# IEC TS 61400-31

Edition 1.0 2023-11

# TECHNICAL SPECIFICATION

colour inside

## Wind energy generation systems –
## Part 31: Siting risk assessment



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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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IEC TS 61400-31 has been prepared by subcommittee PT 61400-31: Wind energy generation systems – Part 31: Siting Risk Assessment, of IEC technical committee 88: Wind energy generation systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

| Draft | Report on voting |
|---|---|
| 88/936/DTS | 88/956/RVDTS |

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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# WIND ENERGY GENERATION SYSTEMS –

## Part 31: Siting risk assessment

## 1 Scope

This part of IEC 61400, which is a Technical Specification, establishes a guideline for the assessment of the risks which a wind turbine may pose to the general public.

Incidents in wind farms causing harm to the general public are very rare events. However, there are requirements to cover this topic in the permitting procedures of several countries. This document aims to facilitate a uniform scope and a uniform use of methods in wind turbine risk assessments.

This document covers harm to the general public. It does not cover occupational exposure, e.g. of personnel involved in the operation and maintenance of the turbine, since occupational risks are usually dealt with in occupational health and safety regulations. The risk of damage to structures or other objects is also not part of this document unless such damage in turn poses a risk to the public.

Harm according to this document can be direct harm or indirect harm via damage to buildings or infrastructure, e.g. gas pipelines, nuclear facilities, dykes, rail infrastructure or roads.

This document covers risk due to internal or external causes, such as technical failures, human errors, extreme wind conditions, turbine icing, lightning strikes, earthquakes, flooding, landslides or fire. However, the specific cause of an incident (e.g. an incident such as a turbine collapse) is irrelevant to the assessment of the consequences. The only relevant factor is the expected probability of occurrence for the incident considered.

In terms of transmission of the hazard to the people affected, this document describes tower collapses, shedding of the nacelle, blade failures, falling or throwing of ice pieces and fire spread.

This document does not cover risks from visual distraction and environmental risk such as noise or shadow flicker.

Wind turbines may pose a hazard to aviation through incidents such as collisions with aircrafts or disturbance of air traffic control radar. These hazards are not covered in this document. In order to mitigate the hazard of aircrafts colliding with wind turbines, aviation lights are installed on wind turbines as covered in IEC 61400-29[1][1].

Risks connected to terrorist attacks and other malicious actions are not covered by this document.



[1] Numbers in square brackets refer to the Bibliography.

This document covers only onshore wind turbines with a horizontal axis and a swept area greater than 200 $m^2$. Substations and other external structures are excluded. Other tall structures associated with a wind farm or wind turbine (e.g. temporary or permanent meteorological masts) also introduce risks related to their possible collapse or failure. Such structures are not covered by this document. Guidance on the risks can be inferred from the reliability classes of the tall structure as determined with reference to EN 1993 Eurocode 3: Design of steel structures [2], including the national annexes where local design requirements are specified.

As to the extent of the harm, this document is limited to the immediate, potentially lethal, physical harm. Non-lethal harm is indirectly covered as described in Clause 6.

This document describes risks during operation of the wind turbine including maintenance, idling and standstill. It does not describe risks during construction, civil works, crane operations, assembly or decommissioning.

Risks according to this document are assessed by prescriptive and/or risk-based methods.

In evaluating risk, the risk is first expressed as a localized risk. Along with the probability of people being present at the location, a risk of lethal harm per year will be used to quantify the risk of harm to people.

This document covers risk reduction measures that might be necessary to reduce risk to a tolerable level.

## 2 Normative references

There are no normative references in this document.

## 3 Terms, definitions and symbols

For the purposes of this document, the following terms, definitions and symbols apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

### 3.1 Terms and definitions

**3.1.1**
**risk**
combination of the probability of occurrence of harm and the severity of that harm

[SOURCE: IEC 60050-903:2013, 903-01-07]

**3.1.2**
**harm**
physical injury or damage to persons, property, and livestock

Note 1 to entry: Harm to property and to livestock is excluded from the scope of this document.

[SOURCE: IEC 60050-903:2013, 903-01-01, modified – addition of Note 1 to entry]

**3.1.3**
**hazard**
potential source of harm

Note 1 to entry: In English, the term "hazard" can be qualified in order to define the origin of the hazard or the nature of the expected harm (e.g. "electric shock hazard", "crushing hazard", "cutting hazard", "toxic hazard", "fire hazard", "drowning hazard").

[SOURCE: IEC 60050-903:2013, 903-01-02, modified – deletion of Notes 2 and 3 to entry]

**3.1.4**
**risk assessment**
overall process comprising a risk analysis and a risk evaluation

[SOURCE: IEC 60050-903:2013, 903-01-10]

**3.1.5**
**quantitative risk assessment (QRA)**
techniques which allow the risk associated with a particular activity to be estimated in absolute quantitative terms rather than in relative terms such as high or low

[SOURCE: ISO/TS 16901:2015, 3.24, modified – deletion of Note 1 to entry]

**3.1.6**
**risk management**
coordinated activities to direct and control an organization with regard to risk

[SOURCE: ISO 31000:2018, 3.2]

**3.1.7**
**risk analysis**
systematic use of available information to identify hazards and to estimate the risk

[SOURCE: IEC 60050-903:2013, 903-01-08]

**3.1.8**
**risk evaluation**
procedure based on the risk analysis to determine whether the tolerable risk has been achieved

[SOURCE: IEC 60050-903:2013, 903-01-09]

**3.1.9**
**risk treatment**
process of selection and implementation of measures to mitigate risk

[SOURCE: ISO 13824:2020, 3.17]

**3.1.10**
**tolerable risk**
risk which is accepted in a given context based on the current values of society

[SOURCE: IEC 60050-903:2013, 903-01-12]

**3.1.11**
**ALARP (as low as reasonably practicable)**
reducing a risk to a level that represents the point, objectively assessed, at which the time, trouble, difficulty, and cost of further reduction becomes unreasonably disproportionate to the additional risk reduction obtained

[SOURCE: ISO/TR 17177:2015]

**3.1.12**
**safe life**
prescribed service life with a declared probability of catastrophic failure

[SOURCE: IEC 60050-415:1999, 415-02-08]

**3.1.13**
**residual risk**
risk remaining after protective measures have been taken

[SOURCE: IEC 60050-903:2013, 903-01-11]

**3.1.14**
**stakeholder**
individual, group or organization that has an interest in an organization or activity

Note 1 to entry: Usually a stakeholder can affect or is affected by the organization or the activity.

[SOURCE: IEC 60050-904:2014, 904-01-10]

**3.1.15**
**risk reduction measure**
**protective measure**
measure intended to achieve adequate risk reduction, implemented:

- by the designer (inherent design, safeguarding and complementary protective measures, information for use) and
- by the user (organization: safe working procedures, supervision, training; permit-to-work systems; provision and use of additional safeguards; use of personal protective equipment)

[SOURCE: IEC 60050-904:2014, 903-01-17, modified – risk reduction measure has been specified as a synonym]

**3.1.16**
**hub height**
height of the centre of the wind turbine rotor above the terrain surface

[SOURCE: IEC 60050-904:2014, 415-05-06, modified – deletion of part of definition referring to vertical axis wind turbines as these are out of scope for this document]

**3.1.17**
**hazard log**
document that records or references the identified hazards, the decisions made, the adopted solutions and the status of implementation

**3.1.18**
**prescriptive approach**
method for controlling risks by prescribing rules reflecting industry experience, engineering judgement, and conservative assumptions

**3.1.19**
**qualitative risk assessment method**
method for assessing risk where experts decide on the acceptability of identified risks based subjective judgement

Note 1 to entry: The outcome of a qualitative risk assessment method is a binary result acceptable/not acceptable.

**3.1.20**
**semi-quantitative risk assessment method**
method for assessing risk that involves a categorization of the likelihood of hazardous events and a categorization of the associated consequences and the assignment of defined risk levels to each combination of these two categories

**3.1.21**
**quantitative risk measures**
standard unit used to express the degree of risk

Note 1 to entry: The risk measures used in quantitative risk assessment relate to 2 objectives:

- The protection of an individual person.
- The protection of a group of people.

**3.1.22**
**individual risk**
risk measure for an individual person calculated for the (usually hypothetical) person with the highest exposure to the hazard

Note 1 to entry: This is an equity-based measure, which starts with the premise that all individuals have unconditional rights to certain levels of protection. This leads to standards, applicable to all, held to be usually acceptable in normal life, or which refer to some other premise held to establish an expectation of protection. In practice, this often converts into fixing a limit to represent the maximum level of risk to which an individual may be exposed. If the risk estimate derived from the risk assessment is above the limit and further control measures cannot be introduced to reduce the risk, the risk is held to be unacceptable whatever the benefits.

The measure is defined for a hypothetical most-critical individual, who is exposed to the risk. This hypothetical person describes an individual, who is in some fixed relation to the hazard and for whom it is assumed, that he/she is most exposed to it. In this way his/her characteristics (time of exposure, place, etc.) make the risk to which she/he is subjected over-arching for each possible realistic individual exposure. By using this approach, it will be guaranteed that each individual person will be protected according to an acceptance framework.

For individual risk, the unit of risk is the loss of life per year.

**3.1.23**
**IRPA (individual risk per annum)**
probability that a specific or hypothetical individual will be killed due to exposure to the hazards or activities during one year

Note 1 to entry: To be able to determine this value, quantitative knowledge is needed about the use of the hazardous area by individuals. In the population that uses the area, a hypothetical individual is defined such that the associated risk is conservative for all individuals in the exposed group. This selected hypothetical person is called the critical individual. When the critical individual is defined as a person who is permanently localized at a given point his IRPA equals the LIRA-value at this location. This can thus be written as

$$\text{IRPA [fatalities yr}^{-1}\text{]} = \text{LIRA [fatalities yr}^{-1}\text{]} \cdot \text{probability of occupancy [-].}$$

**3.1.24**
**LIRA (localized individual risk per annum)**
probability that an average unprotected person, permanently present at a specified location, is killed during one year due to a hazardous event

Note 1 to entry: This value is independent of any specific individual and is defined locally. This probability is defined for the locality in which the exposure is present. Since this value is determined for a specific location, it is possible to draw contours of equal LIRA-values (LIRA-contours) on a map. These LIRA contours are expressed in units of [fatalities $yr^{-1}$ $m^{-2}$].

**3.1.25**
**societal risk**
collective risk measure for a group of people exposed to the hazard

Note 1 to entry: Societal risk reflects the society's point of view. In this perspective, very unlikely hazards with widespread consequence become important. For societal risk, the unit of risk is the loss of life per year. Societal risk is generally expressed by f-N curves

**3.1.26**
**domino effect**
cumulative effect produced when one primary undesired event sequentially or simultaneously triggers one or more secondary undesired events in nearby installations

Note 1 to entry: The domino effect can lead to overall consequences that are much more severe than the consequences of the initial incident. Due to the domino effect, the overall risk of close-by installations can be greater than the combined risk of each of the installations individually. The word domino in this context refers to the triggering of secondary incidents, not to a long chain of subsequent events.

**3.1.27**
**f-N curve**
relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards

Note 1 to entry: An f-N curve plots the annual frequency f of events which cause at least N fatalities against the number N on log-log scales.

**3.1.28**
**ice throw**
ice detaching from the rotor with an initial velocity

Note 1 to entry: The motion of the rotor blade of an operating wind turbine will impart a significant initial velocity to ice pieces shedding from the blade surface. This initial velocity affects the ice pieces' trajectory and their impact position on the ground.

**3.1.29**
**ice fall**
ice detaching from a turbine with no or very little initial velocity

Note 1 to entry: Ice shedding from the rotor blades of a stopped or idling wind turbine will have no or little initial velocity. The ice pieces' trajectories thus result solely from gravity and wind drift.

**3.1.30**
**effect distance**
maximum distance around a wind turbine at which a certain hazard originating from the wind turbine can be expected to have a relevant effect

**3.1.31**
**tip height**
hub height plus half of the rotor diameter



## 3.2 Symbols used in this document

| | | |
|---|---|---|
| $R_m$ | Minimum endogenous mortality (MEM) rate | [$yr^{-1}$] |
| $R_i$ | Maximum allowable additional mortality rate for hazard $i$ | [$yr^{-1}$] |
| $\beta$ | Policy factor for voluntariness and direct benefit | [-] |
| $f$ | Cumulative frequency of $N$ or more fatalities in an f-N plot | [$yr^{-1}$] |
| $N$ | Number of fatalities in an f-N plot | [-] |
| $a$ | Risk version factor; slope in an f-N plot | [-] |
| $k$ | Constant factor in a f-N plot | [$yr^{-1}$] |

| | | |
|---|---|---|
| $P_{\text{death},i}$ | Probability of lethal consequences from hazard $i$ | [yr$^{-1}$] |
| $S_i$ | Survival probability for hazard $I$, $S_i = 1 - P_{death,i}$ | [yr$^{-1}$] |
| $P_{\text{death,tot}}$ | Total probability of lethal consequences from several hazards | [yr$^{-1}$] |
| $m$ | Mass of an ice piece | [kg] |
| $A$ | Frontal area of an ice piece | [m$^2$] |
| $\rho$ | Ice density of an ice piece | [kg m$^{-3}$] |

### 3.3 Abbreviated terms

EMR endogenous mortality rate

MEM minimum endogenous mortality

## 4 Risk assessment process

### 4.1 Overview

A flow chart of the risk assessment, modified from ISO/IEC Guide 51 [3], is illustrated in Figure 1.



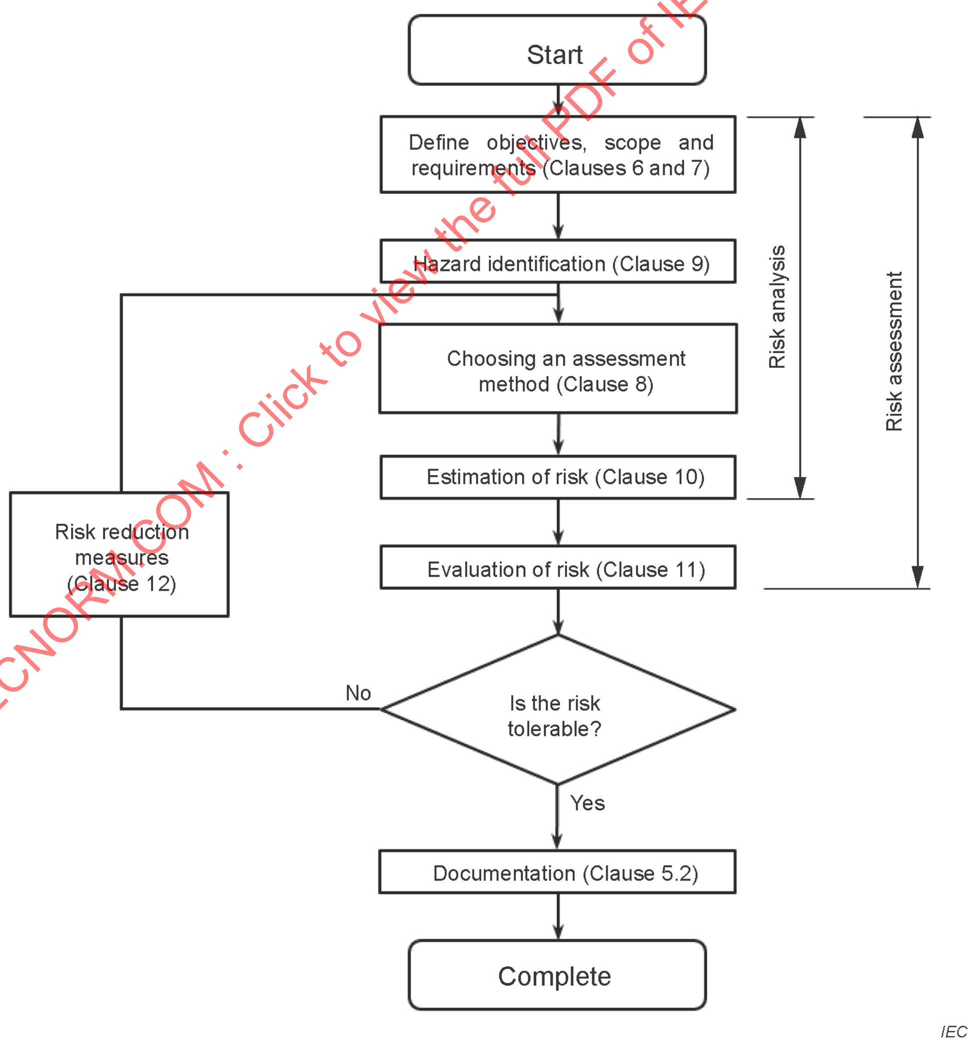


**Figure 1 – Flow chart of the risk assessment process (Modified from ISO/IEC Guide 51 [3])**

Some more details regarding the activities in the risk assessment process are given in Figure 2. In this illustration, motivated by the Norwegian standard NS 5814 [4], the risk assessment process is structured in four main steps.

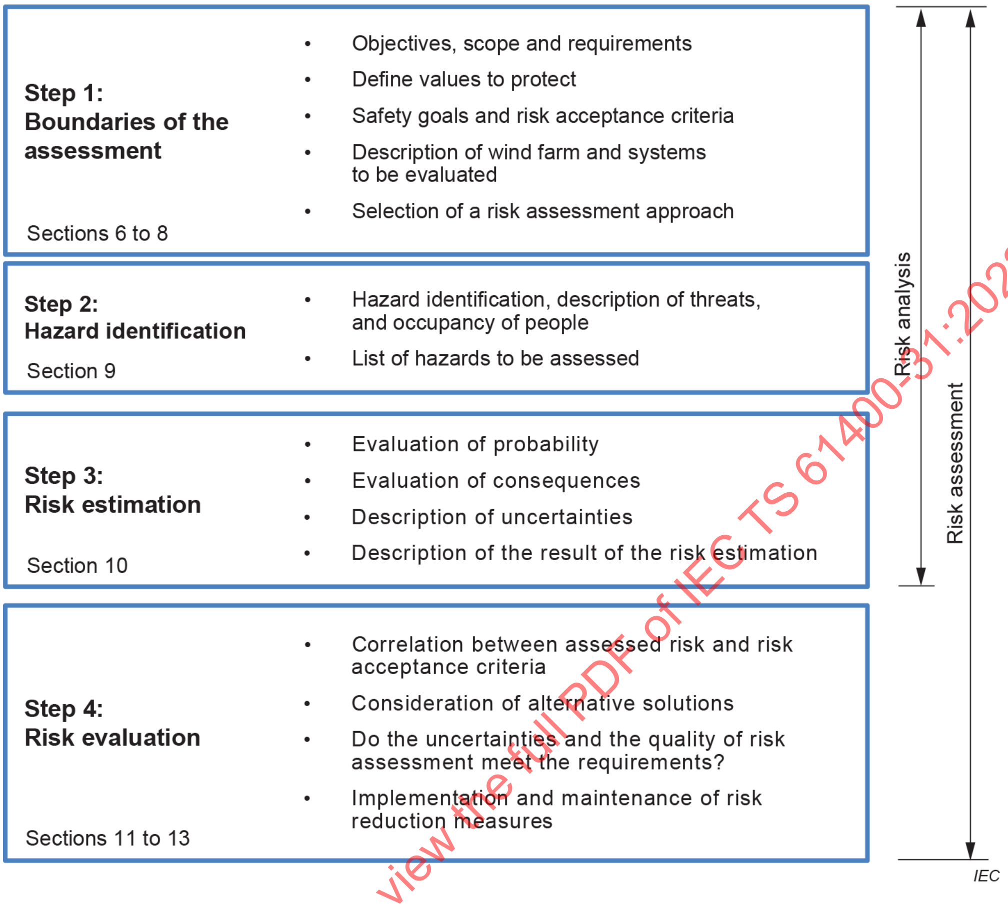


**Figure 2 – The risk assessment process**

## 4.2 Documentation requirements in the risk assessment process

A risk assessment process shall as a minimum cover all four steps as shown in Figure 2. Depending on the results and information obtained throughout the process, it might be necessary to reiterate one or more steps in the risk assessment process until the risk is within acceptable limits.

The result of the risk assessment process shall be documented in a risk assessment report. The report shall at least cover these four steps and make it possible to follow the reasoning in the risk assessment. The choices made in the process shall be accounted for. Any need for further work shall be pointed out.

Any deviations from the requirements in this document shall be described and justified.

If other documents and literature are referenced, these shall be stated.

## 4.3 Involvement of stakeholders

The scope and purpose of the assessment determine the stakeholders that need to be involved in the siting risk assessment. Examples of stakeholders in the risk assessment of a wind farm include developers, investors, original equipment manufacturers, landowners, operators, constructors, neighbors, communities and authorities. This list is non-exhaustive and the relevant stakeholders can be very specific to a particular site.

To perform a siting risk assessment, one should strive to involve all relevant stakeholders in the process of managing risk from a wind farm. The purpose is to ensure that all relevant stakeholders understand the risk and the decisions that are made regarding risk mitigation.

This communication shall support an adequate understanding of all relevant risks and how the risk is mitigated and controlled.

## 5 Risk management throughout service life

### 5.1 Overview

In order to maintain the objectives of the risk assessment during the lifetime of the project, regularly scheduled activities might be needed. Such activities can include upholding of certain risk reduction measures, monitoring for changes regarding the occupation and usage in the environment of the wind farm, and the identification of newly emerging hazardous situations.

Therefore, a risk management process shall be in place throughout the lifetime of the wind farm that at minimum executes the risk management tasks identified in the specific project.

Risk management is the identification, evaluation, prioritization, and treatment of risks (as defined in ISO 31000) followed by coordination of resources to minimize, monitor, and control the probability or impact of unfortunate events. ISO 31000 identifies key risk concepts, roles and responsibilities that should be considered when developing risk management guidelines. For a wind turbine project, the risk management process runs through all of the various project phases:

- Pre-construction, planning and wind farm layout design phase
- Building phase
- Operation phase
- Life extension and upgrading phase
- Decommissioning phase.

The preparation of risk assessments can be a part or a step within a risk management process.

Methods, definitions and goals vary widely according to whether the risk management method is in the context of project management, security, engineering, industrial processes, financial portfolios, actuarial assessments, or public health and safety.

Strategies to manage risks typically include avoiding the risks, reducing the negative consequences or probability of occurrence for a risk, or accepting some or all of the potential or actual consequences of a particular risk. This document covers potentially lethal physical harm to people. Risk transfer to another party (e.g. insurance) is therefore not an option.

### 5.2 Reviewing, documenting and reporting of the risk management process

The risk management process should be reviewed regularly to ensure that the risk management process lives up to its purpose to maintain the risk objectives and to keep up with changing conditions.

The risk management process shall be documented.

Policies and procedures for managing risk shall be updated when operational data, reporting of incidents or near misses at facilities suggest a need for doing so.

A dedicated system, often described as the hazard log, can be used for the documentation and follow-up of hazards and thus form the basis for the on-going risk management process. The log represents a tool to list hazards, how they are handled and followed up. Typical contents of a hazard log are:

- Description of hazard including cause(s), likely consequence, and frequency of occurrence.
- The risks related to the hazard.
- Risk reduction measures implemented or planned to be implemented.
- Date for implementation and responsibility for implementation. This can include regularly scheduled actions.

# 6 Harm to people

## 6.1 Overview

Different wind turbine failure modes, determined by external conditions and factors of influence, can cause immediate potentially lethal injury to people or cause damage to structures, which in consequence can also cause potentially lethal harm to people.

Whether the risk is acceptable shall be determined by a risk assessment based on an evaluation of the risk of death. This document does not cover non-lethal risks and near-misses. Note that injuries are not ignored but are covered in a conservative way as described below.

The most severe harm to a person is death. Because of its overwhelming and irrecoverable impact, the limits for the acceptable risk of death are the most stringent ones. The acceptable limits for lesser harm such as injuries are, by comparison, much higher (see EN 50126-2, Annex A.4 [5]). Thus, even though the probability of occurrence for incidents causing lesser harm will in general be higher than for fatalities, this is more than compensated for by the much higher societally accepted limits for injuries. In the scope of this document, the risk of death is therefore adopted as the relevant variable for risk assessment.

If there are good reasons to assume that a particular case deviates from this general observation, EN 50126-2, Annex A.4 [5] can be used to derive acceptable risk limits for non-lethal harm.

## 6.2 Direct harm

Direct harm is indicated as an immediate effect of a hazardous incident caused by a wind turbine in operating or maintenance mode to one or more people. Direct harm includes all potentially fatal injuries and excludes non-lethal and mental consequences or near misses.

An example of direct harm is a detached blade tip that directly strikes a person who is walking near the wind turbine on a public path.

Direct harm shall be taken into account in the risk assessment.

## 6.3 Indirect harm

Indirect harm refers to incidences where turbine failure, collapse or falling debris cause damage to an enclosure or infrastructure, such as cars, buildings, dykes, nuclear plants, overhead power lines, fuel lines, or fuel storage that then subsequently causes harm to one or several persons. Long-term effects and environmental consequences such as pollution are not in the scope of this document.

An example of indirect harm is a detached blade tip that hits a car on a public road and, while not directly harming the occupants, distracts the driver causing him to veer off the road leading to a traffic accident.

Indirect harm shall be taken into account in the risk assessment, if the indirect harm is potentially lethal.

### 6.4 Domino effect

A domino effect is a scenario in which an incident in a wind farm (e.g. the breakage of a rotor blade) causes the failure of another hazardous installation (e.g. a chemical storage tank) in its vicinity, resulting in a major accident (e.g. the release of hazardous substances). The distinction from indirect harm is that the secondarily affected installation is itself a source of significant hazards. Usually, this hazardous installation will thus be subject to a specific risk assessment. Because of the severe consequences they might cause, domino effect scenarios can be relevant for siting risk assessments, even if they can be classified to have a low probability of occurrence.

When applicable, domino effects shall be taken into account in the risk assessment.

### 6.5 Consequences of impacts of objects

Depending on the hazardous scenario and the bodily injuries under consideration, different criteria can be used to estimate the consequences for unprotected persons from the impact of objects. This includes $u$ (impact velocity), $m \times u$ (momentum of the projectile), $m \times u^2$ (impact energy) and other numerical fitting parameters (for details on types of projectiles, their mass and applicability ranges, see [6] [7]). In many cases the kinetic energy of the fallen or thrown object at the moment of impact will be an appropriate measure to define whether a direct impact has the potential of lethal consequences for a person. The scope of this document is limited to potentially lethal physical harm. Depending on the mass of the projectile, a HSE (Health and Safety Executive) study [8] defines two different kinetic energy thresholds for a high probability of fatality. In the case of smaller, lighter objects, injuries are characterized by penetration or cutting where the object has relatively high velocity. Conversely, larger, heavy objects are more likely to cause blunt trauma injuries causing fatal, internal damage without necessarily significant penetration. The numbers from [8] given below can thus be used for the estimation of the likelihood of lethal consequences from the impact of objects.

- For objects less than or equal to 5 kg mass, the impact energy threshold is 100 J for a 50 % probability of fatality and a person occupying an area of 0,25 $m^2$.
- For objects greater than 5 kg mass, the impact energy threshold is 1 000 J for a 50 % probability of fatality and a person occupying an area of 1 $m^2$.

The numbers given above relate to direct impacts only. Thresholds for indirect impacts and other forms of harm such as poisoning, burning, or crushing shall be determined on a case specific basis. The Dutch document CPR 16E [6] contains a collection of useful methods for the determination of possible harm from many different hazards, including impacts of objects.

Impact energy and impact momentum are also widely used to determine material damages, which are, however, not in the scope of this document.

## 7 Risk assessment approaches and associated acceptance criteria

### 7.1 Risk assessment approaches

During the first step of the risk assessment process (uppermost box in Figure 2) a risk assessment approach shall be chosen.

Risk assessment approaches can either be prescriptive (i.e. rule-based) or risk-based (i.e. based on probabilistic assessment of consequences).

Prescriptive approaches represent industry experience and practices and use conservative rules, engineering judgement, checklists, standards and guidelines. They are relatively quick to execute and economical. Prescriptive approaches lead to a binary result (conform/non-conform) and do not provide a view on the residual risks and are not suited for risk-based decision making.

Risk-based approaches can be separated into:

- Qualitative risk assessment methods: Qualitative risk assessments provide a single point estimate of risk at a site of concern. Qualitative risk analysis is subjective since it makes use of subjective judgement to determine the acceptability of identified risks. They lead to a binary result (judged acceptable/not acceptable) and do not provide a view on the residual risks. As these methods rely on judgement, it is essential that a high level of expertise and experience is available. Therefore, these methods use participative approaches where multi-disciplinary teams of experienced experts employ structured brainstorming techniques based on guidewords of potential safety issues. The applicability of guidewords is assessed as well as the level of acceptability of the related risk. A typical example of such techniques is the HAZID-methodology (see, e.g., [9]).
- Quantitative risk assessment methods: Quantitative risk assessment methods aim to provide a realistic estimate of the risk presented by the facility. Quantitative methods are objective since they make use of statistical data to define the probability (e.g. failures/year) of an event, empirical or theoretical models to calculate the consequences of the event (e.g. number of victims), and quantitative risk measures to calculate the associated risk level. Therefore, these methods need in-depth knowledge of the underlying mechanisms that contribute to the risk such as failure scenarios and their probability distributions, physical models describing the failure dynamics and associated consequences. The assessments follow a well-established methodology and provide a level of residual risk that can be used as a basis for risk decision making. These methods can thus be time consuming which has an associated cost. Clause 9 is dedicated to such quantitative risk assessment methods. Quantitative risk assessment methods are the most precise methods but also the most complex ones.
- Semi-quantitative risk assessment methods: Semi-quantitative methods combine elements of qualitative and quantitative methods and are semi-objective in that way. These methods use categories to estimate both probability and consequences by:
  - Grouping the range of frequency of occurrence of an event in a series of qualitatively defined categories for the frequency of occurrence.
  - Grouping the range of possible consequences of an event in a series of qualitatively defined categories for the severity of the consequences.

    These categories are defined such that personal appraisal to which category an event belongs is possible (e.g.: very improbable to occur, likely to occur during the lifetime of an asset, is unlikely to cause severe harm, is likely to cause a fatality, etc.).

    The combination of a category for the frequency of occurrence and of a category for the severity of the consequences together define a risk level. If for example 5 categories of frequencies and 5 categories of consequences are used, this results in a matrix of 25 risk levels, which then can be assigned to different regions of risk acceptability (e.g. broadly acceptable, tolerable, or unacceptable, see 7.3)

In Figure 3, the different types of risk assessment methods are ordered from left to right with increasing level of fidelity. Figure 3 can be associated with the box labeled "Choosing an assessment method" within the flowchart in Figure 1. In general, a more refined assessment type with acceptable risk levels can supersede a less refined risk assessment with a less favorable risk assessment result. In turn, lower fidelity risk assessment criteria must be set to be conservative so worst-of-worst conditions still yield an acceptable risk level.

More refined methods yield more detailed and accurate results but require more information and a more elaborate analysis.

Risk based approaches shall not be used to deviate from good engineering practice.

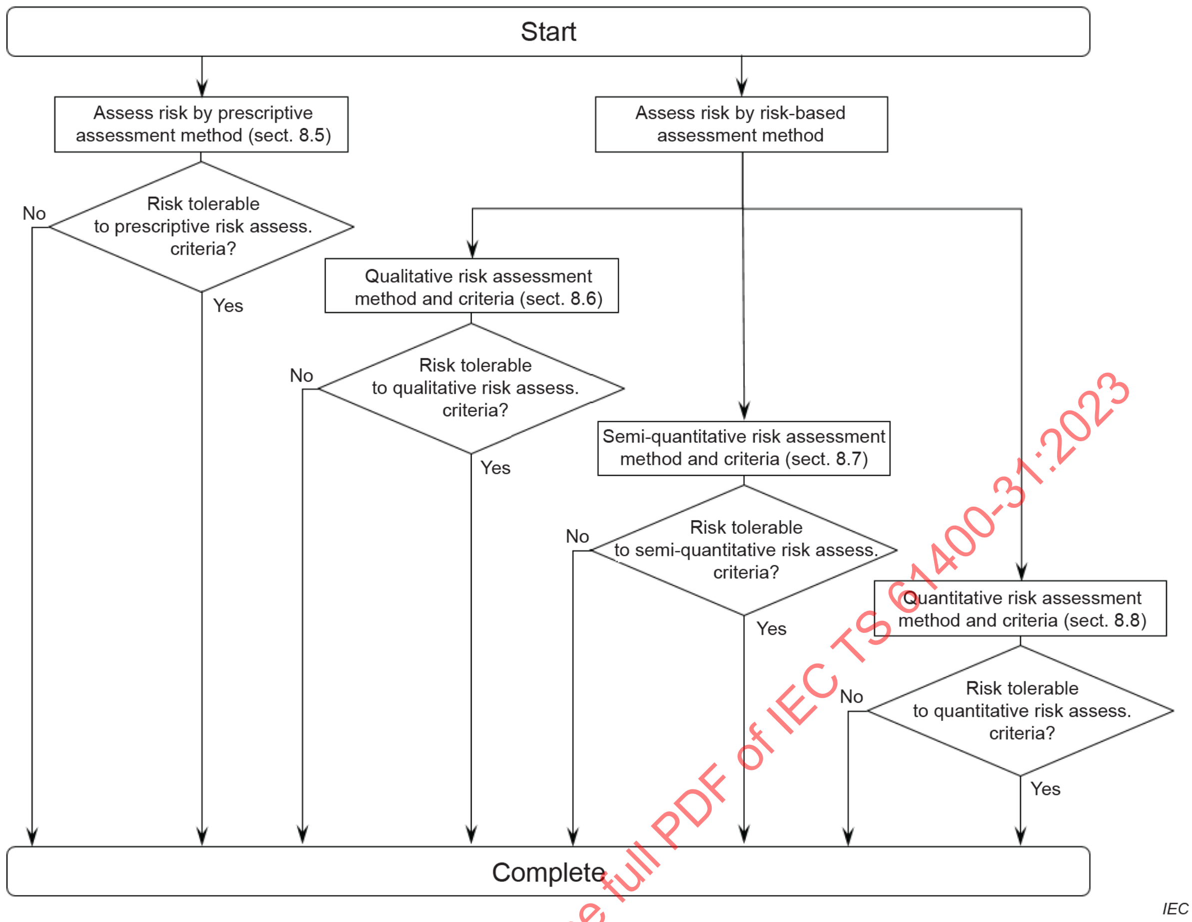


**Figure 3 – Flow chart of the selection of risk assessment methods with different levels of fidelity**



## 7.2 Risk acceptance criteria

No activity is possible without accepting the risk associated with it. Complete avoidance of risk is impossible and everyone has to accept some risks in everyday life. It is thus most important to evaluate the risk associated with certain activities and compare it with what is generally judged acceptable. As illustrated in Figure 2, the definition of risk acceptance criteria is therefore an essential element in the risk assessment process. Risk acceptance criteria allow a comparison of the result of the risk estimation with what is considered as a tolerable risk.

The definition of risk acceptance criteria as part of the risk assessment process shall

- take place during the first step of the process in which the boundaries of the assessment are determined.
- be defined for the purpose of the assessment and in line with the chosen risk assessment approach.
- be based on the inputs of stakeholders that have a responsibility in relation to the acceptance of the residual risk. These stakeholders are:
  - Governmental authorities that by defining national or local regulations take into account the acceptance of risks towards the general public.
  - The operator/owner who is responsible for managing the risk during the operational phase of the asset he operates. This can be based on company risk governance/policies to comply with.

– The supplier of the wind turbine who has a product responsibility in relation to the supplied asset. This can be based on company risk governance/policies to comply with.

  If the input of the different stakeholders gives rise to different acceptance criteria, the most stringent one shall be used.

If the risk acceptance criteria are not defined otherwise, this document offers state of the art guidance for defining risk acceptance criteria that may be used to evaluate the calculated risk levels as obtained from the risk estimation process as described in Clause 9.

NOTE The factors and processes that ultimately decide whether a risk is unacceptable, tolerable or broadly acceptable are dynamic in nature and are sometimes governed by the particular circumstances, time and environment in which the activity giving rise to the risk takes place, etc. For example, standards or public expectations change with time, what is unacceptable in one society or organization may be tolerable in another.

### 7.3 Risk regions

A framework for judging the tolerability of risks should be defined considering:

- A broadly acceptable region.
- A tolerable region.
- An unacceptable region.

As illustrated in Figure 4, these three regions are separated by two boundaries that are defined by two risk level criteria:

- The broadly acceptable level criterion.
- The unacceptable level criterion.

At least two regions shall be defined: an unacceptable region and a (broadly) acceptable region, separated by the unacceptable level criterion.

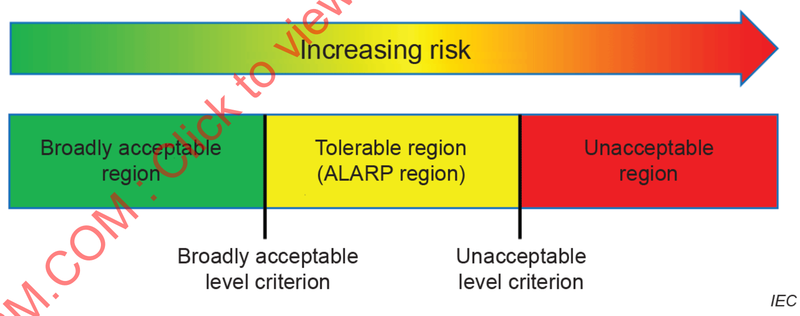


**Figure 4 – Risk regions**

The three regions are defined as follows:

- The unacceptable region: Risks in this region, whatever the level of benefits associated with the activity, will, as a matter of principle, be ruled out, unless there are exceptional reasons for the activity or practice to be retained. Risk reduction measures shall be defined and planned to achieve a lower level of risk.

- The tolerable region: Risks in this region are commonly accepted in a society, in exchange for the many benefits the activity can provide, such as clean energy, creating employment, the maintenance of electrical infrastructure etc. This is based on the presumption that the risks are properly assessed, and the results are used properly to determine control measures and also that the residual risks are not unduly high and kept as low as reasonably practicable (ALARP principle). This risk region is therefore sometimes called the ALARP-region. The ALARP approach involves weighing a risk against the effort, time and money needed to control it. Thus, ALARP describes the level to which we expect to see risks controlled. This is a challenging definition since it requires duty-holders to exercise judgement. In most cases, one can decide by referring to existing 'good practice' that has been established to achieve a consensus about what is ALARP. An ALARP demonstration/justification may be required to demonstrate that risks have been reduced to As Low As Reasonably Practicable.

NOTE An ALARP demonstration is a requirement under national law in some countries.

- The broadly acceptable region: Risks in this region are generally regarded as insignificant and adequately controlled. The levels of risk characterizing this region are comparable or smaller than risks that people regard as insignificant or trivial in their everyday live. In this region, it is not necessary to consider risk reduction measures.

## 7.4 Types of risk criteria

The type of risk acceptance criteria shall be based on the chosen risk assessment approach (see 7.1).

Table 1 gives a brief overview of different kinds of risk assessment criteria in function of the risk assessment approach used (prescriptive, qualitative, semi-quantitative, and quantitative).

**Table 1 – Examples of risk acceptance criteria for different risk assessment approaches**

| Risk assessment approach | | Risk acceptance criteria | |
|---|---|---|---|
| Increased sophistication | 7.5<br>Prescriptive | Observation of minimum standoff distances that can be defined either in absolute units (meters), as a multiplier to turbine dimensions such as total height, or with reference to an assumed, worst-case effect distance for the considered hazard. | |
| | 7.6<br>Qualitative | Qualitative judgement by an expert panel during a participative structured brainstorming (e.g. HAZID-methodology) using guidewords or checklists. | |
| | 7.7<br>Semi-Quantitative | Categorization of likelihood, consequence and risk level (see example in Figure 5). | |
| | 7.8<br>Quantitative | Individual risk, e.g. IRPA or LIRA (see 7.8.2.1) | Risk to Society, e.g. f-N curve (see example in Figure 7) |

## 7.5 Prescriptive risk acceptance criteria

At wind energy sites where ample space is available, the use of prescriptive siting criteria is often considered to be an appropriate and conservative approach for assessing the siting risks of wind turbines. Globally, there are several countries or jurisdictions that provide prescriptive criteria for the siting of wind turbines to ensure the protection of the safety of the public (e.g. United States, Canada, Germany, Denmark and others).

If a prescriptive approach is used, it shall be demonstrated that the associated prescriptive criteria are conservative and that the assumptions used for defining these criteria are valid for the project under consideration.

Prescriptive criteria for wind turbines siting risk can take the form of a set of distance criteria that turbines must be set back from protected objects (e.g. roads, railways, property lines, homes or other buildings). This setback then applies for all hazards and no specific assessment is needed when the criteria are met. Progress in wind turbine technology has led to ever larger and taller turbines. Therefore, fixed setback distance criteria may become outdated or may need to reference the range in turbines that they cover to ensure they are not outdated and continue to align with the risk assessment objectives. Some countries establish setbacks based on fixed multipliers of turbine dimensions, e.g. hub height or total height. These multipliers typically vary depending on the object to be protected.

Another way to define prescriptive criteria is reference to assumed, worst-case effect distances for the considered hazard (e.g. blade failure, ice throw, tower failure, etc.).

Prescriptive setback distances can also involve determining the maximum number of people present within the area.

Examples for prescriptive risk acceptance criteria are:

- No permanent presence of people within a defined distance (e.g. the effect distance for tower failure).
- No property lines or roadways within distance of a multiplier times the total height.
- No storage of dangerous goods within a defined effect distance (e.g. the effect distance for blade failure).
- Maximum number of people allowed to be present within a defined distance.
- No public access to the wind turbine site up to a defined distance in units of the rotor radius.

The use of prescriptive criteria is a one-step or screening level approach that allows for an easy yes/no decision for turbine siting. The risk assessment will be very conservative with the risk level being placed in the broadly acceptable risk region.

However, the use of prescriptive criteria will not be practicable in highly populated or confined areas, since the very conservative approach would unduly restrict the siting options of wind turbines. If the prescriptive criteria are not met or are inapplicable for an individual turbine or project, a more detailed, risk-based assessment method (qualitative, semi-quantitative, quantitative) can be employed to obtain a risk level in the tolerable region or the broadly acceptable region. The result of such a more refined, site-specific, risk assessment method would then supersede the more simplified prescriptive criteria (see 7.1).

### 7.6 Qualitative risk acceptance criteria

In a qualitative risk assessment, subjective, non-quantified expert judgement of the likelihood of a hazardous events and their possible impacts is used to decide on the acceptability of the identified risks. The criteria of risk acceptance thus lies in the collective expertise and experiences assembled in the group of experts that is deciding on the acceptability of the proposed project.

### 7.7 Semi-quantitative risk acceptance criteria

For semi-quantitative risk assessment methods, a level of acceptability of the risk shall be assigned to each combination of the categories for likelihood and consequences. Using, e.g., the three distinct risk regions described in 7.3 (broadly acceptable, tolerable, and unacceptable), such an assignment would lead to a risk matrix as illustrated in Figure 5.

NOTE The categories and the assignment of acceptance levels in Figure 5 are an example only and are not intended by any means to be a recommendation or suggestion for the implementation of a semi-quantitative risk assessment.

| RISK LEVEL CATEGORY | | CATEGORY OF CONSEQUENCES | | | | |
|---|---|---|---|---|---|---|
| | | Class 5 | Class 4 | Class 3 | Class 2 | Class 1 |
| CATEGORY OF LIKELIHOOD | Range 1 | Level 11 | Level 16 | Level 20 | Level 23 | Level 25 |
| | Range 2 | Level 7 | Level 12 | Level 17 | Level 21 | Level 24 |
| | Range 3 | Level 4 | Level 8 | Level 13 | Level 18 | Level 22 |
| | Range 4 | Level 2 | Level 5 | Level 9 | Level 14 | Level 19 |
| | Range 5 | Level 1 | Level 3 | Level 6 | Level 10 | Level 15 |

| CATEGORIES FOR LIKELIHOOD AND CONSEQUENCES | | | |
|---|---|---|---|
| Category of likelihood | Description | Category of consequences | Description |
| Range 1 | Is likely to occur on an annual basis (or more often). | Class 1 | More than 10 fatalities<br>More than 100 people injured or impact on health |
| Range 2 | Is likely to occur several times during service life. | Class 2 | 1-10 fatalities<br>10-99 people injured or impact on health |
| Range 3 | Is likely to occur once during service life. | Class 3 | 2-9 people injured or impact on health |
| Range 4 | Not expected to occur during service life. | Class 4 | 1 person injured or impact on health |
| Range 5 | Extremely unlikely. Never observed in the industry | Class 5 | None or only minor injury or impact on health |

| DEFINED RISK REGIONS | |
|---|---|
| Risk level category | Description |
| Risk region 3 | Situation which is undesirable and must be avoided. Remedial action is required (unacceptable) |
| Risk region 2 | Situation which shall be improved. A level at which it shall be demonstrated that the risk is made As Low As Reasonably Practical (tolerable) |
| Risk region 1 | Broadly acceptable situation that should only be monitored for change |

**Figure 5 – Example tables for a semi-quantitative risk assessment**



## 7.8 Quantitative risk acceptance criteria

### 7.8.1 General

Quantitative risk acceptance criteria are used when quantitative risk estimation methods are employed. These methods quantify risk through the numerical combination of probabilities and consequences of the hazards at hand. The result is one or more quantitative risk values that have a physical meaning and thus can be compared to a criterion that is defined as acceptable from that point of view. Numerous risk quantities and corresponding criteria have been defined throughout industries. The most used quantities and corresponding criteria in the (petro-)chemical industry, which are also used for assessing the risk of wind turbines, are explained in this document.

Quantitative risk assessment methods assess risk to people in two categories:

- Individual risk to a single person (7.8.2)
- Societal risk to a group of people (7.8.3)

When using quantitative risk assessments, both the individual and societal risk acceptance criteria shall be applied and satisfied.

Subclauses 7.8.2 and 7.8.3 give guidance on defining risk measures and associated criteria for both individual risk and societal risk.

### 7.8.2 Quantitative risk criteria for individuals

#### 7.8.2.1 Risk measures for individuals

To quantify the risk for an individual two types of risk measures are commonly used in risk assessments:

| | | |
|---|---|---|
| LIRA | Localized individual risk per annum | [$yr^{-1}$] |
| IRPA | Individual risk per annum | [$yr^{-1}$] |

The LIRA-value is the probability that an average unprotected person, permanently present at a specified location, is killed in a one-year period due to a hazardous event. This value is independent of any specific individual and is defined locally. Since this value is determined for a specific location, it is possible to draw contours of equal LIRA-values (LIRA-contours) on a map. These LIRA contours are expressed in units of [fatalities $yr^{-1}$ $m^{-2}$)].

The IRPA-value is the probability that a specific or hypothetical individual is killed due to exposure to the hazard. To be able to determine this value, quantitative knowledge is needed about the use of the hazardous area by individuals. In the population that uses the area, a hypothetical individual is defined such that the associated risk is conservative for all individuals in the exposed group. This selected hypothetical person is called the critical individual. If the hypothetical individual is defined as a person who is permanently localized at a specific location, his IRPA equals the LIRA-value at this location. This can thus be written as

IRPA [fatalities $yr^{-1}$] = LIRA [fatalities $yr^{-1}$] · probability of occupancy [-].

The LIRA measure for individual risk is very easy to use, since one does not need to consider real exposure and abstraction is made from the way the environment is being used by individuals. Hence, this approach is conservative but in general is considered as a good measure for low probability events related to hazards that are continuously present (such as risk of tower breakage, etc.). For hazards such as ice fall and ice throw, that are only present during a limited timeframe, the LIRA measure can be too conservative to be a useful risk criterion in a siting risk assessment. In this case, the use of the more complex IRPA-measure would be more appropriate.

#### 7.8.2.2 Risk criteria for individuals

Once the value of the risk measure is known, it needs to be compared with a value that is considered as being broadly acceptable/tolerable.

One way to define the acceptability is to compare the value with the Endogenous Mortality Rate (EMR) of an individual. The EMR is the mortality rate focusing only on natural causes of death without any kind of accidents and native malformation influences. In the range between 5 years and 15 years of age for humans, the natural death rate in industrially developed states reaches a minimum for human individuals called the minimum endogenous mortality (MEM) rate. This minimum is defined as $R_m$. EN 50126-2, Annex A.4 [5] gives the following figure for this rate:

$$R_m = 2{,}0 \times 10 - 4 yr^{-1}$$

Based on this value the broadly acceptable level criterion and the unacceptable level criterion can be chosen.

**Broadly acceptable level criterion**

We live in an environment of appreciable risks of various kinds which contribute to a background level of risk – typically a risk of ~0,01 per year averaged over a lifetime. Based on this it is accepted that an individual risk of death of one in a million per annum ($10^{-6}$ $yr^{-1}$) due to hazards related to a technology for the public corresponds to a very low level of risk and could be used as a guideline for the boundary between the broadly acceptable and tolerable regions.

This statement is also very apparent when looking to the MEM value above and other causes of death such as the following examples [8], [10]:

- Smoking $9,00 \times 10^{-3}$ $yr^{-1}$
- Cancer $2,58 \times 10^{-3}$ $yr^{-1}$
- All types of accidents $2,46 \times 10^{-4}$ $yr^{-1}$
- Minimum endogenous mortality (MEM) rate $2,0 \times 10^{-4}$ $yr^{-1}$
- All form of road accidents $5,98 \times 10^{-5}$ $yr^{-1}$
- General air traffic $7,5 \times 10^{-7}$ $yr^{-1}$
- Lightning strikes $1,0 \times 10^{-7}$ $yr^{-1}$



A residual risk of one in a million per year is small when compared to these levels since many of the activities entailing such a low level of residual risk also bring benefits that contribute to lowering the background level of risks. Individual countries or regulatory jurisdictions often establish their own broadly acceptable risk region. This region typically varies from $10^{-4}$ $yr^{-1}$ to $10^{-6}$ $yr^{-1}$. The risk assessor should ensure that the broadly acceptable and tolerable risk region for wind turbine siting align with the country/jurisdiction in which the project is being sited.

It is also possible to assess the risk of a wind farm against the existing risks that are socially accepted at a site prior to the wind farm being build. An example is the socially accepted risk from road traffic on public roads. In that case, the acceptance criterion then shall be that the additional risk from the wind turbines only adds a comparatively insignificant contribution on top of the pre-existing risks. The value 1/100 can be used to determine the allowed additional risk. Note that this criterion refers to locations, and not to individuals with pre-existing risks. Pre-existing, socially accepted risks of individuals (e.g. smoking) must not be used to construe higher permissible risk levels for these individuals.

A possible application could be a risk assessment on a section of a public road: Erection of wind turbines next to the road may cause an additional risk from machine failure for people travelling on the road. This risk is required to be much smaller than the pre-existing risk from road traffic. The total risk, combining traffic accidents and wind turbine incidents, is then essentially unchanged from the previous condition without wind turbines.

If a risk assessment determines a risk to be lower than the broadly acceptable level criterion, the risk assessment needs no further effort to quantify the risk.

**Unacceptable level criterion**

Risks above the broadly acceptable level criterion can still be acceptable, though it needs a more careful investigation. The definition of the unacceptable level criterion is more complicated because elements of voluntariness and direct benefit play a key role in defining what is still acceptable in a particular situation.

Different environmental aspects will play a role in defining the boundary such as: the characteristics of the exposed population (workers, public, children, etc.), the extent to which the exposed population is able to influence and/or accept the risk, and the direct benefit from the wind farm compared to the risks it brings along with it.

A way to define the **unacceptable level criterion** is to assume that the additional overall hazard death rate caused by all technical systems a person is exposed to shall not exceed the minimum endogenous mortality rate $R_m$. If we assume according to EN 50126-2, Annex A.4 [5] that no more than 20 systems impose fatal hazards on a specific group of people at the same time, then the maximum allowable additional rate for a single system should not exceed 5 % of $R_m$.

Based on this, the boundary between tolerable region and unacceptable region would be:

$$R_i < 0{,}05 \cdot R_m = 0{,}05 \cdot 2{,}0 \cdot 10^{-4}\ \text{yr}^{-1} = 10^{-5}\ \text{yr}^{-1}$$

This value does not consider the benefit that the risk presents or the voluntariness of an individual. This is the case when persons are exposed to the risk during their work. In this case the acceptance limit can be multiplied by a certain factor known as the policy factor $\beta$ which depends on the voluntariness and direct benefit.

$$R_i < \beta \cdot 10^{-4}\ \text{yr}^{-1}$$

Some considerations about this policy factor according to [11] are given in Table 2:

**Table 2 – Policy factor according to [11]**

| Policy factor β | Voluntariness | Benefit | Example | Rationale |
|---|---|---|---|---|
| 100 | Entirely voluntary | Direct benefit | Mountaineering | |
| 10 | Voluntary | Direct benefit | Motor biking | |
| 1 | Neutral | Direct benefit | Car driving | |
| 0,1 | Involuntary | Some benefit | Factory | This corresponds to the $10^{-5}$ $\text{yr}^{-1}$ boundary between tolerable region and unacceptable region defined above. |
| 0,01 | Involuntary | No benefit | Fuel station | Same as the boundary between broadly acceptable and tolerable risk. |

NOTE 1 The results of the generally adopted risk analysis procedure as well as the common risk acceptance criteria are given as average values on a yearly basis. Yet, the sources of risk vary over time and in turn so does the risk imposed on individuals. Depending on the context, it can thus be useful or necessary to assess the risk in reference to different time bases, in particular when risk reducing measures are only activated under certain conditions, for instance when ice accretion is detected by ice detection systems or forecasted by meteorological simulations. The process of risk analysis remains the same, aside from being referenced to a suitable time base, e.g. days or hours. For the process of risk evaluation it is however necessary to define reasonable action thresholds on the same time base to be used in place of the yearly-based risk acceptance criteria.

NOTE 2 Many other individual risk limits are known, underlining the fact that setting guidelines is not univocal nor consistent. As an example, for the acceptable cancer risk from air pollution or contaminated sites, the EU and Americas accept values from $10^{-4}$ to $10^{-6}$ $\text{yr}^{-1}$ [12].

### 7.8.3 Quantitative societal risk criteria

#### 7.8.3.1 General

The risk measures and associated criteria outlined in 7.8.2 guarantee that no individual is exposed to undue risk due to the hazard under consideration. They do not say anything about the acceptability of a group of individuals being exposed to the same risk. Government agencies are particularly concerned about infrequent, large fatality events as these cause major disruption to the community. Individual risk does not convey this information and thus decisions based only on individual risk do not address potential disaster scenarios where many may be killed by a single event.

Although the risk of everyone in the group is governed by the criteria related to the critical individual, the risk of an incident with one or more people in a group will increase when the number of exposed persons increases.

### 7.8.3.2 Risk measures for societal risk

To evaluate the societal risk an additional and different kind of risk measure and associated criterion are needed.

The analysis of the societal risk has to be complete, i.e. all combinations of hazards and groups of people exposed to the hazards shall be covered in the assessment. The range in hazards to be considered depends on the scope of the assessment and shall be based on the outcome of the hazard identification step.

An example for a compilation of different hazards and groups of people affected by the hazards is illustrated in Figure 6.

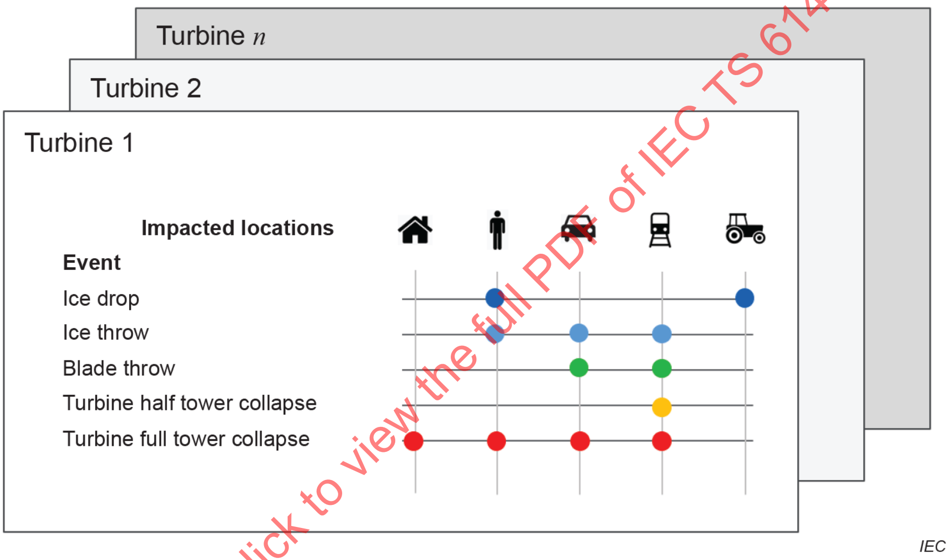


**Figure 6 – Combination of hazards and impacted persons.**

Based on the formal statement which defines societal risk as "the relationship between the frequency and the number of people suffering a given level of harm from the realization of specified hazards" the risk quantification called the f-N curve is commonly used. This is one of the most refined quantitative expressions developed for regulatory control purposes. It is based on a log-log plot of frequency against number of fatalities. The frequency axis is cumulative and is expressed in terms of "N or more". Although the f-N plot is not as easily understood as the individual risk measure, it does present a form of risk measure that is very important to regulators.

Figure 7 gives an example of such an f-N plot.

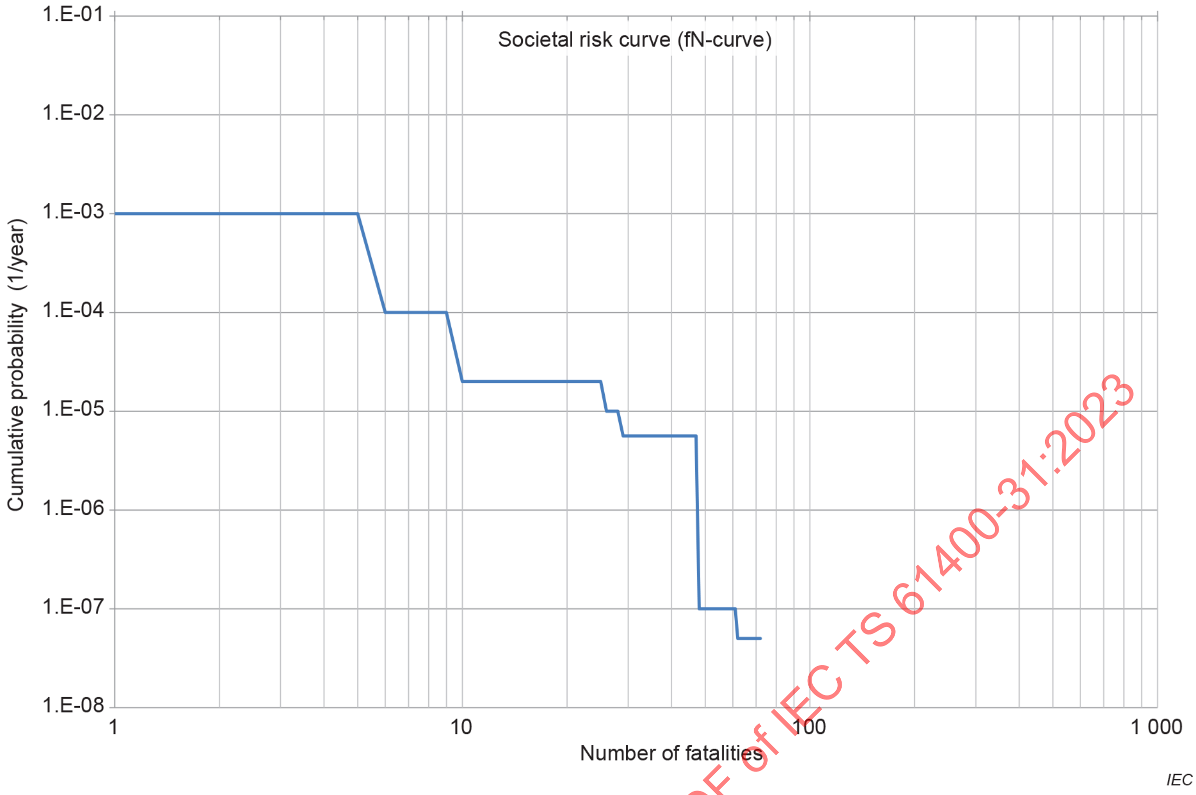


**Figure 7 – Example of an f-N plot**



To construct an f-N diagram, first plot all events, indifferent of type of hazards and categories of people. Cumulation is performed by starting at the frequency of the event with the highest number of casualties, then draw a horizontal line to the next one down in terms of number of casualties. There, the frequency of that event is added to the previous sum, etc.

#### 7.8.3.3 Risk criteria for societal risk

To evaluate the societal risk measure against respective criteria, boundaries corresponding to the broadly acceptable and the unacceptable level criterion, separating the 3 risk regions as defined in 7.3, can be entered into the f-N diagrams.

These criteria are defined as lines in the f-N plot that are mathematically represented as:

$$f = k \cdot N^{-a}$$

Where

$f$ = the cumulative frequency of $N$ or more fatalities

$N$ = the number of fatalities

$a$ = the aversion factor

$k$ = a constant factor

The slope $-a$ of the societal risk criterion plotted on a log-log scale is called the risk aversion factor and represents the degree of aversion to multi-fatality events embodied in the criterion. When the slope of the f-N curve is equal to -1, the risk criterion is termed 'risk neutral'. In this case, the risk criterion requires that the frequency of an event with 100 or more fatalities must be 10 times lower than the frequency of an event with 10 or more fatalities. A risk criterion with a slope of the f-N curve below -1 is said to be more risk averse to single events with large number of fatalities; i.e. the risk criterion reflects a greater concern for events causing larger numbers of fatalities in one event. If, for example, the slope of the f-N curve is equal to -2, the risk criterion requires that the frequency of an event with 100 or more fatalities must be 100 ($10^2$) times lower than the frequency of an event with 10 or more fatalities.

By using this definition, the criteria are defined by

- The definition of $k_a$ and $a_a$ for defining the broadly acceptable level criterion.
- The definition of $k_u$ and $a_u$ for defining the unacceptable level criterion.

An example for an f-N plot including these criteria is illustrated in Figure 8.

In general, there is no international consensus about the criteria to be used for evaluating societal risks. Both $k$- and $a$-values differ significantly among different countries so that deciding which values are to be embodied in a societal risk criterion is a choice that an organization should make, ideally with regard to societal values and in coordination with regulators and other stakeholders.

To illustrate the range of different concepts and risk acceptance criteria in use, Annex B gives an overview of risk acceptance criteria from different countries.



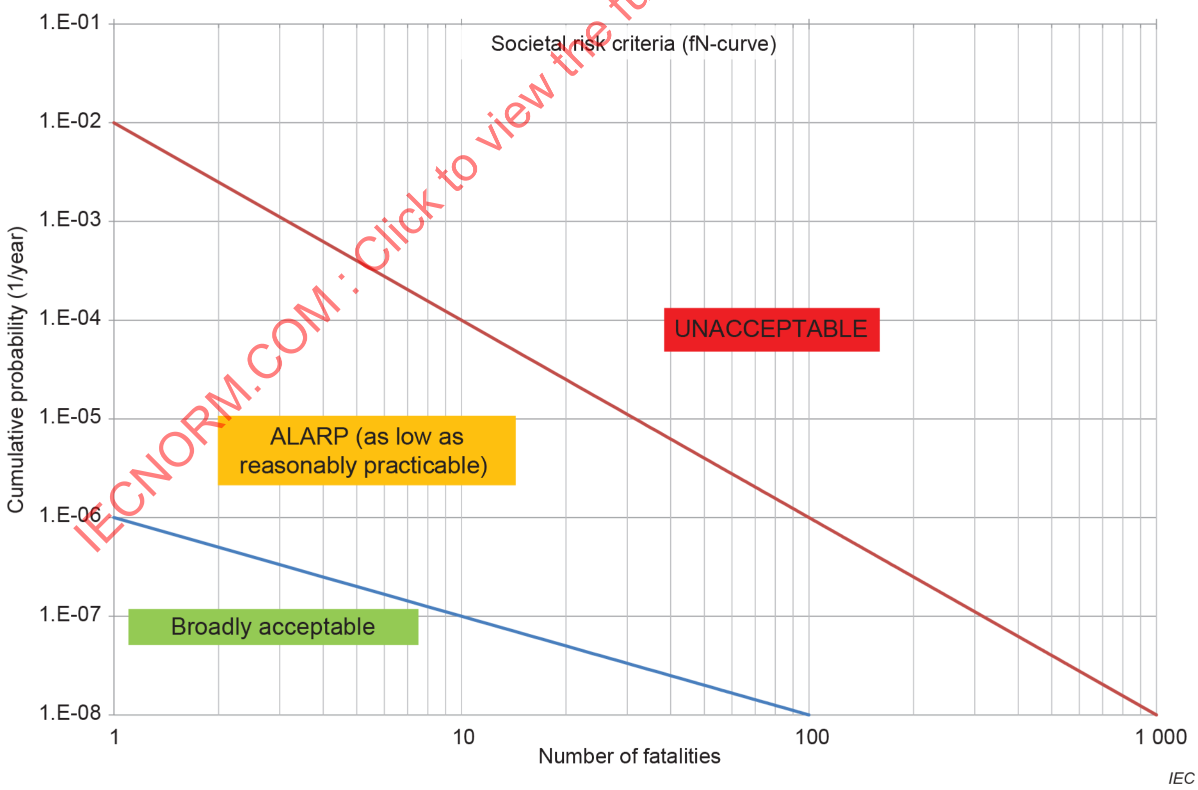


**Figure 8 – Example of societal risk criteria**

# 8 Hazard identification

## 8.1 General

This clause describes different wind turbine failure modes and other non-failure related scenarios (e.g. ice throw), which constitute potential hazards and therefore shall be considered in a risk assessment using the methods and criteria described in this document.

## 8.2 General principles of hazard identification

As far as possible, hazard identification shall be based on operational data, reporting of incidents or near misses at facilities. Such information can be facility-specific or gathered from a broader (e.g. regional) data basis. Hazard logs (see 5.2) can be a useful tool in this process.

## 8.3 Wind turbine failure modes

### 8.3.1 General

The risk from structural failures of wind turbines or wind turbine components shall be considered in the hazard identification phase of a siting risk assessment.

Wind turbines, in general, are safe machines and a mature technology. Major structural failures are thus very rare events with return frequencies on the order of $10^{-4}$ per year [13], i.e. one incident in about 10 000 years of wind turbine operation. The causes of failures of wind turbines or wind turbine components are diverse and can include:

- Wear and material fatigue as well as general technical malfunctions.
- External influences such as extreme wind conditions, which can lead to excess loads on structural components, or lightning strikes, which can trigger a structural failure directly (e.g. delamination) or indirectly (through turbine fires).
- Faulty fabrication or erection including faulty mechanical or electrical execution.
- Errors in wind turbine design.
- Errors in operation and maintenance (human failure).
- Errors in the assessment of site conditions (e.g. wind conditions or soil properties).

The specific causes of a turbine or component failure are however irrelevant to the assessment of the consequential risk. The only relevant factor is the expected probability of occurrence. The expected probability of failure is determined on the basis of statistics of actual incidents.

### 8.3.2 Tower collapse

Tower collapse includes foundation failure, failure of the tower wall (including buckling as a result of the impact of a rotor blade) or breakage at one of the flanges between the tower segments.

### 8.3.3 Shedding of hub or nacelle

Shedding of the hub or nacelle includes breakage of the rotor shaft or the hub, causing the entire rotor to fall to the ground, and breakage in the area of the uppermost tower flange/yaw bearing, in which case the nacelle including the rotor will fall to the ground.

### 8.3.4 Rotor blade failure

#### 8.3.4.1 General

Rotor blade failure can refer to breaking or fracturing of the blade at any point along the length of the blade, whereby blade fragments of different sizes (a few centimeters to whole blades) can fall to the ground, or failures in the area of the pitch bearing or of the blade bolts, causing the loss of the entire rotor blade. In addition, smaller components such as blade tips or lightning receptors can detach from the rotor blade.

Depending on the operational state of the wind turbine, blades and blade fragments can be either thrown from the rotating rotor (including over-speed) or being dropped from the rotor at locked rotor or idling.

#### 8.3.4.2 Classification of blade failures

Blade failures shall be classified according to the rotational speed at failure. Furthermore, blade failures shall be classified by the percentage of the blade length that has broken off. In this definition, parts that are still attached to the rotor are an elevated danger, as they may fall off, whereas in the failure statistics these would not qualify as having fallen.

#### 8.3.4.3 Rotational speed classes

The evaluation of hazards due to blade failure shall consider operation at the rotational speed for rated power. For variable speed turbines, a more sophisticated evaluation of the representative rotor speed may be justified and can be used to avoid over conservatism.

An over-speed/runaway condition of the wind turbine can be considered in the evaluation of hazards due to blade failure. Where data exist on the speed attained during over-speed/runaway of the specific turbine model, then this rotational speed should be used. If no such data exists, an over-speed of two times the rated speed, as suggested by [14], can be used.

#### 8.3.4.4 Length of failed blade

Failure at the blade root shall be assumed (i.e. the entire blade is being lost).

Partial breakage of the blade along its length should be assumed. If no other information is available, breakage at structural joints or at 1/3 of the blade length from the blade root should be assumed.

Furthermore, if the blade is not a continuous structural element but has smaller attached, moveable or removable components (e.g. blade tips, root extenders or blade tips which can be pitched for control purposes), those components falling or being thrown on failure shall each be considered as a separate hazard.

### 8.4 Ice fall and ice throw

If the climatic conditions on a site do not exclude the occurrence of icing, the risk of ice fall and ice throw shall be considered in the hazard identification phase of a siting risk assessment.

Under certain meteorological conditions, atmospheric ice may form on the surface of wind turbines and, in particular, on the rotor blades of wind turbines. Ice forms from atmospheric water: i.e. water droplets of different size, from fog to freezing rain. The build-up occurs either when super-cooled water droplets instantly freeze when hitting a surface. This process yields amorphous, milky white ice (rime ice) which exhibits a low density and low mechanical strength. Ice can also form when liquid water droplets hit a surface with a surface temperature below the freezing point. In this case, liquid water will have some time to flow and spread on the surface leading to the formation of solid clear ice which is characterized by a higher density and higher mechanical strength.

Icing can also often occur in non-pure forms and mixed forms may be produced when the ice formation conditions change over time.

Hazards related to wind turbine icing can be separated in two distinctive categories:

- Ice throw refers to the situation where the motion of the rotor blade of an operating wind turbine imparts a significant initial velocity to ice pieces shedding from the blade surface.
- Ice fall refers to ice pieces dropping off a turbine in standstill or idling mode.

Because of the initial velocities, ice pieces can reach larger distances for ice throw than for ice fall. For operating turbines, the rotation of the rotor also causes an additional motion of the blade surface relative to the air-suspended water droplets thus significantly affecting the ice formation process.

In some countries, it is not permitted to operate wind turbines once atmospheric ice has formed on the blades. In geographical areas where ice accumulation on the rotor blades might occur, ice detection systems can be installed which will cause the turbines to shut down under icing conditions. In such cases, ice throw conditions can be largely avoided.

## 8.5 Fire

The hazard from wind turbine fires shall be considered in the hazard identification phase of a siting risk assessment.

Fire on a wind turbine may cause direct or indirect harm to people. For example, a fire may cause structural failure, resulting in collapse of the turbine or blades. Fire in the nacelle may cause burning debris or embers to fall to the ground, setting fire to objects in the surroundings and thus causing harm to people.

## 8.6 Occupancy

In the context of this document, a hazard can only cause potentially lethal harm if a person or people are present in the affected area. Therefore, the identification of hazards shall also include documenting and quantifying:

- The locations where people could be present such as fields, roads, paths, houses, etc. and in what situation, e.g. on foot, on bicycle, or in a vehicle or building.
- The frequency, how often are people present. This frequency of presence can apply to the same person or to different persons.
- The duration, how long are people present; e.g. are people walking past, driving past at a certain speed or stopping for a certain period of time.
- The density, how many people are present at any one time.

The extent of the area to be investigated for occupancy is determined by the nature of the hazard, e.g. the maximum calculated effect distances or upper estimates thereof. If the extent of the area is unknown at the beginning of the assessment, a conservatively large area shall be assumed and verified at the end of the assessment.

Information on the above parameters can be obtained from various sources, such as inspection of detailed maps showing public roads, footpaths and cycle paths, road authority statistics, showing usage and average speeds of specific roads, facility operators such as ski slope operating companies and local councils. Where details are lacking and occupancy is expected to be critical, a specific usage survey shall be conducted. Furthermore, different countries can have different levels of protection (and thus identification) based on any of the above four characteristics. For example, some countries do not evaluate risks on passers-by or roads or outdoor presence.

### 8.7 Project relevant hazards

When initiating a project risk assessment, all potential hazards that are relevant for that project shall be identified. However, not all conceivable hazard scenarios will be relevant for a given project. The required level of detail for the risk assessment may also vary.

Criteria for the identification of relevant hazards can be:

- Site-conditions such as temperature and climate, wind and icing conditions, extreme weather events, and earthquakes.
- National or regional regulations that include requirements concerning specific hazards.
- Distance to infrastructure such as roads, railways, paths, oil and gas pipelines, and overhead power lines.
- Distance to facilities with hazardous substances.
- Distance to dwellings such as cabins, private homes, villages, and cities.
- Distance to public places, tourist attractions, and leisure areas.

Depending on the situation on the project site, it can also be possible to exclude certain hazards, e.g.

- For a project in tropical climate, ice throw hazard can be excluded without a dedicated ice throw risk assessment. However, some countries might have a low, yet non-negligible ice throw risk. Here the IEA ice map [15] can serve as a guidance combined with other criteria such as distance to infrastructure and dwellings.
- If a wind farm is situated far (several kilometers) from the nearest dwellings and there are no public roads or paths in the project area, it can be possible to exclude a hazard from turbine collapse and rotor blade failure to the public.

The above lists are not exhaustive and each project shall be considered in its own right.



## 9 Estimation of the risk

### 9.1 General

This clause describes methods to estimate the risks resulting from the hazards identified in Clause 8 from the frequency and the severity of hazardous events. This clause thus applies only to quantitative risk assessments (see 7.1). Such methods shall include:

- Approximation of the failure scenarios or incidents identified in Clause 8 in models or assumptions.
- Determination of the required information from measurements, observations from historical incidents, design data, or estimation.
- Calculation of the consequences of the failure scenarios or incidents in the vicinity of the turbine (e.g. impact of machine components on the ground).

### 9.2 Wind turbine failures – tower collapse, shedding of hub or nacelle and rotor blade failure

#### 9.2.1 General

In the assessment of the effects of structural failure of wind turbines on their immediate vicinity, the following three failure scenarios shall be considered:

- Tower collapse (8.3.2)
- Shedding of hub or nacelle (8.3.3)
- Rotor blade failure (8.3.4)

The specific cause of a turbine or component failure is irrelevant to the assessment of the consequential risk. Failure rates for a given failure mode will have to include all failure causes. The expected failure rate for risk assessment shall be based on statistics of actual incidents.

One published source for failure rates is the Dutch "Handboek Risicozonering Windturbines" [16], which has been updated in 2021 [13]. The failure rates of [13] are given in Annex A. Other sources or data for failure rates can be used when available for a specific project. Such data could, e.g., be provided by the turbine manufacturer.

Design requirements with regard to failure rates are part of design codes for wind turbines or wind turbine components (e.g. IEC 61400-1 [17]). Such design failure rates shall not be used for risk assessments and actual failure rates shall be used instead.

When there are reasons to assume that a published source of failure rates is based on a statistical ensemble that is not representative for the project at hand and that this might lead to an underestimation of the risk, additional safety factors should be applied.

Failure rates are likely not to be constant during the lifetime of a wind turbine. One might, e.g., suspect higher failure rates in the initial operating phase after commissioning and towards the end of the machine lifetime. However, if there is no clear evidence allowing a quantification of this variability, constant failure rates over the whole lifetime shall be assumed.

### 9.2.2 Input information

The calculation of the effects of failure scenarios of wind turbines should be based on the specific properties of the wind turbine and the conditions on the site, such as:

- Wind turbine characteristics such as turbine geometry, component masses, mass distributions (e.g. for blades), construction methods, and materials.
- Wind turbine operational characteristics such as cut-in and cut-out wind speeds, rotational speed, etc.
- Site conditions such as orography, elevation, relative position of infrastructure and roadways, etc. If there are indications that specific external influences are relevant on a site (e.g. earthquakes, floods, etc.), they should be considered in the assessment.
- Information on the historical weather conditions on the site may include distributions of wind speed and wind direction, the vertical wind profile, and possibly also probabilities for extreme wind conditions. In many cases, information on the wind conditions will be available from a wind site assessment.

### 9.2.3 Additional assumptions/models

Modelling of failure scenarios requires assumptions. These shall be decided upon based on a combination of available information, extrapolation of available information or experience in similar situations (see Clause 12 for details). Such assumptions can include:

- Failure modes
- External conditions at the time of failure (e.g. wind speed and direction)
- Wind turbine operation at the time of failure (rotor speed, pitch angle, etc.)
- Breakage points along the blade or along the tower (yielding lengths of blade or tower fragments).
- Simplified geometry and properties (including aerodynamic coefficients) of full blades, segments of broken blades, tower segments and other machine components.

For the estimation of the possible harm to people caused by wind turbine failures, it usually will not be necessary to consider the impact energy or impact momentum of the machine parts. Except for very small debris, these values will almost always be beyond the lethal thresholds and lethal consequences should be assumed.

#### 9.2.4 Tower collapse

In a majority of cases, failure of the tower will not occur at the foundation but at some point along its length. The impact position of the nacelle on the ground may thus be at any point between the tower foundation and a distance of the hub height. In order to obtain conservative values, the calculation of maximum effect distances shall be based on the entire length of the tower. For calculation of impact probabilities on the ground, a distribution of impact distances of the nacelle from the tower base shall be assumed.

When tower collapse is caused by a failure of the foundation, the radius of the foundation shall be added for the calculation of the maximum effect distance to allow for tilting the foundation on its outer edge.

The dynamics of a collapsing wind turbine can be affected by the angular momentum of the rotor and by the elastic forces released, when heavy machine parts separate from each other. A prediction of the direction of fall, solely based on the distribution of wind directions, is therefore not possible. In the absence of numerical simulations reliably describing the dynamics of a collapsing wind turbine, calculations of impact probabilities on the ground shall thus assume a random distribution of the direction of fall.

Calculation of impact positions on the ground or of maximum effect distances shall consider the dimensions of the nacelle and of the rotor blades.

#### 9.2.5 Shedding of hub or nacelle

Because of the large mass of these components, aerodynamic forces will only have a minor effect on the fall trajectory and the impact positions on the ground will thus be close to the tower base.

Calculation of impact positions on the ground or of maximum effect distances shall consider the dimensions of the nacelle and of the rotor blades.

#### 9.2.6 Blade breakage

Once detached from the blade, an object or blade segment will travel through the air, starting from the initial conditions (position, velocity, rotation) and affected by the gravitational force and the aerodynamic forces and moments resulting from the action of the relative wind speed on its surface. The motion of the object in its six degrees of freedom (3 translational, 3 rotational) is thereby described by the equations of motion. Annex C provides an introduction to trajectory models for blades and blade fragments.

The gravitational force acts on the object's center of mass whereas the aerodynamic forces may be separated in drag (along the axis of the relative motion through the air) and lift (perpendicular to the axis of the relative motion through the air). In general, the vectors of action of lift and drag will be offset with respect to the center of mass and thus impart aerodynamic moments upon the object.

The position of the center of mass of the detached blade segment/object and the moments of inertia shall be computed from its known or assumed geometry and mass distribution.

The initial position and velocity of a blade fragment or object detaching from the blade are given from the geometry of the wind turbine, the radial position of its center of mass along the blade at the time of separation, and the rotational speed at the time of separation. Pitch angle and deflection of the blade under wind loads can be considered.

In a realistic scenario, one would assume that in the course of breaking up, forces are transmitted between the blade or blade root and the detaching object or blade segment. This in turn can also impart an additional rotational velocity on the detaching object. In simplification, such forces can be omitted assuming a clean, force-free separation.

To obtain the impact probability and the distribution of the impact energy at a certain point near the wind turbine, a series of trajectories shall be computed through numerical integration of the equations of motion.

This set of solutions shall cover at least:

- All relevant failure scenarios with their respective probability of occurrence (whole blade, blade segments of different length, objects from the blade).
- Different rotational position of the blade at the time of breakage.
- A distribution of wind speeds and wind directions.
- The operational state of the turbine.

Overspeed condition can be considered.

The combination of the impact probabilities for the different scenarios then yields a statistical distribution of impact locations, from which impact probabilities shall be computed. The coverage of different failure scenarios, initial conditions, and external conditions can be achieved, e.g., through a suitably set up Monte Carlo simulation. Single worst-case trajectories may be used to compute a maximum physically possible throw distance but do not provide statistical information upon which impact probabilities or risk can be calculated.

A blade segment falling on the ground affects, by its physical size, an area much beyond the impact point of its center of mass, therefore when computing the impact probability at a certain point on the ground, the dimensions of the blade segment/detached object shall be considered.

### 9.2.7 Summation of impact probabilities and risks

The overall impact probability at a certain point on the ground resulting from different failure scenarios is obtained by summation of the individual impact probabilities. When including impact from low mass objects (e.g. ice pieces), impact probabilities shall refer only to impacts of particles which potentially may have lethal consequences.

The maximum effect distance of several failure scenarios is obtained as the maximum of the individual maximum effect distances.

The overall risk to an individual person emerging from different scenarios is computed from the product of survival rates $P_{\text{death, tot}} = 1 - \prod_i S_i$ where the individual survival rates are given by $S_i = 1 - P_{\text{death, }i}$. For small risks, this total risk equals to the sum of the individual risks $P_{\text{death, tot}} \cong \sum_i P_{\text{death, }i}$ in very good agreement.

## 9.3 Ice fall and ice throw

### 9.3.1 Input information

The calculation of the effects of ice fall or ice throw from wind turbines should be based on the specific properties of the wind turbine and the conditions on the site, such as:

- Wind turbine characteristics such as hub height, rotor blade size and shape.
- Wind turbine operational characteristics such as cut-in and cut-out wind speeds, rotational speed, etc.
- If blade heating devices are installed, then extent, performance characteristics, and operational mode of blade heating.
- Site conditions such as orography, elevation, relative position of infrastructure and roadways, etc.

- Wind conditions (distributions of wind speed and wind direction, vertical wind profile) and icing conditions (number, duration, and severity of icing events). In many cases, information on the wind conditions will be available from a wind site assessment.

The IEA Wind Recommended Practices 13 [15] give a scheme to assign icing conditions on a site – expressed as number of icing events, duration of icing or production losses due to icing – to a number of distinct classes (IEA Icing Classes I to V).

### 9.3.2 Additional assumptions/models

Modelling of ice fall or ice throw events requires assumptions. These shall be decided upon based on a combination of available information, extrapolation of available information or experience in similar situations (see Clause 12 for details). Such assumptions can include:

- Average number of safety relevant ice pieces (i.e. above a certain mass threshold[2]) per wind turbine and year.
- Characteristics of ice pieces: mass distribution, size distribution, and ice density. Typical values for the ice density are $\rho$ = 600 kg m$^{-3}$ for rime ice and $\rho$ = 900 kg m$^{-3}$ for clear ice [18].
- Aerodynamic coefficients of the ice pieces.
- Distribution of ice along the rotor blade length.

The formation and shedding of ice pieces on wind turbines depends on meteorological factors of influence such as humidity, temperature, amount of precipitation, wind direction and wind speed. Other technical factors of influence are the presence and characteristics of ice detection systems and de-icing or anti-icing systems. Though these technical systems are often implemented in areas where a high risk of ice fall and ice throw is expected, there is currently insufficient data available for a reliable quantification of their risk reducing effects.

Information on the number of ice pieces for different IEA Icing Classes can be found in the IEA Wind, Task 19 Ice Fall Recommendations [19].

The mass $m$ and the frontal area $A$ of the ice pieces enter the equations of motion of the ice pieces only in the form of the fraction $A/m$. Ice particles with the same $A/m$ will therefore follow the same trajectories and give the same ice fall distances and impact distributions, independently of the size and ice density of the ice pieces. Furthermore $A/m$ also proved to be a useful variable for combining data from ice piece collection campaigns from different sites [19]. $A/m$ should therefore be a main parameter to describe the characteristics of ice pieces. Statistical data for typical $A/m$ ratios are discussed in [19].

### 9.3.3 Calculation of trajectories of ice pieces

For the calculation of a risk due to ice fall or ice throw, the trajectories of the ice pieces shall be computed. IEA Wind, Task 19 International Recommendations for Ice Fall and Ice Throw Risk Assessments [19] presents a set of equations for trajectory modeling of ice pieces shed from wind turbines. Due to the smaller size and the stochastic geometry of the ice pieces, a solution in the three translational degrees of freedom is sufficient for the calculation of the impact distribution of the ice pieces on the ground, i.e. the effect of the rotation of the ice pieces can be omitted. Similarly, modelling of the aerodynamic forces perpendicular to the particles' relative motion though the air (lift force) is not required.



2 Using conservative assumptions (spherical projectile, ice density of 900 kg m$^{-3}$, terminal free-fall velocity) and the impact energy thresholds from 6.5, one arrives at safety relevant mass threshold for ice pieces of around 80 Grams. Ice pieces less massive than that can thus be assumed not to pose a potentially lethal hazard.

The initial position and velocity of an ice piece detaching from the blade surface are given from the geometry of the wind turbine, the radial position of its center of mass along the blade at the time of separation, and the rotational speed at the time of separation. Pitch angle and deflection of the blade under wind loads can be considered.

For the calculation of the impact distribution of the ice pieces on the ground, a representative coverage of the variation of all determining factors shall be obtained. This includes the:

- Distribution of wind conditions during the time where icing may occur.
- Distribution of ice piece characteristics (e.g. in the form of the A/m ratio).
- Distribution of ice along the blade.
- Wind turbine operation during icing conditions (idling, rotational speed, blade position at time of release).

Impact probabilities may be computed from the statistical distribution of impact locations. Single worst-case trajectories do not provide statistical information upon which impact probabilities or risk can be assessed.

### 9.4 Wind turbine fire

In the case of a wind turbine fire – probably different from the hazards from ice fall/throw or machine failure – the hazardous situation can be assumed to be obvious for people near the burning wind turbine. Accordingly, the exposure of people to the hazard of wind turbine fires depends on the human error probability that either a person willfully and knowingly enters the hazardous area or underestimates the hazard. While it can be assumed that there is usually no direct risk to people, this aforementioned human error probability should be taken into account for the risk assessment, specifically considering the situation on site.

If there are inhabited or frequently occupied buildings in close proximity to the wind turbines, the probability of a wind turbine fire spreading to these building shall be calculated and evaluated.

If it is necessary to include the risk from wind turbine fires in the risk assessment, the risk estimation of the fire hazard from burning wind turbine fragments and flying sparks shall be based on a calculation of the falling trajectories of the pieces under the influence of wind.

The risk estimation of wind turbine fires shall include burning or glowing particles (e.g. fragments of a nacelle housing made from glass-reinforced plastic (GRP)) that are carried by the wind and potentially can set fire to an object where they meet the ground. For the size and mass of the pieces, a distribution should be estimated, considering, very small particles (< 1,5 g, large GRP fibers (> 30 g) as well as larger fragments and machine parts.

### 9.5 Calculation of the risk

#### 9.5.1 General

As defined in 3.1.1, risk is defined as the combination of the probability of occurrence of harm and the severity of that harm. This document only covers potentially lethal harm (see Clause 1). The severity of harm is therefore a fixed quantity by definition. The remaining information needed for the calculation of risks is thus the probability of occurrence of harm.

In the case of the hazards identified in Clause 8, the probability of occurrence of harm will be calculated as the product of the probability of a hazardous scenario (impact of a machine part or an ice piece on the ground) and the probability of people being present at this place at the time of impact. The determination of the first factor is described above in 9.2, 9.3, and 9.4, the second factor is discussed in 8.6.

For simplicity, it is usually assumed that these probabilities are independent, i.e. the risk reduction from the tendency of people avoiding dangerous situations or fleeing an immediate threat is not taken into account.

### 9.5.2 Effective cross-section for people and cars

The vulnerable cross section for people depends on the hazard scenario and on the mass and size of the impacting object. For impacts of small objects such as ice pieces, lethal consequences are mainly to be expected for impacts on the head. In [19], an effective cross section of a person's head of 0,04 $m^2$ is suggested. In other scenarios, the combined area of head and torso would be an appropriate cross sections for impacts with lethal consequences. The dimensions of a $50^{th}$ percentile male crash test dummy suggest a cross section of the torso of 0,14 $m^2$.

Cars are designed to protect occupants in traffic accidents and thus offer some level of protection, at least from the impact of smaller mass objects. On the other hand, impacts on cars might lead to secondary traffic accidents causing indirect harm (see 6.3). The main vulnerable area of a car, also because of the forward motion of a car, is the front windscreen. In [19] an area of 2 $m^2$ is assumed for the dimensions of a vehicle's windscreen.

## 9.6 Analysis of domino effects

The first step in the analysis of a possible domino effect is the identification of hazardous installations which are (1) within the maximum effect distances of hazardous events at the wind turbines, and (2) would be vulnerable due to these specific hazardous events. For doing so, a maximum effect distance shall be calculated or defined for each root cause. Likely root causes for domino effects triggered by wind turbines are machine failure scenarios: tower collapse, shedding of hub or nacelle, and rotor blade breakage. These maximum distances will depend on the characteristics of the wind turbine and on the conditions on site. Any hazardous installation identified in this way shall be recorded and further investigated.

In many cases, there will be an existing risk assessment for this hazardous installation. This risk assessment should be updated to cover any new hazardous scenarios triggered by the wind turbines. The methods for this risk analysis should be chosen specific to the nature of the affected hazardous installation.

Table 3 gives some examples of relevant hazardous installations in relation to important failure modes.

**Table 3 – Examples for hazardous installations that could be affected by domino effects triggered by wind turbine failures**

| Failure mode | Separation distance | Possible affected installations |
|---|---|---|
| Blade breakage | See calculated effect distances. | • Chemical plants.<br>• Establishments containing large amounts of GHS[3] Part 2 or 3.1 substances.<br>• LPG/LNG/CNG/H2 filling stations.<br>• Above-ground pipelines containing GHS Part 2 and 3.1 substances.<br>• Pressure reducing stations. |
| Tower collapse and foundation failure | Tower breakage and foundation failure impact zone including vibrations. | • Underground pipelines with GHS Part 2 or 3.1 substances.<br>• Installations listed above for blade breakage. |

3 GHS: United Nations (2019) GHS Globally Harmonised System of Classification and Labelling of Chemicals $8^{th}$ revision 2019 New York and Geneva. Part 2 describes products which can cause physical hazards. Part 3.1 describes products with acute toxicity

## 10 Risk evaluation

The purpose of risk evaluation is to support decisions using the risk acceptance criteria defined in Clause 7. Risk evaluation is the procedure based on the risk estimation to determine whether the risk acceptance criteria have been met.

If the results of the estimation of the risk meet the risk acceptance criteria, it may lead to a decision to not take further measures or to maintain existing controls and to declare that the risk evaluation procedure has been completed.

If the results of the risk estimation do not meet the corresponding risk acceptance criteria, then the user should select and incorporate suitable risk reduction measures (as described in Clause 11) or select a more refined assessment approach (as described in 7.1) and repeat the steps of hazard identification, estimation of risk, and risk evaluation, to make sure the results of the risk estimation reach the risk acceptance criteria. Alternative solutions to the project at hand shall be considered.

It shall be considered whether the uncertainties and the quality of risk assessment are adequate for the purpose of the assessment.

Note that the decisions at this stage should consider the broader context as well as actual and perceived consequences for external and internal stakeholders. All results of the risk evaluation shall be recorded, reported, and then accepted at the appropriate level of the organization.

## 11 Risk treatment

### 11.1 General

The purpose of risk treatment is to ensure that the best risk reduction measures are selected and implemented for the mitigation of risk, considering the interests of all stakeholders involved.

Hazards shall be identified and recorded when they become known, which can be in a very early project development phase. This ensures that associated risk reduction measures are put in place at the right moment during the project lifecycle. A hazard log (see 5.2) can be a useful tool to record hazards, to document the selection of risk reduction measures, and to follow-up with the implementation of the risk reduction measures in the project.

### 11.2 Selection of risk reduction measures

Risk treatment involves balancing the potential risk reduction effect against costs of implementation and operation. In general, the priority in risk treatment should be to

1) avoid the risk by removing the hazard,
2) reduce the probability of an event to take place,
3) reduce the possible consequences.

Emergency preparedness planning should be based on the identified risk but should not be accounted for as a preferred risk reduction measure.

### 11.3 Examples of risk reduction measures

Risk reduction measures for risk treatment can be separated in technical risk reduction measures and organizational risk reduction measures.

Risk reduction measures can be either implemented by the wind turbine designer (e.g. inherent design, safeguarding and complementary risk reduction measures, information for use) or by the user of the wind turbines (e.g. safe working procedures, supervision, training; permit-to-work systems; provision and use of additional safeguards; use of personal protective equipment; information and risk communication to the public; warning signs; temporary or permanent access restrictions)

Typical technical risk reduction measures in wind farms include:

- Condition monitoring systems for early detection of failures of safety critical equipment.
- Systems such as fire detection system, overspeed protection system, blade position system, leak detection system, ice detection system, etc.
- Blade anti-icing or de-icing systems, if configured for risk reduction (see 11.4)
- Changed turbine operation based on signals from an ice detection system.
- Use of failure detection systems.
- Monitoring system to detect need for maintenance.
- Measuring and alerting systems for environmental conditions.
- Inherently safe design of components.

Typical organizational risk reduction measures in wind farms include:

- Risk communication and information strategy and plan to neighbors and users of the wind farm area.
- Warning signs or information brochures.
- Restrictions in operation of the wind turbine (e.g. by sectoral de-rating or wind speed cut-outs).
- Permanent or seasonal restrictions in use of the surrounding area, e.g. by fencing, or by blocking access to roads or areas.
- Temporary restrictions in use of the surrounding area (e.g. based on weather forecasts or measured icing conditions).
- Stringent controlling and inspection routines.
- Preventive or predictive maintenance programs (see also IEC 61400-28 [20]).

### 11.4 Ice detection systems and rotor blade heating systems

Ice detection systems and rotor blade heating systems can be used to reduce the risk from ice fall and ice throw.

Rotor blade heating can be operated either in *de-icing* mode, i.e. removing ice once it has formed on the rotor blade, and in *anti-icing* mode, referring to preventive heating under icing condition to inhibit ice formation in the first place.

The presence of ice on the surface of the rotor blade can be detected with ice detection systems. This information can then be used for the control of blade heating systems, to issue warnings about the potential ice fall risk to people near the wind turbine (e.g. though warning lights), or to stop the operation of the wind turbine in order to avoid ice pieces being thrown from the rotating rotor.

Ice detection systems are usually designed for operational purposes and production optimization. Therefore, they are usually not certified according to IEC 61508-1 [21] as a safety function with an allocated risk reduction. Nevertheless, a shutdown caused by the ice detection system can be used as a risk reduction measure. IEC 61508-5 [22] suggests the application of a failure rate of 10 % for systems that are not certified safety functions.

The failure rate of an ice detection system is not directly correlated with the risk reduction obtained from the ice detection system. Instead, a risk profile might be modified: For example, stopping an iced-up wind turbine transfers the risk from a point further away from the wind turbine (no ice throw) to shorter distances (ice fall from the wind turbine in idling mode). In such cases, it is not possible to calculate a quantitative risk reduction.

If there is evidence of the rate of risk reduction, it can be taken into account. For the application of stopping wind turbine operation once ice has formed on the blades, the failure rate of an ice detection system can be allowed for by assuming ice fall for 90 % of the time, and ice throw (i.e. detection failure) for the remaining 10 % of the time.

If multiple ice detection devices are installed, it cannot be assumed that each extra detector will reduce the remaining failure rate by the reliability of the added detector. Instead, only if the additional detector is based on different physical principles and is located at a different position on the wind turbine more than two meters away from the other detector, it can be assumed to reduce the risk of the first sensor failing to detect ice.

## 12 Uncertainties in risk assessments

The assessment of hazardous events necessarily involves the simplification, idealization, and parametrization of actual processes and dependencies. Uncertainties in the results of risk assessments can arise from each parameter, assumption, or data entering the analysis. Incomplete or erroneous hazard identification can also systematically affect the results of a risk assessment.

Mathematical models used for the estimation of risks are always a simplification and idealization of the real-world conditions. For example, the trajectory of a detached rotor blade fragment depends on a myriad of factors and therefore individual trajectories appear to behave chaotically and unpredictable. A mathematical model describing the main forces on such a blade fragment and reasonable assumptions for the wind field will in general be unable to predict the trajectory in an individual case, but nevertheless might be able to derive valid results for a large statistical ensemble of such trajectories. Mathematical models used in risk assessments should be thoroughly reviewed before they are applied. When new knowledge or data emerges, the mathematical models should be updated accordingly. Whenever possible, modelling methods should be verified with observational data.

An important source of uncertainties in risk assessments of wind farms are the uncertainties in input data and parameters. Hazardous events are usually also rare events and reliable statistical data (e.g. on failure rates) is thus often hard to obtain. Therefore parameters in risk assessments often have to be selected on the basis of reasonable assumptions or order-of-magnitude estimates. Conservative assumptions should be made for parameters that have a clearly predictable effect on the overall risk (e.g. probability of occupation). For some of these parameters it is easy and useful to define an upper bound (e.g. a probability of occupation of unity), for other parameters such upper bounds are hard to deduce. Parameters that do not have a clearly predictable effect on the risk (e.g. the coefficient of drag affecting the transport distance of an ice piece) should be estimated in the best possible way, based on available data, literature or comparative calculations. Sensitivity analyses can be a useful way to estimate the effect of parameters or modelling assumptions on the results of risk assessments.

Risk assessments usually describe rare events. Their results are therefore essentially statistical statements and as such not directly applicable to each individual case. In particular, an assessment will be based on plausible assumptions and existing data and experience. Exceptional events and circumstances are therefore covered only to a limited extent.

The uncertainties discussed above may lead to significantly different results when risk assessments for the same installation are performed by different people, using different methods, data, and assumptions. It is thus the responsibility of the analyst performing an assessment, to select appropriate methods, data, and assumptions.

A pragmatic approach to treat uncertainties within a risk assessment report is for example the Strength of Knowledge Index [23]. The following criteria can be applied to assess the strength of knowledge regarding a certain aspect:

- The reasonability of the assumptions made
- Amount and relevance of data used
- Agreement/consensus among experts on the aspect
- How well the phenomena involved are understood

A scale to classify the strength of knowledge can be of the following manner

- Poor background knowledge
- Medium strong background knowledge
- Strong background knowledge

This approach enables also uninformed readers to easily understand the confidence in the results of a risk assessment report. Nonetheless, this or any other approach for the treatment of uncertainties shall be clearly motivated and described in the risk assessment report.

# Annex A
(informative)

## Summary of failure frequencies published by the Dutch RIVM

The publications of the Dutch Rijksinstituut voor Volksgezondheid en Milieu (RIVM) [16] [13] are a well-researched and impartial source of failure frequencies for wind turbines. As these publications are only available in Dutch language, Table A.1 summarizes the main results from the 2021 update of the failure frequencies [13]. The information Table A.1 is not regularly updated when the failure frequencies from [13] are supplanted by a newer document.

**Table A.1 – Failure frequencies from [13] in units of failures per turbine and year.**

| | Blade loss[4] | Blade breakage | Tower failure | Rotor collapse | Nacelle collapse |
|---|---|---|---|---|---|
| Expected value '2021' | $1,1 \times 10^{-4}$ | $1,5 \times 10^{-4}$ | $4,5 \times 10^{-5}$ | $1,4 \times 10^{-5}$ | $1,5 \times 10^{-6}$ |
| 95 % confidence value '2021' | $1,4 \times 10^{-4}$ | $1,8 \times 10^{-4}$ | $6,1 \times 10^{-5}$ | $2,4 \times 10^{-5}$ | $7,1 \times 10^{-6}$ |



4 With unknown rotational speed, i.e. no differentiation between normal operation and overspeed.

# Annex B
(informative)

## Overview of used risk criteria in different countries

Table B.1 gives an overview of different risk acceptance criteria from different countries. The purpose of Table B.1 is to illustrate the range of different concepts and threshold values in use. It does not constitute any advice on legal requirements and all information is given without liability. The information in Table B.1 is not regularly updated in case of regulatory changes.

**Table B.1 – Overview of used risk criteria in different countries**

<table>
<tr><th rowspan="2">Country</th><th colspan="3">Used risk assessment method</th><th colspan="2">Nature of risk evaluated</th><th rowspan="2">Used acceptance criteria</th><th rowspan="2">Remarks</th><th rowspan="2">Reference</th></tr>
<tr><th>Prescriptive</th><th>Semi-quantitative</th><th>Quantitative</th><th>Direct</th><th>Indirect</th></tr>
<tr><td rowspan="2">Belgium</td><td>X</td><td></td><td>X</td><td>X</td><td></td><td>Prescriptive criteria<br>Separation distance to be respected for housings, schools and vulnerable locations, based on maximum effect distances for different failure modes<br>Quantitative criteria<br>LIRA: $10^{-5}$, $10^{-6}$ and $10^{-7}$<br>f-N with k = $10^{-2}$ and a = 2</td><td rowspan="2">A two-step approach is used: in step 1 the location is evaluated against calculated separation distances. If these are not fulfilled a quantitative approach is used</td><td rowspan="2">[24]</td></tr>
<tr><td>X</td><td></td><td>X</td><td></td><td>X</td><td>Prescriptive criteria<br>Separation distance to be respected for in relation to assets containing dangerous goods (storage, pipelines, etc.).<br>Quantitative criteria<br>Demonstrate that the new failure rate of the asset is less than 10 % higher than the initial.<br>Demonstrate that criteria valid for the asset are met taken influence wind turbine into account.</td></tr>
<tr><td>China</td><td>X</td><td></td><td></td><td>X</td><td></td><td>Separation distance to railways, highways > 1,5 times the falling tower distance.</td><td>Minimum distances to various objects (roads, cables, facilities ...) are determined based on a risk threshold. These risk thresholds are determined from various international guidelines and experiences, there is NO LEGAL FRAMEWORK IN CHINA for individual or societal risk.</td><td>[25]</td></tr>
</table>

| Country | Used risk assessment method | | | Nature of risk evaluated | | Used acceptance criteria | Remarks | Reference |
|---|---|---|---|---|---|---|---|---|
| | Prescriptive | Semi-quantitative | Quantitative | Direct | Indirect | | | |
| Denmark | X | | | X | | Minimum separation distance to houses is 4 times the tip height.<br>Minimum separation distance to High -Voltage overhead lines is one tip height + 15m.<br>Minimum separation distance to underground cables is 50m.<br>Minimum separation distance to railroads and state roads is 1,7 times tip height.<br>1,0 to 1,7 times tip height can also be accepted but will require further investigation and dispensation.<br>For other roads, the minimum distance is decided by the municipality, based factors such as road occupancy and risk of ice throw. | Minimum distance to houses, does not apply to wind turbine owners or in industrial areas. | [26] |
| The Netherlands | X | | | X | | A maximum localized risk (LIRA) is used (Max $10^{-6}$ per year) as a risk criteria for ‘vulnerable locations’ and ‘limited vulnerable locations’ (Max $10^{-5}$ per year). | ‘Vulnerable locations’ are:<br>• Residential buildings of more than 2 per hectare.<br>• Large office buildings (>1 500 $m^2$).<br>• Buildings for vulnerable people (hospitals, elderly homes, children's day care …).<br>• Any other buildings where a large group of people can remain during a large part of a day.<br>• Camp sites and other recreational areas with more than 50 people during multiple days of attendance.<br>‘Limited vulnerable locations’ are:<br>• All other buildings where people can stay in / work in basically | [27], [14] |
| | X | | | | X | For assets containing dangerous goods that can be hit by falling wind turbine parts the Hit Frequency has to be calculated. This is the yearly frequency that any part of the dangerous installation can be hit. This frequency must be implemented in the risk evaluation of the dangerous good itself. These risk evaluations of dangerous installations cause their own localized risk contours and group risk evaluations. If these increase due to the wind turbine hit frequency until specific laws (per dangerous installation) are broken than the wind turbine cannot be placed. A maximum hit frequency of 10 % from the wind turbine as compared with the own specific failure frequency of the affected installation is often used as a safe cut-off criteria in which further research is not needed. | | [27], [14] |