

## Impacts, Vulnerabilities and Adaptation to Climate Change in Establishments with Major-Accident Hazards in Italy

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The main scientific sources agree that, in the next decades, European and Mediterranean regions (including Italy) will have to face the negative consequences of climate change, which are producing extreme events with an increase in frequency and/or intensity of: a) extreme temperatures (heatwaves); b) ultraviolet radiation; c) heavy rainfall; d) drought; e) wildfires; f) strong winds, etc., etc. In the absence of drastic and immediate mitigation policies (which address the causes), climate change is bound to continue, making complementary adaptation actions (which address the consequences) necessary at various levels, aimed at limiting the vulnerability of exposed systems and strengthening their resilience, while preventing or reducing the risks associated with climate change. Industrial activities, particularly those falling within the scope of the legislation on major accident hazards (European Directive 2012/18/EU), almost never take into account adaptation measures to the effects of climate change.

Although never explicitly highlighted, various parts of Directive 2012/18/EU can be combined into a single strategy that takes climate change adaptation into account. The purpose of this article, following the institutional experience of the authors, is to provide useful elements for the climate adaptation of industrial establishments with major-accident hazards, with the aim of revising and integrating: safety reports, emergency plans (both internal and external), documents related to the control of urbanization surrounding these establishments, documents related to domino effects, etc. etc. In this way, the negative effects of climate change can be reduced on: 1) the safety and health of workers and citizens living near industrial plants; 2) the environment; 3) economic damage to production.

**Keywords:** Climate change, Seveso Directive, major-accident hazards, workers' health, citizens' health

### 1. Introduction: causes of climate change

The term climate change refers to a change in the state of the climate that persists for an extended period, typically decades or longer, and which can be detected by changes in the mean and/or variability of its properties. Even without neglecting the effects of natural phenomena, the majority of the international scientific community agrees that "*much of the warming observed over the past 50 years is attributable to human activities*" (Intergovernmental Panel on Climate Change, IPCC, 2022). Industry, agriculture, animal husbandry, transportation, the heating and cooling of homes, and waste management are human activities considered responsible for the uncontrolled increase of "greenhouse gases" in the atmosphere. This results in the intensification of the greenhouse effect, which is responsible for the increase in the Earth's global average temperature. Among the anthropogenic greenhouse gases, for which a significant increase in atmospheric concentrations is being recorded, we recall: a) carbon dioxide (use of fossil fuels); b) methane (animal husbandry, agriculture, landfills); c) nitrous oxide (use of fossil fuels, fertilizers, waste); d) fluorinated gases (artificial gases used for refrigeration).

Even if greenhouse gas emissions were to drop to zero immediately, the global climate system would continue to change for a long time because the concentrations of these gases would remain high.

The main scientific sources agree that in the coming decades European and Mediterranean regions will have to face particularly negative impacts from climate change which, combined with other effects due to human activity, will make Southern Europe and the Mediterranean area the most vulnerable areas in Europe.

The expected climate changes in Italy over the coming decades will lead to meteorological events such as heavy rains, lightning strikes, strong winds, storm surges, and extreme temperatures. All of this will cause significant impacts on civil and industrial structures and infrastructure. Although global efforts to reduce emissions are growing in numerous countries around the world and awareness of the importance of reducing climate-altering emissions is gaining increasing political weight (mitigation), some aspects of climate change are inevitable, and therefore complementary actions to adapt to its effects are necessary.

The IPCC (2022) defines mitigation as a human intervention aimed at reducing sources of production or improving the absorption of greenhouse gases, while adaptation is defined as an adjustment of natural or human systems in response to current or foreseeable climatic stimuli in order to limit potential damages as much as possible and exploit positive opportunities. Mitigation measures therefore aim to reduce the causes of climate change by attempting to contain its negative effects. Adaptation measures, on the other hand, are designed to reduce the inevitable impacts of climate change both in the short and long term.

This article focuses on the topic of adaptation to climate change with exclusive reference to industrial activities with a major accident hazard in Italy.

## 2. Vulnerability and resilience to climate change. Potential impacts and residual impacts.

Industrial activities, particularly those falling within the scope of the legislation on major accident hazards (European Directive 2012/18/EU, the so called “Seveso Directive”), almost never take into account adaptation measures to the effects of climate change. Although not explicitly highlighted, various parts of the Seveso Directive can be integrated into a single strategy that considers climate change adaptation.

IPCC (2022) defines vulnerability as *“the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt”*.

Resilience, vice versa, is defined *“as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation”* (IPCC, 2022).

Therefore, vulnerability and resilience are intertwined concepts: a system vulnerable to climate change will have low resilience, and vice versa.

According to the recent approach of the IPCC, the concept of risk associated with climate change is based on three fundamental components: hazard, vulnerability and exposure. Risk arises when, in a specific place and at a specific time, a vulnerable receptor, which can suffer the consequences triggered by the danger, is exposed to a source of danger.

The impacts of climate change are defined by the IPCC (2022) as the consequences of realized risks on natural and human systems, where risks result from the interaction of climate-related hazards (including extreme climatic events) with exposure and vulnerability. These impacts can be classified into (Fig. 1): a) Potential impacts: all impacts that may occur as a result of a projected climate change, in the absence of adaptation; b) Residual impacts: impacts that would occur after adaptation. For risk assessment purposes, these residual impacts must be within acceptable limits.

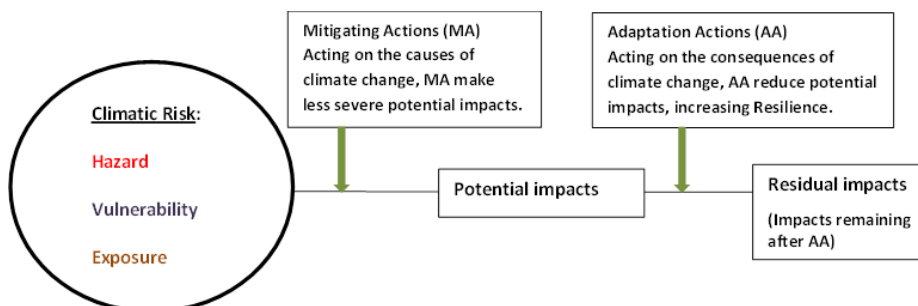


Figure 1: Relationship between climate risk, potential impacts and residual impacts

### 3. Climate change: vulnerability of critical elements in establishments at risk of major accidents (Seveso)

In this article, critical equipment refers to the technical systems for the primary containment of hazardous substances that may be involved in incident sequences caused by meteorological events such as heavy and/or extreme rainfall, lightning strikes, strong winds, and extreme temperatures.

Such extreme weather events can give rise to Natech events (Natural Hazard Triggering Technological Disaster), such as fires, explosions, and toxic releases, which may extend beyond industrial facilities (Muratore et al., 2022; Muratore et al., 2024). In this way, the negative effects of climate change can be extended on: 1) the safety and health of workers and citizens living near industrial plants; 2) the environment; 3) economic damage to production. The facilities where these primary containment technical systems are present include the chemical and process industry, fuel storage facilities (liquid or gaseous), etc.. In order to identify the vulnerability of these primary containment technical systems for hazardous substances, based on field experience, the authors believe that such vulnerability mainly depends on: a) the type of equipment (e.g., atmospheric tank or pressure tank); b) the type of hazardous substance; c) the operating conditions (pressure, temperature, physical state, volume); d) the different types of damage mechanisms associated with each type of equipment. It is proposed to identify the critical equipment by following these 4 steps:

**1° step:** Distinction of equipment containing hazardous substances: atmospheric or pressurized.

**2° step:** Type of hazardous substance contained in the equipment. It is essential to catalogue the hazardous substances present in the installations by analysing the safety data sheets, using the hazard indications (Hazard statements H or supplementary hazard information EUH 0xx reported in the European CLP Regulation No. 1272/2008). In particular, we can encounter: Heat-sensitive substances (H251, H252, H240, H241, H242, H230, H231), water-reactive substances (H260, H261, EUH 014, EUH 029, EUH 031, and EUH 032), air-reactive substances (H250, EUH 019).

**3° step:** Working conditions. It is necessary to take into account the process and storage conditions of these hazardous substances and how they influence potential accidental scenarios. For example, some qualitative considerations are provided, which typically aid in risk analysis:

a) The higher the storage and processing temperature of the hazardous substances present, the greater the damage resulting from release scenarios.

b) High pressure generates a driving force that results in a high release velocity of hazardous material in case of rupture or leakage of a primary container holding a dangerous substance. Additionally, if a gas is under pressure, it means that a larger quantity of the substance is stored. Furthermore, in the event of a structural failure of a pressurized storage system, the projection of fragments in all directions must be taken into account.

c) The physical state of the substance influences the amount of hazardous substance present. Liquids contain a higher amount of hazardous substances per unit volume compared to gases. However, gases have other properties that make them dangerous. They are usually stored and processed under high pressure.

d) Liquefied gases under pressure (e.g., LPG, LNG) have hazardous properties as they have a high density, comparable to that of liquids, are stored under pressure, and evaporate immediately upon release into the atmosphere.

e) Superheated liquids behave similarly to liquefied gases under pressure. Liquefied gases at very low temperatures exhibit the same behavior as liquids and generally do not ignite upon release. However, they evaporate much more rapidly than most liquids.

f) Importance of the volume of hazardous substances. Some processes are inherently larger than others, meaning they involve greater quantities of hazardous substances. In such cases, the potential accident scenarios are significantly extensive, and in some instances, these scenarios extend beyond the boundaries of the facility.

**4° step:** It is necessary to take into account the different modes of damage depending on each type of equipment. Table 1 presents the main modes of damage observed in Seveso establishments, based on the authors' experience, in relation to events resulting from climate change: heavy and/or extreme rainfall, lightning, strong winds, and extreme temperatures (both low and high).

*Table 1: Main damage mechanisms occurring in Seveso establishments due to events related to climate change (heavy and/or extreme rainfall, lightning, strong winds, and extreme temperatures).*

Damage Mode	Heavy/extreme rainfall	Lightning	Wind	Extreme temperatures (low/high)
Buckling			X	
Rupture of pipes and fittings			X	X
Tearing			X	
Support leg failure			X	
Displacement			X	
Overturning			X	
Puncturing damage		X	X	
Ignition and sparking		X		
Overfilling	X			
Fixed roof damage	X	X	X	X
Floating roof damage	X	X	X	X

Below is a concise description of the main damage mechanisms affecting equipment in Seveso establishments. Furthermore, for each type of damage, it is specified whether it affects atmospheric tanks (fixed or floating roof) or pressurized tanks:

**Buckling damage.** Deformation of metal enclosures in case of strong wind. This type of damage mainly occurs in atmospheric tanks.

**Rupture of pipes and fittings.** Damage to piping generally leads to a loss of containment. This type of damage can occur primarily in atmospheric tanks and pressure tanks.

**Tearing of metal shell.** In the case of strong winds, if the deformation is sufficiently large, the sheets composing the shell of a tank may delaminate and cause a loss of containment (LOC). This type of damage primarily occurs in atmospheric tanks.

**Support leg failure.** Many pieces of equipment are equipped with support legs to bear their weight. If these support legs are not designed to withstand horizontal forces (such as seismic activity, water mixed with debris, wind, etc.), they may lead to the collapse of the entire technical system, resulting in the release of hazardous substances. This type of damage can occur primarily in atmospheric and pressurized tanks.

**Displacement and overturning.** Strong winds (like earthquakes and floods) can exert significant forces on equipment, causing translation and rotation phenomena that may lead to content loss. This type of damage can occur primarily in atmospheric and pressurized tanks.

**Puncturing damage.** Sharp objects propelled by winds, floods, earthquakes, etc., against equipment and pipes can cause deformations and punctures, leading to content leakage. This type of damage can occur primarily in atmospheric tanks.

**Ignition and sparking.** In addition to lightning, another cause of ignition is earthquakes and floods. They can induce violent movements of metal parts that may collide or brush against each other, generating sparks. This type of damage primarily occurs in atmospheric tanks.

**Overfilling.** During floods, water can spill into critical units containing hazardous substances. In this case, the unit is not technically damaged but its operation is affected, and containment is still compromised. This is a frequent Loss of Containment (LOC) event for parts of process plants. This type of damage primarily occurs in atmospheric tanks.

In conclusion, it is highlighted:

- atmospheric tanks (both fixed-roof and floating-roof) are subject to various damage mechanisms related to events driven by climate change. Given that atmospheric tanks are generally large in size, incidents involving them are almost certainly major accidents, potentially causing fires, explosions, and environmental damage due to the release of hazardous substances.
- pipes have different types of damage in relation to events resulting from climate changes. However, considering that the volumes of hazard substances are generally much lower than atmospheric tanks, there will be no major accidents.
- pressure equipment (columns, vessels, spheres, heat exchangers, reactors, pressure tanks, etc.) have fewer damage mechanisms compared to atmospheric tanks. However, given their operating conditions (pressure, temperature, etc.), the failure of such equipment almost inevitably leads to major accidents, causing fires, explosions, and environmental damage due to the release of hazardous substances.

#### 4. Operational experience in Seveso establishments following extreme meteorological events

Below are some cases observed by the authors during their field experience, when exceptional meteorological events affected establishments with a major accident hazard, placing the facilities in critical conditions and putting safety systems under stress.

**A) Emergency situations due to heavy and/or extreme rainfall.** The exceptional occurrence of high and/or extreme rainfall caused the overflow of the storage tanks dedicated to collecting wastewater from containment basins and yards, further exacerbated by a power blackout. The blackout made the automatic emergency shutdown procedures ineffective, causing the overflow of storage tanks, and prevented the proper functioning of the pumping system for emptying the collection tank, containing water potentially polluted by hydrocarbons. **Corrective actions:** In both cases, an emergency procedure must be planned, including equipment (e.g., diaphragm) to mitigate the damage caused by exceptional events, as well as emergency power supply systems.

**B) Monitor the level of wastewater collection tanks.** B1) Due to the significant amount of rainfall collected by the yard drainage pumps during heavy/extreme rainfall, the collection tank was overfilled, leading to an overflow into the containment basin. **Corrective actions:** Appropriate level gauges have been installed in the tanks, with feedback in the control room and high-level alarm signaling.

B2) After heavy and/or extreme rainfall, the influx of wastewater raised the maximum level admitted in the tank, causing overflow through the overflow outlet and directing the water into the drainage collection pit, which is protected by normally closed valves. **Corrective actions:** The lack of an adequate procedure for the controlled emptying of the basins and a filling level signaling system for the tank was identified. Therefore, a tank level monitoring system was installed.

**C) Sudden flooding.** In a coastal fuel storage facility, strong winds caused a storm surge which, combined with heavy rainfall, led to a rise in sea level, hindering the drainage of rainwater and resulting in the flooding of the site and the collapse of the embankment of the adjacent canal. All this can occur due to a lack of maintenance of the channels adjacent to the plant. The flooding of the site caused a sudden shutdown of the facilities, resulting in a service disruption to the telephone network as well. **Corrective actions:** a) Establish a dedicated operational procedure for managing flood events. b) Implement alternative communication systems in case of emergency.

**D) Damage to structures.** D1) A windstorm caused the collapse of the perimeter wall of a facility, affecting the adjacent road and making it necessary to remove debris and secure the area. D2) Strong gusts of wind caused the detachment of the site's entrance gate, requiring structural and electrical restoration. D3) The heavy rainfall caused the collapse of part of the perimeter wall of the warehouse. **Corrective actions:** The event required the temporary restoration of the fence and the continuous monitoring of the area's subsidence while awaiting the design of a new containment structure.

#### 5. Effects on the health of workers, population and on the environment

Stormy winds, heavy and/or extreme rainfall can cause damage and/or collapse of structures, as well as the displacement and subsequent rupture of pressure tanks and/or atmospheric tanks and/or pressurized pipe located within the facility. The equipment generally does not leave the facility, but the loss of its integrity can cause fires, explosions, and the release of toxic substances. These circumstances can cause the following effects on the health of workers and population (Grillone et al. 2024): 1) in the event of a fire involving flammable substances, the effects of heat and combustion fumes can cause burns, intoxication and damage to the respiratory tract; 2) in the event of an explosion, the effects due to the shock waves can show distant throwing of material, causing trauma; 3) in the event of toxic release (substances released in the gaseous state), there may be cases of acute intoxication caused by inhalation, ingestion or contact with the toxic substances, causing malaise, watery eyes, nausea, difficulty breathing, loss of consciousness and, in more severe cases, lethal effects. Obviously, the effects of the accident are much more serious on workers, especially those who are close to the site of the accident and in any case within the plant, than population, because, although they are trained for such eventualities, they may be unprepared due to the speed and proximity to the accident site or a delay in the implementation of appropriate protective measures (e.g., putting on suitable masks or leaving the hazardous area and/or the establishment in an appropriate manner) and due to the shock of the accident itself. The effects in the areas surrounding the facility can be summarized as follows: 1) in the case of toxic release there is a possible contamination of the soil, water, atmosphere and food by the released substances; 2) damage to neighboring structures and in particular collapse of buildings or parts thereof, breaking of glass, damage to the plants with further explosions, fires (possible domino effect).

The corrective actions suggested to the employer, in order to promptly respond to incidental events in the initial phase, consist of continuous training and education of plant personnel, timely communication with the competent public authorities, and adequate information for the population living in areas near establishments at risk of major accidents, with particular attention to emergency-related information.

In relation to the above, the manager/employer of the establishment at risk of a major accident must collect, in the safety report, historical information, including data on extreme meteorological events (European Directive 2012/18/EU), and implement the corrective actions deemed most appropriate for their specific case.

## 6. Conclusions

Industrial activities are generally not perceived as sectors vulnerable to climate change.

The purpose of the article, in light of the authors' institutional experience in Italy, is to provide guidance on climate change adaptation to managers/employers of establishments with a risk of major accidents. The aim is to ensure that the safety report of the facility includes historical information on extreme meteorological events (such as heavy and/or extreme rainfall, lightning, strong winds, and extreme temperatures). Such events can cause stress on facilities and their related safety systems, potentially triggering major accidents (Natech). In this regard, it is advisable to adapt safety management systems (which are mandatory for Seveso establishments, as required by the Seveso Directive), as well as internal and external emergency plans in cases of accidents resulting from such events.

In the article, four steps provide further guidance to identify the vulnerability of the main critical elements in establishments with a major accident hazard to climate change.

Finally, following cases of operational experience in Seveso establishments, appropriate corrective actions have been identified, both from a technical and procedural perspective, to address exceptional meteorological events.

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