ANN M. SMITH

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Judge Mike Campbell
Commissioner Chase Broussard
Commissioner Johnny Gee
Commissioner Richard Lowery
Commissioner John McGregor
County Attorney Seth C. Slagle

December 9, 2019

REGARDING: PROPOSED PUBLIC SAFETY ORDINANCE

CLAY COUNTY COMMISSIONER'S COURT,

Included in this package of information regarding the subject public safety ordinance:

- "Summary of Proposed Wind Farm Safety Order" – a brief summary that outlines the order, provides background information, and details why the order is needed.
- The proposed public safety ordinance. It is complete and ready to pass as an order from the Commissioner's Court.
- "Wind Farm Safety Order Proposal – a brief summary, using bar chart graphics, of safety incidents around the world, with focus on the United States.
- "Summary of Wind Turbine Accidents" – the details behind the data summarized in the previous document.
- "A method for defining wind turbine setback standards" – a scientific study that is focused on blade / ice throw. It is this study that confirms the need for the 2,000ft setback distance.
- A copy of my remarks as read to the Court.

I ask only that you remain focused on public safety as you discuss this proposal, today and in the future. In passing this ordinance, and I hope you do, you will uphold your duty to protect the public.

Thank you for your time and attention.

Sincerely,

Ann M. Smith

Summary of Proposed Wind Farm Safety Order

Public Safety Ordinance

Presenter: Ann M. Smith
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Summary of Details and Provisions

- Setback distances:
  - Turbines -- 2,000 ft or 3-times the total turbine height (whichever is greater).
  - Related Equipment -- 1,500 ft or lease provisions (whichever is greater).
- Proposes establishment of above setback distances from:
  - Public roads – measured from the leading edge of turbine perimeter footprint and from the edge of any related equipment to the center of the road.
  - Property lines – measured from the leading edge of turbine perimeter footprint and from the edge of any related equipment to the property line of any unleased land adjacent to the wind farm project.
- A waiver of this setback distance is allowed for property lines only
  - Waiver does not allow a distance less than any lease provision for setbacks
- Structures are NOT included in order to preserve property rights

Reasons for the Setback Distance

- Carefully chosen based on science rather than an arbitrary distance.
- Focused on public safety regarding blade and ice throw; though other safety hazards are mitigated as well (fire or tower collapse, for example).
- References:
  - Calculating Wind Turbine Setbacks With Science
    - https://northeastwindmills.com/calculating-wind-turbine-setbacks-with-science-instead-of-politics/
  - A method for Defining Wind Turbine Setback Standards
    - http://camm.gatech.edu/images/7/7a/Wind_Turbine.pdf

Summary of Safety Incidents – Danger is Real

- As of September 2019 there are 2559 safety incidents worldwide
- Of these, 882 occurred in the United States
- Most of the United States safety incidents have occurred since 2010 (a total of 636).
    - As the presence of turbines increases, so does the hazard to the public
- More than 10% of these incidents have occurred in Texas
    - 83 incidents – including blade failures, ice throw, tower collapse, and fire
- Most recent Texas incidents:
    - August 2019 (Taylor County) – Rhodes Ranch fire caused by a turbine
    - November 2018 (Hale County) – road impassable due to construction damage
    - August 2018 (Mitchell County) – out of control turbine puts family out of their home
    - February 2018 (Dallas County) – blade failure; surrounding structures damaged
    - June 2017 (Clay County) – collapse at midpoint of tower; unknown reason
    - June 2017 (Donley County) – turbine fire causes damage to surrounding land
    - 2016 (estimate, Cooke County) – ice throw; surrounding structures damaged

Why the Ordinance is Needed

- To project the safety of the public in the event that:
  - Current wind farm companies leasing in Montague County decide to build without a reinvestment zone or tax abatement (they are making this threat, probably to encourage land holders to lease).
  - Future wind farm companies decide to consider development in Montague County.

Order No. _______

An Order to provide for the safety, health and well-being of the citizens of Clay County, Texas, and to the general public, by establishing appropriate setback standards of turbine electrical generating facilities which produce electrical power.

The Commissioners Court of Clay County finds it necessary to make this order because of the health and safety hazards due to a falling objects risk in the form of blade, or ice, throws from a spinning wind turbine. The Commissioners Court believes it has a duty to protect the health, safety, and property rights of Clay County citizens by providing setback distances for those whose property is not, or is not expected to be, included in a Wind Energy Conversion System (WECS).

This Order is intended to promote safeguards that will ensure the health, safety, and welfare of the citizens of Clay County and the general public. The site-specific application of this Order shall occur only in a manner that provides a harmonious balance between suitability of a project site with existing land use and physical surroundings.

IT IS ORDERED THAT:

This order applies to Wind Energy Conversion Systems (WECS) to be developed within the boundaries of the unincorporated areas of Clay County, Texas, other than the extraterritorial jurisdiction of a municipality located in Clay County, Texas.

SETBACKS

This order establishes the following setback distances from public roads and property lines to the Wind Energy Conversion Unit ("WECU").

Public Roads: A minimum distance of 2,000 ft or three times the total turbine height, whichever is greater from the center of the public road to the leading edge of the turbine perimeter footprint.

A distance as defined by lease provisions or 1500 ft, whichever is greater, from all related equipment within the project boundary to the center of the public road.

Property lines: A minimum distance of 2,000 ft or three times the total turbine height, whichever is greater, from the ownership property line, or ownership property island, to the leading edge of the turbine perimeter footprint and where the ownership property line, or ownership property island, is adjacent to the project boundary or within the ownership setback zone.

A distance as defined by lease provisions or 1500 ft, whichever is greater, from all related equipment within the project boundary from any ownership property line, or ownership property island, that is adjacent to the project boundary or within the ownership setback zone.

Waiver: A waiver of this setback distance is allowed for property lines only. It must be requested, and obtained, from any property owner that lies outside the project boundary and whose property is adjacent to the project boundary, an ownership property island, or within the ownership setback zone. All property owners within the same ownership setback zone must agree to the waiver. In no case shall the waiver allow a distance that is less than any lease provisions for other types of setbacks.

SEVERABILITY

If any part of this Order is held to be invalid and/or unenforceable, then the remainder of this Order shall nevertheless remain in full force and effect.

DEFINITIONS

The following definitions apply to this Order and it application.

Blade Throw: A fragment of, or entire, blade that is or can be thrown from a WECU during normal spinning or rotation.

Ice Throw: Accumulated frozen moisture or ice buildup on the rotor and/or blades of a WECU that is or can be thrown during normal spinning or rotation.

Leading Edge: The edge of one boundary that is closest to another entity. For example, the edge of the turbine perimeter footprint that is closest to a public road or ownership property line.

Ownership Property Line: A continuous line surrounding all contiguous adjacent parcels of property owned by a person or persons, company, corporation, partnership or other legal entity.

Ownership Property Island: A parcel, or parcels, of property owned by a person or persons, company, corporation, partnership or other legal entity that is surrounded by a WECS project (but is not part of that project).

Ownership Setback Zone: A parcel, or parcels, of property owned by a person or persons, company, corporation, partnership or other legal entity that is not adjacent to the project boundary, but is adjacent to, or within 2,000 ft of, land that contains a portion of the project boundary.

Project Boundary: A continuous line, which encompasses all property under lease to be used in association with a WECS project; including internal boundaries that represent Ownership Property Islands that are not part of the project.

Property Line: The recognized and described or mapped property parcel boundary line.

Public Road: Any state, federal, or locally (county) maintained road, or designated, maintained, and identified private road, within the boundaries of Clay County, Texas; the surface does not have to be paved.

Related equipment: Transformers, wind test and other towers, electrical conductors, termination points, switches, fences, substations, and any other equipment necessary to operate a WECS.

Setback: The minimum allowable horizontal distance from a given point or line of reference, such as a thoroughfare right-of way, water line, or prospective line to the nearest vertical wall or other element within the project boundary

Total Turbine Height: The distance between the ground at normal grade and the highest point of the installed WECU (being the tip of the blade when the blade is in the full vertical position).

Turbine: A wind driven machine that converts wind energy into electrical power, also known as a wind energy conversion unit.

Turbine Perimeter Footprint: A circle with a radius established as being from the center of the tower to the tip of a blade when the blade is in the horizontal position.

Wind Energy Conversion Unit (WECU): A wind driven machine with an output rating greater than 20 Kilowatts (kw) or with a total height of greater than 125 feet that converts wind energy into electrical power for the primary purpose of sale, resale, or off-site use, and shall include regulated wind test/monitor towers. The WECU includes the tower, turbine, footings, and all equipment associated with individual units including the land area beneath encompassing the equivalent area of the circumference of the rotors.

Wind Energy Conversion System (WECS): All WECUs, related transformers, electrical conductors, substations, and connection points to transmission or distribution lines, and including regulated wind test/monitor towers.

Windmill: A wind-driven machine that does not produce electricity and is under 50 feet in height.

Wind Test/Monitor Tower: The tower on which meteorological equipment is located to measure wind speed, direction, strength, etc., for the purpose of evaluating a potential for WECS site.

Adopted on DATE.

Ayes:
Judge Mike Campbell
Commissioner Richard Lowery
Commissioner Johnny Gee
Commissioner John McGregor
Commissioner Chase Broussard

Remarks – Clay County Commissioner's Court December 9, 2019

Good morning, my name is Ann Smith and I live just outside Bowie, precinct two in Montague County.

I am not here to discuss the merits of wind farms, nor any future reinvestment zone(s) or tax abatements. Some may also question my right to be here, since I don't live in Clay County. Keep in mind, should any of these wind farms get developed, I AM affected as they are targeted to cover parts of BOTH Clay and Montague Counties.

Today, I am focused solely on public safety and I am here to formally present a Public Safety Ordinance for Wind Farms to the Court. I have a package of information for each of you, the cover letter in the package explains the contents.

This ordinance was originally drafted by me. It has since been reviewed, modified, and formatted in a manner consistent with Texas law, by retired Judge Frank Douthitt. Thus, I am confident that it is properly formed and ready to pass by this Court.

The ordinance does the following:

- Creates a setback distance from turbines of 2,000 ft or 3-times the total turbine height (whichever is greater). This distance was, carefully, chosen based on science, rather than some arbitrary number, and is focused on blade, or ice, throw. For your reference, the best of these scientific studies is included in the package.
- It also creates a setback distance from related equipment of 1,500 ft or lease provisions (whichever is greater).

It proposes establishment of these setback distances from:

- Public roads – to protect passing vehicles and their occupants.
- Property lines – to protect people, livestock, and structures on neighboring properties.
- The ordinance includes the ability to request a waiver of this setback distance for property lines only

Note that structures were left out of the ordinance in order to preserve property rights. For example – a property owner, that has signed a lease, has his homestead in the center of several thousand acres. The lease provides for a setback that is less than the 2,000 ft in the ordinance -- the owner has accepted that turbines may be closer to his occupied structure(s) than this ordinance allows. The Commissioner's Court should not pass an ordinance that prevents the property owner from adhering to the lease provisions ON HIS OWN LAND.

The danger to the public is real folks – there are a couple of documents in the package that show this. Briefly:

- As of September 2019 there are 2,559 safety incidents worldwide
- Of these, 882 occurred in the United States. Most of these incidents have occurred since 2010 (a total of 636). Thus, as the presence of turbines increases, so does the hazard to the public.
- More than 10% of these occurred in Texas (83 incidents). Briefly:
    - August 2019, a turbine fire caused the Rhodes Ranch fire in Taylor County
    - August 2018, an out of control turbine puts a family out of their home in Mitchell County
    - February 2018, blade failure caused damage to surrounding structures in Dallas County
    - June 2017, collapse at midpoint of tower for unknown reason in Clay County (interesting to note that a similar collapse occurred, one week prior, in Nebraska of the same turbine model).
    - 2016 (estimated), ice throw caused damage to surrounding structures in Cooke County.

  Additional incidents are outlined in the package.

This ordinance is needed, primarily for two reasons:

1. While setbacks, as defined in this ordinance, are typically put in place during the definition of the reinvestment zone and associated tax abatement, current wind farm companies leasing in Montague County may never approach the Court with a request for such a zone. Thus, they may decide to build without a reinvestment zone or tax abatement.
2. Future wind farm companies may decide to consider development in Montague County; and they, too, could decide to do so without a reinvestment zone or tax abatement.

In conclusion, I urge you to focus on public safety as you discuss this ordinance ... both today, and in the future. If you remain focused on public safety, I am confident that you will see the only reasonable path is to put this ordinance in place. Remember, this is all about public safety, and nothing else.

Wind Farm Safety Order Proposal

Public Safety Ordinance

Presenters: Ann Smith, Tim Hall, Frank Douthitt

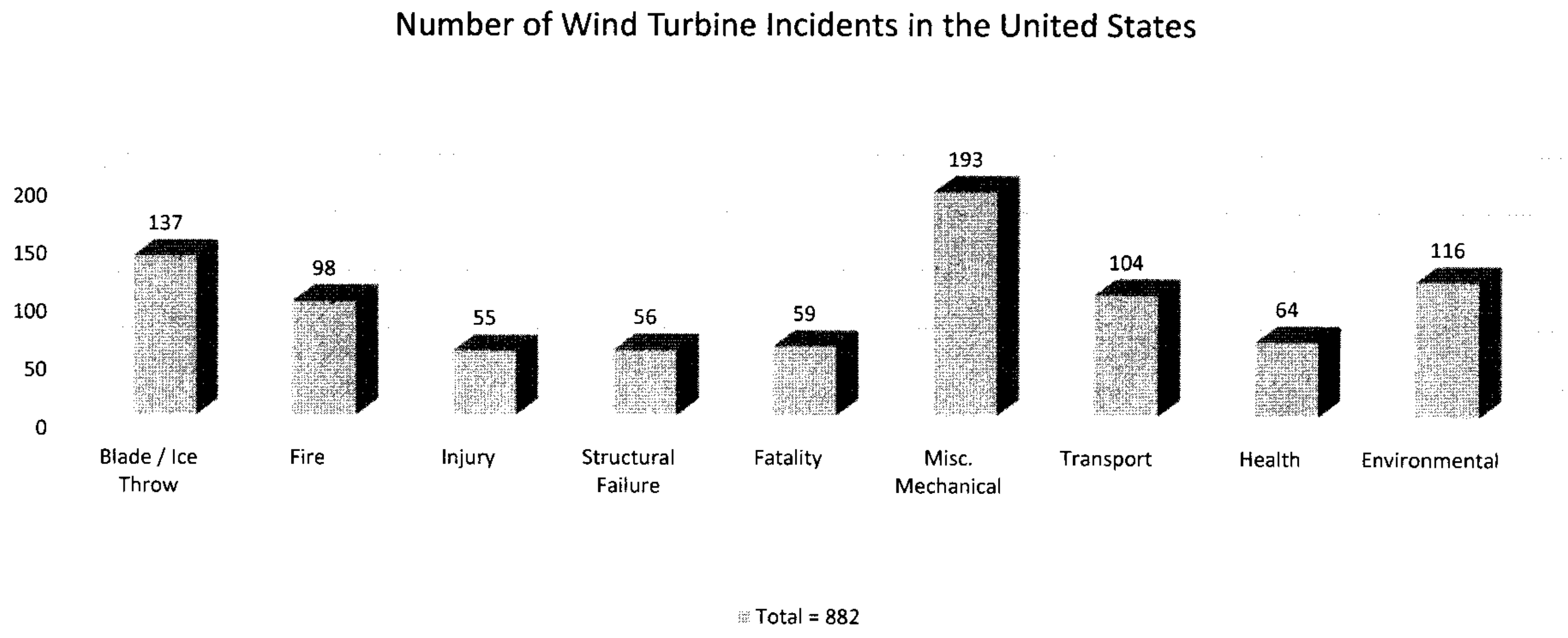
Defining the Setback Distance

- Scientific studies conclude that a distance of 2,000 ft from Wind Turbines is a prudent choice to protect public safety
  - Calculating Wind Turbine Setbacks With Science
    - https://northeastwindmills.com/calculating-wind-turbine-setbacks-with-science-instead-of-politics/
  - A Method for Defining Wind Turbine Setback Standards
    - http://camm.gatech.edu/images/7/7a/Wind_Turbine.pdf
      - Wind turbine setback standards designed to protect people, property and infrastructure from impact by thrown blade fragments play an important role in wind farm planning and can often be a determining factor in the number of turbines that can be placed within a given parcel of land. Given the critical importance of these regulations, there is a desire to develop setback standards based on a physical model of blade throw rather than arbitrary rules of thumb.

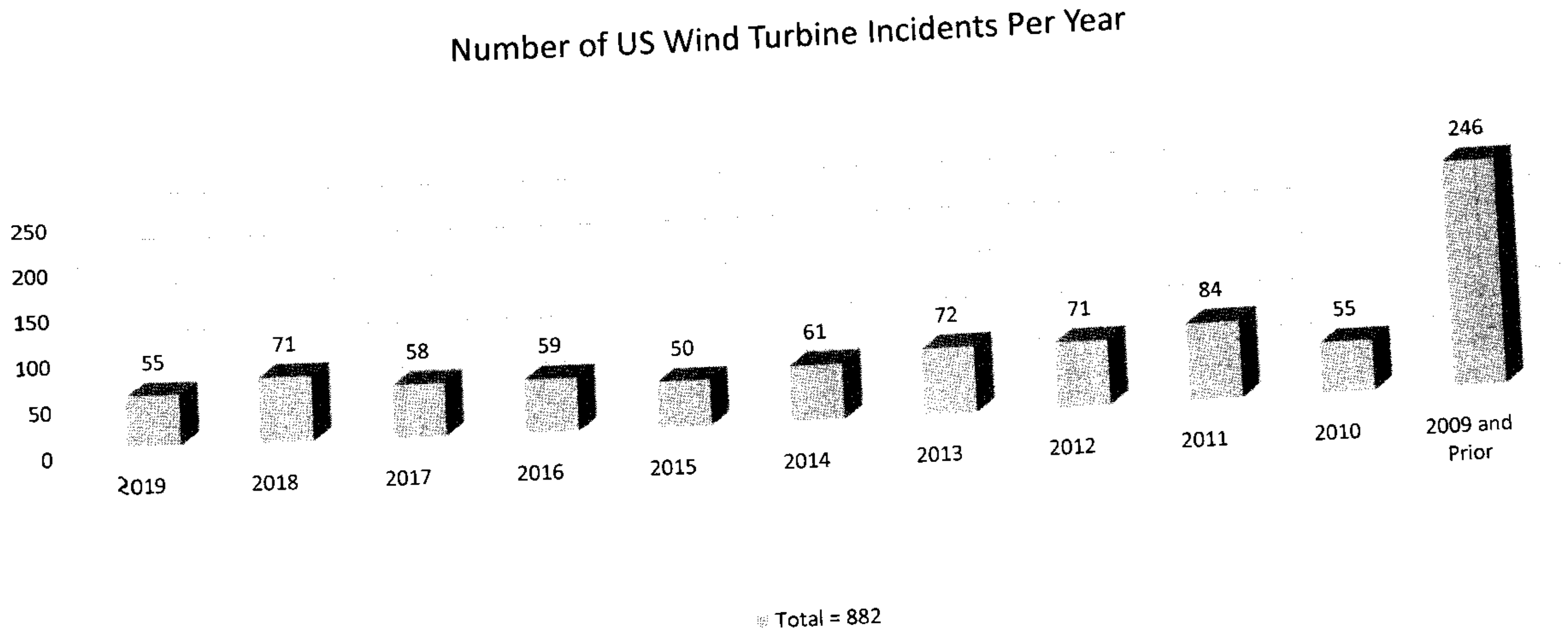
Public Safety – Wind Turbine Incidents World Wide

- Total number of incidents, through September of 2019 = 2559
- Including (but not limited to):
  - 426 blade failures
  - 379 fires
  - 212 structural failures
  - 45 incidents of ice throw
- Above from the following summary document:
  - http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm
- Next pages from the following spreadsheet / table
  - http://www.caithnesswindfarms.co.uk/fullaccidents.pdf

Public Safety – Wind Turbine Incidents in the United States Alone

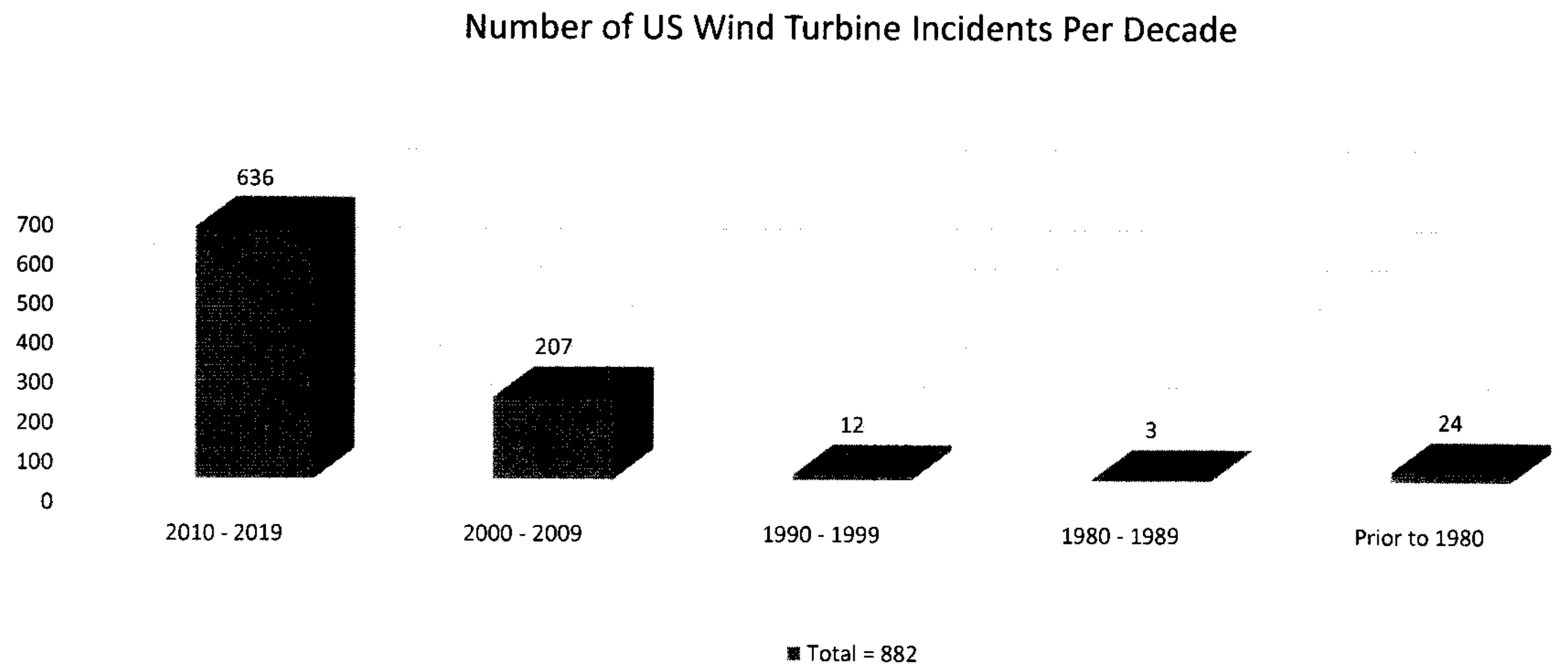


Public Safety – United States Incidents by Year



Number of US Wind Turbine Incidents Per Year

Public Safety – United States Incidents by Decade



Summary of Wind Turbine Accident data to 30 September 2019

These accident statistics are copyright Caithness Windfarm Information Forum 2019. The data may be used or referred to by groups or individuals, provided that the source (Caithness Windfarm Information Forum) is acknowledged and our URL www.caithnesswindfarms.co.uk quoted at the same time. Caithness Windfarm Information Forum is not responsible for the accuracy of Third Party material or references.

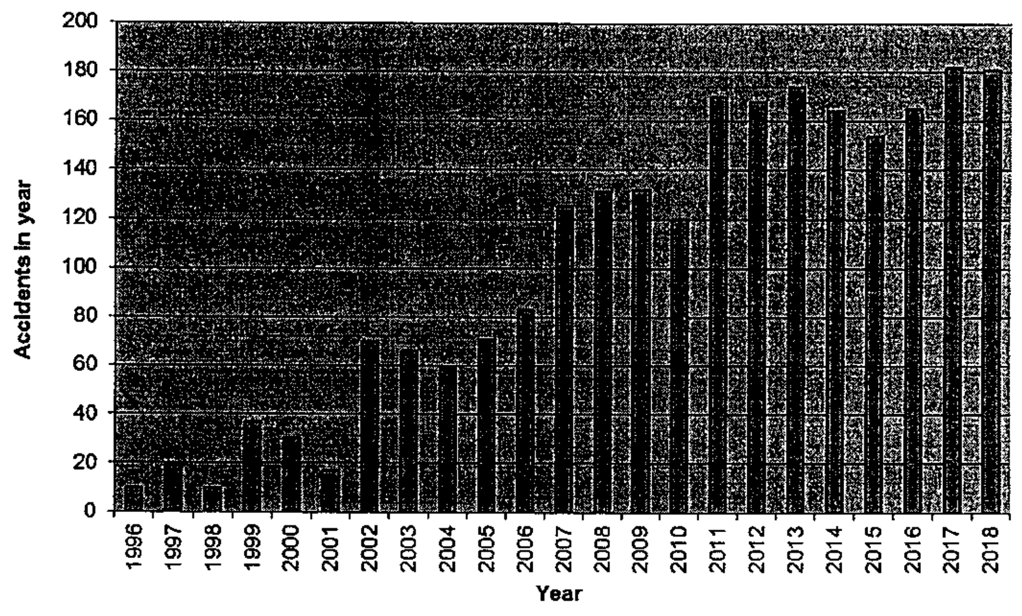
Please do not link to this file or reproduce the tables on your website as they will cease to be current.

The detailed table includes all documented cases of wind turbine related accidents and incidents which could be found and confirmed through press reports or official information releases up to 30 September 2019. CWIF believe that this compendium of accident information may be the most comprehensive available anywhere.

Data in the detailed table is by no means fully comprehensive – CWIF believe that it may only be the "tip of the iceberg" in terms of numbers of accidents and their frequency. Indeed on 11 December 2011 the Daily Telegraph reported that RenewableUK confirmed that there had been 1500 wind turbine accidents and incidents in the UK alone in the previous 5 years. In July 2019 EnergyVoice and the Press and Journal reported a total of 81 cases where workers had been injured on the UK's windfarms since 2014. The CWIF data has only 15 of these (<19%).

Additional evidence that CWIF data only represents the "tip of the iceberg" can be found in the 13 August 2018 publication by Power Technology https://www.power-technology.com/features/golden-hour-paramedics-saving-lives-offshore-windfarms/ The article reports 737 incidents were reported from UK offshore windfarms during 2016 alone, with the majority occurring during operations rather than development. 44% of medical emergencies were turbine related. In comparison, only 4 UK offshore incidents are listed in the CWIF data - equivalent to 0.5%.

The CWIF data does however give an excellent cross-section of the types of accidents which can and do occur, and their consequences. With few exceptions, before about 1997 only data on fatal accidents has been found.



The trend is as expected – as more turbines are built, more accidents occur. Numbers of recorded accidents reflect this, with an average of 44 accidents per year from 1999-2003 inclusive; 95 accidents per year from 2004-2008 inclusive; 156 accidents per year from 2009-2013 inclusive, and 174 accidents per year from 2014-2018 inclusive.

This general trend upward in accident numbers is predicted to continue to escalate unless HSE make some significant changes – in particular to protect the public by declaring a minimum safe distance between new turbine developments and occupied housing and buildings.

In the UK, the HSE do not currently have a database of wind turbine failures on which they can base judgements on the reliability and risk assessments for wind turbines. Please refer to http://www.hse.gov.uk/research/rrpdf/rr968.pdf.

This is because the wind industry "guarantees confidentiality" of incidents reported. No other energy industry works with such secrecy regarding incidents. The wind industry should be no different, and the sooner RenewableUK makes its database available to the HSE and public, the better. The truth is out there, however RenewableUK don't like to admit it.

Some countries are finally accepting that industrial wind turbines can pose a significant public health and safety risk. In June 2014, the report of the Finnish Ministry of Health called for a minimum distance of 2 km from houses by concluding: *"The actors of development of wind energy should understand that no economic or political objective must not prevail over the well being and health of individuals."* In 2016 Bavaria passed legislation requiring a minimum 2km distance between wind turbines and homes, and Ireland are considering a similar measure.

The Scottish government has proposed increasing the separation distance between wind farms and local communities from 2km to 2.5km (http://www.bbc.co.uk/news/uk-scotland-scotland-politics-26579733) though in reality the current 2km separation distance is often shamefully ignored during the planning process.

Our data clearly shows that blade failure is the most common accident with wind turbines, closely followed by fire. This is in agreement with GCube, the largest provider of insurance to renewable energy schemes. In June 2015, the wind industry's own publication "WindPower Monthly" published an article confirming that "Annual blade failures estimated at around 3,800", based on GCube information. A GCube survey in 2013 reported that the most common type of accident is indeed blade failure, and that the two most common causes of accidents are fire and poor maintenance. A further GCube report in November 2015 stated that there are an average 50 wind turbine fires per year, and this remains unchanged in the latest 2018 GCube publication http://www.gcube-insurance.com/reports/towering-inferno/

The 50 fires per year is over double the reported CWIF data below, further underpinning that data presented here may only be "the tip of the iceberg".

The 2018 GCube report also notes the following:

- Wind turbine fires are greatly outnumbered by problems relating to blades and gear boxes;
- Failure of operators to undertake sufficient due diligence through maintenance checks is of increasing concern, and;
- Operating wind farms outwith their design parameters has been noted as a significant contributor to fires.

Data below is presented chronologically. It can be broken down as follows:

Number of accidents

Total number of accidents: 2559

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	109	244	72	83	125	135	132	124	171	174	181	167	160	166	185	194	137

** to 30 September 2019*

Fatal accidents

Number of fatal accidents: 148

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	24	12	4	5	5	11	8	8	15	17	5	3	8	6	9	3	5

** to 30 September 2019*

Please note: **There are more fatalities than accidents as some accidents have caused multiple fatalities.**

Of the 195 fatalities:

- 122 were wind industry and direct support workers (divers, construction, maintenance, engineers, etc), or small turbine owner /operators.
- 73 were public fatalities, including workers not directly dependent on the wind industry (e.g. transport workers). 17 bus passengers were killed in one single incident in Brazil in March 2012; 4 members of the public were killed in an aircraft crash in May 2014 and a further three members of the public killed in a transport accident in September 2014. This includes several suicides from those living close to wind turbines.

Human injury

177 accidents regarding human injury are documented.

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	5	11	6	10	16	18	9	14	12	15	9	9	9	10	13	4	7

** to 30 September 2019*

Please note: **There are more injuries than accidents as some accidents have caused multiple injuries.**

During the 177 accidents, 207 wind industry or construction/maintenance workers were injured, and a further 78 members of the public or workers not directly dependent on the wind industry (e.g. fire fighters, transport workers) were also injured. Eight of these injuries to members of the public were in the UK.

Human health

Since 2012, 163 incidents of wind turbines impacting upon human health are recorded.

By year:

Year	12	13	14	15	16	17	18	*19
No.	6	27	19	13	17	36	28	17

** to 30 September 2019*

Since 2012, human health incidents and adverse impact upon human health have been included. These were previously filed under "miscellaneous" but CWIF believe that they deserve a category of their own. Incidents include reports of ill-heath and effects due to turbine noise, shadow flicker, etc. Such reports are predicted to increase significantly as turbines are increasingly approved and built in unsuitable locations, close to people's homes.

Blade failure

By far the biggest number of incidents found was due to blade failure. "Blade failure" can arise from a number of possible sources, and results in either whole blades or pieces of blade being thrown from the turbine. A total of 426 separate incidences were found:

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	35	53	12	17	23	20	26	20	20	29	36	32	22	21	18	27	15

** to 30 September 2019*

Pieces of blade are documented as travelling up to one mile. In Germany, blade pieces have gone through the roofs and walls of nearby buildings. This is why CWIF believe that there should be a minimum distance of at least 2km between turbines and occupied housing, in order to adequately address public safety and other issues including noise and shadow flicker.

Fire

Fire is the second most common accident cause in incidents found. Fire can arise from a number of sources – and some turbine types seem more prone to fire than others. A total of 379 fire incidents were found:

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	7	63	14	12	21	17	18	16	22	23	26	19	21	28	25	27	20

** to 30 September 2019*

The biggest problem with turbine fires is that, because of the turbine height, the fire brigade can do little but watch it burn itself out. While this may be acceptable in reasonably still conditions, in a storm it means burning debris being scattered over a wide area, with obvious consequences. In dry weather there is obviously a wider-area fire risk, especially for those constructed in or close to forest areas and/or close to housing. Five fire accidents have badly burned wind industry workers.

Structural failure

From the data obtained, this is the third most common accident cause, with 212 instances found. "Structural failure" is assumed to be major component failure under conditions which components should be designed to withstand. This mainly concerns storm damage to turbines and tower collapse. However, poor quality control, lack of maintenance and component failure can also be responsible.

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	15	32	7	9	13	9	16	9	13	10	15	13	12	11	14	9	5

** to 30 September 2019*

While structural failure is far more damaging (and more expensive) than blade failure, the accident consequences and risks to human health are most likely lower, as risks are confined to within a relatively short distance from the turbine. However, as smaller turbines are now being placed on and around buildings including schools, the accident frequency is expected to rise.

Ice throw

45 reports of ice throw were found. Some are multiple incidents. These are listed here unless they have caused human injury, in which case they are included under "human injury" above.

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	9	8	4	3	0	3	4	1	1	1	0	1	1	3	1	2	3

** to 30 September 2019*

Ice throw has been reported to 140m. Some Canadian turbine sites have warning signs posted asking people to stay at least 305m from turbines during icy conditions.

These are indeed only a very small fraction of actual incidences – a report* published in 2003 reported 880 icing events between 1990 and 2003 in Germany alone. 33% of these were in the lowlands and on the coastline.

** ('A Statistical Evaluation of Icing Failures in Germany's '250 MW Wind' Programme – Update 2003, M Durstwitz, BOREAS VI 9-11 April 2003 Pyhätunturi, Finland.)*

Additionally one report listed for 2005 includes 94 separate incidences of ice throw and two reports from 2006 include a further 27 such incidences. The 2014 entry refers to multiple YouTube videos and confirmation that ice sensors do not work.

Transport

There have been 222 reported accidents – including a 45m turbine section ramming through a house while being transported, a transporter knocking a utility pole through a restaurant, and various turbine parts falling off and blocking major highways. Transport fatalities and human injuries are included separately. Most accidents involve turbine sections falling from transporters, though turbine sections have also been lost at sea, along with a £50M barge. Transport is the single biggest cause of public fatalities and injuries.

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.		7	6	6	19	12	11	11	24	17	14	17	14	16	19	14	15

** to 30 September 2019*

Environmental damage (including bird deaths)

263 cases of environmental damage have been reported – the majority since 2007. This is perhaps due to a change in legislation or new reporting requirement. All involved damage to the site itself, or reported damage to or death of wildlife. 87 instances reported here include confirmed deaths of protected species of bird. Deaths, however, are known to be far higher. At the Altamont Pass windfarm alone, 2400 protected golden eagles have been killed in 20 years, and about 10,000 protected raptors (Dr Smallwood, 2004). In Germany, 32 protected white tailed eagles were found dead, killed by wind turbines (Brandenburg State records). In Australia, 22 critically endangered Tasmanian eagles were killed by a single windfarm (Woolnorth). Further detailed information can be found at: www.iberica2000.org/Es/Articulo.asp?Id=3071

600,000 bats were estimated to be killed by US wind turbines in 2012 alone. 1.4 million bird fatalities per annum are estimated if the US reaches it's 20% target for wind generation.

1,500 birds are estimated to be killed per year by the MacArthur wind farm in Australia, 500 of which are raptors.

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	1	11	7	5	10	21	13	20	20	20	16	21	18	22	16	24	18

** to 30 September 2019*

Other (miscellaneous)

524 miscellaneous accidents are also present in the data. Component or mechanical failure has been reported here if there has been no consequential structural damage. Also included are lack of maintenance, electrical failure (not led to fire or electrocution), etc. Construction and construction support accidents are also included, also lightning strikes when a strike has not resulted in blade damage or fire. A separate 1996 report** quotes 393 reports of lightning strikes from 1992 to 1995 in Germany alone, 124 of those direct to the turbine, the rest are to electrical distribution network.

*** (Data from WMEP database: taken from report "External Conditions for Wind Turbine Operation – Results from the German '250 MW Wind' Programme", M Durstewitz, et al, European Union Wind Energy Conference, Goeteborg, May 20-24, 1996)*

By year:

Year	Before 2000	2000-2004	05	06	07	08	09	10	11	12	13	14	15	16	17	18	*19
No.	13	47	12	16	18	24	27	25	43	36	33	33	42	32	34	56	32

** to 30 September 2019*

Caithness Windfarm Information Forum
30 September 2019

WIND ENERGY
Wind Energ. (2011)

RESEARCH ARTICLE

A method for defining wind turbine setback standards

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ABSTRACT

Setback distances established by regulatory authorities to minimize the probability of blade fragment impact with roads, structures and infrastructure can often have a significant impact on wind farm development. However, these minimum distance requirements typically rely on arbitrary rules of thumb and are not based on a physical or probabilistic analysis of blade throw. The work reported here uses a probabilistic approach to evaluate the effectiveness of current standards and to propose a new technique for determining setback distances. This is accomplished through the use of a dynamic model of wind turbine blade failure coupled with Monte Carlo simulation techniques applied to three different wind turbines. It is first shown that common setback standards based on turbine height and blade radius provide inconsistent and inadequate protection against blade throw. Then, using a simplified dynamic analysis of a thrown blade fragment, it is shown that the release velocity of the blade fragment is the critical factor in determining the maximum distance fragments are likely to travel. The importance of release velocity is further verified through simulation results. Finally, a new method for developing setback standards is proposed based on an acceptable level of risk. Given specific wind turbine operational parameters and a set of failure probabilities, the new method leverages realistic blade throw modeling to produce setback standards with a valid physical foundation. Copyright © 2011 John Wiley & Sons, Ltd.

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NOMENCLATURE

h	height of turbine rotor hub
I	blade fragment moment of inertia matrix about mass center expressed in blade-fixed frame
$\vec{I}_B, \vec{J}_B, \vec{K}_B$	unit vectors in frame B
L, M, N	total external moment exerted on blade fragment about mass center expressed in blade-fixed frame
l	distance from rotor hub to nacelle vertical axis of rotation
m	mass of blade fragment
q_0, q_1, q_2, q_3	quaternion orientation parameters of the blade fragment
p, q, r	angular velocity components of the blade fragment expressed in the blade-fixed reference frame
R	rotor radius
r_{CG}	distance from blade root to blade
T_{IB}	transformation matrix from blade-fixed reference frame to inertial reference frame
u, v, w	translational velocity components of the blade fragment mass center expressed in the blade-fixed frame
x, y, z	position coordinates of the blade fragment mass center expressed in the inertial frame
X, Y, Z	total external force exerted on blade fragment
θ	rotor plane cant angle
ψ	rotor plane azimuthal angle
φ	rotor blade roll angle
Ω	rotor rotational speed

1. INTRODUCTION

Increasing demand for wind energy production has led to unprecedented wind farm development over the past decade. State and local regulations specifying required setback distances between wind turbines and property lines, roads and other infrastructure can have a significant impact on the number of turbines that can be installed on a given site. These setback standards are intended to protect people and property from rotor blade fragments released from failed wind turbine blades. However, required setbacks are often based on rules of thumb involving some combination of turbine height and blade radius and typically have little or no rigorous physical foundation. There is currently a strong demand for re-evaluation of turbine setback distances in view of both increased turbine reliability and the desire to install more large turbines on small parcels of land. Specifically, it would be desirable to provide a technique that allows regulators and wind farm developers to determine setback requirements given a specific turbine model, the site parameters and an acceptable level of risk. This new methodology would provide developers, regulators and insurers with a setback corresponding to a specific risk level that is generated through probabilistic dynamic modeling techniques rather than arbitrary rules of thumb.

Several investigators have studied blade fragment release from a failed wind turbine blade, beginning with Eggwertz *et al.*[1] The authors used a point-mass dynamic model to show that the probability of blade impact with the ground beyond 1.8 times the overall turbine height was low. Similarly, Macqueen *et al.*[2] demonstrated through the use of a point-mass model that a person being struck by a blade fragment at a distance greater than 220 m from the turbine base was extremely unlikely. Turner,[3] also employing a point-mass model, used Monte Carlo simulation techniques to construct a statistical distribution of blade fragment impact. Eggers *et al.*[4] likewise exercised a point-mass model for blade fragments using Monte Carlo methods and obtained results similar to that of Macqueen *et al.*[2] The first investigation of fragment throw using full six-degree-of-freedom modeling was performed by Montgomerie,[5] who reported very high maximum distances. Sørensen[6,7] also analysed full rigid body motion of the blade fragment and reported how maximum throw distance varied as a function of aerodynamic characteristics, fragment center of gravity location, pitch angle and wind velocity. Turner[8] provided a similar rigid body analysis and obtained results similar to those of Sørensen.[6,7] Finally, Slegers *et al.*[9] investigated blade fragment impact with power transmission lines. It was shown that transmission line impact probability is a strong function of line distance from the turbine as well as orientation of the line with respect to the axis of rotor rotation. Whereas numerous researchers have simulated the blade throw problem to determine expected impact distances, Rademakers and Braam[10] have conducted a statistical analysis of reported blade failures to determine the overall probability of blade failure occurring. Their analysis suggests an overall probability of blade failure of 2.6×10^{-4} per turbine per year, or approximately 1 in 3800. This is a non-trivial probability that further highlights the need for universal and effective setback standards to protect against blade throws.

Despite significant research analysing the physics of blade fragment release and failure probabilities, many previous investigations lack clear guidance in determining safe setback distances. Furthermore, the variety of models and assumptions made by each investigator has led to differing technical conclusions. The result is that technical analyses of blade throw are often ignored and rules of thumb are employed at a local level. In California, for instance, five different counties use a variety of setback standards all based on overall turbine height to ensure the safety of the surrounding buildings, properties and roads.[11]

The work reported here first demonstrates that many setback standards currently in use provide little or no protection against blade fragment throw for several example turbine designs. A six-degree-of-freedom model is used to simulate a failed rotor blade fragment in free flight and is exercised through Monte Carlo simulations to obtain a statistical distribution of blade fragment impact with the ground. It is shown that for all three turbines studied, a significant portion of blade fragments impact outside the distance specified by example setback standards that are currently in use. Then, by using a simplified dynamic model of blade fragment motion, it is shown analytically that blade release velocity plays the largest role in maximum throw distance. This is verified through Monte Carlo simulation results. Finally, a new methodology is proposed to determine setback standards based on turbine physical parameters, failure probabilities and the regulator's acceptable level of risk. This methodology allows the setback developer to mitigate risk using probabilistic dynamic modeling of blade failure, thereby avoiding the use of arbitrary rules of thumb.

2. DYNAMIC MODEL AND SIMULATION METHODOLOGY

2.1. Blade throw dynamic model

An abbreviated version of the dynamic model used to simulate the flight of a released blade fragment is presented here. A full description of the dynamic model can be found in Slegers *et al.*[9] As shown in Figures 1 and 2, three reference frames are employed in the dynamic model of blade motion, namely, the ground-based frame I, the turbine-fixed frame R and the blade-fixed frame B. The blade-fixed reference frame B is oriented such that the $\vec{K}_B$ axis is aligned with the blade spanwise axis. The inertial reference frame is oriented such that $\vec{K}_I$ points straight down and $\vec{I}_I$ lies in a plane formed by

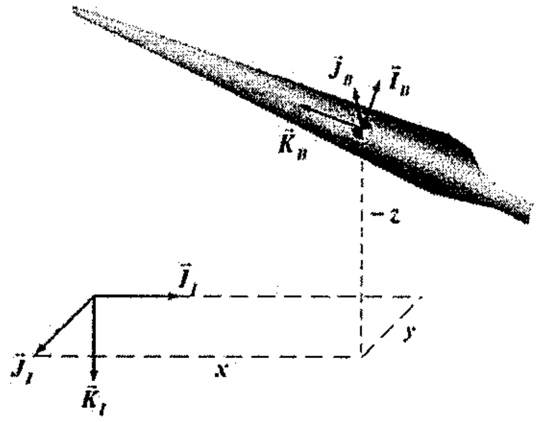

Figure 1. Blade reference frame schematic.

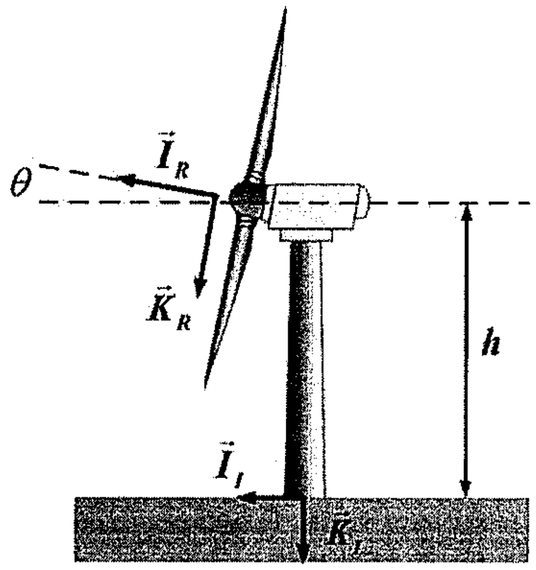

Figure 2. Turbine reference frame schematic.

the rotor hub and the turbine nacelle. The R frame is fixed to the turbine, with $\vec{I}_R$ aligned with the rotor's axis of rotation. Figures 2–4 demonstrate blade geometry including turbine azimuth angle ψ_T, wind azimuth angle ψ_W, hub cant angle θ and blade roll angle φ. As shown in Figure 4, blade roll angle is referenced from the $\vec{K}_R$ axis. Note that within this section, the following shorthand notation with be used for trigonometric functions: $\sin(\alpha) = s_\alpha$, $\cos(\alpha) = c_\alpha$ and $\tan(\alpha) = t_\alpha$.

The dynamic model of the blade fragment in free flight consists of 13 scalar differential equations, given by equations (1)–(4). The states of the system are defined as follows: blade mass center position with respect to the inertial frame (x, y, z), mass center translational velocity resolved in the blade-fixed frame (u, v, w), quaternion rotational parameters describing blade orientation (q_0, q_1, q_2, q_3) and angular velocity components resolved in the blade-fixed frame (p, q, r).

$$\begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{Bmatrix} = [T_{IB}] \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{Bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \begin{Bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{Bmatrix} \tag{2}$$

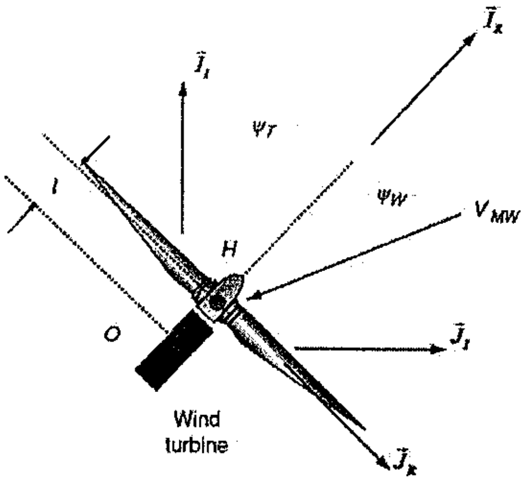

Figure 3. Rotor angle definitions.

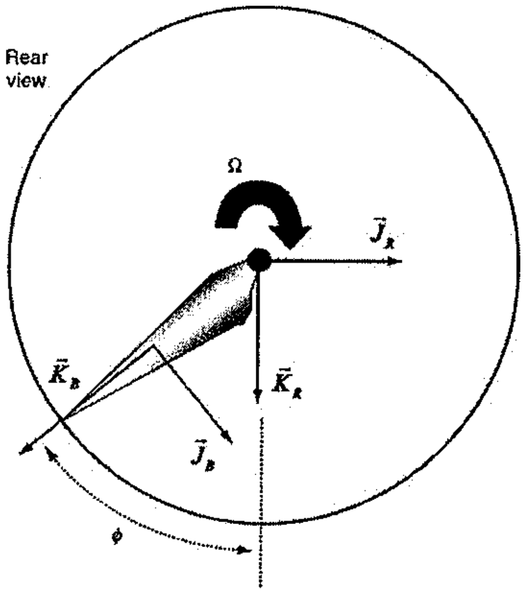

Figure 4. Blade roll angle definition.

$$\begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} = \begin{Bmatrix} X/m \\ Y/m \\ Z/m \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} = [I]^{-1} \left(\begin{Bmatrix} L \\ M \\ N \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} [I] \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \right) \tag{4}$$

Note that in equations (3) and (4), the terms X, Y, Z and L, M, N, respectively, denote the total external force and the moment exerted on the blade in the blade-fixed frame. External force on the blade consists of the sum of aerodynamic and gravity forces, whereas aerodynamic moment is the sole source of moments on the blade. The matrix T_{IB} is the transformation matrix from the blade-fixed to inertial frames, and the matrix I is the moment of inertia matrix of the blade about its mass center with respect to blade-fixed coordinates. Aerodynamic forces were calculated using strip theory by considering the blade as a lifting surface with a general angle of attack. This angle of attack is calculated within the simulation given blade orientation and velocity and subsequently used to generate aerodynamic forces and moments on the blade. Details of aerodynamic forces, moments as well as the weight force are omitted here for brevity; however, a full description is provided in Slegers.[9]

Given a set of blade fragment release conditions, equations (1)–(4) can be integrated numerically forward in time using a Runge–Kutta algorithm until blade fragment mass center impacted with the ground. The simulation architecture, written in FORTRAN, was optimized to run Monte Carlo cases efficiently. Simulation cases were ran in an automated fashion on a computing cluster, allowing thousands of blade throws to be simulated in a reasonable amount of time.

2.2. Monte Carlo simulation description

The dynamic simulation described previously is used to generate a probabilistic analysis of wind turbine setback standards. This is accomplished through the use of tens of thousands of simulations with randomized initial conditions. The Monte Carlo simulation architecture generates initial conditions for each fragment throw by varying six different release parameters in a random fashion. These six parameters are blade roll angle (φ), cant angle (θ), azimuthal angle (ψ), rotor rotational speed (Ω), wind speed and wind angle (ψ_W). Note that all Monte Carlo results are relative to a nominal prevailing wind value, with the assumption that the turbine is nominally facing into the wind. All parameter distributions are assumed to be normal with the exception of roll angle and wind speed. Blade roll angle at release is a uniform random variable between 0 and 360°. Wind speed is varied according to a Rayleigh distribution assuming a median value of 8.5 m s^{-1}. Note that this distribution reflects standard winds expected at an International Electrotechnical Commission Class 2 wind farm installation. Table I describes the statistics associated with each parameter for all cases in Section 3.

Given a randomized set of these six parameters, as well as physical characteristics of the turbine, the initial conditions for all the states of the blade fragment at release were generated. Blade fragment position and velocity at the time of release were determined using

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{Bmatrix} l c_{\psi_T} \\ l s_{\psi_T} \\ -h \end{Bmatrix} + [T_{IB}] \begin{Bmatrix} 0 \\ 0 \\ r_{CG} \end{Bmatrix} \tag{5}$$

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \begin{Bmatrix} 0 \\ -r_{CG}\Omega \\ 0 \end{Bmatrix} \tag{6}$$

where r_{CG} represents the distance from the blade root to the blade center of mass and l is the distance between the rotor hub and the origin. The initial orientation and the angular velocity of the thrown blade fragments were calculated according to

$$q_0 = \cos\left(\frac{\psi_T}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\phi}{2}\right) + \sin\left(\frac{\psi_T}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\phi}{2}\right) \tag{7}$$

$$q_1 = \cos\left(\frac{\psi_T}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\phi}{2}\right) - \sin\left(\frac{\psi_T}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\phi}{2}\right) \tag{8}$$

$$q_2 = \cos\left(\frac{\psi_T}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\phi}{2}\right) + \sin\left(\frac{\psi_T}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\phi}{2}\right) \tag{9}$$

$$q_3 = \sin\left(\frac{\psi_T}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\phi}{2}\right) - \cos\left(\frac{\psi_T}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\phi}{2}\right) \tag{10}$$

Table I. Monte Carlo simulation random parameter statistics.

Parameter	Mean	Standard deviation
Roll angle, φ (degree)	0.0	−180 to 180 (uniform)
Cant angle, θ (degree)	4.0	1.0
Azimuthal angle, ψ_T (degree)	0.0	10.0
Rotor rotational speed (rad s^{-1})	Turbine dependent	0.1
Wind speed (m s^{-1})	Rayleigh distribution, median 8.5 m s^{-1}	N/A
Wind angle ψ_W (degree)	0	3.0

$$\begin{Bmatrix} p \\ q \\ r \end{Bmatrix} = \begin{Bmatrix} \Omega \\ 0 \\ 0 \end{Bmatrix} \tag{11}$$

In Section 3, Monte Carlo simulations are performed for specific turbines using various blade fragment sizes. Because of a lack of statistics regarding the likely size of thrown blade fragments, all fragment sizes were considered. Thus, blade fragment size was varied using outer 20, 40, 60 and 80% and the entire blade throws.

2.3. Simplified point-mass blade fragment analysis

Although a ballistic point-mass analysis, especially one that neglects aerodynamic effects, is highly unsuitable for a detailed dynamic analysis of blade throw, it does provide simplified expressions that can assist in characterizing the most important factors in maximum lateral throw distance (longitudinal throw distance is largely a function of prevailing wind speed and thus cannot be addressed using an analysis that neglects aerodynamics). Because lateral throw distance is often the driving factor in setback development, this simplified analysis can provide rough bounds on expected setbacks for a given set of turbine parameters. Consider the scenario shown in Figure 5 in which a blade fragment at the tip of the blade is thrown at a certain height h_T and velocity v_T. We consider the blade fragment to be a point mass that impacts the ground at a lateral distance D from the turbine base after a time of flight T. Neglecting aerodynamics and considering only two dimensions, two equations of motion are given by

$$h - Rc_{\theta_T} + v_T s_{\theta_T} T - \frac{1}{2} g T^2 = 0 \tag{12}$$

$$D = v_T c_{\theta_T} T \tag{13}$$

where g denotes acceleration because of gravity. Eliminating T, equations (12) and (13) can be combined to yield

$$\frac{gD^2}{v_T^2} = 2\left(h - Rc_{\theta_T}\right)c_{\theta_T}^2 + 2Ds_{\theta_T}c_{\theta_T} \tag{14}$$

Equation (14) is a quadratic function of D. In order to find the angle of maximum throw as a function of h, R and v, one would typically take the derivative of equation (14) with respect to θ_T, set it equal to zero and solve for $\theta_{T_{\mathrm{MAX}}}$ as a function of h, R and v. However, a solution in closed form cannot be found since it is not possible to solve the resulting

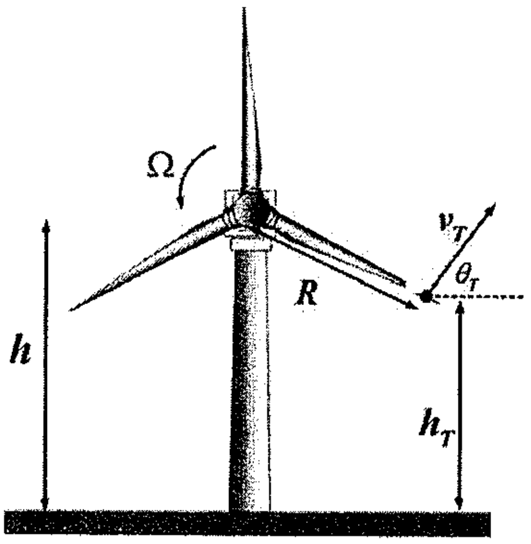

Figure 5. Blade fragment throw diagram.

expression for θ_T. Therefore, determination of the optimum release angle must be found numerically on a turbine-specific basis. Nevertheless, the roots of equation (14) are given by

$$D = \frac{v_T^2 s_{\theta_T} c_{\theta_T} \pm v_T^2 \sqrt{s_{\theta_T}^2 c_{\theta_T}^2 + 2\frac{g}{v_T^2}\left(h - R c_{\theta_T}\right) c_{\theta_T}^2}}{g} \tag{15}$$

In equation (15), it is clear that the range of blade fragment flight is highly dependent on release velocity and release angle and less dependent on turbine height and blade radius. Specifically, lateral distance is a function of the square of the release velocity but only of the square root of turbine height and radius. Although in modern turbines there is some correlation between height, radius and release velocity (since blade fragments at the end of a longer blade travel faster than the fragments at the end of a shorter blade and longer blades are typically found on taller turbines), it is important to note that blade fragment velocity is the real driver behind maximum throw distance. As a result, setback standards based on mass center velocity of the minimum size fragment of concern will yield far more effective protection than a setback distance based on radius or height.

3. RESULTS

3.1. Monte Carlo simulation ground impact results

Monte Carlo simulations were performed for three example turbines of varying sizes, namely, 0.66, 1.5 and 3.0 MW. These turbines cover a range of size and power representative of those installed in typical modern wind farms. Table II lists the physical and operational parameters associated with each turbine.

Five Monte Carlo simulations consisting of 10,000 blade throws each were performed for each turbine, corresponding to the five blade fragment sizes of 20, 40, 60, 80 and 100% as previously outlined. As demonstrated in the Monte Carlo simulation results shown in Slegers,[9] smaller blade fragments consistently fly farther than larger fragments because of higher initial release velocity. Figures 6–11 show ground impact results of each Monte Carlo simulation for the three turbines for the 40% blade throw case. Figures 6, 8 and 10 show specific ground impact points for each turbine, whereas Figures 7, 9 and 11 show histograms of cross-range impact point location. Note that in Figures 6, 8 and 10, the turbine base is located at the origin. Also, note that the wind arrows in Figures 6, 8 and 10 specify the approximate direction of oncoming wind, since the exact direction is randomly distributed for each blade throw case. Although not shown here, plots of ground impacts for larger blade fragments showed a similar dispersion pattern but a smaller range of distances. In addition, histograms for all fragment sizes showed peaks directly below the turbine and slightly behind the turbine, as well as two lateral peaks near the maximum range of blade fragment throw. The peak directly below the turbine represents failures occurring at blade roll angles between approximately 235 and 325°, since these trajectories fly roughly straight down and are unaffected by winds because of the short time of flight. The more scattered distribution behind the turbine is due to fragments released straight upward (approximately between roll angles of 45 and 135°). The relatively long times of flight exhibited by these cases mean that they are more affected by winds.

Table II. Wind turbine physical and operational parameters.

Parameter	660 KW turbine	1.5 MW turbine	3.0 MW turbine
Blade radius (m)	23.5	35.0	45.0
Blade weight (N)	21,287	49,050	64,746
Blade CG from root (m)	11.75	17.5	22.5
Blade I_{XX} (kg m^2)	100,121	511,000	1,115,840
Blade I_{YY} (kg m^2)	99,891	510,000	1,113,830
Blade I_{ZZ} (kg m^2)	282	1233	2175
Rotational speed (rad s^{-1})	2.98	2.3	1.69
Maximum blade chord (m)	2.0	2.1	3.51
Tip blade chord (m)	0.34	0.94	0.45
Root blade pitch (degree)	10.5	10.5	16.6
Tip blade pitch (degree)	−0.5	−0.5	−0.85
Hub height (m)	50.0	80.0	80.0

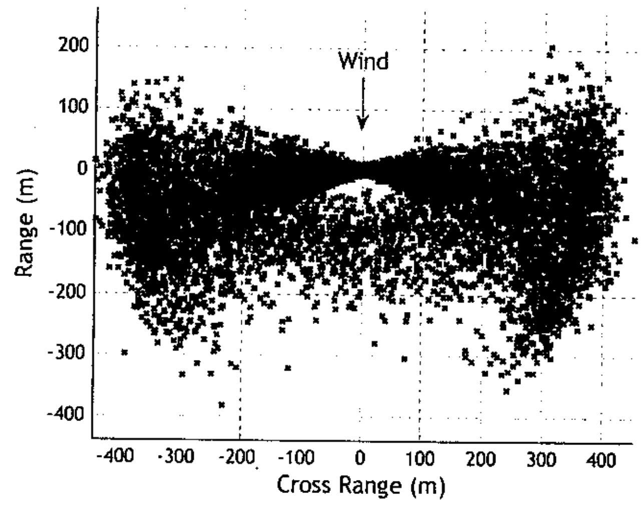

Figure 6. Ground impacts, 0.66 MW turbine, 40% fragment.

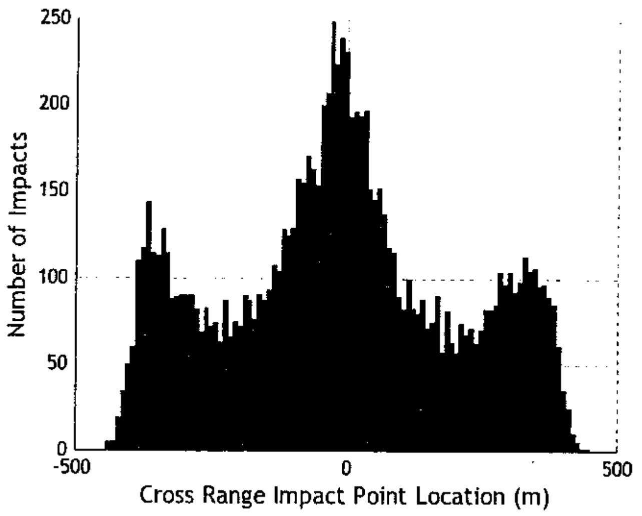

Figure 7. Histogram of cross-range impact location, 0.66 MW turbine, 40% fragment.

3.2. Evaluation of current setback standards

Current setback standards often rely on multiples of tower height, blade radius or both to form the basis for setback distances. To demonstrate the shortcomings typical of standards that rely on these parameters, two example setback distances are evaluated against the Monte Carlo data for three turbines shown in Section 3.1. The first setback originates from the minimum setback distances from the power transmission lines of Southern California Edison (SCE). SCE's Wholesale Generation Interconnection Technical Requirement document[12] states that 'the Producer shall not locate any part of a wind-driven wholesale generating unit ... within three rotor blade diameters of an existing electric utility 220 or 500 kV transmission line right of way or future electric utility 220 or 500 kV transmission line right of way for which SCE may seek regulatory approval of construction.' The second example setback is taken from a report[13] prepared by the State of New York to provide guidance to local communities developing local ordinances governing wind energy. The report proposes the following setback requirement: 'The minimum setback distance between each wind turbine tower and all the surrounding property lines, overhead utility or transmission lines, other wind turbine towers, electrical substations, meteorological towers, public roads and dwellings shall be equal to no less than 1.5 times the sum of proposed structure height plus the rotor radius.' These two setbacks, given by three times the rotor diameter and one and a half times the total turbine height, are representative of many current setback standards and will be evaluated against the three example turbines described earlier.

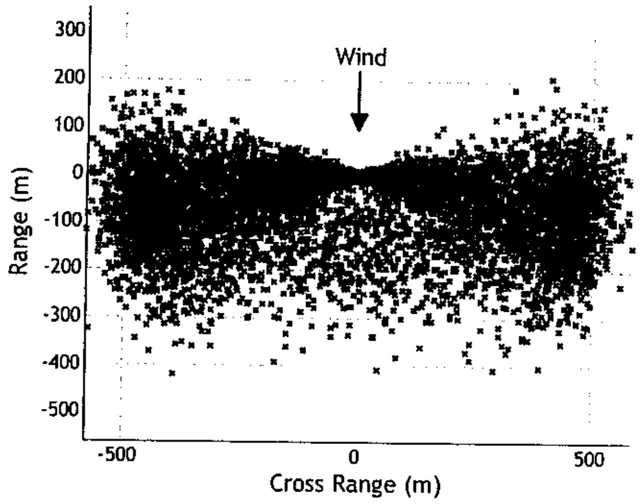

Figure 8. Ground impacts, 1.5 MW turbine, 40% fragment.

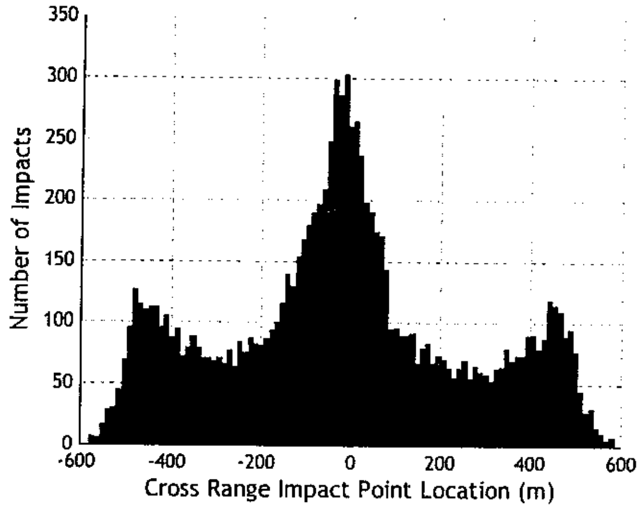

Figure 9. Histogram of cross-range impact location, 1.5 MW turbine, 40% fragment.

In order to evaluate the effectiveness of these example setbacks, circles of varying radius, centered at the turbine base, were considered for each turbine. For each circle, the percentage of blade fragment impacts that landed within this circle was determined. This was repeated for each blade fragment size, and the entire process was performed for each of the three turbines considered. Figures 12–14 show the percentage of impacts within circles of varying radii for each turbine. Also shown are the two example setback standards applied to the specific turbine under consideration.

Several interesting features are apparent in Figures 12–14. First, note that the percentage of impacts that fall within a circle varies somewhat linearly as the radius of the circle grows until greater than 95% of impacts are considered, especially for larger fragments. For smaller fragments at large throw distances, winds tend to have a more significant effect and carry the fragments farther because of longer times of flight, causing the non-linear behavior observed for small fragments at large throw distances. Second, as expected, smaller blade fragments fly farther, and thus, larger circles must be used to contain a given percentage of their impacts. Finally, note that neither of the example setbacks provides protection against a large percentage of blade fragment ground impacts for any of the three turbines. For the 0.66 MW turbine, 60–65% of ground impacts for fragment sizes of 20% fall outside these example setbacks. For the 1.5 and 3.0 MW turbines, 40–50% of ground impacts for 20% blade fragments fall outside these example setbacks. It is important to note that 20% blade fragments are close to 10 m long and can pose a significant hazard.

This analysis of representative setback standards leads to the conclusion that current methods for determining proper setback standards are inadequate. In the cases considered here, setback distances provide little or no reasonable protection

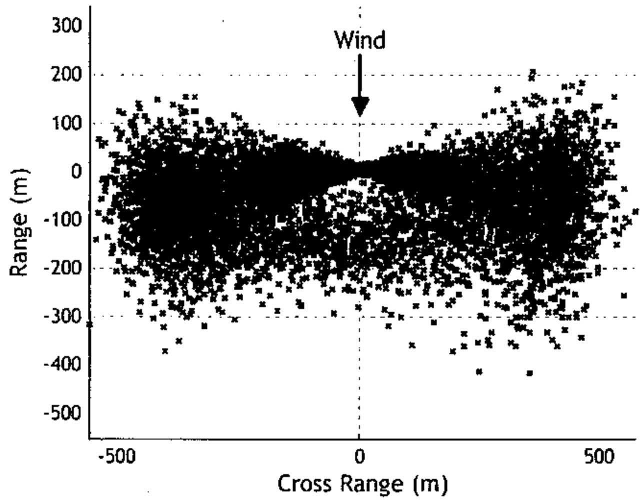

Figure 10. Ground impacts, 3.0 MW turbine, 40% fragment.

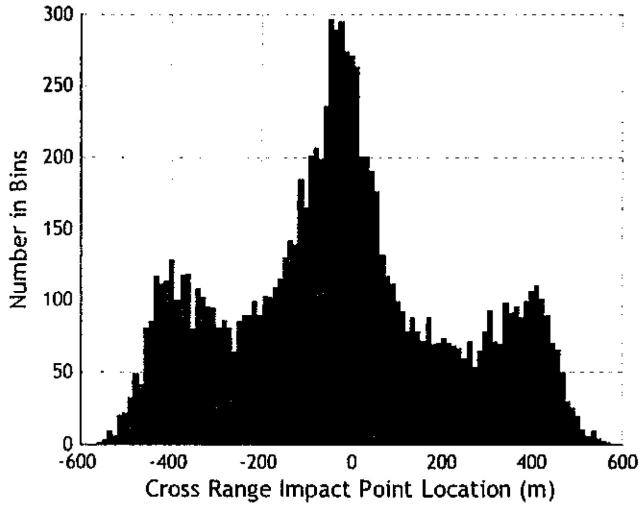

Figure 11. Histogram of cross-range impact location, 3.0 MW turbine, 40% fragment.

against blade fragment impact since there is a significant chance that a thrown blade fragment could impact beyond the setback distance. Even in the case when a setback might provide adequate protection for a specific turbine, the same setback applied to a different turbine could potentially provide no protection at all. Therefore, it would be useful to develop a methodology for determining setbacks that could provide uniform protection for various turbine sizes.

3.3. Normalization by blade fragment mass center velocity

Overlaying percentage-distance traces from Figures 12–14 for each turbine demonstrate how blade fragment throw distance varies for turbines of different size. Figure 15 shows the percentage of blade fragment ground impacts contained within circles of varying radii for 20 and 100% blade throw for each turbine. Note that although the curves have similar shape, they spread out considerably for distances greater than that corresponding to 50% of impacts contained. Furthermore, despite conventional rules of thumb stipulating that maximum throw distance increases with turbine size, Figure 15 demonstrates that the 1.5 MW turbine displays a maximum throw distance of approximately 200 m farther than the 3.0 MW turbine for 20% fragments, even though the 3.0 MW turbine has a larger blade radius and identical rotor hub height.

The fact that the largest throw distance occurs for the 1.5 MW turbine is explained by noting that this turbine has the largest tip velocity of the three examples considered. As described in Section 2.3, blade fragment release velocity is the

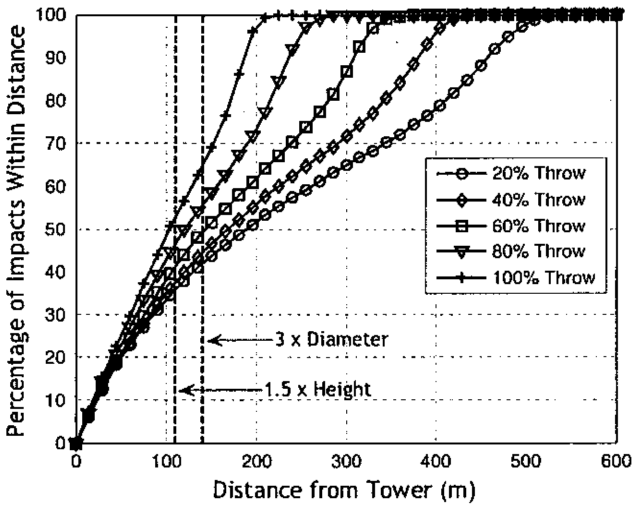

Figure 12. Percentage of impacts within distance versus distance from tower, 0.66 MW turbine.

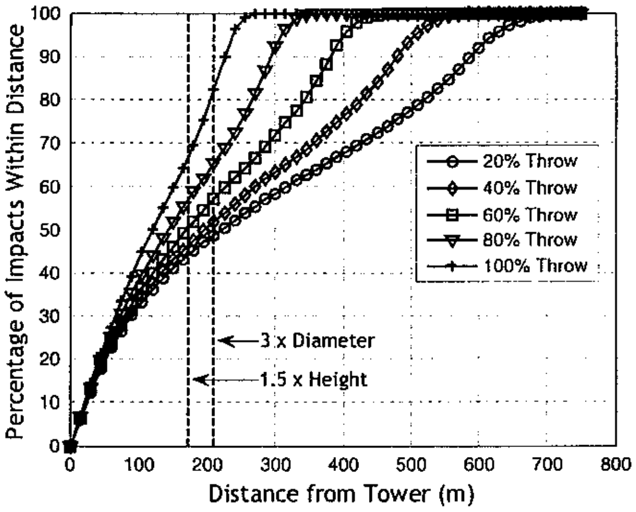

Figure 13. Percentage of impacts within distance versus distance from tower, 1.5 MW turbine.

driving factor in the determination of the maximum lateral throw distance. To verify this, the expression in equation (15) was used to numerically determine the maximum theoretical lateral throw distance of each example turbine for a 20% blade fragment. The results are shown in Table III. The lateral throw distances in Table III are somewhat less than the maximum throw distances determined through Monte Carlo simulation, since the equation does not include the effect of fragments being carried by the wind, which causes significant longitudinal displacement of impacts. However, the estimates in Table III verify that the 1.5 MW turbine should achieve the largest throw distance overall, assuming that blade fragments from all turbines are equally affected by wind after release.

Normalizing throw distance by the velocity of the blade fragment mass center for each fragment size accounts for variations in tip speed for different turbine models. This normalization procedure causes all percentage-distance traces to move significantly closer to one another regardless of fragment size. Figure 16 shows percentage-distance traces normalized by fragment mass center velocity for 20 and 100% blade fragments. Unlike Figure 15, traces are much more uniform, especially for larger fragment sizes which are less affected by winds. Figure 17 generalizes this result to all fragment sizes, showing 15 different percentage-distance traces corresponding to the five different blade fragment sizes varying from 20 to 100% for the three turbines considered. For the most part, the traces are similar and close together. However, as fragment size decreases, wind effects become more pronounced, and fragments are carried farther. This accounts for the slight spreading of the curves near maximum range.

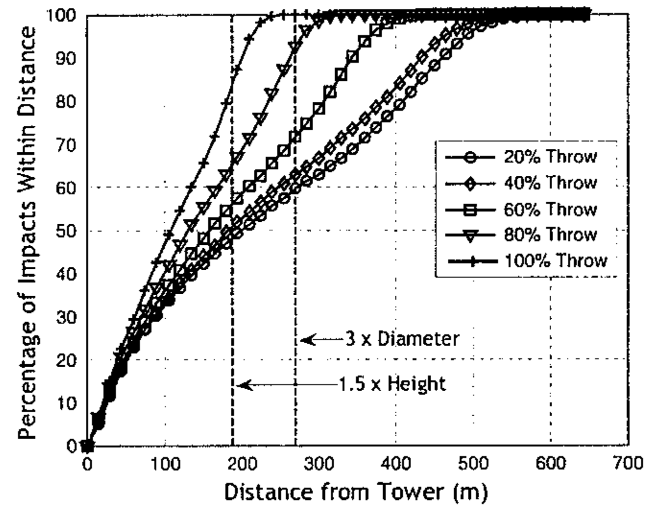

Figure 14. Percentage of impacts within distance versus distance from tower, 3.0 MW turbine.

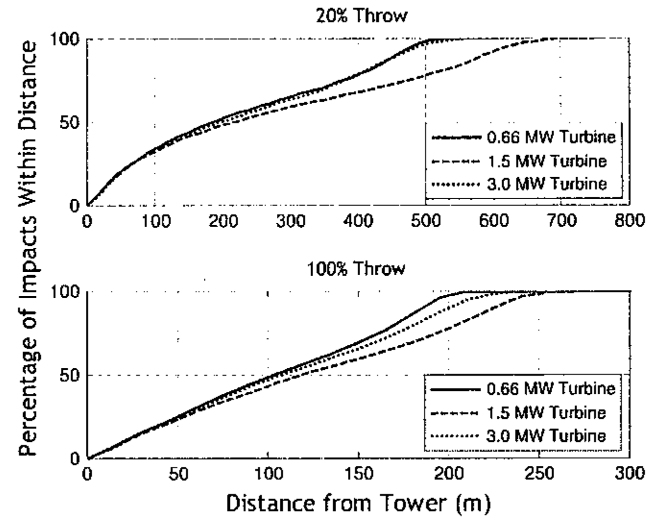

Figure 15. Percentage of impacts within distance versus distance from tower for each turbine.

Table III. Example turbine tip speed and theoretical maximum lateral throw distance of 20% fragment.

Turbine (MW)	Tip speed (rad s^{-1})	Theoretical maximum throw distribution (m)
0.66	70.03	439
1.5	80.50	590
3.0	76.05	526

3.4. Risk-based setback standard development

The normalized percentage-distance curves shown in Figure 17 form the basis for the development of a new turbine setback standard. The relationship shown in Figure 17 can be accurately approximated using a best-fit line. This best-fit line, shown in Figure 18, is given by

$$\text{Percentage of impacts inside distance} = 11.9\,\text{s}^{-1} \times \frac{\text{Distance from tower (m)}}{\text{Fragment CG release velocity (m s}^{-1}\text{)}} \tag{16}$$

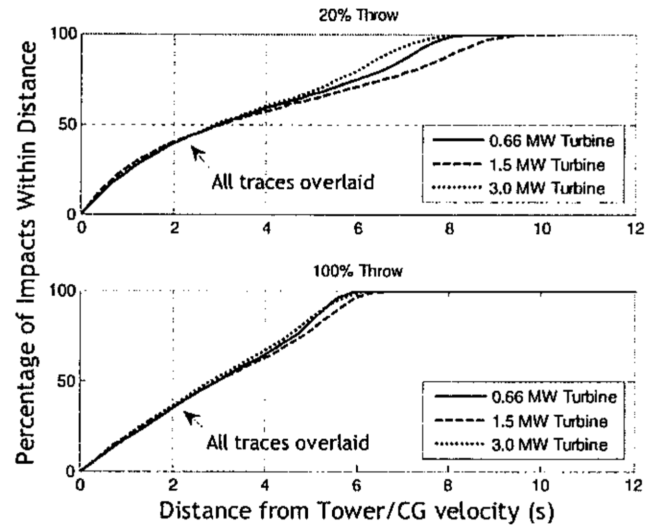

Figure 16. Percentage of impacts within distance versus normalized distance for each turbine.

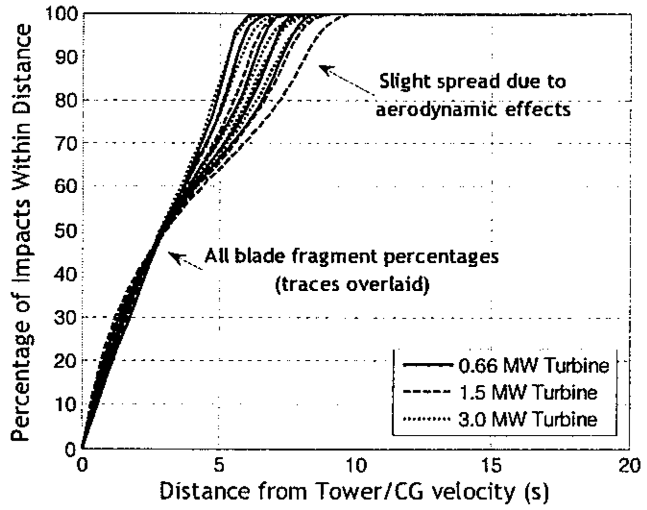

Figure 17. Percentage of impacts within distance versus normalized distance for each turbine, all fragment sizes.

It is clear based on the relationship shown in equation (16) that 99.9% of blade fragment impacts falls within a circle of radius 8.4 times the fragment CG release velocity in meters per second, where the multiplier 8.4 has the unit of seconds. Note that this can be easily computed for a specific turbine and a fragment of a given size.

Equation (16) is a powerful tool that can be used to compute appropriate setback distances for a wide variety of turbine platforms. However, this expression must be used in conjunction with several other parameters in order to produce a meaningful setback. These parameters are the probability that the turbine throws a blade or blade fragment over a given period of time, the minimum size blade fragment of concern, and the desired probability of impact greater than or equal to a certain distance if a blade throw does occur.

The following is an example case demonstrating how equation (16) can be used to determine a risk-based setback. Suppose a regulator or wind farm developer wishes to determine the proper setback distance for a single Vestas 2.0 MW turbine (Vestas Wind Systems A/S, Randers, Denmark) such that in a single year, the probability that a blade fragment will be thrown a distance equal to or beyond the setback is 5.0×10^{-5} (or one occurrence per year for every 20,000 turbines). Further, suppose that the regulator or developer is concerned only with the impact of fragments greater than or equal to 2 m in length. Table IV describes specifications of the Vestas 2.0 MW turbine under consideration here. First, by using the specifications outlined in Table IV, the 2 m blade fragment mass center release velocity is found to be 68.3 m s^{-1},

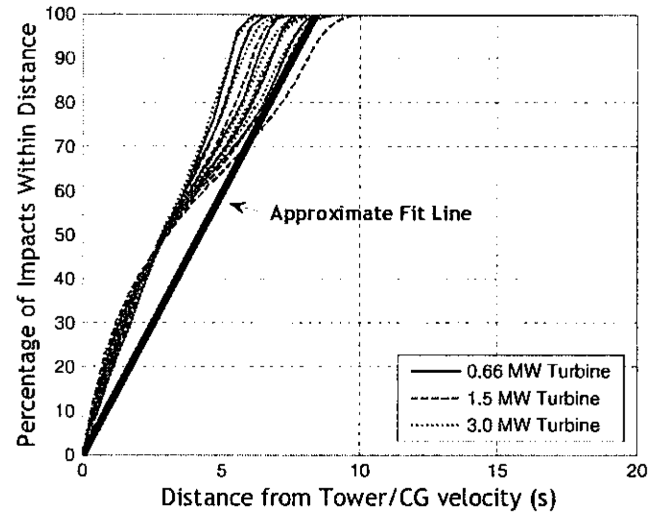

Figure 18. Linear fit to percentage versus distance data.

Table IV. Specifications for Vestas 2.0 MW turbine.

Rotor radius (m)	40
Tower height (m)	67
Rotor rotational speed (rad s^{-1})	1.75

assuming the fragment mass center is located in the middle of the fragment. Second, the probability that given a blade fragment release, the fragment lands outside the setback distance must be computed. This is accomplished by dividing the desired yearly probability that a fragment will fly to or beyond the setback by the probability that a blade failure will occur in a given year. A commonly accepted probability of blade failure per turbine per year, outlined in Rademakers and Braam,[10] is 2.6×10^{-4}. Therefore, the probability that given a fragment release, the fragment will land outside the setback distance must be equal to 0.1923. The percentage of impacts contained within the setback distance from the turbine base, the left-hand-side of equation (9), is given by $100 \times (1-0.1923) = 80.77\%$. Thus, equation (16) can be used to compute the desired setback distance of approximately 463 m. Note that this identical analysis can be universally applied to a variety of modern turbine designs, fragment sizes and accepted risk levels. Also, it should be noted that only the smallest fragment size of concern should be used in the proposed method of setback determination, since in general, the smallest fragments will fly farthest because of higher release velocities at the fragment mass center. Thus, all larger fragments will have a lower probability of impact outside the computed setback distance.

It is important to note that rotor overspeed situations can lead in some cases to blade throw and are not taken into account in the setback development proposed here. However, after extensive study of actual wind turbine blade failures over the course of many years, Rademakers and Braam[10] place the probability of blade failure because of an overspeed situation at 5.0×10^{-6} per turbine per year. This probability is far less than the overall blade fragment release probability of 2.6×10^{-4}, since such incidents would require the failure of multiple safety mechanisms that are becoming increasingly reliable, and thus, rotor overspeed scenarios are not included in the analysis conducted here.

4. CONCLUSION

Wind turbine setback standards designed to protect people, property and infrastructure from impact by thrown blade fragments play an important role in wind farm planning and can often be a determining factor in the number of turbines that can be placed within a given parcel of land. Given the critical importance of these regulations, there is a desire to develop setback standards based on a physical model of blade throw rather than arbitrary rules of thumb. First, a physical model for full or partial blade throw based on rigid body dynamics was described. This model, coupled with Monte Carlo simulation techniques, was used to simulate tens of thousands of blade throws for three example wind turbines of varying size. It was shown that typical current setback standards do not provide adequate protection in most cases. Then, the importance of fragment release velocity in determining maximum throw distance was analytically demonstrated, and its effect verified through analysis of Monte Carlo results. Normalizing throw distance by fragment release velocity yielded a near-linear relationship between this normalized distance and the percentage of impacts that lie within this distance from the turbine. A final example used this relationship to determine a proper setback distance for an example turbine based on an acceptable level of risk. Setback development using this methodology allows regulators to mitigate risk using valid engineering analysis rather than arbitrary rules that provide inconsistent and inadequate protection.

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