centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 12
Wind turbines and safety

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see
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Centre for Sustainable Energy, June 2017

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

Common concerns about wind power (2nd edn)

Chapter 12
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The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

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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.

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; namely, 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.

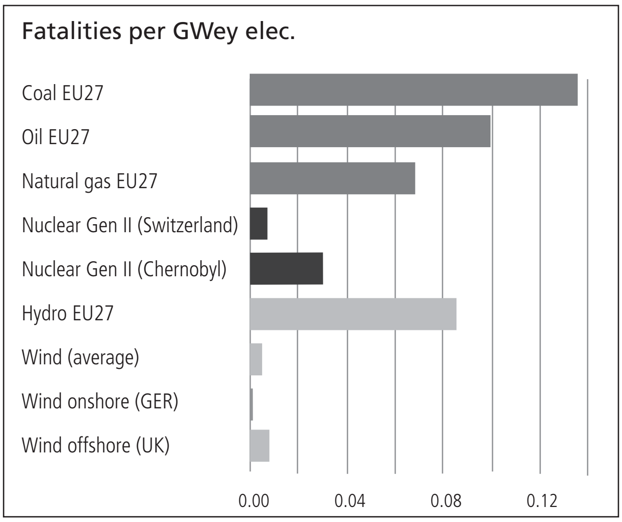
It is clear that maintaining an energy supply carries a human cost, but the superior safety profile of wind energy is evident. Going back to the UK's electricity generation over five years, from 2009 to 2013 natural gas and coal were used to deliver 146 GW_y of electricity at a supposed rate of 14 fatalities, 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.

** 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.

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.



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 readily adopted standards for wind turbine design that improve safety for personnel, especially as turbines have grown in size from small kilowatt-scale units to enormous multi-megawatt machines.[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 spaced 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. air, rail or motor transport), 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.