

ORIGINAL ARTICLE

Industrial emergencies caused by extreme wind

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Abstract

The paper deals with the effects of extreme storms and tornadoes on industrial facilities and the possible occurrence of emergencies. The paper aims to determine the potential emergency scenarios associated with these events and to learn from them. For this purpose, available data on emergencies were collected mainly from the ARIA industrial accident database and from available scientific articles. The study was focused on incidents caused mainly by forces associated with the action of extreme storms. The collected data have 40 items, which were subsequently analyzed. Most of these items are located in the European Union. The results of the analysis of the available data indicate that the most frequent consequence was financial damage, often caused by structural damage, power outages, and consequent loss of production. Environmental impacts, such as the release of hazardous chemicals, were also significant. The paper includes lessons learned based on the data collected and analyzed.

KEYWORDS

accident scenarios, European Union, lessons learned, NaTech, storms

1 | INTRODUCTION

Natural Hazard Triggering Technological Disasters (NaTech) is a challenge in the field of process risk prevention. In recent decades, there has been an increasing trend of incidents where natural disasters, such as earthquakes, floods, or extreme weather, have caused secondary technological accidents with environmental, economic, and human-health impacts.¹ It is therefore a challenge that is likely to increasingly affect our society in the future.

The authors Ricci et al. report that of the sample studied, up to 74% of NaTech events were triggered by extreme weather events such as on-land storms or tropical over-water storms, or lightning.¹ A storm can be accompanied not only by an extreme wind gust reaching speeds of more than 200 km per hour but also by a large amount of rainfall in a short period or by a discharge of atmospheric electricity. An extreme wind gust can exert direct dynamic forces on industrial installations, compromising the integrity of the installation,² or the wind can cause waves to rise and flood or damage offshore or onshore installations, as was the case, for example, in Hurricanes Rita or Katrina.³

High rainfall, water level rise, or wave run-up appear to play a significant role in the occurrence of hazardous chemical spill incidents. For example, during tropical cyclone Harvey in 2017, most events were related to flooding caused by atmospheric precipitation or water level rise.⁴ A similar situation occurred in the case of Hurricane Katrina.⁵ However, the force effects of wind were also responsible for structural damage to structures, especially storage tanks, interruption of power supply to critical systems, etc.⁴

There have also been devastating storms in Europe in the past. These include Kyrill⁶ and Lothar.⁷ The authors Gregow et al. report that the average intensity of the most destructive storms in Europe increased more than threefold in the period 1951–2010.⁸ Going forward, the frequency of damaging convective weather events including lightning, hail, and strong wind gusts can be expected to increase in Europe.⁹

Based on the study of past events, accident scenarios can be drawn up and then included in the risk analysis. This enables safety engineers to take measures in an industrial plant to mitigate the negative effects of these atmospheric phenomena. It is advantageous to learn from incidents that have occurred outside the location of the

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industrial plant, even though the climate may be different. In the future, atmospheric phenomena will likely start to occur in some locations that were previously unthinkable in that location.

The aim of this paper is to identify accident scenarios associated with high wind speeds based on information from past events and to draw lessons from these events.

2 | METHODS

Incident information found primarily in the ARIA industrial accident database¹⁰ as well as scientific articles searched in scientific databases were used to identify incidents. Keywords and combinations of keywords such as “wind,” “windstorm,” “hurricane,” and “accident” or their equivalent in French such as “tempête de vent,” “tornado,” “typhon,” and “ouragan” were entered into a search engine for the search.

Using these keywords, a total of 143 records were found in the ARIA database. From these records, 37 entries were selected for further analysis. The selection criteria were as follows:

- The emergency must have been caused by dynamic or static forces caused by wind action, or by flying debris set in motion by the wind.
- Where the incident was caused by high water, flooding, or torrential rainfall, these records were discarded.
- Storms that affected a facility that processes or stores hazardous chemicals were included.
- Also included in the selection were incidents that occurred at facilities that, while not part of the process industry, may have lessons of interest to the process industry. These were mostly waste management facilities and some agricultural-industry facilities.

To this number of events, events identified in scientific papers were added. The final number of records that were subsequently analyzed was 40 records. The analysis of the events focused on the frequency of events in the industries of interest and the consequences that

these natural phenomena caused. Threats and top events were also identified in the event description text so that possible accident scenarios could be constructed. In accordance with CCPS,¹¹ for the purposes of the paper, a threat is defined as “A possible initiating event that can result in a loss of control or containment of hazard” and the term Top Event as: “...a central event lying between a threat and a consequence corresponding to the moment when there is a loss of control or loss of containment of the hazard.”

3 | RESULTS

3.1 | Analysis of events

Of the 40 records, a total of 34 records were located in the European Union. The events were mostly recorded in France. It is understandable because the ARIA database is operated by the French authorities. Figure 1 shows the distribution of events in each year. The highest frequency was recorded in 2023, when storm Ciaran struck France and the United Kingdom. In most cases (28 in total) these were orcane-related (hurricane-related) emergencies. The remaining 6 cases were tornado emergencies.

The sector of economic activity of the establishment where the incident occurred has been grouped into six categories. The relative representation of each category is presented in Figure 2. The largest category is the “Chemical and petrochemical industry,” but the representation of the different categories is fairly balanced. The category “Energy” includes both power plants and biogas plants or natural gas distribution facilities. The “Other” category includes, for example, the steel industry or cement and lime works.

A total of 5 consequence groups were identified in the sample of European events:

- Financial damage
- Aquatic environmental damage
- Creation of an explosive atmosphere

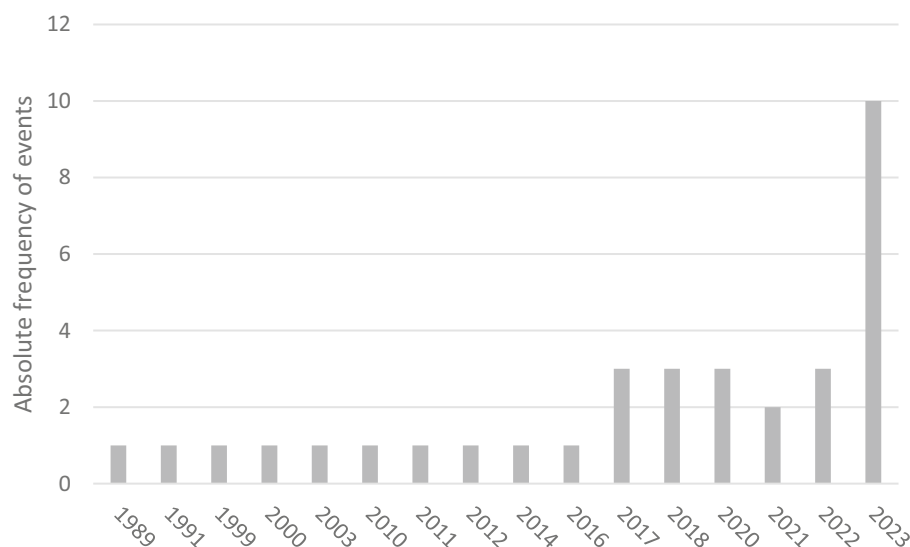


FIGURE 1 Absolute frequency of emergencies occurring in Europe.

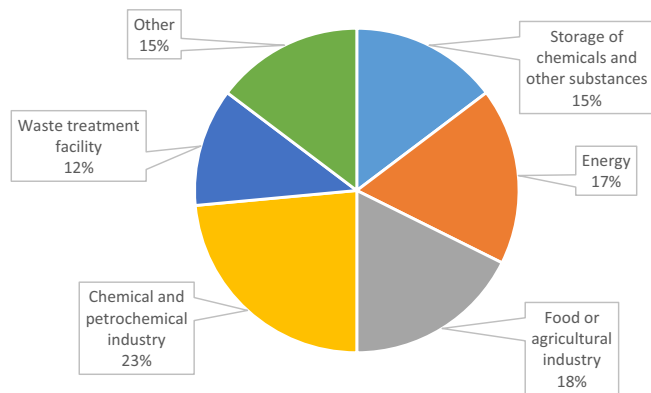


FIGURE 2 Relative representation of different types of sectors of economic activity.

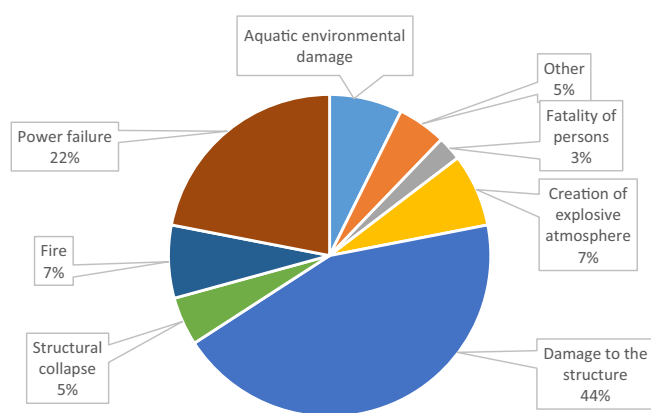


FIGURE 3 Relative representation of each group and subgroup of consequences.

- Fatality of persons
- Other

In most cases, these were financial damages that could be classified into other subgroups. These were financial damages caused by:

- Power failure
- Structural collapse
- Fire
- Other damage to the structure

The relative representation of the different groups and subgroups can be seen in Figure 3. For some records, more than one consequence could be listed. For this reason, some outcomes were counted more than once. Figure 3 shows that financial damage accounted for the largest proportion of consequences, that is, 78%, with financial damage due to structural damage accounting for the largest proportion. In the majority of cases, damage to roofing and cover sheets, and in the case of biogas plants, damage to the gas house membrane or digestate storage occurred. However, the damage to the roofing led to other effects, such as power failure or exothermic reaction of water and

hydrochloric acid. There was only one fatality, and that was due to the fall of a crane cab that was hit by a tornado. The power outage was probably further caused by objects falling on the electrical substation, damage to a transformer, or damage to power lines outside the affected building. The financial damage was not only due to direct damage to the substation equipment but also due to the interruption of production, which, according to the records, lasted between 3 and 5 days. The environmental damage was mainly due to the leakage of petroleum hydrocarbons that were released from the damaged storage tanks.

3.2 | Identification of accident scenarios

The identification of accident scenarios was based on the information recorded in the author's database; that is, both European and non-European. Furthermore, expert sources such as technical reports¹² or technical rules¹³ were used. Examples of these scenarios are presented in Table 1 below.

The accident scenarios listed in Table 1 are certainly not a definitive list. The list of scenarios can be extended depending on the type of operation. In the risk analysis, it is also necessary to consider other concomitant effects which, although not leading to an accident or near accident, may complicate the emergency response. For example, telecommunication network failure (e.g., due to congestion, damaged BTS—Base Transceiver Station). People moving outdoors may be hit by flying debris, fires are fanned by the wind, firefighting water disperses in strong winds, and the firefighting water flow changes direction in strong winds.

4 | DISCUSSION

Most of the events in the authors' database were due to wind storm Ciarán, which hit Europe in October/November 2023. The maximum horizontal wind speed was measured in France and was 208 km per hour. Several tornadoes of maximum intensity IF3 (International Fujita Scale, the central value of wind speed is 80 m/s) were also produced in association with this storm.¹⁵ It is clear that Europe, including France, has been hit by more intense storms in the past, such as Storm Lothar in 1999. However, there is only a single record from that year in the author's database. The multiple records for Storm Ciarán are probably more indicative of the increased interest in the impacts of wind storms on industrial facilities and other NaTech events, rather than there being less impact on industry in 1999.

The majority of the assessed events were recorded in connection with windstorm activity. A minority of records (8 in total, 6 of which in Europe) were related to tornadoes. Tornadoes are specific in that they affect a relatively small area and have a short duration. Tornadoes have a high rotation speed, to which is added a translational velocity. In addition, they produce strong, upward air currents that can also cause upward suction.¹³ Thus, the force on the structure of an object may be different from the forces produced by an orcan

TABLE 1 Examples of identified wind accident scenarios.

No.	Threat	Top event	Consequences
1	Damage to the roof covering, subsequent leakage into the control room, command room, etc. Damage to the electrical substation due to a falling object (tree, flying debris, etc.) or overturning of the substation Breakage of electrical wires leading to process equipment (caused by flying debris, falling objects, etc.) Damage to the power system outside the affected structure	Loss of process control due to power failure	Loss of process control can lead to a number of consequences, such as financial losses due to production shutdown, and product damage. It can also lead to unwanted chemical reactions, explosive mixtures and their ignition in process vessels, etc. Other effects can also occur, such as the death of livestock in livestock production. An example of this is an event where the power supply was cut off, the ventilation system was shut down and 40,000 poultry died
2	The same threats in scenario 1 can be considered	Sprinkler system shutdown due to power failure	Financial damage is caused by firefighting water from the sprinkler system
3	Damage to the roof structure of the building where the process unit is located	Loss of process control due to water ingress into the process unit	The occurrence of an uncontrollable chemical reaction. For example, water can promote the self-heating process of some solids or cause an exothermic chemical reaction
4	Profile vibrations due to dynamic wind forces (e.g., vortex induced lateral vibrations, galloping vibrations, interference galloping, wake-galloping, flutter)	Damage or collapse of the tower structure due to fatigue fracture of struts or other elements	For example, the financial damage caused by long-term interruptions in production. Fatalities of persons on the structure may also occur
5	Overturning of tanks Tank deformation (buckling) Puncture of tank structure by flying debris Dropping of an object on the tank (e.g., tree) ^a Displacement of the tank and subsequent damage to the connection pipe	Total loss of liquid volume in the atmospheric tank	Spillage of a hazardous chemical into the aquatic environment, damage to biodiversity. Release of a flammable product (e.g., propane, butane), initiation of a cloud, explosion, affecting people and property. Release of a toxic substance, affecting people
6	Rupture of the gas holder membrane due to wind forces Loss of pressure in the gas seal pressure circuit due to loss of electrical power ^b Tearing of the straps ensuring the sealing and fastening of the gas holders (e.g., due to vibration)	Total gas volume loss from the membrane gas holder ^c	Financial losses caused by interruption of production or material losses. Environmental damage due to methane leakage into the air. Certain probability of explosive atmosphere and its initiation
7	Overturning of tank Displacement of the tank and loss of the integrity of the supply lines Puncture of the tank by flying debris Damage to piping supply lines due to vibration, flying debris, torsional forces, etc.	Gas leak from the pressure tank	See previous
8	Fall of a tree on a gas substation or pipeline in outer space	Leakage of natural gas from distribution equipment	See previous
9	Spillage of reactive material in the open space ^d Transport of hot particles by wind ^e	Fire occurrence due to wind	Financial losses caused by interruption of production or material losses, etc.

^aThis is a real case where a small-volume atmospheric storage tank was damaged by a falling tree.

^bMembrane gas storage tanks are used, for example, in plants for the production and energy recovery of biogas.

^cThis is one method of anchoring an integrated gas storage tank. For more information, see for example Reference 14

^dWind can be one of the cofactors in a fire of loose piles, for example, metal chips.

^eThis was a case of a fire in the vicinity of a carbonization furnace, where strong winds increased the open flame and the transfer of embers from the furnace to surrounding objects. Subsequently, a fire started.

(hurricane). The European Standard¹⁶ focuses on wind loads acting on objects by horizontal forces. A tornado is thus different from the types of winds mentioned in this standard, as also pointed out in the German technical rules TRAS 320. For this reason, it is interesting to

study the effects of tornadoes on industrial buildings. In the authors' database, the effects of small tornadoes, apparently up to intensity EF1, where damage to the roofs of industrial buildings has occurred are listed. The authors Prevat et al. report the consequences of

tornadoes of EF3 intensity on nuclear power plant objects in 2011 in the USA.¹⁷ The plant's nuclear reactors went into standby mode due to the loss of external power supplies. The external impact was extensive damage to the energy network in the vicinity and significant power outages. In the Czech Republic in 2021, the most intense tornado in this territory was recorded so far. It had an intensity of F4. In the vicinity of the impact of this tornado, there is a facility with a risk of a major accident in terms of the relevant legislation on the prevention of major accidents. Some objects of this facility were hit, but apparently the intensity was lower in the place of impact. Storage tanks with methanol were overturned, roofs of shelters were damaged, etc.

As part of this risk analysis, it is possible to proceed deterministically; that is, to expect a storm or tornado of the highest possible intensity that occurred at the given location, or the worst possible scenario. However, in some countries, such as Germany, the rules allow extremely improbable phenomena to be excluded in the risk analysis. An example can be a tornado of intensity F5 (Fujita Scale, wind speed 261–318 mph), which has not been reliably proven in this area based on current knowledge.¹³

The effects of wind are also associated with threats that may not receive much attention in the area of accident prevention, but at the same time have been known for a relatively long time. These are, for example, vibrations of undamped structures due to wind.¹⁸ Even tall and slender process vessels used in the process industry can be exposed to induced vibrations. This can ultimately lead to fatigue fractures and subsequent vessel damage.¹⁹

The analysis also shows that due to the impact of strong storms, an emergency shutdown of a plant may occur. Shutting down and starting up processes are non-routine operations that are prone to human error. Some accidents occurred days after a storm ended. From this point of view, it is very important to have developed and practiced procedures for shutting down and starting up processes, including hazard analyses of these procedures.

5 | LESSONS LEARNED

The following recommendations and suggestions resulted from this study:

1. Since power failure was one of the very common phenomena that resulted in emergencies, a power-loss hazards analysis should be carried out, which should include the identification of critical systems and elements that may be affected by a power outage, including the identification of possible consequences and the determination of power outage procedures.
2. Procedures should be established that take into account that movement of people in the facility may be very difficult in the event of an emergency (e.g., operators may be struck by flying objects). Thus, safe passageways should be provided for emergency escape to refuges, or necessary equipment should be provided for persons who will need to remain in shelter.
3. In the event of loss of communication between workers (overloaded telecommunications network, damaged BTS—Base Transceiver Station, etc.), communication alternatives should be developed, such as interconnection of the internal network with a satellite system.
4. Since power to critical systems could be interrupted by mechanical damage to electrical conductors (e.g., from flying debris), power cables should be protected by installing in conduit rather than exposed in cable trays.
5. For some critical systems, a backup power supply should be installed in the immediate vicinity of the critical system (however, other risks need to be assessed, e.g., in conjunction with a battery backup power supply fire).
6. If there is an early warning of an approaching wind event, the following steps could be taken in preparation:
 - a. Limiting production to critical facilities only;
 - b. Providing special elevated storage for water-reactive substances, catalysts, and other high-value substances;
 - c. Provide protected storage for materials that might not be completely contained, such as flexible and rigid intermediate bulk containers.
 - d. Adjust delivery schedules, and limit (or completely cancel) material deliveries before the storm hits;
 - e. Ensure that fuel supplies in backup sources are full and that battery sources are fully charged;
 - f. Warn employees not to come to work on the day of the storm, or send them home, except for specified persons (e.g. those operating critical equipment or systems);
 - g. Test backup power supplies and re-train personnel in emergency procedures;
 - h. Test emergency shut-off valves to and from atmospheric and pressure storage tanks, in the event of damage to the pipelines (e.g., due to displacement of the tank).
 - i. Provide passive barriers or restraints for lightweight structures such as shelters, walkway covers, and shed roofs.
 - j. A protection zone, that is, the minimum distance that must be maintained between the protected equipment and a potential hazard, should be provided around vulnerable equipment such as aboveground natural gas or product pipelines, electrical substations, transformers, and gas regulating stations. Such hazards may include trees, cranes, slender process equipment, or other objects that could fall due to wind and cause damage to the equipment.
 - k. Ensure that the full start-up procedures are followed when processes are shut down deliberately or as a result of power failure, rather than attempting “hot starts” without the full procedure.
 - l. Tall and slender equipment that could be susceptible to wind-caused vibration should be identified to determine the extent of hazard and the vibration-control measures that might be needed.

6 | CONCLUSION

Studying past events and identifying accident scenarios provides valuable insights that can be used to increase the safety of industrial

facilities to extreme weather events. Despite the relatively small amount of records obtained on extraordinary events caused by wind, it is possible to learn from this information. The effect of wind is not the most common cause of NaTech,²⁰ but even here, significant damage occurs, especially financially. From the literature search, it also seems that there is no comprehensive information about this phenomenon and its effect on the industry. From this point of view, the knowledge base about this phenomenon needs to be expanded. Gathering information plays a vital role in this. An interesting initiative in this regard is the creation of the eNATECH database,²¹ where it is possible to obtain some information about NaTech. It currently contains 89 records of varying degrees of detail.

One of the key aspects is the preparedness of operators for situations where the power supply to critical systems is interrupted. Part of the risk analysis should be the identification of critical systems dependent on electrical power and the determination of procedures for their safe shutdown and start-up. Due to climate change, it may be advisable to assume an increase in the frequency of storms and their intensity. This fact should also be reflected in the risk analysis.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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