, and when the wind turbine and associated connector lines were shut off completely. The shut-off readings enabled the researchers to see that the background magnetic flux density was 0.03 μT. When turbines were generating for the grid or simply switched on, magnetic flux density varied between 0.09 and 0.11 μT; note, however, that these readings rapidly diminished after moving two metres away from the base of the turbine, whence they became imperceptible from the background level. Further measurements around high voltage lines and substations in the wind farm site showed that the highest reading was 1.65 μT directly below a high-voltage collector line, which diminished to the background level within 25 metres at most. Perhaps most importantly, recordings taken outside houses closest to the wind farm (500 metres) showed levels were just 0.04 μT. Any slight increase from the background level of 0.03 μT is due to the wiring normally present in residential buildings.(16) The authors note that the levels recorded were significantly lower than electromagnetic fields generated within residential buildings by common appliances, such as refrigerators and dishwashers (which generate around 4–10 μT).

Autism

In early 2010, a planning application for a wind farm was refused on the grounds that the impact on twin autistic children living nearby would be unacceptably high. The children in question had a particular obsession with spinning and turning objects, and the concern was that if they could see the turbines from their home, watching them persistently would exacerbate this already obsessive tendency[††].The fact that a planning application was refused in this individual case has led to an increased discussion about autism and wind power on online forums, and this particular planning refusal seems to have become conflated with the general idea that the presence of wind turbines can both cause and exacerbate the symptoms of autism.

There is simply no evidence within the scientific literature at all that there is any causal link between the development of a new wind power installation and people nearby developing autism spectrum disorders or having the symptoms of an existing autism spectrum disorder made worse. In the absence of any peer reviewed papers on this issue, the National Autism Society, a leading advice provider for autistic people and their families were asked for a statement on this matter. NAS confirmed that this is not an issue that service users or members have raised as a concern, and that they are also not aware of any evidence suggesting a link. Their response is produced below:

> *'A low level but slowly increasing number of references are being found in anti-wind development literature to a link between autism and wind power. These reports seem originate*

[**] For example, see in the British Columbia Teachers' Federation magazine: L. Quiring, 'Should Wi-Fi be used in classrooms?' Teacher, v.23, No.1, September 2010, available at www.bctf.ca/publications/NewsmagArticle.aspx?id=21558.

[††] http://news.bbc.co.uk/1/mobile/england/humber/8646326.stm

from the time of the refusal of planning permission in a particular case where the impacts of a wind farm development were likely to have detrimental impacts on the behaviour of twin children with autistic spectrum disorders already living nearby, and where one of the symptoms for these particular children happened to be a specific obsession with spinning objects. The concern was that for these particular children, the turbines would represent such a distraction as to make daily life very difficult for their entire family.

There is no evidence whatsoever that visibility or noise from wind turbines causes autistic spectrum disorders in previously undiagnosed individuals, or that visibility or noise from wind turbines exacerbates the symptoms of autistic spectrum disorders in most people already diagnosed with the condition.

However, as this case shows, a very specific planning issue could arise in the rare incidence that a household with an autistic family member is near to a proposed wind farm site, and where that family member's symptoms include an obsessive interest in (or particular anxiety caused by the presence of) large structures, spinning or moving objects. Such a case would be for the local planning authority to determine, in the same way that they would determine detrimental impacts of any new infrastructure on nearby residents, especially where those residents are vulnerable to change in the wider environment due to diagnosed sensory or autistic spectrum disorders. It is important to note that such considerations are an essential part of any planning application and are not limited to consideration of wind farm planning applications; such a household could be equally negatively impacted by the construction of a new road, or pedestrian crossing that adds new lights and sounds into the local environment.

The fact that an individual planning application has been refused on the grounds that a local resident with autism could have been severely affected by the introduction of wind turbines into their local environment in no way suggests *that the presence of wind turbines can trigger autism in otherwise unaffected individuals or routinely exacerbates the symptoms for individuals with previously diagnosed autistic spectrum disorders.'*

Pers. Comm., Head of Centre, National Autistic Society, 22/02/16

Conclusion

The hypothesis that operating wind turbines are responsible for a number of non-specific health issues, collectively grouped as 'wind turbine syndrome' lacks both plausibility and evidence, as does the suggestion that wind power can cause or exacerbate autism. In the 2000s, objection to wind turbines on the basis that low-frequency noise or infrasound was hazardous to health prompted several observational studies on the nature of sound generated by wind turbines. Whilst it is certainly the case that the noise spectrum of wind turbines has a proportionally large low-frequency and infrasonic component, measurements of environmental exposure due to operating wind farms have repeatedly failed to show that infrasound can have a demonstrable physiological effect on nearby residents.[3,5,21,29] Adverse effects on humans are only evident at infrasound levels far exceeding that generated by operating wind turbines.[5,6] The UK Health Protection Agency welcomed additional research in the field of environmental infrasound in a 2010 report, whilst acknowledging the lack of evidence supporting wind turbine-generated infrasound as a health risk.[37] Studies published since then have continued to show that infrasound from wind turbines is at levels below audibility and within guidelines.[48] The recognition that the noise spectrum of wind turbines warrants investigation using different weightings more suited to low-frequency noise has been taken on board in more recent studies, but the evidence still shows the same results, and it is highly likely that the more conventional weighting (A-weighting) remains an adequate reflection of human perception of noise.[34,48] Indeed, in many cases, G-weighted measurements suggest wind turbine infrasound is less than the infrasound produced by naturally occurring phenomena.[25,30,31]

Similar to infrasound, another concern that has appeared with greater regularity in the last decade is the fear that wind turbines generate electromagnetic fields. This is raised as another objection on the grounds that it poses a risk to residents' health.[3,14,16] Measurements of electromagnetic fields generated by wind turbines suggest the strength of these fields are comparable to background levels, becoming imperceptible when moving just a few metres away from the turbine.[16,46] The history of health scares relating to electromagnetic fields echoes to a large extent similar headlines about the 'silent menace' of infrasound. The rise in the number of complaints about 'electrosensitivity' since the 1970s has failed to demonstrate any link between exposure to electromagnetic fields and symptoms.[28] What is clear is that people's perceived exposure is a consistent predictor of non-specific health conditions being reported.[49–51] Increased reporting of 'scare stories' that attribute a variety of non-specific health problems to the technological trappings of modern society set up an expectation in the minds of many, increasing their anxiety and subsequently manifesting as broad symptoms, including ear symptoms, headache, fatigue, dizziness and sleep problems, that may become quite debilitating for some of those affected.[6,17,28,43] There is evidence that suggests this nocebo effect is behind the increase in self-reported symptoms attributed to nearby wind farms.[4,15,18] This seems plausible in light of similar findings regarding electromagnetic fields and negative expectations, and may shed some light on why exposure to objectively measured noise from wind turbines does not match up with subjectively reported symptoms.[3,6,40]

Why is the propagation of the 'wind turbine syndrome' myth and the perception of harm to health from wind power so important? To be absolutely clear, although infrasound is demonstrably not causing harm, there is much stronger evidence that audible sound from wind turbines can be a source of annoyance and have a negative impact on quality of life for a small number of nearby residents.[52,53] This is discussed in detail in chapter 14. Creating conditions such as 'wind turbine syndrome', despite the lack of any corroborating evidence, is a confusing and unnecessary addition to the real and complex problem of noise disturbance.[19] The widespread dissemination of these and similar 'health scares' through avenues for public discourse – particularly the internet – has led to an alarming amount of unsubstantiated reporting among groups with a vested interest in opposing wind farm developments, which further increases the potential for these reports to trigger anxiety among sections of the population.[17,43]

Reinforcing the belief that wind turbines are the cause of underlying health issues confounds the treatment of sufferers, because they are fixated on an external agency as the cause of their distress, despite the lack of evidence for a direct pathophysiological relationship between infrasound and their symptoms.[19,27,54] This has important implications, given the power that negative expectations have on how wind turbine noise is perceived by residents.[18,43,54,55] There is an important and powerful social dimension to the interaction between wind power and communities, and the undue influence that myths such as 'wind turbine syndrome' continues to exert only serves as an unnecessary and harmful distraction from the real issues that planners and communities should address.

References

1. Hanning CD, Evans A. Wind turbine noise. BMJ. 2012; 344:e1527–e1527.
2. Chapman S. Editorial ignored 17 reviews on wind turbines and health. BMJ. 2012; 344:e3366–e3366.
3. Knopper LD, Ollson CA, McCallum LC, Whitfield Aslund ML, Berger RG, Souweine K, et al. Wind turbines and human health. Front Public Health. 2014; 2:Article 63.
4. Chapman S, St. George A, Waller K, Cakic V. The pattern of complaints about Australian wind farms does not match the establishment and distribution of turbines: Support for the psychogenic, 'communicated disease' hypothesis. PLoS ONE. 2013; 8(10):e76584.
5. McCunney RJ, Mundt KA, Colby WD, Dobie R, Kaliski K, Blais M. Wind turbines and health: a critical review of the scientific literature. J Occup Environ Med. 2014; 56(11):e108–30.
6. Leventhall G. Low Frequency Noise. What we know, what we do not know, and what we would like to know. J Low Freq Noise Vib Active Control. 2009; 28(2):79–104.
7. Pierpont N. Wind turbine syndrome: a report on a natural experiment. Santa Fe, N.M.: K-Selected Books; 2009. 294 p.
8. Nissenbaum MM. Affidavit of Dr. Michael M. Nissenbaum [Internet]. National Wind Watch. 2010 [cited 2016 Jan 20]. Available from: www.wind-watch.org/documents/affidavit-of-dr-michael-m-nissenbaum-m-d/
9. Harry A. Wind turbines, noise and health. 2007 Feb [cited 2016 Jan 20]. Available from: www.wind-watch.org/documents/wind-turbines-noise-and-health
10. Branco NAAC, Alves-Pereira M. Vibroacoustic disease. Noise Health. 2004; 6(23):3–20.
11. Chapman S, St George A. How the factoid of wind turbines causing 'vibroacoustic disease' came to be 'irrefutably demonstrated'. Aust NZ J Public Health. 2013; 37(3):244–9.
12. Alves-Pereira M, Castelo Branco NAA. In-home wind turbine noise is conducive to vibroacoustic disease. Second International Meeting on Wind Turbine Noise, Lyon, France, September 20–21, 2007.
13. Knopper LD, Ollson CA. Health effects and wind turbines: A review of the literature. Environ Health. 2011; 10(1):78.

14. Baxter J, Morzaria R, Hirsch R. A case-control study of support/opposition to wind turbines: Perceptions of health risk, economic benefits, and community conflict. Energy Policy. 2013; 61:931–43.
15. Deignan B, Harvey E, Hoffman-Goetz L. Fright factors about wind turbines and health in Ontario newspapers before and after the Green Energy Act. Health Risk Soc. 2013; 15(3):234–50.
16. McCallum LC, Whitfield Aslund ML, Knopper LD, Ferguson GM, Ollson CA. Measuring electromagnetic fields (EMF) around wind turbines in Canada: is there a human health concern? Environ Health. 2014; 13(1):9.
17. Witthöft M, Rubin GJ. Are media warnings about the adverse health effects of modern life self-fulfilling? An experimental study on idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF). J Psychosom Res. 2013; 74(3):206–12.
18. Crichton F, Dodd G, Schmid G, Gamble G, Petrie KJ. Can expectations produce symptoms from infrasound associated with wind turbines? Health Psychol. 2014; 33(4):360–4.
19. Leventhall G. Concerns about infrasound from wind turbines. Acoustics Today. 2013; 9(3):30–8.
20. O'Neal RD, Hellweg RD, Lampeter RM. Low frequency noise and infrasound from wind turbines. Noise Control Eng J. 2011; 59(2):135.
21. Møller H, Pedersen CS. Low-frequency noise from large wind turbines. J Acoust Soc Am. 2011; 129(6):3727.
22. International Organisation for Standardisation. ISO 226:2003: Acoustics – Normal equal-loudness-level contours. Geneva: ISO; 2003 Aug. p. 18.
23. Dommes E, Bauknecht HC, Scholz G, Rothemund Y, Hensel J, Klingebiel R. Auditory cortex stimulation by low-frequency tones—An fMRI study. Brain Res. 2009; 1304:129–37.
24. Hensel J, Scholz G, Hurttig U, Mrowinski D, Janssen T. Impact of infrasound on the human cochlea. Hear Res. 2007; 233(1-2):67–76.
25. Leventhall G. What is infrasound? Prog Biophysics Mol Biol. 2007; 93(1-3):130–7.
26. WHO. Burden of disease from environmental noise: Quantification of healthy life years lost in Europe. Theakston F, editor. Copenhagen: World Health Organization, Regional Office for Europe; 2011. 106 p.
27. Leventhall G, Benton S, Robertson D. Coping strategies for low frequency noise. Low Freq Noise Vib Active Control. 2008; 27(1):35–52.
28. Baliatsas C, Bolte J, Yzermans J, Kelfkens G, Hooiveld M, Lebret E, et al. Actual and perceived exposure to electromagnetic fields and non-specific physical symptoms: An epidemiological study based on self-reported data and electronic medical records. Int J Hyg Environ Health. 2015; 218(3):331–44.
29. Bolin K, Bluhm G, Eriksson G, Nilsson ME. Infrasound and low frequency noise from wind turbines: exposure and health effects. Environ Res Lett. 2011; 6(3):035103.
30. Turnbull C, Turner J, Walsh D. Measurement and level of infrasound from wind farms and other sources. Acoust Aust. 2012; 40(1):45–60.
31. Evans T. Macarthur Wind Farm Infrasound & Low Frequency Noise: Operational Monitoring Results. Report No.: A12130RP3 Revision B. Adelaide: Resonate Acoustics; 2013 Jul. p. 78.
32. Hayes McKenzie. The measurement of low frequency noise at three UK wind farms. URN 06/1412. London: Department of Trade and Industry; 2006. p. 105.
33. Hepburn HG. Acoustic and geophysical measurement of infrasound from wind farm turbines. Can Acoustics. 2006; 34(2):51–67.
34. Tachibana H, Yano H, Fukushima A, Sueoka S. Nationwide field measurements of wind turbine noise in Japan. Noise Control Eng J. 2014; 62(2):90–101.
35. Salt AN, Hullar TE. Responses of the ear to low frequency sounds, infrasound and wind turbines. Hear Res. 2010; 268(1-2):12–21.
36. Sense organs. In: Saladin KS. Anatomy & physiology: the unity of form and function. 6th ed. New York, NY: McGraw-Hill; 2012. 582–632.
37. HPA. Health effects of exposure to ultrasound and infrasound: Report of the independent Advisory Group on Non-ionising Radiation. Report No.: RCE-14. London; Chilton, Didcot: Health Protection Agency; Centre for Radiation, Chemical and Environmental Hazards; 2010. p.180.
38. Jakobsen J. Infrasound emission from wind turbines. Low Freq Noise Vib Active Control. 2005; 24(3):145–55.
39. Roberts JD, Roberts MA. Wind turbines: is there a human health risk? J Environ Health. 2013; 75(8):8–17.
40. Feder K, Michaud DS, Keith SE, Voicescu SA, Marro L, Than J, et al. An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines. Environ Res. 2015; 142:227–38.
41. Todd NPM, Rosengren SM, Colebatch JG. Tuning and sensitivity of the human vestibular system to low-frequency vibration. Neurosci Lett. 2008; 444(1):36–41.
42. Todd N [Internet]. IoS letters, emails & online postings (9 August 2009) | Voices | Letters. Independent. 2009. Available from: www.independent.co.uk/voices/letters/ios-letters-emails-online-postings-9-august-2009-1769575.html. [Accessed 5 Jan, 2016]
43. Rubin Gj, Burns M, Wessely S. Possible psychological mechanisms for 'wind turbine syndrome'. On the windmills of your mind. Noise Health. 2014; 16(69):116.
44. WHO [Internet]. Electromagnetic fields and public health. Fact sheet 322. World Health Organization. 2007. Available from: www.who.int/peh-emf/publications/facts/fs322/en/. [Accessed 24 Jan, 2016]
45. WHO [Internet]. Electromagnetic fields (EMF): What are electromagnetic fields? World Health Organization. 2014. Available from: http://www.who.int/peh-emf/about/WhatisEMF/en/. [Accessed 18 Aug, 2014]
46. Israel M, Ivanova P, Ivanova M. Electromagnetic fields and other physical factors around wind power generators (pilot study). Environmentalist. 2011; 31(2):161–8.
47. European Parliament and the Council of the European Union. 1999/519/EC: Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). Official Journal. 30 Jul, 1999; 42:L199/59–70.
48. Berger RG, Ashtiani P, Ollson CA, Whitfield Aslund M, McCallum LC, Leventhall G, et al. Health-based audible noise guidelines account for infrasound and low-frequency noise produced by wind turbines. Front Public Health. 2015.
49. Röösli M, Frei P, Mohler E, Hug K. Systematic review on the health effects of exposure to radiofrequency electromagnetic fields from mobile phone base stations. Bull World Health Organ. 2010; 88(12):887–96F.
50. Rubin GJ, Hillert L, Nieto-Hernandez R, van Rongen E, Oftedal G. Do people with idiopathic environmental intolerance attributed to electromagnetic fields display physiological effects when exposed to electromagnetic fields? A systematic review of provocation studies. Bioelectromagnetics. 2011; 32(8):593–609.
51. Baliatsas C, Van Kamp I, Bolte J, Schipper M, Yzermans J, Lebret E. Non-specific physical symptoms and electromagnetic field exposure in the general population: Can we get more specific? A systematic review. Environ Int. 2012; 41:15–28.
52. Pedersen E. Health aspects associated with wind turbine noise—Results from three field studies. Noise Control Eng J. 2011; 59(1):47.
53. Onakpoya IJ, O'Sullivan J, Thompson MJ, Heneghan CJ. The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies. Environ Int. 2015; 82:1–9.
54. Crichton F, Petrie KJ. Health complaints and wind turbines: The efficacy of explaining the nocebo response to reduce symptom reporting. Environ Res. 2015; 140:449–55.
55. Crichton F, Dodd G, Schmid G, Petrie KJ. Framing sound: Using expectations to reduce environmental noise annoyance. Environ Res. 2015; 142:609–14.

Chapter 16

Wind farms and radar

Summary

The rapid expansion in the 21st century of onshore and offshore wind farms has led to an increasing number of objections being raised to developments for reasons of aviation safety and military security. The central reason for this is that wind turbines positioned in critical areas can have adverse effects on radar performance. Turbines possess a radar cross-section that is a result of the tower, nacelle and blades all being able to reflect the radio waves used by radar systems, which produces 'clutter' that can obscure a target of interest making it difficult or impossible to track. This can drastically reduce the effectiveness of air defence surveillance and air traffic control radar, especially civil systems used to track incoming aircraft and weather fronts in the vicinity of airports. Interference from wind turbines can therefore present a danger to civilian air passenger safety, and can degrade military capabilities with regards to early warning systems and radar defence.

In some cases, the presence of obsolete radar systems is a contributory factor to the problem, but even modern systems may require significant upgrades to ensure interference is effectively mitigated. Ultimately, radar technology has proven very capable of adapting to the problems posed by the increasing deployment of wind farms, but it requires meaningful cooperation between wind farm developers and the civil and military aviation authorities. Several solutions have already been implemented, involving improved software, additional 'infill' radar systems and the replacement of ageing equipment. The UK has taken a leading role in showing how constructive dialogue and a flexible, collaborative approach to mitigation measures can remove planning obstacles resulting from conflicts with radar. In the last decade, a significant amount of UK wind capacity has been 'unlocked' through early stakeholder engagement and the successful implementation of cost-effective solutions.

What is this based on?

The word 'radar' is now used as a common noun in the English language, but it is from the acronym, 'RAdio Detection And Ranging'. This describes the basic operating principle of radar, which is to locate a distant target using radio waves and supply meaningful information regarding its range, altitude, speed and direction of movement. Radar detection relies on objects reflecting and scattering the radio waves that are broadcast by the radar transmitter. When some of those reflected waves are returned in a certain direction they can be picked up by a radar receiver. The power of the returned radio signal and the degree of scattering, combined with knowledge of the location of the radar transmitter and receiver, allows one to calculate the position of the reflecting object.* Note that whilst the transmitter and receiver are usually located close to each other, this is not always the case.

In addition, modern radar systems employ sophisticated processers to analyse the return signals, which helps enhance object tracking by giving information on an object's size and aspect, reducing signal noise and background interference, and filtering out 'clutter' caused by other objects reflecting the radio waves, such as buildings, hills, sea swell and precipitation (weather radar obviously does not filter out the latter).

A further enhancement of radar detection is achieved by exploiting the Doppler effect. You may remember the Doppler effect from learning about soundwaves and how the sound of an approaching or receding object (like a train horn) can change in pitch. If the source of noise continues to move towards you, successive sound waves are bunched closer together and this results in a higher frequency – the sound of the train's horn rises in pitch. Conversely, if the source of noise is moving away, then successive sound waves are spread further apart and you hear a lower frequency sound – the pitch of the train's horn goes down. This phenomenon is associated with any type of wave and, hence, because radar relies on the propagation of radio waves, the Doppler effect can be observed.

When sucessive radio waves bounce off of a moving object and are returned to the receiver, the degree to which these waves are bunched together or spread apart over time gives useful information about the speed and direction of the object. This makes radar extremely useful for ranging airborne objects, whether tracking civilian aircraft as part of air traffic control or for

---

* Note this is a very simplified description. These calculations also account for factors such as the gain of the transmitter, the area of the receiving dish, the pattern of propagation, the refractive index of the atmosphere and the scattering coefficient of the reflecting object.

targeting moving objects that may pose a threat; it also allows useful data to be gathered regarding the movement and precipitation of weather fronts.

Why do wind turbines present a special problem for radar detection? Modern wind turbines are large structures: typical hub heights for the 1.5–3.0 MW designs used onshore range between 70 and 120 m; the hub height for offshore designs is usually in the same range even though the turbines are rated higher (3.0–6.0 MW), because the wind conditions out to sea allow more energy extraction at a given height than occurs on land.[1,2] In addition to being tall structures, wind turbines have moving parts. The rotating face of the blades on a turbine can sweep across a significant area (roughly 5,000 to 7,000 square metres), with each blade in the region of 30 to 50 m in length.[3] Turbines being designed and built for future planned expansion both onshore and offshore will incorporate even higher hub heights and longer blades, with one offshore design already unveiled that uses 75 metre-long blades.[4] Thus, wind turbines can present a large radar cross-section to a radar system operating in the vicinity, which can interfere with detection even over quite large distances if the turbines are clustered in the line of sight of a long-range radar.[5,6]

The large steel structure of a wind turbine tower and hub, plus the exposed face of the blades, all contribute to creating false 'echoes' and scattering radar transmissions, which leads to direct interference. This interference can mask a target of interest or overload the receiver with unwanted signals, making it difficult to maintain effective tracking.[5] A group of wind turbines will present a radar cross-section that is significantly larger than a passenger airliner, which can render a surveillance radar system incapable of detecting such aircraft when they fly in the 'shadow' of a wind farm.[7] Indeed, the radar clutter of a wind farm can make it difficult to identify whether an airplane emerging from the shadow is the same one that flew into the shadow or an alternative airplane.[†]

The movement of the blades also causes Doppler interference, as radio waves are reflected at different points and different times across the area of the rotor face.[5] Radar systems have developed to effectively filter out the radar cross-section of background objects and acquire the characteristic signal obtained from large aircraft that typically fly at predicable elevations and are in constant motion.[7] The Doppler effect that results from rotating wind turbines confounds many radar systems, as they cannot distinguish between the two moving radar cross-sections produced by the rotating blades and a moving aircraft.[‡] The blade tip speed on a large wind turbine can be in the region of 180 mph, well within the range of smaller airplanes or low-flying aircraft (such as airliners approaching for a landing), but even if the speed of the rotating blades is less than an aircraft's speed the signal can still confuse the surveillance radar.[3,5,8] As aircraft traverse the area of a wind farm, the radar may even merge the target with the signal from a turbine, especially if the turbine spacing in a wind farm is relatively dense. This can cause the aircraft track to become associated with overlapping signals from the turbines, resulting in loss of target (known as 'target seduction').[9]

An important role for radar is that of weather prediction, which is essential for monitoring severe weather in real time; Doppler weather radar can also be used to provide estimates of wind speed.[10] Wind turbine clutter appears very similar to typical radar signatures produced by weather phenomena, particularly fronts containing precipitation.[11] Similar to target tracking for aviation radar, weather radar can typically filter out clutter from stationary objects, even structures like the turbine tower itself. However, most algorithms that do this cannot distinguish the Doppler shift caused by the rotating blades, especially as the returns from these moving components can result in quite complex signatures.[12] The short time window of dynamic weather features, including hazardous phenomena, means radar is the only effective way to monitor these events. Aggregated wind turbines in a poorly sited wind farm can significantly degrade radar performance for weather prediction.[13]

What is the evidence?

Hardware considerations

As wind farm development began to accelerate in the early 2000s, military and civil aviation authorities, meteorological organisations and seismic monitoring stations all realised the potential impact.[14] Measurements across several sites in Europe have shown that existing wind farms can have a significant impact on weather radar performance, sometimes over distances of 60 km (37 miles) or more.[13] There are also several examples of wind farms, large and small, affecting nearby weather radar systems at critical points across England, Wales and Scotland.[9] In one instance, a three-turbine development in Wales was still capable of casting a significant radar shadow.

Studies by the Royal Air Force (RAF) and US military have also demonstrated the deleterious effects wind farms can have on radar systems, and this has led to many

---

[†] Ian Chatting interviewed in: Reuters, '"Stealth" wind turbine blade may end radar problem,' CNET, 27 Jan, 2010, www.cnet.com/news/stealth-wind-turbine-blade-may-end-radar-problem.

[‡] A key feature of the filtering carried out by radar systems is the ability to suppress signals from stationary objects, but the changing echoes from rotating blades means this cannot be applied to wind turbines without unreasonably lowering the detection threshold of the whole system.

projects being blocked by defence departments due to concerns over the surveillance capabilities being compromised.[6,7] The blocking effect caused by wind farm clutter observed on RAF surveillance radars led to the recommendation that any proposed wind turbine installation situated in direct line of sight must undergo consultation with the Ministry of Defence regardless of distance (the limit had previously been set at 74 km).[6]

High frequency radar is also used for monitoring conditions at sea and for seagoing vessels to forewarn themselves of nearby objects. The increasing number of offshore wind farms around UK coastal areas have been seen to interfere with these radar systems, reducing their effectiveness with regards to marine navigation, wave measurements, and search and rescue capabilities.[15–18] Those involved with marine spatial planning must ensure that owners of UK offshore wind projects are fully cognisant of the constraints that come from developing in areas that include some of the busiest waterways in the world.[19]

Despite these issues, there are a number of solutions that have been proven to mitigate the impact of wind turbines on nearby radar installations, or show a great deal of promise for future implementation.[20] These vary in cost and are most effectively applied in combination with non-technical solutions, such as clear zoning policies and better stakeholder collaboration.[14] Technical solutions incorporate various computational advances (i.e. improved software applied to existing systems), upgrades to obsolete equipment, and also the placement of infill (or gap fill) radar systems. The latter approach is particularly attractive, since it employs existing 'off-the-shelf' equipment,[9] is relatively cost-effective (at least for large developments) and is readily applicable to existing developments that are stuck in the planning stage.[14]

The principle of infill radar is simple – a new surveillance source is created to help 'fill in' the gaps on a surveillance display that are due to the presence of wind turbines.[20] The infill approach uses a secondary radar that is either strategically positioned so that it cannot see the turbines but still illuminates aircraft of interest, or a specially designed system that is optimised to distinguish the Doppler shift produced by a spinning turbine from a moving target. Systems that use X band radar, which uses a narrow beam radar signal and a higher frequency band of radio waves, have been shown to be capable of providing effective infill coverage. Trials of radar systems in the UK, and elsewhere in Europe and the USA, have successfully passed the requirements necessary to mitigate wind turbine interference, making it possible to 'unlock' considerable levels of renewable generating capacity.[9,14,21] Recent trials conducted in 2014 under the auspice of the UK's national air traffic control service (NATS) have shown that infill radar using off-the-shelf systems can be used by airports to reliably detect aircraft moving through wind farms, even up to 40 nautical miles.

An obvious alternative is relocating existing radar stations. This solution may involve turning one station into two, hence, the new sites provide equivalent coverage to the old one.[22] In fact, developers of Europe's second largest wind farm, Whitelee Wind Farm in central Scotland, have employed both strategies: a Met Office radar at nearby Corse Hill was replaced with two new installations at Holehead and Munduff Hill, with great success;[22] in addition, following consulation between the developer and the air navigation service provider for Glasgow airport, a new infill radar was installed at Kincardine to provide an unaffected radar feed that removed the surveillance clutter produced by the Whitelee site.[21,23] Both strategies were hallmarked by a consultative process that was instigated early on in the planning process by the wind farm developer to research options in collaboration with the relevant authorities. It is acknowledged that the UK has been one of the leading nations in championing this approach, with demonstrable success.[14]

However, one aspect of the Whitelee development that should not be overlooked is the cost. The wind farm developer funded most of the additional cost of implementing both solutions, although, since costs involve proprietary company information, the exact details are not publically available.[22,23] Estimates vary, with a figure of £250,000 quoted for the installation of the infill radar system and a £3,000,000–£5,000,000 final cost for the integration of the Kincardine radar data with air traffic control.[14,23] This level of cost might be considered the equivalent of two or three additional turbines. For large sites this represents a few percent of total construction costs for the wind farm itself, but it may not be a viable solution for a small, community-led development.

Software consideration

Radar systems can also receive software upgrades, which may involve digitising older radar sets. This is an alternative to upgrading the radar hardware itself, which can be an expensive option.[14] Software upgrades can improve long-range radar performance, since known wind turbine positions can be integrated into the radar signal processor data to help suppress unwanted returns by applying a 'constant false alarm rate' (CFAR) algorithm for areas that have constant high background levels. This can markedly improve detection of aircraft passing over these areas, i.e. airplanes traversing a wind farm. Using this processing technique may not be

---

§ See: 'New airport radar to mitigate impact of wind turbines', NATS, 8 Oct, 2014, www.nats.aero/news/new-airport-radar-mitigate-impact-wind-turbines. This trial tested the same system used in ref. 9.

effective if a slow-moving aircraft stays in the area for several sweeps of the radar transmitter, or if the strength of the return signal is not very strong (the radar cross-section of wind turbines can often be greater than even large aircraft).[20]

Using CFAR algorithms is not always effective in situations where turbines are placed relatively close together, as might occur in regions where space is constrained (for example, the Swedish Lillgrund offshore wind farm, which lies in a constrained area close to an approach corridor for Copenhagen airport).[9] Densely packed turbines result in high background levels across all 'cells' scanned by a radar, and CFAR thresholds cannot be usefully applied.[14] Overlapping signals from adjacent turbines can even coalesce, preventing radar from accurately mapping the turbines' position and increasing the risk of target seduction when an aircraft passes through the affected cells. Video processing techniques to 'mask' the returns generated by the turbines can significantly reduce this artefact, allowing moving aircraft to once again be successfully tracked whilst entering, traversing and leaving the wind farm area.[9]

Other software enhancements enable long-range surveillance radar to 'look over' turbines by raising the antenna tilt and altering the transition of the transmitter beam, but this can reduce the radar's low-level coverage.[14,20] More sophisticated signal processing software can also be taught to maintain tracking of identified targets using a range of probabilistic techniques (such as predicting the forward track of an aircraft), and by rejecting new target tracks that arise in a cell where there is a wind turbine, but retaining pre-existing tracks that enter the same cell from elsewhere.[20] Other research has focused on developing high-resolution 'clutter maps' for stationary background objects. By integrating these maps into the memory circuits of the radar the unwanted returns can be filtered out from the background more effectively on each sweep.[20] However, this requires processing large volumes of data across a wide bandwidth, and many radar sets are also limited by the maximum number of cells they can analyse in each sweep. Thus, it may not be possible for the radar system to accommodate a clutter map of sufficient complexity to account for a wind farm, and essential components of older radar sets may require a complete redesign if they are to use clutter maps effectively.[14,20]

By analysing the predominant Doppler shift within a scanned cell it is also possible to filter out the erroneous background targets that are created by the rotating blades of a turbine, so getting around the problem of wind turbine clutter (this is 'adaptive moving target indication').[20] This type of detailed analysis of the spectral characteristics of wind turbine clutter can also be used to create algorithms that are able to filter out the Doppler shift for weather radar systems, resulting in weather maps that are free from contaminating signals from a nearby wind turbine.[12] These filtering algorithms can even be applied to groups of turbines together, so providing mitigation for wind farms, not just single turbines.[24]

Collaborative considerations

Replacing ageing equipment with more modern radars can markedly improve aircraft detection in the presence of wind turbines.[14] In particular, the Lockheed Martin TPS-77 radar system has been trialled in the UK, and has enabled the MoD to remove its objections to several significant wind farm projects totalling more than 3 GW in capacity.[21] Modern systems such as the TPS-77 can significantly reduce the size of areas that are shadowed by wind farms, and are far more amenable to the kind of software upgrades discussed above. The cost of these new systems are likely to be the limiting factor, since only large developments or projects involving multiple developers can absorb the multi-million pound price tag.[14] Nonetheless, service improvements remain a core part of military preparedness, and as ageing and obsolete systems are naturally replaced it is probable that the newer equipment can cope much better with wind farm interference.

Finally, for wind farm developments still at the planning stage, there remains the option of tailoring wind turbine placement and aspect to mitigate some of the projected problems.[20] There has also been research into improving the characteristics of the turbines themselves, through the use of radar-absorbing material (RAM) being applied to the turbine structures that minimises the reflection and scattering of radar transmissions. This so-called 'stealth' turbine technology has met with limited success, and is unlikely to be a solution that will be viable in the near future.[14] Aerodynamic losses from coating the blades with RAM and the added weight are not considered to be worth the reduction in radar cross-section that can be achieved. Currently, materials are also expensive and bandwidth-specific, so the solution is costly but may not even resolve all the issues.[5,14] Attempts to model the shape of turbine face and tower to reduce its radar cross-section would require knowledge of the radar system in question, and may inadvertently cause an increase in radar cross-section from a different angle.[5]

Zoning policies have existed for a long time in the UK, and many sites selected for a wind farm must undergo mandatory consultation insisted on by the Civil Aviation Authority (CAA), the MoD or the Met Office, to safeguard surveillance capability.[14,20,22] It is noteworthy that the UK, unlike other jurisdictions, has explicitly chosen a collaborative approach between the renewable energy industry and concerned stakeholders, culminating in a Memorandum of Understanding in 2008 between RenewablesUK and the relevant government agencies concerned with energy, defence and air traffic safety.[**] At its heart, this memorandum lays out the responsibility of each side to engage with one another to find effective solutions:

> *'The wind industry recognises that it is the responsibility of the wind farm developer to achieve an acceptable aviation mitigation solution when required in cooperation with the aviation industry. The aviation industry recognises that it is the responsibility of the aviation stakeholder to engage with the developer in a manner that will allow for reasonable, consistent and timely advice on the identification of mitigation solutions.'*
> *(MoU, 2010 update, p.3, para 15.)*

This collaborative approach has been a key factor in the success of several wind farm developments, which has allowed many gigawatts of clean energy to be deployed by resolving radar issues and opening up wind resources. It has enabled both wind farm developers and air safety service providers to accrue a substantial body of knowledge, with the issues and their potential mitigation solutions being assessed and resolved with increasing effectiveness.20 The UK's success in this regard has led to calls for a similar framework to be adopted in the USA.14

Conclusion

Wind farms can have a marked impact on radar systems in general, leading to reductions in radar performance. This raises legitimate concerns over safety from the standpoint of national security, air traffic safety and meteorological forecasting. Whilst a single wind turbine may be accommodated by nearby radar stations, even a small number grouped together can have a notable effect – larger groupings that are typically found in major wind farm developments only exacerbate the impact. The high radar reflectance of turbines creates large shadows in coverage and excessive signal clutter that masks or drowns out genuine targets of interest. Moreover, although wind turbines are ostensibly stationary objects, their large rotating blades produce a particular effect on signals (a Doppler effect) that is frequently interpreted by radar systems as being a moving target or particular weather pattern. Thus, many surveillance systems cannot effectively track moving aircraft through or beyond a wind farm, and weather radars are unable to correctly assess the level and type of precipitation across a wide geographical area.

Despite the detrimental effects on radar performance caused by wind farms, there are numerous solutions that have been proven to effectively mitigate these problems. There are several advanced signal processing algorithms that can correctly identify wind turbine signatures and filter them out, many of which can be applied to existing radar systems via software upgrades, although older and non-digitised radar sets may not suitable. Another effective solution is the use of infill radar that employs a secondary radar source to provide coverage of the area affected by the wind farm shadow. A substantial body of knowledge has built up in the UK over the last decade thanks to successful collaborative efforts between the wind industry and government agencies, which has resulted in productive stakeholder engagement and discourse to deliver workable solutions in situations where wind developments conflict with radar systems. In addition to the solutions mentioned, the better understanding of the issues involved means risk assessments are more accurate and mitigation solutions can be discussed early during planning and development.

Inevitably, there will be some instances where the physical constraints of a site will mean development cannot go ahead. It should not be forgotten that many of the options employed currently may be too costly for a small project to absorb, and such schemes may require extra support to be able to implement an effective solution. Nonetheless, recent progress has shown that there is little reason to believe radar interference will continue to be the insurmountable hurdle it once was. Both the wind industry and those working with radar technology have demonstrated the flexibility and capability necessary to adapt, thus ensuring low-carbon energy can be delivered without compromising the safety and security that radar systems provide.

[**] 'Wind turbines and aviation radar mitigation issues: memorandum of understanding, 2010 update,' available from: www.gov.uk/government/publications/wind-turbines-and-aviation-radar-mitigation-issues-memorandum-of-understanding-2011-update (shortened URL: www.bit.ly/1DAghBr)

References

1. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.
2. Raadal HL, Vold BI, Myhr A, Nygaard TA. GHG emissions and energy performance of offshore wind power. Renew Energy. 2014; 66:314–24.
3. Kulpa JS, Baczyk MK, Kurowska A, Rzewuski S. Wind farm interferences in Passive Coherent Location. *RADAR Proceedings.* IEEE International Conference on Radar, September 9–12, 2013, Adelaide. 64–68.
4. REN21. *Renewables 2013 Global Status Report.* Paris: REN21 Secretariat; 2013. 51–52.
5. Jenn D, Ton C. Wind turbine radar cross section. Int J Antennas Propag. 2012; Article ID 252689:1–14.
6. RAF Air Warfare Centre. *Further evidence of the effects of wind turbine farms on AD radar.* London: Ministry of Defence; Aug 2005. 56 p.
7. Auld T, McHenry MP, Whale J. US military, airspace, and meteorological radar system impacts from utility class wind turbines: Implications for renewable energy targets and the wind industry. Renew Energy. 2013; 55:24–30.
8. NATS Safeguarding Office. *Options for mitigating the impact of wind turbines on NERL's primary radar infrastructure.* Doc. ref. SUR/RPT/02. Whiteley, Hants: NATS Ltd; 18 Dec 2006. 11 p.
9. Hansen K, Thomsen ACK, Riis MA, Marqversen O, Pedersen MØ, Nielsen E. Detection and tracking of aircraft over wind farms using SCANTER 4002 with Embedded Tracker 2. IET International Conference on Radar Systems, 22–25 October, 2012, Glasgow. 1–6.
10. Met Office. *Safeguarding our observations. Met Office guidelines for wind farm developers: meteorological radar and other technical sites used for meteorology.* Exeter: Met Office; Apr 2012. 28 p.
11. Isom BM, Palmer RD, Secrest GS, et al. Detailed observations of wind turbine clutter with scanning weather radars. J Atmos Oceanic Technol. 2009; 26(5):894–910.
12. Hood K, Torres S, Palmer R. Automatic detection of wind turbine clutter for weather radars. J Atmos Oceanic Technol. 2010; 27(11):1868–1880.
13. Chèze J-L, Haase G. *Radar site selection and protection.* OPERA deliverable: OPERA_2010_04. Brussels: EUMETNET; 2010. 17 p.
14. Auld T, McHenry MP, Whale J. Options to mitigate utility-scale wind turbine impacts on defence capability, air supremacy, and missile detection. Renew Energy. 2014; 63:255–262.
15. Brown C, Howard M. *Results of the electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm by QinetiQ and the Maritime and Coastguard Agency.* MNA 53/10/366. Maritime and Coastguard Agency; 15 Nov 2004.
16. MARICO Marine. *Investigation of technical and operational effects on marine radar close to Kentish Flats offshore wind farm.* London: BWEA; Apr 2007. 52 p.
17. Wyatt LR, Robinson AM, Howarth MJ. Wind farm impacts on HF radar current and wave measurements in Liverpool Bay. Proceedings of Oceans, 6–9 June, 2011, Santandar, Spain. IEEE; 2011. 1–3.
18. Stanley JM. *Offshore wind farm helicopter search and rescue trials: 8. Report of the Officer Commanding C Flight, 22 Squadron.* Maritime and Coastguard Agency; 5 Apr 2005.
19. Toke D. The UK offshore wind power programme: A sea-change in UK energy policy? Energy Policy. 2011; 39(2):526–534.
20. CAA. *CAA policy and guidelines on wind turbines.* CAP 764. London: Published by TSO (The Stationery Office) on behalf of the UK Civil Aviation Authority; Jun 2013. 91 p.
21. See: 'MOD paves way for new wind-farm-friendly radars,' *gov.uk,* 12 January 2012, www.gov.uk/government/news/mod-paves-way-for-new-wind-farm-friendly-radars (last accessed 7 Aug, 2014); and 'ScottishPower Renewables offers radar solution to help unblock major wind power projects in central Scotland,' *ScottishPower Renewables,* 12 July 2012, www.scottishpowerrenewables.com/news/pages/scottishpower_renewables_offers_radar_solution_to_help_unblock_major_wind_power_projects_in_central_scotland.asp (last accessed 11 Aug 2014).
22. Hutchingson G, Miles R. The protection of weather radar networks. The UK experience. Proceedings of Fifth European Conference on Radar in Meteorology and Hydrology, Helsinki (ERAD 2008). 1–5.
23. Pager Power. *Whitelee case study – The largest onshore wind farm in Europe: Executive Summary.* Sudbury, Suffolk: Pager Power; May 2010. 2 p. Available from: http://www.pagerpower.com/media/Case-Studies/Whitelee-Radar-Infill-Case-Study.pdf (last accessed 11 Aug 2014).
24. Naqvi A, Ling H. Signal filtering technique to remove Doppler clutter caused by wind turbines. Microwave Opt Technol Lett. 2012; 54(6):1455–60.

centre for sustainable energy

OFFICE	3 St Peter's Court Bedminster Parade Bristol BS3 4AQ
PHONE	0117 934 1400
EMAIL	info@cse.org.uk
WEB	cse.org.uk
TWITTER	cse_bristol
CHARITY	298740
COMPANY	2219673
FOUNDED	1979