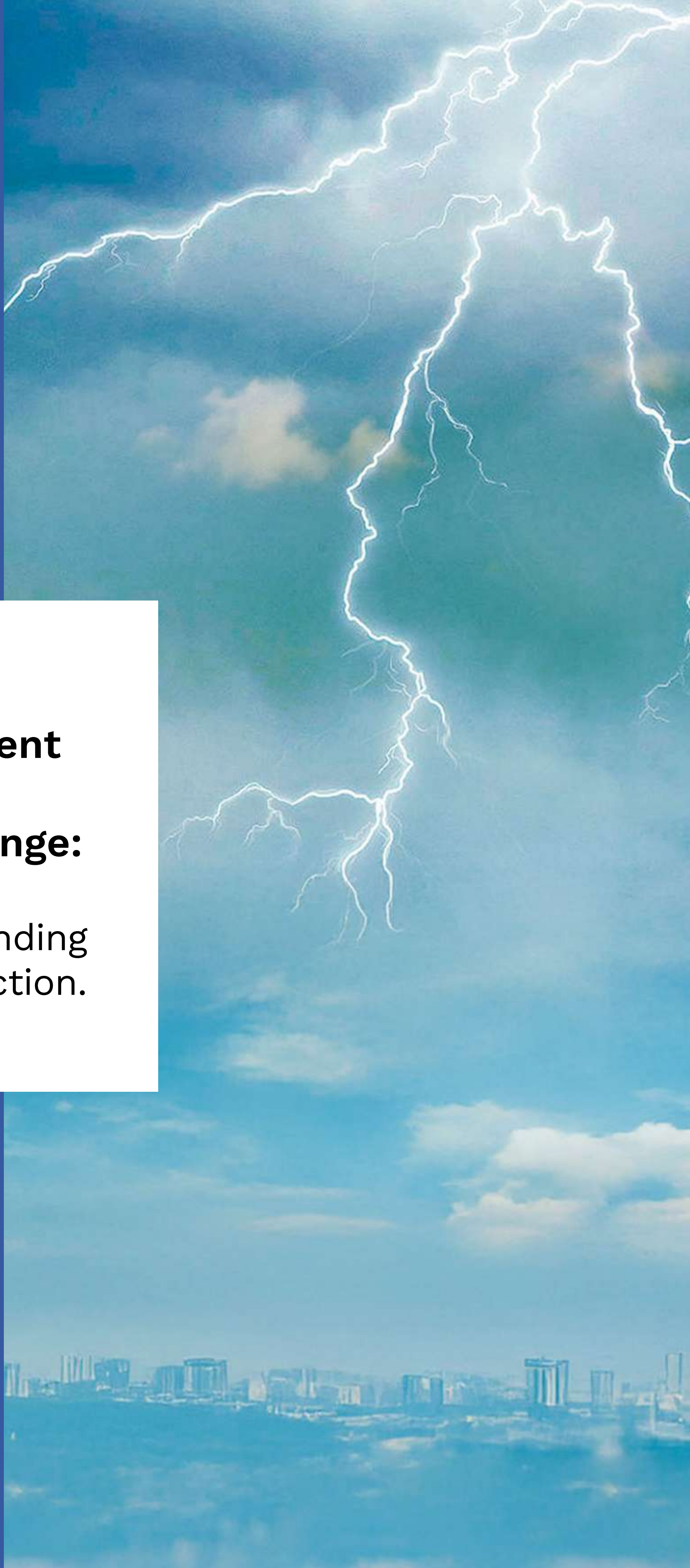
EY Shape the future with confidence

Lightning risk management in the age of climate change:

Better understanding for better protection.



Indelec
SMART LIGHTNING SOLUTIONS

Summary

1— Introduction

Lightning, a major and underestimated risk that engages the responsibility of many professional.

Lightning is a frequently underestimated hazard, yet it carries severe consequences for human safety, business continuity, infrastructures, and the cost of damage.

In a context where extreme weather events are multiplying worldwide, mastering lightning risk has become a major technical, regulatory, and economic challenge.

Lightning is a complex phenomenon, often poorly understood and misunderstood.

This white paper is designed **to raise awareness and provide clear information** on these issues, in accessible language, to **professionals exposed to such risks** in the course of their activities:

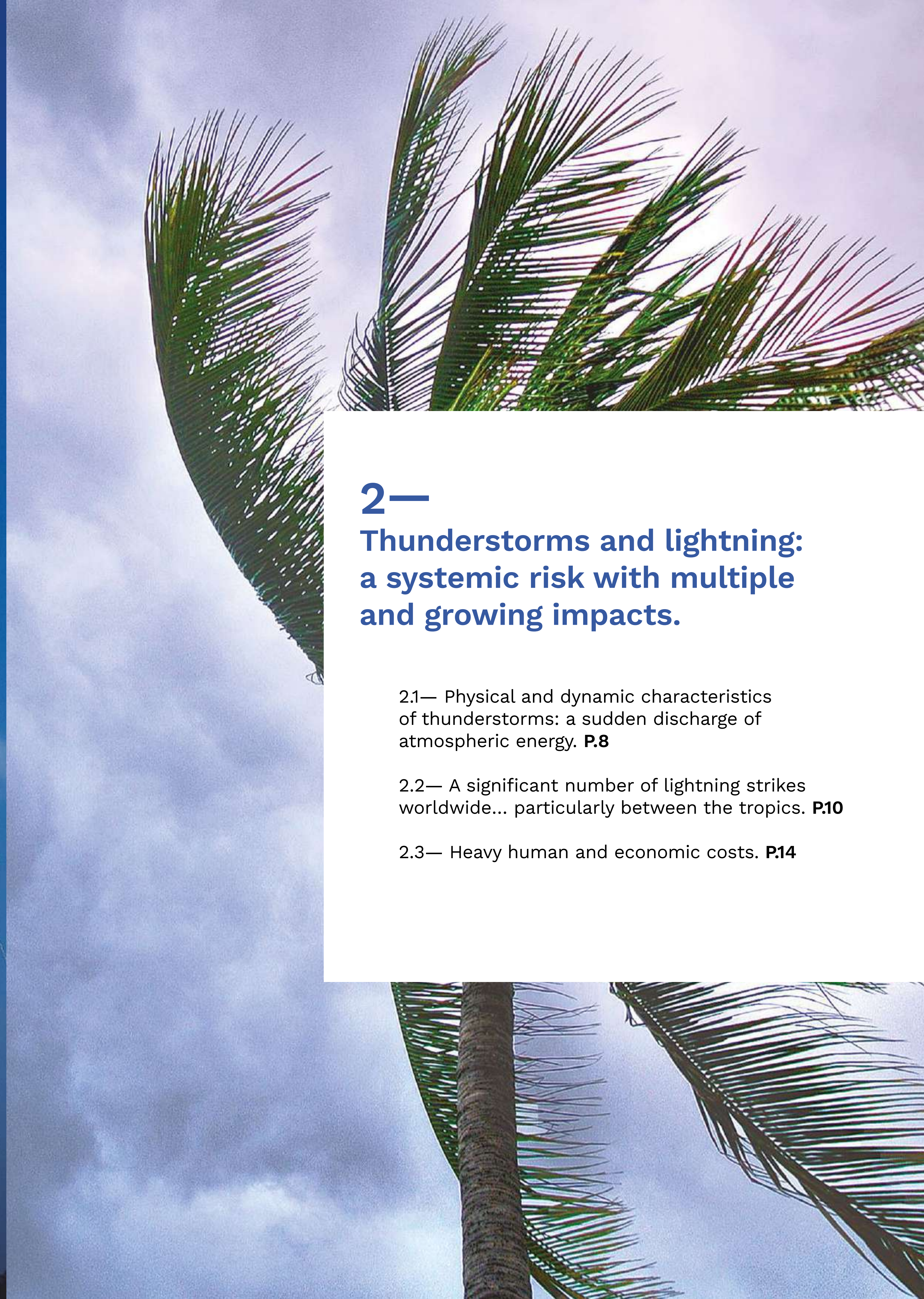
> Design engineers, maintenance managers, technical specifiers, managers of public buildings, insurers and operators of critical infrastructures…

Based on a **study conducted by Ernst & Young Advisory ("EY") on behalf of Indelec**, it relies on a plural methodological foundation:

- **+15 interviews carried out as part of this study** (with standardization experts, industrial project owners, international engineering consultancies, and distributors operating in the most exposed regions);
- **Indelec's internal data**, derived from field experience feedback;
- **Indelec client case studies** in real operational contexts;
- **Analyses conducted by EY** on several dimensions indirectly linked to lightning protection (e.g. claims costs, climate trends, prospective studies, etc.).

These findings show that **the demand for expertise is growing**.
However, lack of awareness of the risk, the complexity of standards, and the absence of reliable benchmarks continue to hinder the widespread adoption of solutions that are both available and effective.

→ **This white paper therefore aims to strengthen the understanding of lightning risk, provide technical keys to interpretation, and support decision-makers in making informed choices.**



2—
Thunderstorms and lightning: a systemic risk with multiple and growing impacts.

2.1— Physical and dynamic characteristics of thunderstorms: a sudden discharge of atmospheric energy.

Thunderstorms rank among the most spectacular and dangerous meteorological phenomena. They manifest through a combination of intense events: **electrical discharges (lightning and strikes), violent winds, torrential rainfall, hail, and even abrupt variations in atmospheric pressure**. Far from being anecdotal events, they reflect a violent **energy imbalance** between atmospheric layers and the ground, unleashing forces capable of inflicting significant human, material, economic, and environmental damage.

Among the most striking manifestations of thunderstorms, lightning is a phenomenon of **extreme physical intensity**. Each lightning strike can represent over one billion volts and carry an average current of 30,000 amperes, with peak intensities exceeding 200,000 to 300,000 amperes in extreme cases. The temperature in the lightning channel can exceed 30,000°C — about five times hotter than the surface of the Sun. Such energy can instantly carbonize a tree, pierce a roof, ignite an electrical installation, or trigger critical shutdowns in energy, communication, or transport networks.

Yet lightning represents only one dimension of the threat. Downdrafts associated with certain thunderstorms can exceed 150 km/h, causing damage comparable to that of a tornado. Hailstones, sometimes several centimeters in diameter, can destroy roofs, greenhouses, vehicles, crops, and industrial equipment. Intense rainfall can also cause flash floods, endangering entire areas, often with very little time to react.

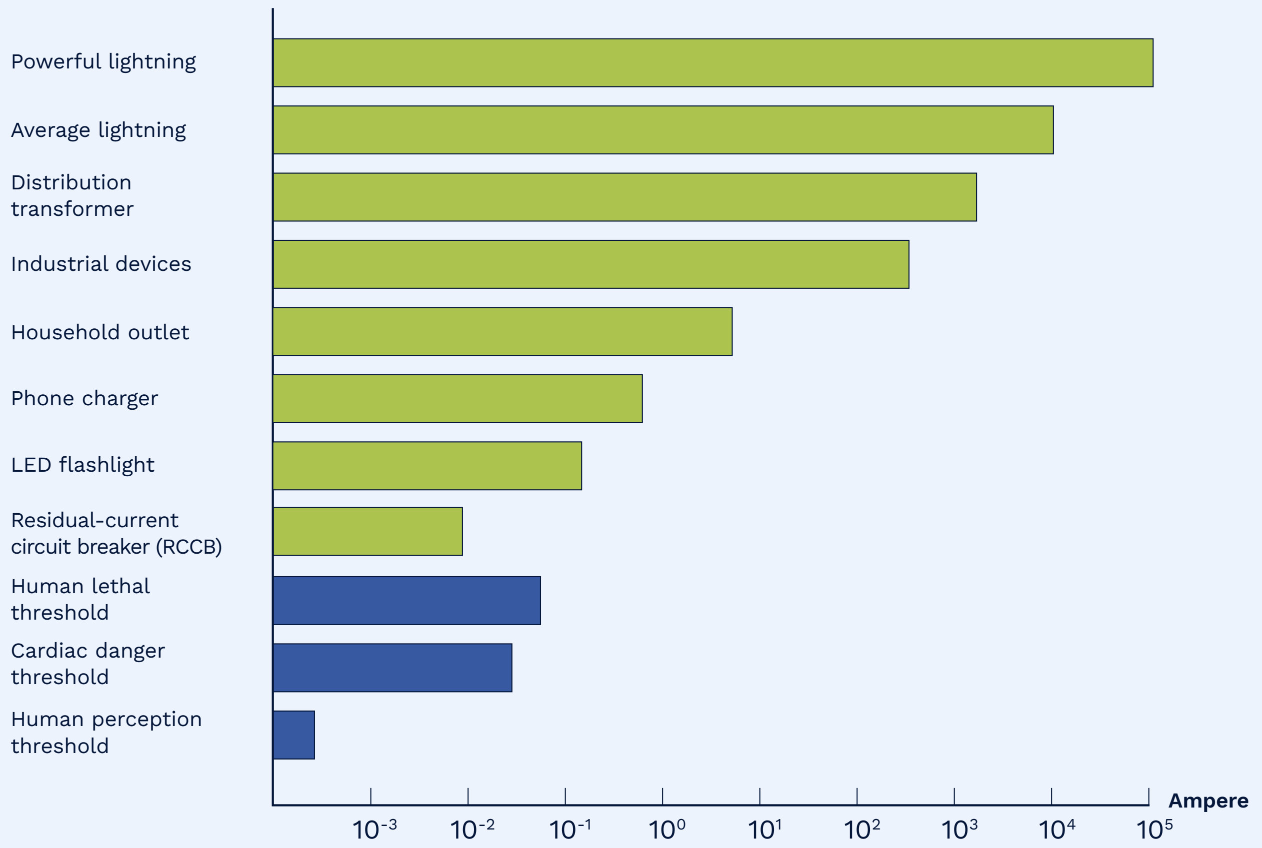
The recurrence of these phenomena on the same site (sometimes several dozen times a year) makes them a chronic risk rather than a rare hazard.

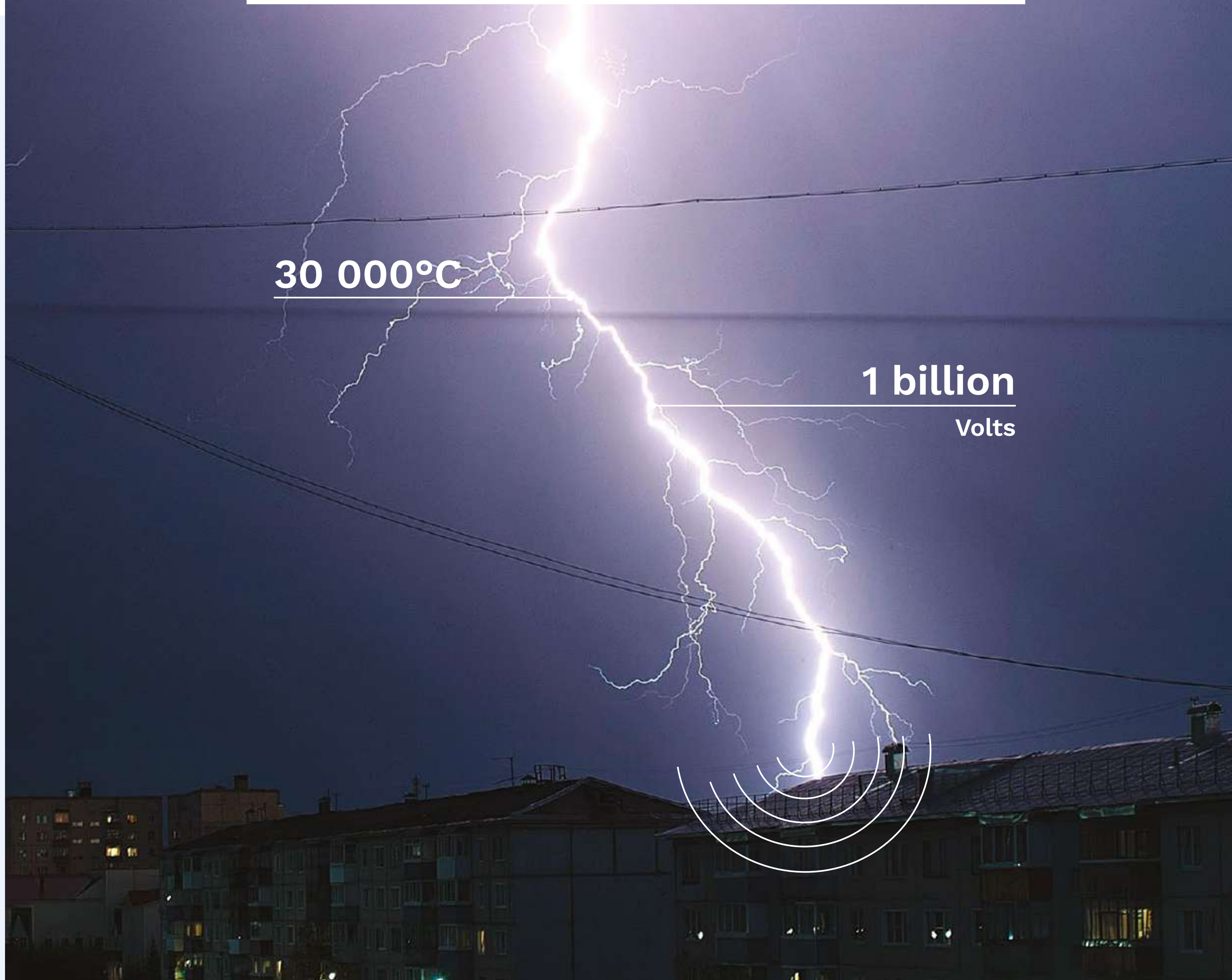
Their intensity, frequency, and diversity render thunderstorms particularly formidable in a context where infrastructures are increasingly dense, interconnected, and therefore fragile.

These infrastructures now house critical electronic and IT equipment, **highly vulnerable to surges and induced discharges from lightning.**

It is this complexity of storm-related risk, of which lightning is one of the most powerful markers, that must today be **better understood, anticipated, and controlled.**

Comparative overview of electrical intensities, from everyday life to extreme phenomena.





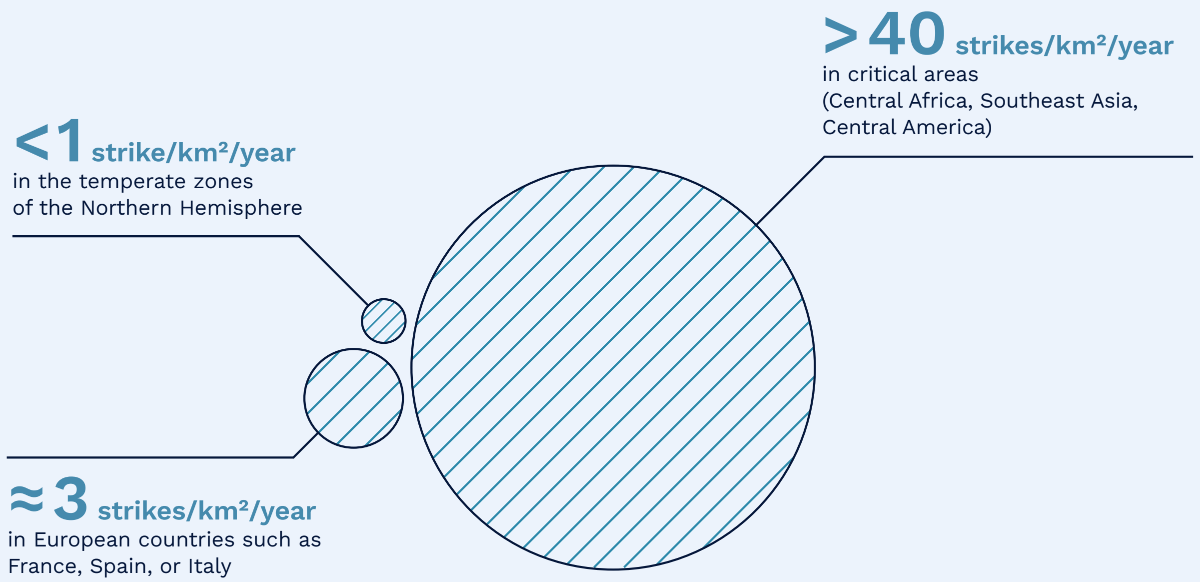
2.2— A significant number of lightning strikes worldwide... particularly between the tropics.

Every year, several tens of millions of lightning strikes hit the ground across the globe. Satellite data show that lightning ground flash density (Ng) follows a relatively stable distribution over time:

- **Land areas are more affected than seas,** due to stronger thermal contrasts.
- **While activity is particularly intense in certain tropical and subtropical regions** — where high humidity, heat, and ascending air currents favor the formation of powerful, frequent, and sometimes stationary storm cells — the risk is far from confined to these zones.

However, this situation could change: several scientific studies (see section 3 “Climate change aggravates lightning risk”) suggest that **climate change may significantly increase storm activity, even in regions currently considered moderate.**

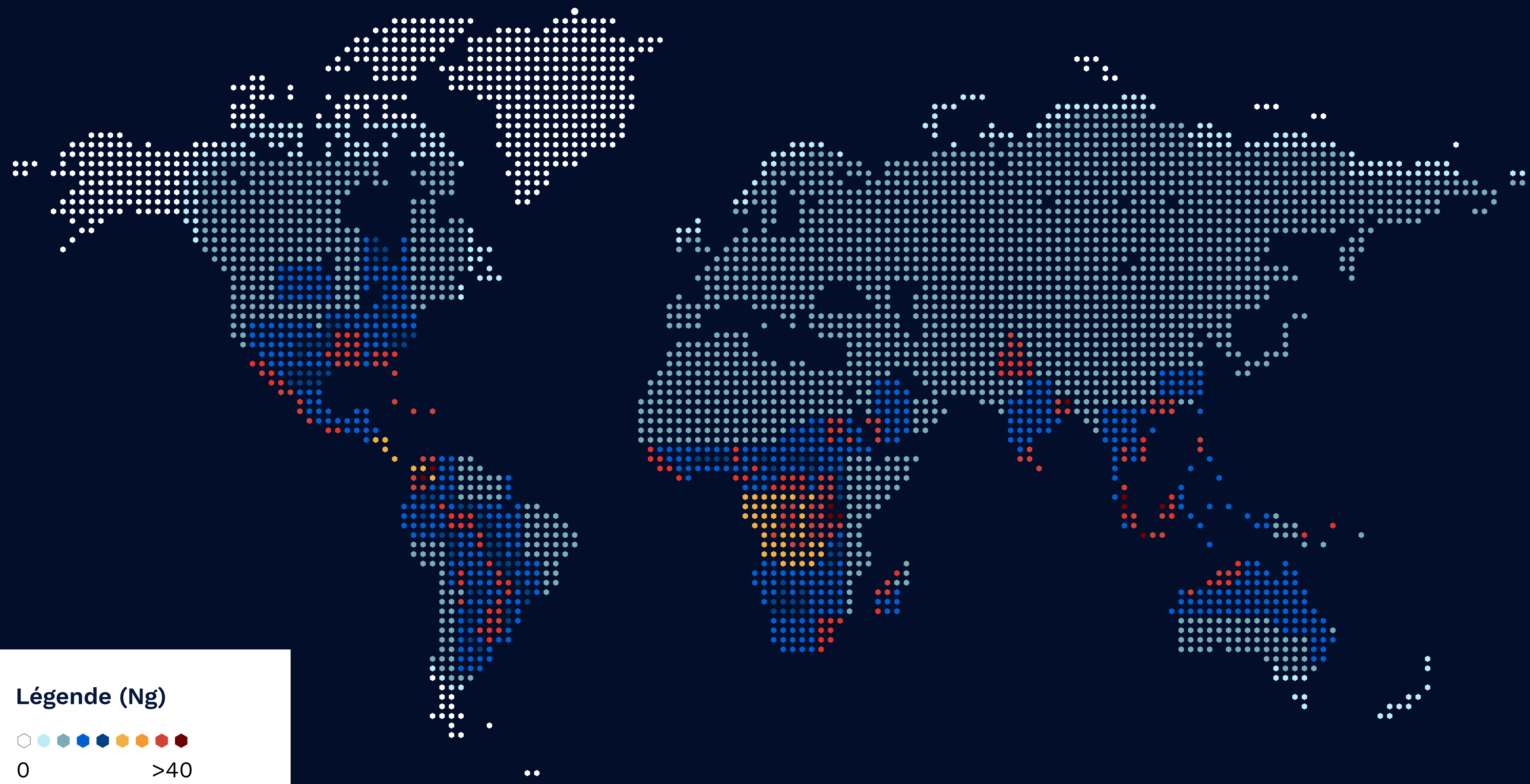
The average Ng observed is:



Every year, **several tens of millions of lightning strikes** hit the ground around the world.

→ Well-identified lightning *hotspots*.

Equatorial Africa, Southeast Asia, and Central America are among the most lightning-prone areas in the world, but **no inhabited region is completely spared.**



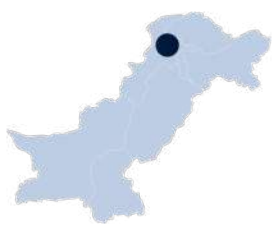
Légende (Ng)

0 >40

Cáceres, El Tarra (Colombia)
In Colombia's mountainous and tropical regions, certain municipalities face particularly critical lightning strike frequency, affecting both rural areas and urban infrastructures.

Kuala Lumpur (Malaysia)
Kuala Lumpur, the capital of Malaysia, is today considered the most lightning-struck city in the world. Thunderstorm activity peaks during the monsoon season, with extremely high localized ground flash density.

Daggar (Pakistan)
During the monsoon, the city of Daggar, in the Khyber Pakhtunkhwa region, experiences exceptionally violent thunderstorms, with frequent lightning strikes and destructive winds.



Kabare (Democratic Republic of Congo)
The municipality of Kabare, in eastern DRC, records one of the highest keraunic levels (Nk) in the world, with a ground flash density (Ng) exceeding 40 strikes/km²/year. The entire African Great Lakes region is highly storm-prone.

Lake Maracaibo (Venezuela)
Located in northwestern Venezuela, Lake Maracaibo is the most lightning-struck region in the world, with activity almost daily. Up to 60 flashes per minute are observed, amounting to around 1.2 million lightning flashes per year. This phenomenon, known as the "Relámpago del Catatumbo", is linked to the site's unique geographical and climatic configuration.

* Nk: Value corresponding to the number of thunderstorms heard during a given period in a given location.

2.3— Heavy human and economic costs.

Thunderstorm phenomena — and lightning in particular — are responsible every year for dramatic loss of life and major material damage. Too often regarded as isolated events, they in fact represent a **structural risk for many territories and sectors of activity**. These losses are all the more concerning as they are rising in certain parts of the world, driven by the combined effects of growing urbanization, climate change, and the persistent under-protection of exposed populations.

A DEADLY HAZARD: Lightning still kills thousands of people every year.

Lightning remains today one of the deadliest natural phenomena. According to data compiled by NASA , **around 24,000 people die each year as a result of lightning strikes, and more than 240,000 are injured**. These figures are likely underestimated, especially in countries where monitoring and reporting systems are incomplete.

Persistently high mortality in some countries.

In India, **nearly 1,900 lightning-related deaths** are recorded every year, making it one **of the three leading causes of weather-related mortality. More than 100,000 people lost their lives to lightning there between 1967 and 20203**, with a sharp increase in fatalities during the last decade. Other highly exposed tropical countries (such as the Democratic Republic of Congo, Bangladesh, Myanmar, and Brazil) also record high levels of mortality, particularly in poorly equipped rural areas.

Severe physiological effects.

Direct lightning strike victims may suffer from severe trauma:

- Immediate **cardiac or respiratory arrest;**
- Deep internal and external **burns;**
- **Long-term neurological damage** (memory loss, cognitive disorders, brain lesions);
- **Deafness, blindness, or partial paralysis;**
- **Secondary injuries** from falls, blast effects, or panic situations.

Even when survival occurs, the consequences can be long-lasting and disabling, both physically and psychologically.

Preventing the worst: safety measures to adopt.

A large share of fatalities could be avoided through **better awareness of risky behaviors** and the dissemination of good practices:

- **Never seek shelter under an isolated tree;**
- **Avoid hilltops and open fields;**
- **Stay away** from windows, metal piping, and electrical appliances;
- Inside a **closed vehicle, keep windows shut** and avoid contact with metal parts;
- **Wait 30 minutes after the last lightning flash** before resuming outdoor activity;
- **Anticipate as much as possible and take shelter in a secure building,** ideally equipped with a compliant and regularly inspected lightning protection system.

HEAVY FINANCIAL LOSSES for economic actors impacted by lightning.

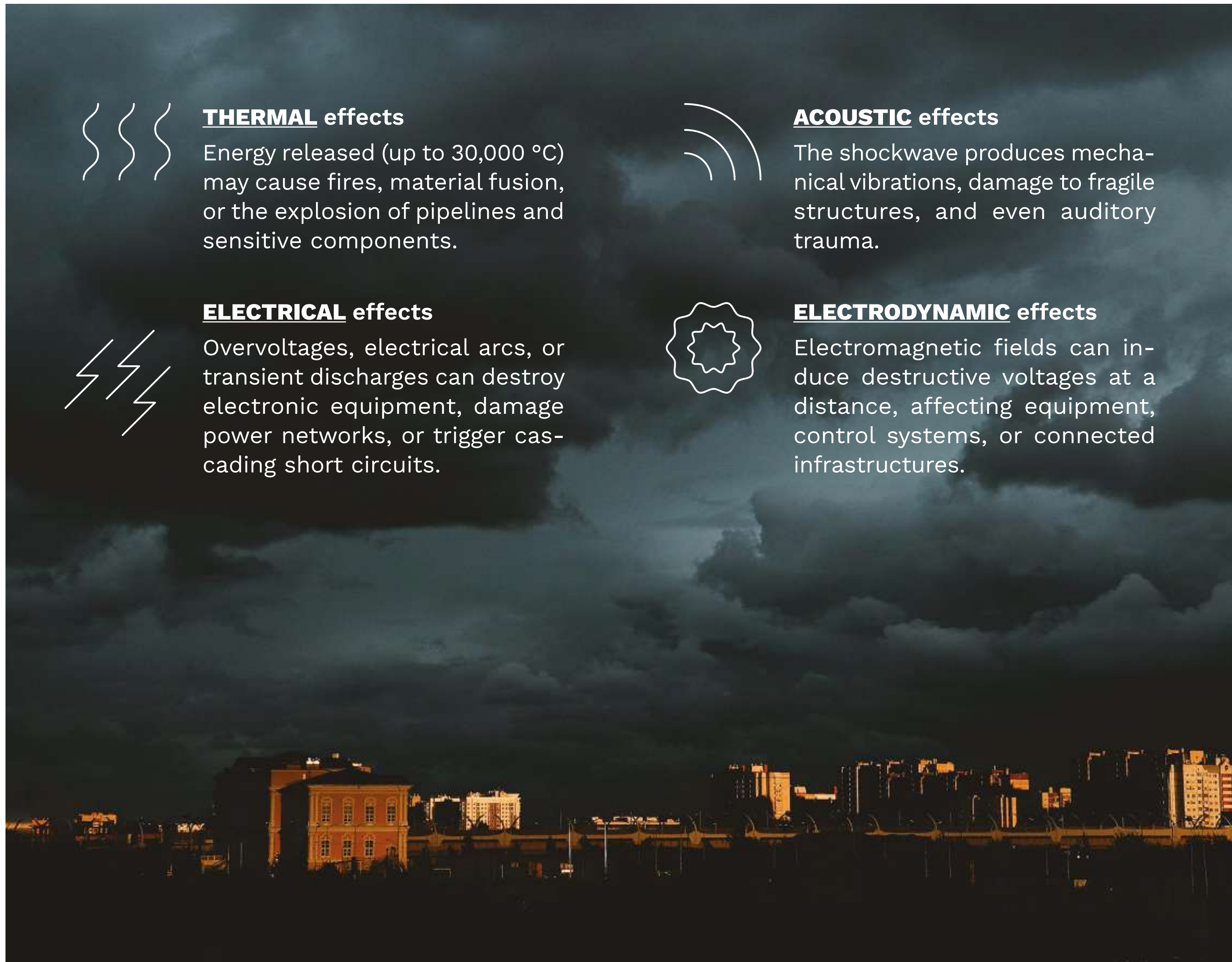
Beyond its human consequences, lightning generates **major economic losses** for both public and private stakeholders. Each strike or thunderstorm episode can damage or paralyze critical equipment, disrupt supply chains, halt production or commercial activities, and generate high costs for repair, compensation, or regulatory compliance.

The losses are not limited to visible damage: they also include **indirect effects** (business interruption, crisis management expenses, increased insurance premiums), and become even heavier when protection systems are absent, outdated, or poorly designed.

This vulnerability is further exacerbated by the increasing technologization of buildings, now equipped with sensitive electronic devices, IT networks, and automated control systems.

Varied and often severe damage to structures and equipment.

Lightning can generate **multiple types of destructive effects**, and **no type of infrastructure is spared**: commercial buildings, industrial sites, power lines, telecom antennas, agricultural equipment, wind turbines, solar panels, port facilities, or sensitive sites such as hospitals or data centers.



A record global bill in 2023: thunderstorms among the most costly natural disasters.

Lightning, as a key component of severe convective storms (SCS), contributed to making **2023 an unprecedented year in terms of insured storm-related damages**.

> **"Thunderstorms in North America and Europe have been more destructive than ever."**
>
> **– Munich Re,**
> 2024 Global Natural Catastrophe Report[3]

The key figures opposite, taken from the latest annual report by Munich Re, one of the world's leading reinsurance companies, help to grasp the scale of the phenomenon. →

Concrete and recent examples

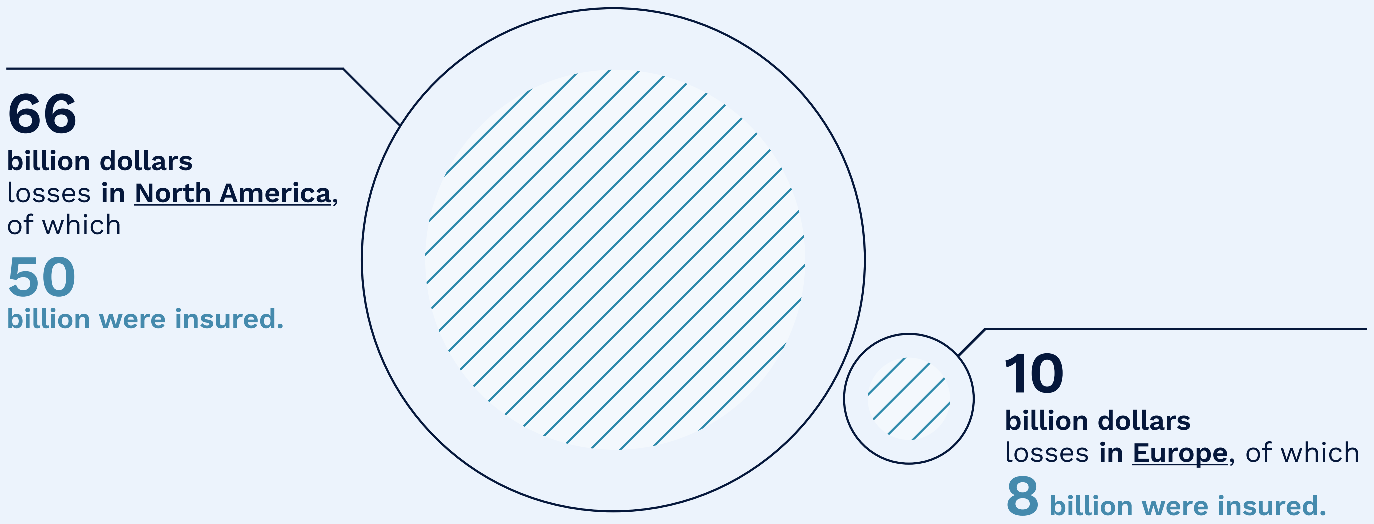
DATACENTERS
A striking example is the series of four successive lightning[8] strikes that hit the local power grid near a Google data center in Belgium. The building itself was not directly struck, but surges were induced through the grid, resulting in partial data loss on some hard drives. Even without a direct strike, lightning can disrupt or damage critical systems through connected networks.

OIL STORAGE facility
On 5 August 2022, lightning struck a fuel tank at the Matanzas[9] oil storage facility in Cuba, triggering a massive explosion and fire. The disaster killed 17 firefighters, injured between 80 and 125 people, and forced the evacuation of nearly 5,000 residents. The blaze spread to multiple tanks, releasing toxic smoke that reached Havana and raised fears of acid rain and energy shortages.

INDUSTRIAL incidents
Databases such as StruckByLightning record hundreds of incidents each year, ranging from explosions at petrochemical sites to production shutdowns in agri-food factories[4].

WIND farms
Numerous lightning strikes on wind turbines are reported. In the United States, for example, according to a 2023[5] analysis, 31% of U.S. wind farms experienced on average at least one strike per turbine, with some sites recording more than 10 strikes per turbine per year, causing annual losses estimated at several tens of millions of dollars (equipment damage, production downtime, etc.). (E.g. BBC[6], Le Marin[7])

Key figures



For context: **insured losses from SCS averaged USD 15 billion per year** over the past five years. In other words, **2023 losses were more than three times that average**.

> **"There have been loss spikes in the past, but 2023 is truly an exceptional year."**
>
> **– Steve Bowen**, meteorologist and Senior Vice President for Natural Catastrophe Solutions at Munich Reinsurance America

A CRITICAL RISK for a wide range of sensitive sites.

Lightning represents a **major cross-cutting risk** that threatens a wide diversity of high-value sites — whether economic, human, cultural, or strategic. Depending on the type of activity, the consequences of a strike can range from temporary service interruption to irreversible human, patrimonial, or environmental losses.

The complexity of these environments (technical, regulatory, operational) often **makes securing them challenging, and the consequences of under-protection potentially disastrous**.

1 Public venues, tourism, and leisure sites.

Outdoor public spaces are particularly vulnerable, due to the **direct exposure of people** and the **difficulty of managing evacuations** in the event of a storm.

- **Campsites, festivals, amusement parks, stadiums:** large open areas, high concentration of people, difficulty ensuring rapid sheltering.
- **Hotels, cultural centers:** risks of panic evacuation, business interruption, legal exposure in the event of an incident.
- **Remote sites (guest houses, mountain refuges):** complicated access for emergency services, extended response times.

Key issues

- Public safety,
- Reputation,
- Legal liability,
- Business interruption.

2 Industrial production sites.

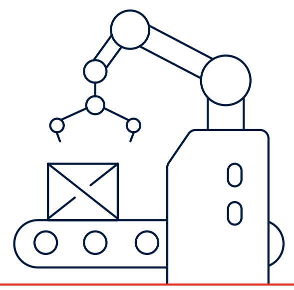
Some facilities **cannot afford even brief interruptions** to their operations.

Examples include:

- **Automated production lines** (robots, conveyors, sensors): unplanned shutdowns = immediate economic losses.
- **Electronic equipment** (PLCs, drives, switchboards): highly vulnerable to surges, costly failures and damage.
- **Sectors handling hazardous substances:** risk of fire or explosion in case of impact.

Key issues

- Business continuity,
- Installation safety,
- Financial losses,
- Insurance liability.



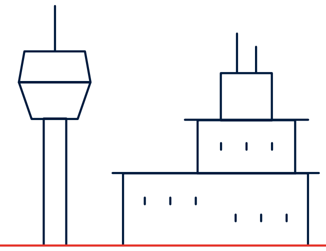
3 Critical service continuity sites.

Some sites **cannot tolerate the slightest downtime, even temporary**.

- **Data centers:** server destruction, data loss, cloud or hosted service outages, breach of contractual SLAs.
- **Air, rail, or maritime traffic control centers; radio/TV broadcasters; streaming platforms:** signal or communication outages.
- **Hospitals:** immediate danger to patients reliant on electronic medical devices.
- **Train stations, airports, metro systems:** logistical disruption, overcrowding, revenue losses.

Key issues

- User safety,
- Credibility,
- Contractual penalties,
- Systemic consequences.



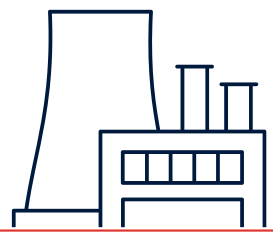
4 Sensitive or high-risk infrastructures.

Some sites, by their **strategic nature**, require maximum levels of protection.

- **Nuclear, petrochemical, explosive or fuel depots:** any incident could trigger a large-scale disaster.
- **Transformers, high-voltage substations, dispatching centers:** a single fault may lead to a regional blackout.
- **Military installations, defense radar or communication systems:** jeopardizing sovereignty and a state's capacity to react.

Key issues

- National security,
- Geopolitical vulnerability,
- Potentially extreme human and financial costs.



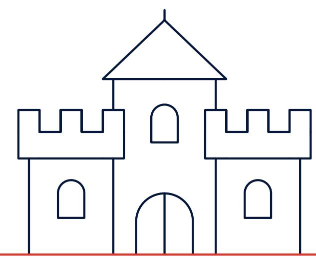
5 Heritage and cultural buildings.

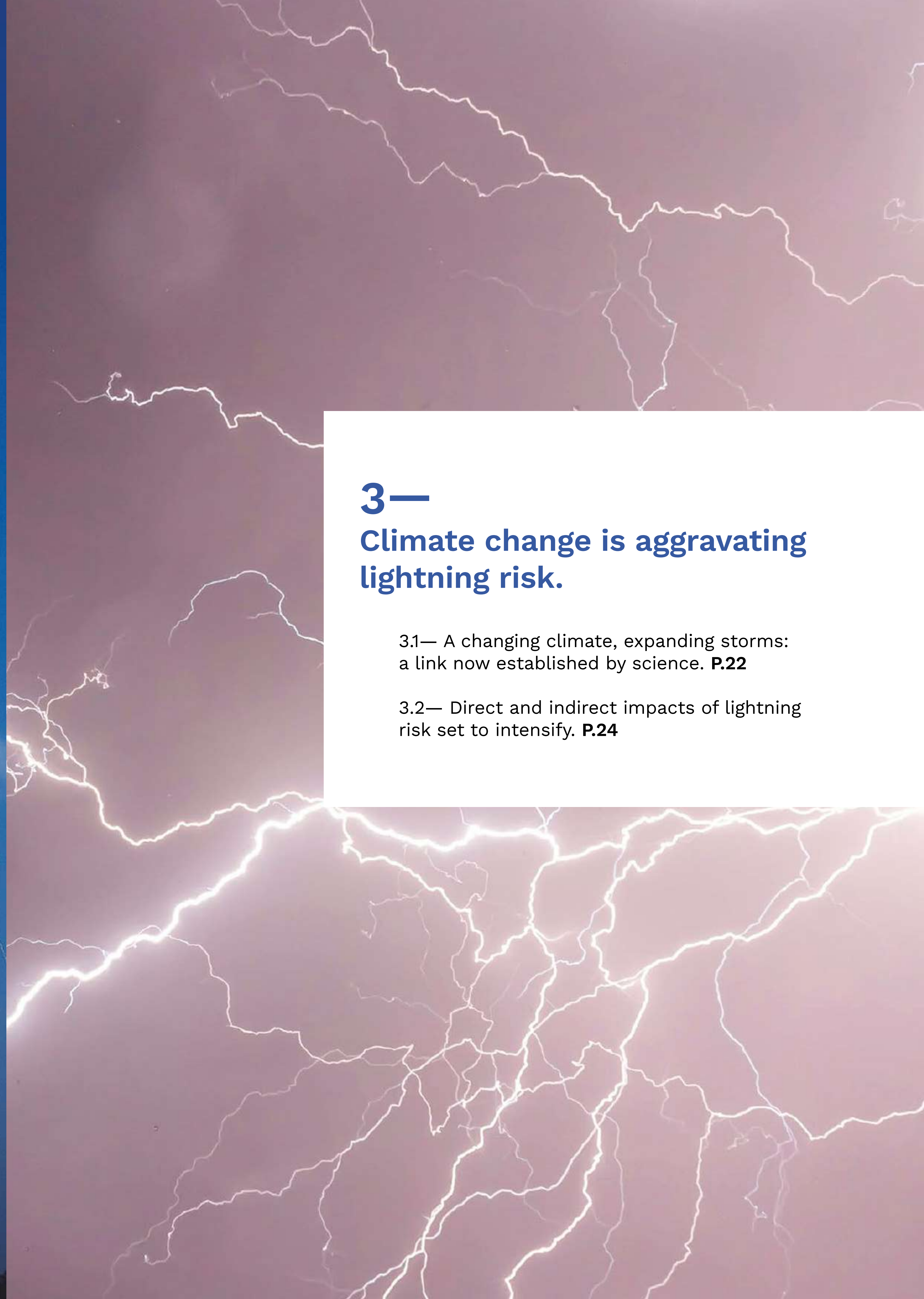
Historical monuments are **highly exposed and difficult to secure without compromising their aesthetic or architectural integrity**. In many cases, it is collective memory itself that is at risk through the loss of irreplaceable cultural heritage.

- **Churches, cathedrals, castles, historic theaters:** risk of fire, cracks, or collapse.
- **Museum collections:** damage due to surges, HVAC shutdowns, security failures.
- **Restoration works:** lengthy, costly, sometimes impossible to carry out identically.

Key issues

- Preservation,
- Restoration costs,
- Institutional reputation damage.





3—
Climate change is aggravating lightning risk.

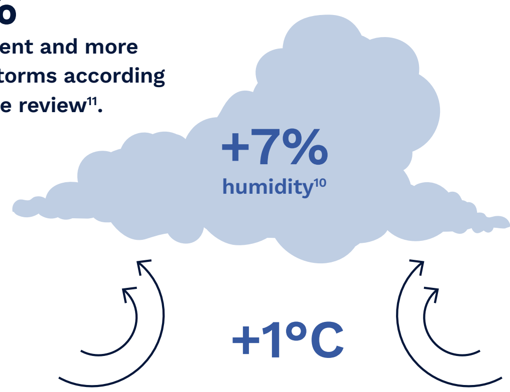
3.1—
A changing climate, expanding storms: a link now established by science.

Lightning is not exempt from the effects of climate change. Although often absent from discussions on natural disasters, it is now attracting growing attention from the scientific community. **Convective storms — of which lightning is a central component — are expected to become more frequent, more intense, and more widespread**, including in regions historically little affected.

A warmer atmosphere leads to more thunderstorms.

The principle is well known: **each additional degree of warming allows the atmosphere to hold about 7% more humidity** — a key factor in the development of storm cells. This phenomenon strengthens convection, i.e. the vertical movements of warm, moist air that feed thunderstorms. This applies both to **isolated thunderstorms** and to **supercells**, including in temperate regions (Europe, North America, Asia).

+12%
More frequent and more powerful storms according to a Science review[11].



Worrying numerical projections.

Climate models are consistent: lightning activity is clearly **projected to increase** over the coming decades. This increase is not just a matter of numbers: it means **greater risks for infrastructures, more potential victims, and higher economic losses** in regions that until now were only moderately exposed.

Most affected areas:

+50%
lightning strikes expected in the United States by 2100[12].

+41%
long-continuous-current (LCC) strokes expected by 2090 in some regions[6].

Air pollution: an unexpected amplifying factor.

The role of aerosols — fine particles from human activity — is increasingly being studied. Several recent works have highlighted a **correlation between atmospheric pollution and storm activity.**

Case study n°1[14]

Italy, Europe, spring 2020

During lockdown, **the Po Valley experienced a 70% drop in atmospheric electrical activity**. This decline coincided with the **sharp reduction in road and industrial traffic.**

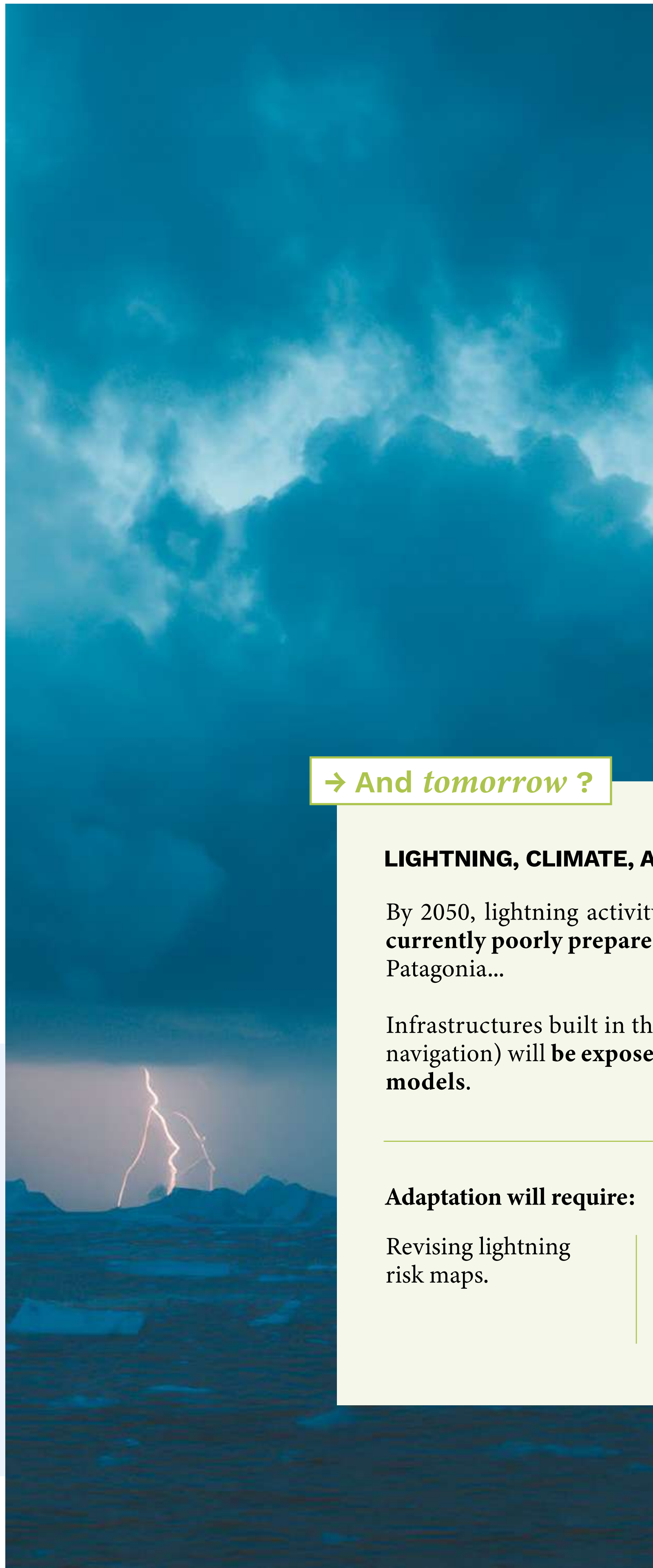
→ Researchers estimate that **36% of the decrease** in lightning was **directly linked to reduced fine particle emissions**.

Case study n°2

Strait of Malacca, Southeast Asia

On all the lightning data analyzed, over a period of 10 years, scientists demonstrated that **highly polluted maritime corridors showed intensified storm activity**[15].

→ **Pollution** linked to maritime traffic could **stimulate regional thunderstorm activity**.



The Arctic: a new storm theater.

A powerful symbol of this shift, the Arctic — long considered a "lightning-free zone" — is becoming a **new hotspot of storm activity**.

In 2010, the region accounted for only 0.2% of global lightning strikes. By 2020, this share had surged, with scientists recording an **800% increase in lightning activity** in the Arctic[13].

This spectacular evolution can be explained by several combined factors:
- **Accelerated ice melt**;
- **Rising summer temperatures**;
- The emergence of **unprecedented convective conditions** at high latitudes.

This disruption opens the door to **new risks** for northern populations, polar infrastructures, and Arctic navigation — all still poorly prepared for this emerging threat.

→ And *tomorrow* ?

LIGHTNING, CLIMATE, AND EMERGING RISK ZONES.

By 2050, lightning activity is expected **to increase significantly in regions currently poorly prepared**: Scandinavia, Russia, northern Canada, the Alps, Patagonia...

Infrastructures built in these areas (pipelines, roads, scientific bases, Arctic navigation) will **be exposed to a hazard still largely overlooked in resilience models.**

Adaptation will require:

Revising lightning risk maps.	Integrating lightning protection into sustainable building standards.	Investing in research to anticipate the "new red zones" of the 21st century.

3.2—
Direct and indirect impacts of lightning risk set to intensify.

The intensification of climate change does not only lead to an increase in the number of thunderstorms or lightning strikes. It is also **profoundly transforming the nature and scope of impacts**. These now extend **far beyond direct human or material damage**, with cascading effects on the environment, agriculture, ecosystems, and public health. Among these secondary impacts, the **link between lightning and wildfires** is today one of the major concerns of scientists and risk managers.

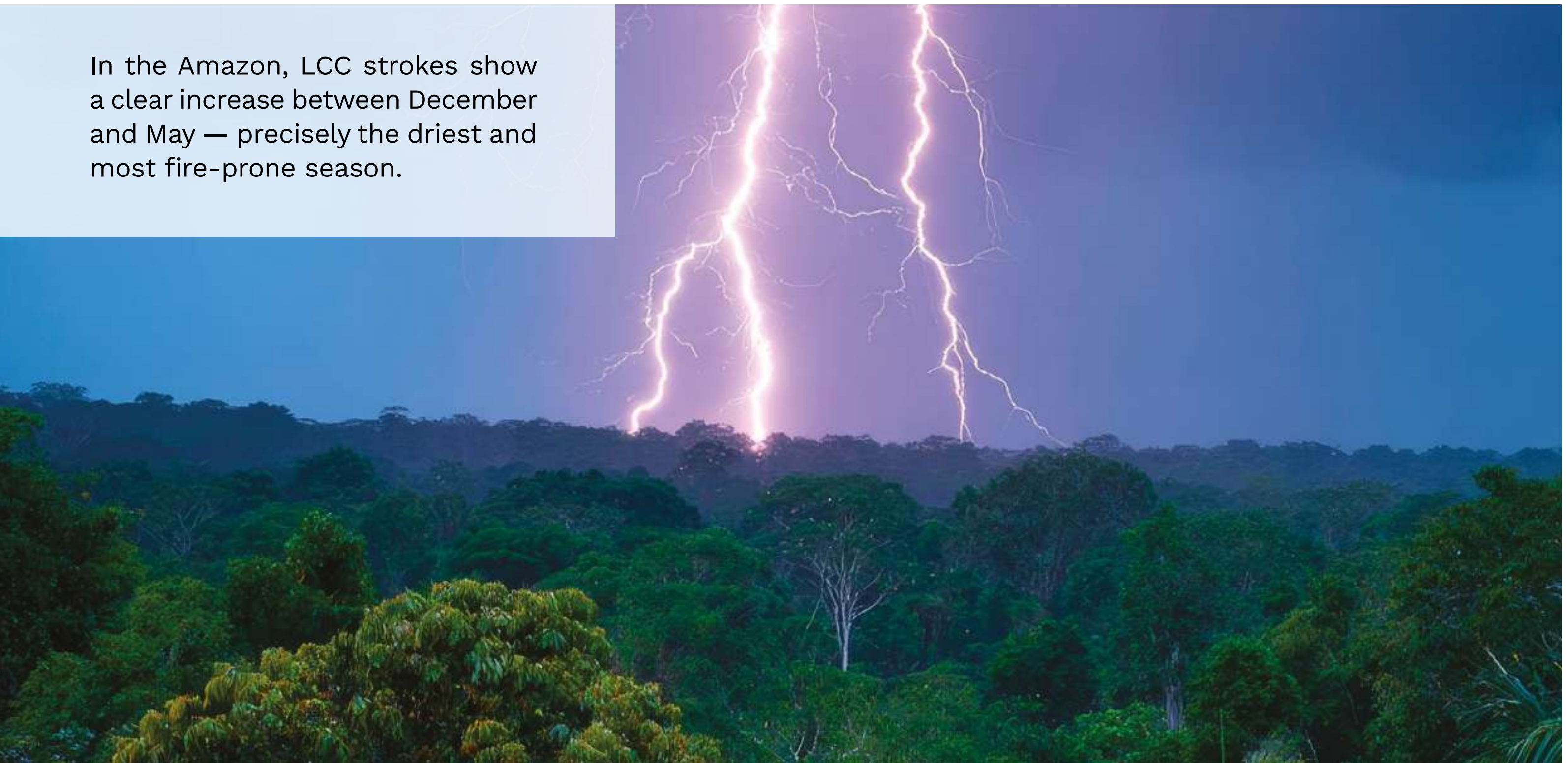
Lightning and wildfires: a critical relationship.

Feared for their ignition potential, long continuing current (LCC) lightning strokes are becoming key drivers of wildfire risk on a global scale. When they strike desiccated vegetation or soils already vulnerable due to lack of moisture, they trigger fires with devastating efficiency. And **everything indicates that such episodes will become more frequent**.

Climate projections published in Nature[16] are unequivocal: **56% of studied regions could face an increase in lightning-induced wildfire risk** by 2090. As mentioned above, and even more worrying, **a 41% rise in LCC strokes is anticipated** in the coming decades. In some areas, the link between global warming and the multiplication of lightning-caused wildfires is now well documented.

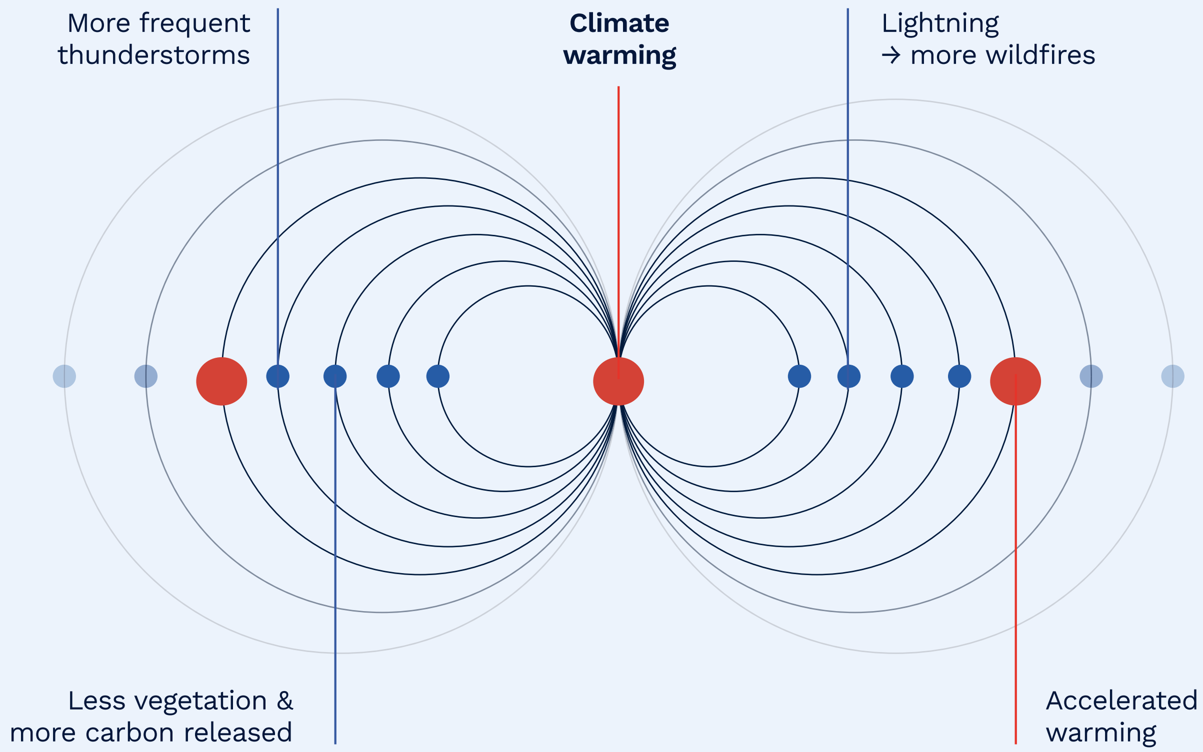
Which regions are most at risk?
The Amazon rainforest, African savannas, Australian plateaus, North American coastlines, and the Mediterranean slopes of Europe are all threatened. Even polar regions, long spared, could see their exposure rise by 57%.

These wildfires will not depend on lightning alone. Other meteorological conditions will play a decisive role: **high temperatures, insufficient rainfall, low relative humidity, a high lightning-to-rainfall ratio, as well as storm-cell downdrafts** that can both trigger ignition and accelerate the spread of flames. In many regions, these variables are deteriorating simultaneously, multiplying conditions favorable to wildfire outbreaks.



In the Amazon, LCC strokes show a clear increase between December and May — precisely the driest and most fire-prone season.

The cascading effects of climate change:



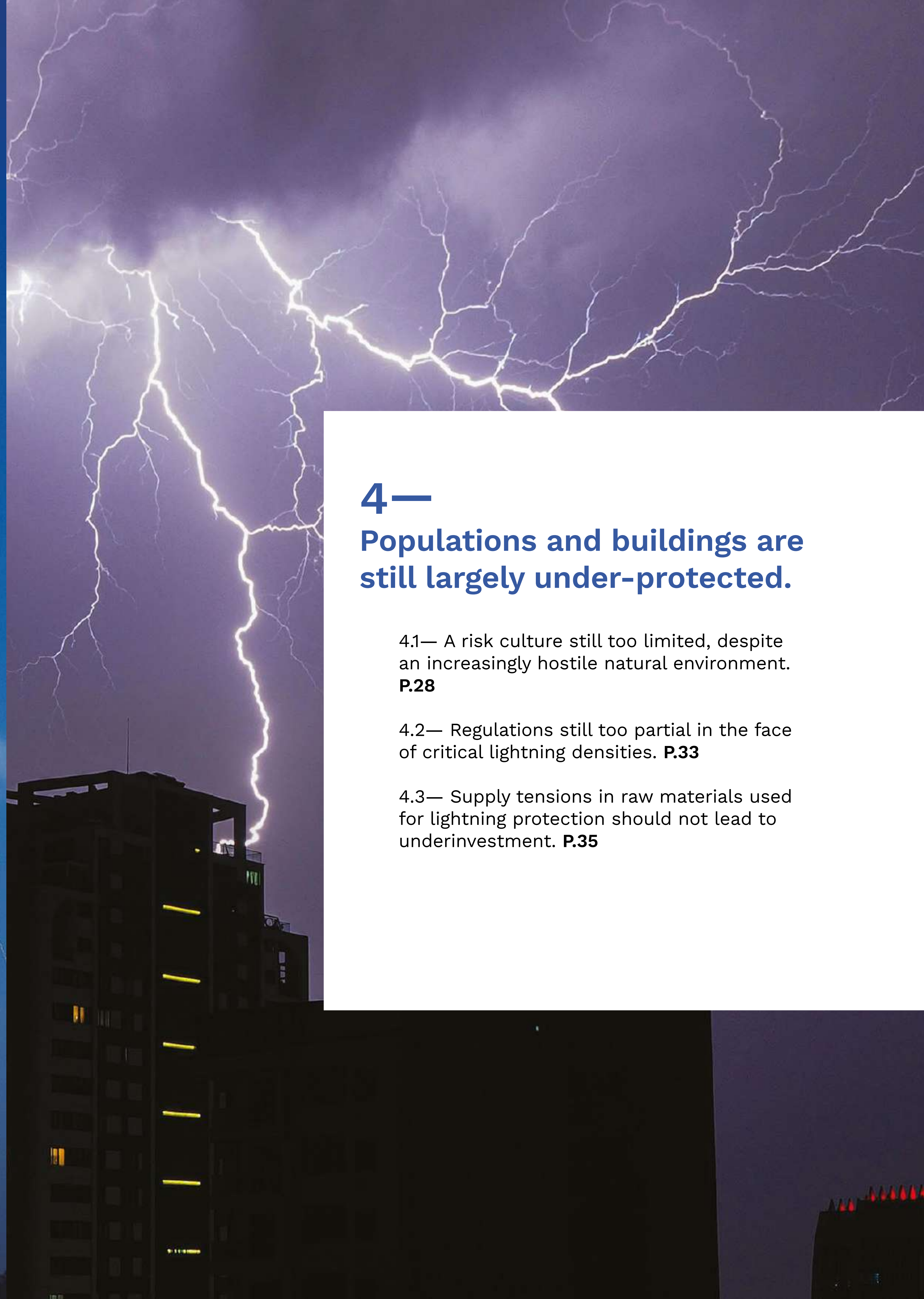
Other indirect impacts to monitor.

The resurgence of severe thunderstorms and lightning also **affects broader domains:**

AGRICULTURE
- Lightning strikes on agricultural equipment and silos;
- Increased water stress for crops;
- Yield losses linked to wildfires or hail.

BIODIVERSITY
- Destruction of natural habitats by fire;
- Disruption of reproduction cycles;
- Loss of protective vegetative cover.

PUBLIC HEALTH
- Increased risk of burns and electrical accidents;
- Decline in air quality due to wildfires;
- Heat stress, atmospheric pollution, impacts on vulnerable populations (children, elderly).



4—
Populations and buildings are still largely under-protected.

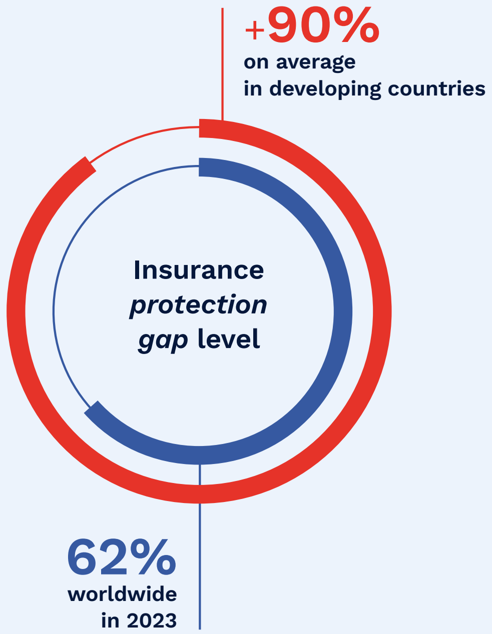
4.1—
A risk culture still too limited, despite an increasingly hostile natural environment.

In many countries, the **weak perception of natural hazards** — whether lightning, storms, floods, or heatwaves — is a major obstacle to the implementation of effective protection measures.

Insurance coverage: still a weak link in the face of natural disasters.

The most recent data illustrates the extent of vulnerability:

The insurance *protection gap* – the portion of disaster losses not covered by insurance – exceeds 90% in developing countries on average (less than one-tenth of disaster losses in poorer nations are insured). At the global level, the global protection gap was 62% in 2023 (only 38% of NatCat losses were insured) (World Bank[18]).



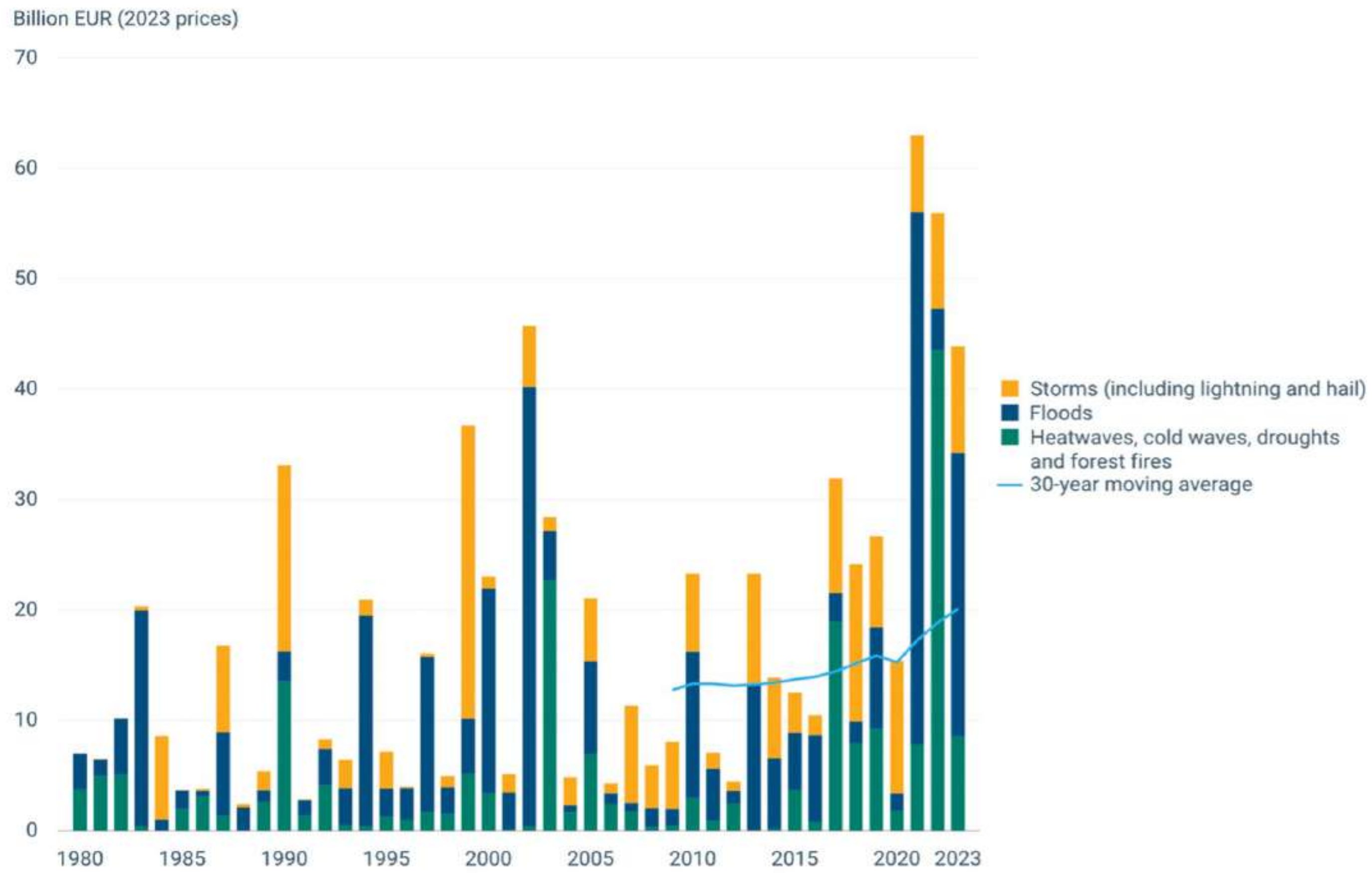
This coverage gap applies both to **direct damages** (material, human) and to **indirect losses** linked to business interruptions or cascading effects (fires, surges, etc.).

This highlights a **structural vulnerability**, where too many stakeholders are **exposed without a safety net or real coverage**. Yet economic losses linked to weather and climate-related events have surged since 1980.

Only 18%
of Europeans report having **insurance covering natural disasters**[17].

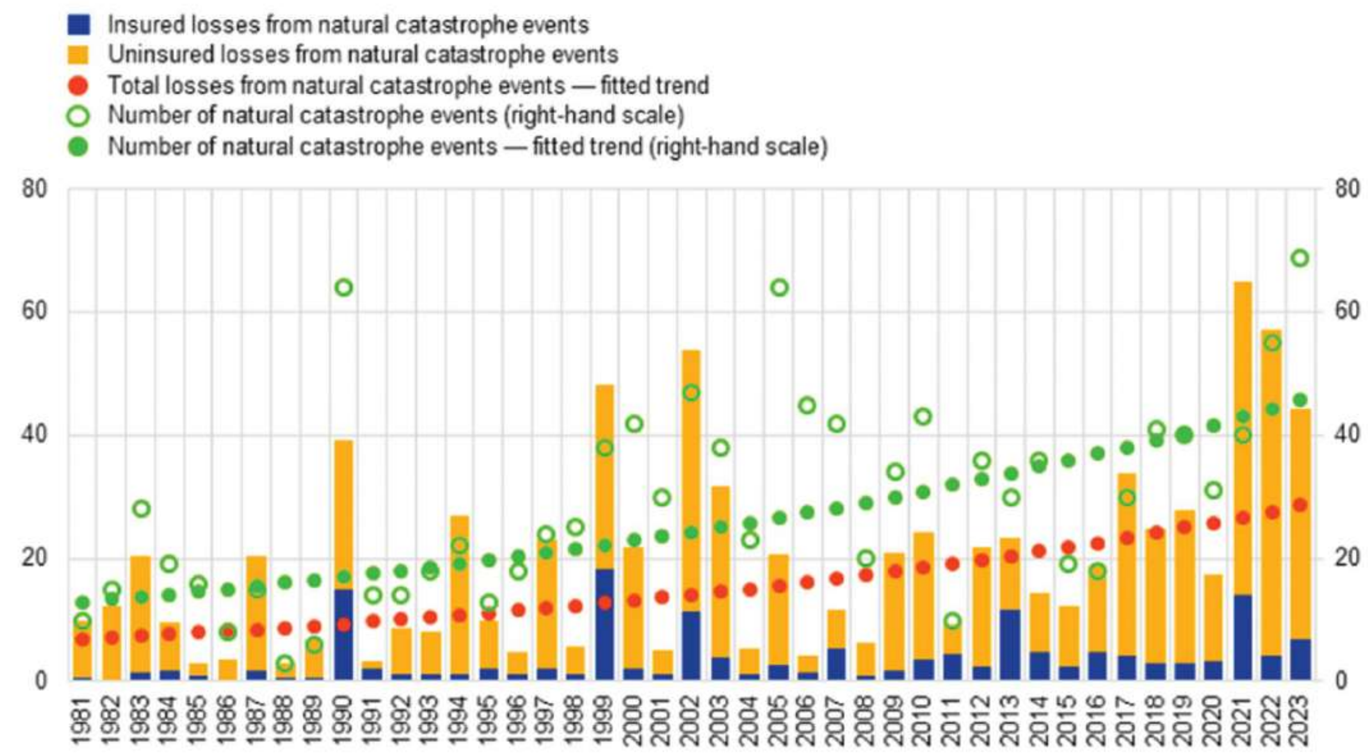
€738 billion
in damages in Europe
were caused by natural disasters[8].

Annual economic losses caused by weather-and climate-related extreme events in the EU Member States[19]



According to official data, **only about a quarter of the losses caused by natural disasters in the EU over the past 42 years were insured,** and the **level of coverage is declining**[8].

Economic losses from and number of natural catastrophes in the EU[20]
(1981-2023; EUR billions as measured in 2023 values, number of events)



Thus, in many countries, risk perception and insurance mechanisms are not evolving at the same pace.

"The speed at which losses occur, their frequency, and their impact are increasing to such an extent that it is really concerning: how are we going to be able to cover this?"

– Petra Hielkema,
Chair of the European Insurance Authority,
quoted by the Financial Times (2024)[21]

The growing severity of events is also confirmed by reinsurers :
(Financial Times, 2024)[22]

"Whether it was the earthquake in Türkiye, the floods in Germany, or the hailstorms in Italy, the models were exceeded not by 10 or 20%, but by a far higher factor."

– Gianfranco Lot,
Chief Underwriting Officer, Swiss Re

Swiss Re further adds that this underestimation is a systemic issue:

"It comes from a lack of data on real exposures and current risk values."

A risk perception often disconnected from reality.

Even in technologically advanced countries frequently struck by lightning, **lightning risk culture remains marginal**:

- The phenomenon is still too often considered **unpredictable or inevitable**, whereas it can be modeled, anticipated, and managed.
- **Investments in lightning protection systems are usually triggered only after incidents**, rarely within a preventive logic.

In its **Global Assessment Report 2024**[23], the UNDRR (United Nations Office for Disaster Risk Reduction) warns:

"A majority of at-risk populations worldwide remain poorly informed, underprepared, and insufficiently protected against climate-related disasters, including lightning."

The organization calls for **systematically integrating risk management into public policies**, beyond just seismic or flood-prone areas. It also recommends **strengthening community awareness** through **multi-channel campaigns** (schools, municipalities, social networks, etc.), to reach all audiences, especially the most vulnerable. Finally, it stresses the need to **expand access to risk-financing solutions**, notably by **developing more affordable parametric climate insurance**.

This underestimation holds back proactive investment in protection systems — **decision-making is often post-incident rather than prevention-driven**.

Towards greater accountability.

The challenges ahead highlight the urgency of a **cultural and operational shift:**

LOCAL AUTHORITIES
Integrate thunderstorm and convective risk into asset management plans.

INDUSTRIALS
Anticipate operational disruptions caused by climate-driven overloads (lightning, hail, violent winds).

INDIVIDUALS
Strengthen the protection of homes against increasing electrification, sensitive equipment, and extreme hazards.

4.2— Regulations still too partial in the face of critical lightning densities.

While detection and prevention tools are advancing, **the regulatory and normative framework remains largely lagging** in many countries, compared to the actual level of lightning exposure. This generates a **worrying paradox**: some of the most lightning-prone areas in the world are also those with the weakest — or even nonexistent — protection requirements.

Extreme exposure zones, yet poorly protected.

Global detection networks such as **Blitzortung, Météorage**, or **Vaisala GLD360** accurately identify very high lightning density regions: **Equatorial Africa, the Amazon, Southeast Asia, Northern India, Bangladesh, the Gulf of Mexico**, and some **subtropical U.S. regions**.

Yet, in many of these territories, **lightning protection remains marginal**:

- **Few countries have mandatory national regulations**, or they are limited to high-risk sites (Seveso, military installations, chemical depots...);
- **Public and private investment levels remain very low compared to the danger**, particularly in tropical areas and low- to middle-income countries;
- Some highly exposed states, such as those in Equatorial Africa (e.g. Democratic Republic of Congo), **have no specific legislation** nor incentives to equip schools, hospitals, or sensitive public buildings.

Regulation often reactive... and insufficient.

Even in countries that have adopted advanced technical standards — such as **NF C 17-102** in France, **NFPA 780** in the United States, or the international **IEC 62305** standard — enforcement obligations remain partial and conditional:

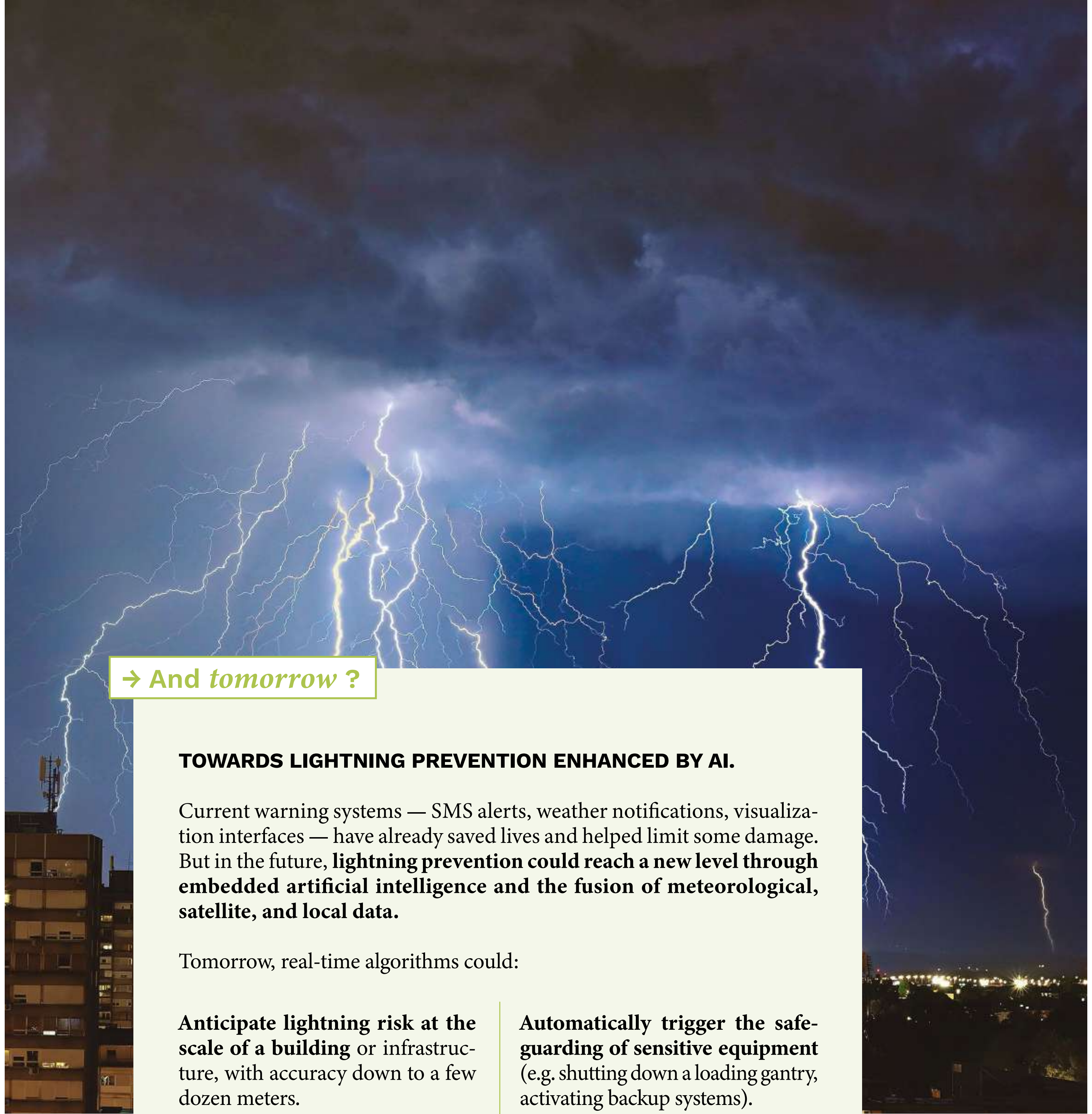
- They depend on the **type of activity** (e.g. industrial or sensitive), without systematically accounting for **human or territorial vulnerability**;
- They are **not always accompanied by inspections or sanctions**, limiting their real effectiveness;
- They are **rarely integrated into climate policies** or natural risk prevention plans.

As a result, there are **large disparities in per-capita investment**, with no clear correlation to exposure levels.

A telling example: the **United Kingdom**, with low lightning density (Ng < 1), nevertheless has comprehensive and widely applied regulation. By contrast, regions such as **South Asia** or **Central America** — among the most heavily struck — **remain severely under-equipped**.

Portugal: an example of proactive and ambitious regulation.

Faced with these shortcomings, **some countries are beginning to adopt more systematic approaches. Portugal**, in particular, has recently established an **exemplary regulatory framework**. **The Technical Note of October 2022**[24] now places **lightning protection on the same level as fire protection** for all buildings, regardless of their function. This standard, **overseen by civil protection services**, illustrates a **coherent and proactive integration** of lightning protection into building safety policies.



→ And *tomorrow* ?

TOWARDS LIGHTNING PREVENTION ENHANCED BY AI.

Current warning systems — SMS alerts, weather notifications, visualization interfaces — have already saved lives and helped limit some damage. But in the future, **lightning prevention could reach a new level through embedded artificial intelligence and the fusion of meteorological, satellite, and local data.**

Tomorrow, real-time algorithms could:

Anticipate lightning risk at the scale of a building or infrastructure, with accuracy down to a few dozen meters.

Automatically trigger the safeguarding of sensitive equipment (e.g. shutting down a loading gantry, activating backup systems).

Dynamically adapt the operation of industrial or agricultural sites depending on strike probability.

In parallel, **new-generation connected objects (IoT)** — such as Prevectron 3 Connect lightning rods or autonomous measurement stations — will be able to continuously transmit **exposure data**, feeding **predictive learning systems** to refine lightning risk mapping.

4.3— Supply tensions in raw materials used for lightning protection should not lead to underinvestment.

Lightning protection still relies heavily on raw materials under pressure, such as copper.

In particular, copper **remains central to meshed cage systems** (see section 5.2), which require large quantities of conductors.

But this material faces growing constraints:

- **Demand is booming** (renewables, electric vehicles, etc.) while deposits are being depleted;
- **Prices more than doubled between 2020 and 2024**[25] (London Metal Exchange);
- **Only 17% of global copper production comes from recycling**[19]**;**
- **International initiatives** (EU, China) **aim to reduce the carbon footprint** of resource-intensive materials such as copper — a clear signal that **regulations could restrict or increase its industrial cost**.

Impact on protection technologies.

Copper tensions have differentiated impacts depending on the technologies used. **Traditional meshed systems** are particularly copper-intensive, with typical consumption of **190 kg of copper per installation, compared with 48 kg** for a single lightning rod (ESE technology) **— a ratio of 1 to 4**[26].

This cost gap makes meshed solutions **economically less attractive** for the future, without guaranteed superior effectiveness in all cases.

Conversely, this favors **lighter or alternative technologies**, such as:

- Early Streamer Emission (ESE) lightning rods;
- Connected systems;
- **Aluminum**, particularly **recycled** aluminum, which can deliver **better environmental performance** than new copper. However, aluminum **cannot be buried**, under EN 62561-2, due to its **sensitivity to corrosion**. Its use is therefore limited to the **above-ground part of installations**.

Reducing investment in lightning protection for raw material cost reasons would be a strategic mistake. **The challenge lies instead in evolving technological choices:**

- Opting for systems with **lower copper consumption**;
- **Anticipating raw material volatility** and future carbon regulations when selecting protection technologies;
- **Integrating innovation** (intelligent diagnostics, optimized materials) into protection systems.

5—
Multiple technologies exist to protect against lightning.

5.1—
How does lightning protection work?

WHAT IS LIGHTNING?
Understanding an electromagnetic phenomenon of extreme power.

Lightning is an extremely powerful **natural electrical discharge**, caused by an imbalance of electric charges in the atmosphere. Though familiar to all, its physical functioning remains largely misunderstood.

Thunderstorms capable of producing lightning form under specific atmospheric conditions, generally during the development of **cumulonimbus clouds**. These towering cloud masses, often recognizable by their anvil shape, develop vertically over several kilometers.

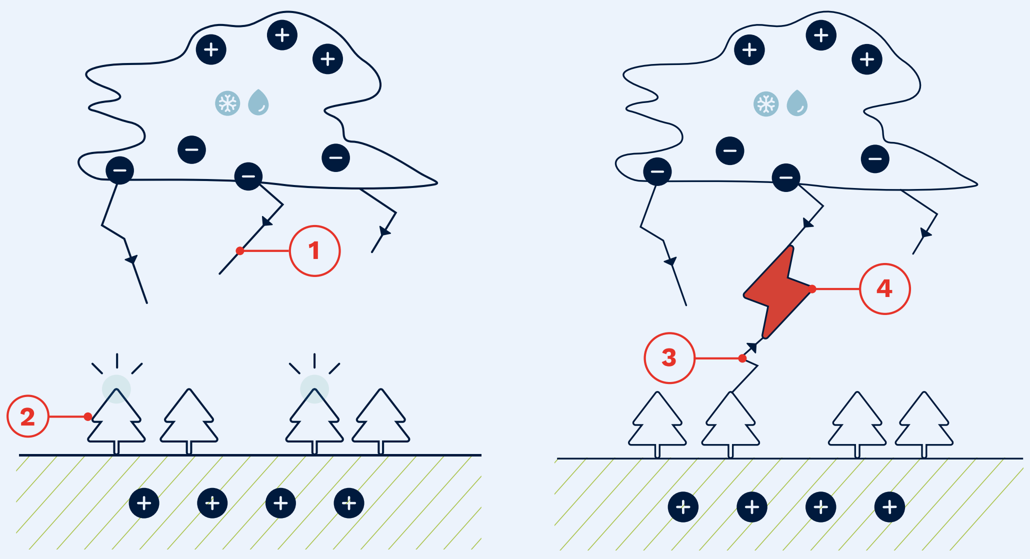
Driven by strong updrafts, particles inside the cloud (water droplets, ice crystals) become electrically charged.

It results in a **clear charge separation**:

- The top of the cloud becomes **positively charged;**
- The base becomes **negatively charged**, sometimes with a **positive pocket trapped** inside.

This imbalance creates an intense electric field between the cloud and the ground. In response, the ground **polarizes positively**, particularly on pointed or elevated objects. When this field exceeds a critical threshold — typically 10–15 kV/m — it becomes sufficient **to trigger an atmospheric discharge: lightning**. A lightning strike may consist of **several successive impulses**, separated by fractions of a second.

FORMATION OF A THUNDERSTORM:
a large-scale electrical imbalance.



Phase n° 1
Descending leader: a faintly luminous pre-discharge zigzags from the cloud toward the ground.

Phase n° 2
Point / corona effect: on the ground, elevated structures (trees, pylons, antennas) emit ionization, sometimes visible as St. Elmo's Fire.

Phase n° 3
Upward leader: a discharge rises from the ground toward the cloud.

Phase n° 4
Connection of the two leaders: when they meet, an ionized channel is created, allowing **intense current flow that produces the visible flash** (light) and thunder (shockwave).

HOW DOES LIGHTNING PROTECTION WORK?

1 EXTERNAL protection system

→ **It captures lightning** before it strikes the structure. It includes:

- **Air terminals**, whether simple rods or Early Streamer Emission (ESE) devices;
- **Down conductors** guiding the current to the ground;
- **A dedicated earthing system** able to dissipate energy effectively.

2 GROUNDING system

→ It ensures **safe dissipation of lightning current** into the ground, preventing return currents into structures. It must be designed with low impedance, appropriate soil depth, and supplementary electrodes if needed.

3 INTERNAL protection
(against surges)

→ It **protects** sensitive electrical and electronic equipment **from transient overvoltages** generated by a strike. It relies on **surge protective devices** (SPDs) installed at the service entrance, in distribution boards, or near critical equipment.

4 EQUIPOTENTIAL bonding
(or equipotential bonding)

→ It **connects** all earthing systems and metallic masses of a site (pipes, structures, frames, etc.) **to avoid dangerous potential** differences and arc risks.

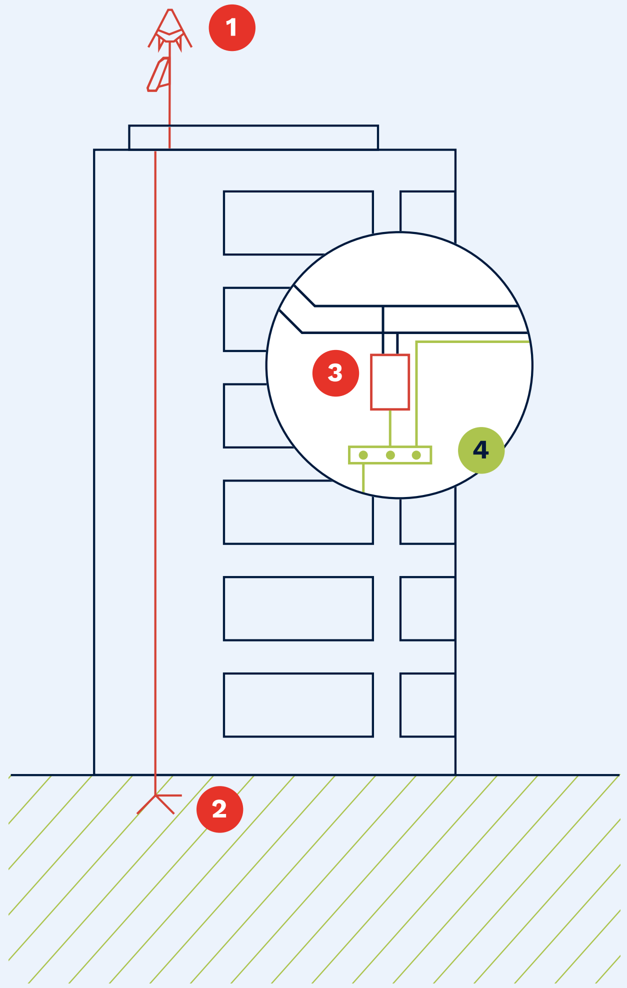


Diagram of a lightning-protected building.

A system tailored to each site.

Lightning protection is not a one-size-fits-all solution. **Each building, activity, and configuration requires specific technical choices, based on:**

- Site size;
- Type of activity (industrial, heritage, hospital, events, etc.);
- Geographic location (local lightning density, altitude, proximity to trees or water);
- Regulatory and architectural constraints.

Examples:

→ An extensive industrial site will require comprehensive, scalable coverage.

→ A listed or heritage building will favor discreet devices integrated into architecture.

→ Outdoor infrastructures (stadium, campsite, amusement park) will require protection adapted to open areas and moving crowds.

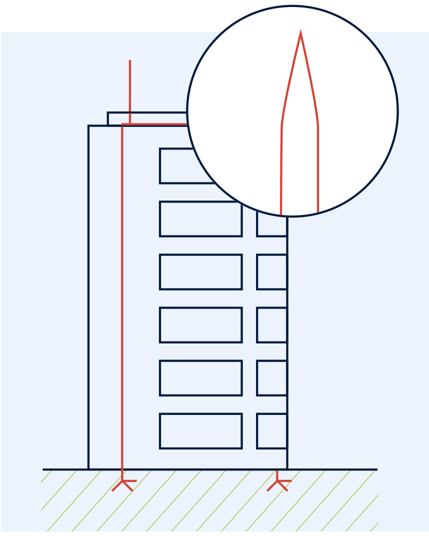
5.2—
Overview of lightning protection technologies.

Since the 18th century, societies have developed various technologies to protect against lightning. These devices have evolved over time, based on fundamental discoveries in electromagnetism (Franklin, Faraday, Melsens) as well as more recent standardization and industrialization efforts.

Today, **four major families of lightning protection systems are recognized and used worldwide**, in line with IEC 62305, NF C 17-102, UNE 21186 and NP 4426 standards:

- **Simple** rod lightning conductor;
- **Meshed cage** system;
- **Wire** system;
- **Early Streamer Emission (ESE)** lightning rod.

Alongside these proven technologies, certain experimental concepts (e.g. *Charge Transfer Systems* – CTS, or *repellers*) remain scientifically and normatively unvalidated, and are not part of applicable prescriptions for regulated buildings.



Simple rod lightning conductor (Franklin rod)

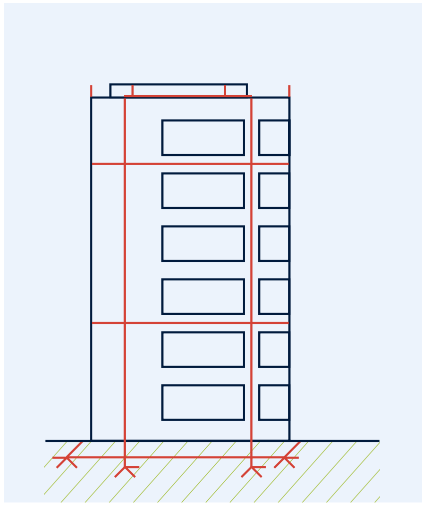
→ Principle
Originating from the 18th century work of Jacques de Romas and Benjamin Franklin, the simple rod remains a **reference technology** for small, low-exposure buildings.

A metal rod is installed at the highest point of the building, connected by two down conductors to two earth electrodes. The protection radius is limited (≈ 30 m in best case, Level IV, 60 m height).

→ Advantages
- Simple design and implementation;
- Cost-effective for small projects;
- Can be integrated into certain architectures.

→ Limitations
- Limited protection radius;
- Less competitive for large complexes;
- Sensitive to mechanical constraints on masts.

→ Applicable standards
- Components: IEC 62561
- Installation: IEC 62305-3



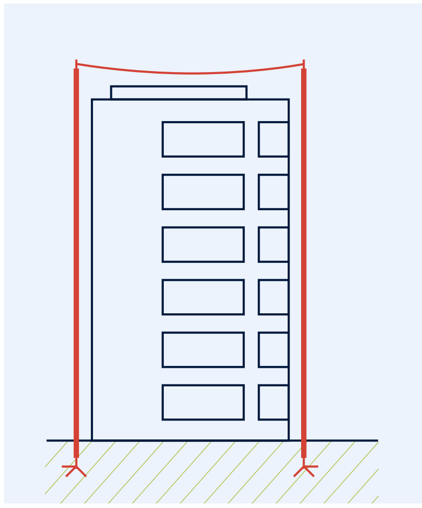
Meshed cage systems

→ Principle
Inspired by the principles of Faraday and Melsens in the 19th century, the **meshed cage surrounds a structure** with a conductive grid integrated into the roof and façades, connected to a closed-loop earthing system (Type B). Capture rods are also placed on elevated parts.

→ Advantages
- Reduces internal electromagnetic field;
- Ensures good distribution of lightning currents;
- Suitable for sensitive buildings.

→ Limitations
- Complex and costly to implement;
- Material-intensive;
- Limited adaptability to existing structures.

→ Applicable standards
- Components: IEC 62561
- Installation: IEC 62305-3



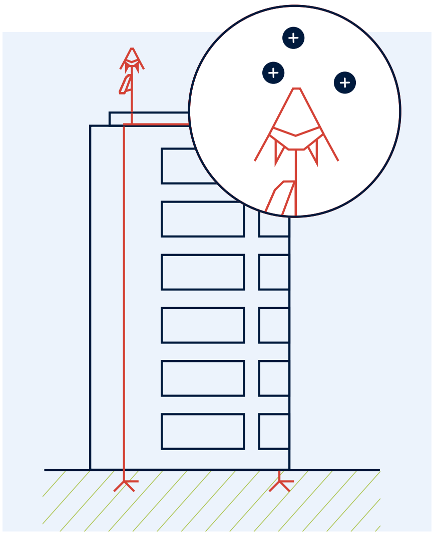
Wire systems

→ Principle
Widely used for protecting overhead power lines, wire systems operate on the same principle as meshed cages, but with **conductors placed at a distance from the building**. This allows the structure to be physically isolated from lightning current.

→ Advantages
- Good coverage of open areas;
- Reduction of electromagnetic radiation effects;
- Suitable for sensitive industrial environments.

→ Limitations
- Complex logistics (space, guying, maintenance);
- Negative visual impact;
- Safety risks in traffic areas (machinery, vehicles).

→ Applicable standards
- Components: IEC 62561
- Installation: IEC 62305-3



Developed in the 1980s in France with CNRS support, ESE technology is based on the **early generation of an upward leader**, in order to capture lightning **earlier** and **higher** than surrounding building features. This early triggering capability allows the device **to extend its protection zone**.

Early Streamer Emission (ESE) lightning rods

→ Principle

During a thunderstorm, the ground electric field gradually rises. The ESE device initiates **controlled ionization**, releasing seed electrons that **generate an upward leader** before nearby structures can. This increases the chance of intercepting the descending leader from the cloud, making the ESE the **preferred strike point**.

Two technical principles coexist:

- **Electronically triggered ESE** (ionization via a device powered by a battery or ambient field);
- **Geometrically triggered ESE** (no electronics, operation relies solely on shape, internal configuration, and materials of the ESE).

→ Advantages

- Large protection radius (up to 107 m);
- Compact and discreet solution;
- Economical at scale.

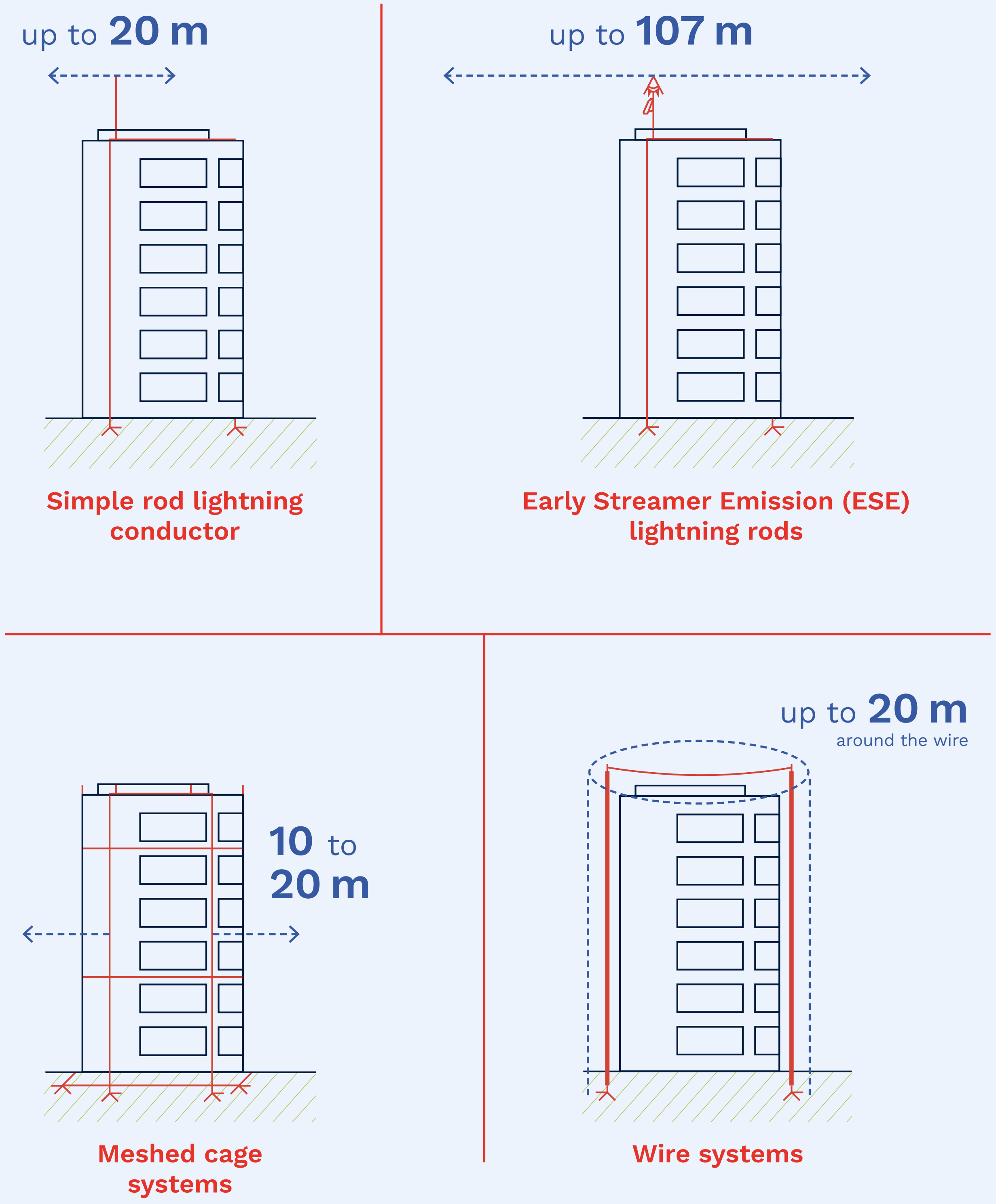
→ Limitations

- Specific requirements for anchoring and masts.

→ Applicable standards

- Components: NF C 17-102 – NF EN 62561
- Installation: NF C 17-102 – UNE 21 186 – NP 4426

Comparative diagram of the 4 recognized technologies.



Non-standardized technologies: CTS and other exploratory research.

Some emerging technologies are currently under experimental research but are **not recognized by major international standards** (IEC 62305, NF C 17-102, etc.). They are therefore **neither certified nor prescribed** for regulated safety projects.

→ *Charge Transfer Systems* (CTS) and *repellers*

These systems aim **to dissipate local surface charges to prevent the formation of upward leaders**, thereby reducing the probability of a strike. Whether called "repellers" or CTS, they are based on the same principle: **avoiding lightning rather than capturing it**.

However, their effectiveness remains **highly controversial**:

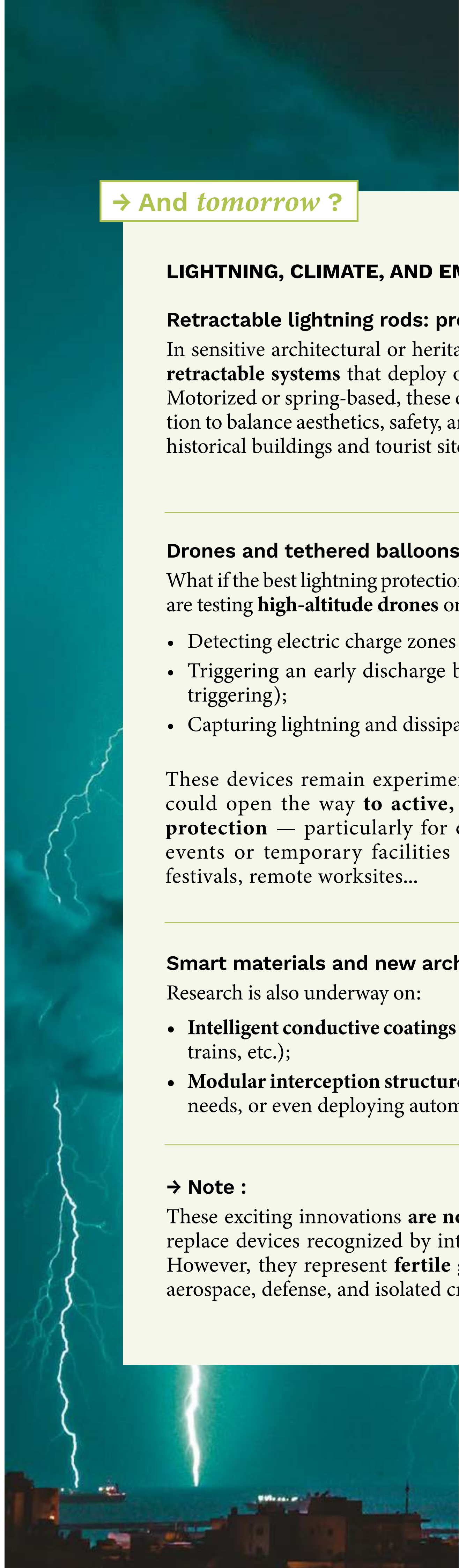
- **No independent validation** has demonstrated reliability under real conditions;
- They are **not recognized by any national or international standard**;
- Their use is **not recommended in high-risk contexts**, neither by regulators nor by certification bodies.

→ Other researches: lasers, drones

More recent research explores innovative, still-experimental approaches:

- **High-energy laser** (Switzerland, 2023)[27]: researchers at the University of Geneva tested a system capable of **guiding lightning remotely** using an ultra-intense laser that ionizes air over several hundred meters. Trials at the top of Säntis Mountain showed promising results but remain **far from reliable industrial application**.

- **Charge-dispersing drones** (Japan, 2025)[27]: **autonomous drones able to release charged particles at altitude** to disrupt critical electric fields around sensitive infrastructures (see prospective box *And tomorrow?* p.45).



→ And *tomorrow* ?

LIGHTNING, CLIMATE, AND EMERGING RISK ZONES.

Retractable lightning rods: protection with discretion.

In sensitive architectural or heritage contexts, manufacturers are experimenting with **retractable systems** that deploy only when imminent thunderstorm risk is detected. Motorized or spring-based, these devices combine weather sensors and smart automation to balance aesthetics, safety, and protection. They are already being tested on listed historical buildings and tourist sites, particularly in Europe.

Drones and tethered balloons: the era of mobile protection.

What if the best lightning protection came from the sky? Laboratories in Europe and Asia are testing **high-altitude drones** or **conductive balloons** capable of:

- Detecting electric charge zones in the atmosphere;
- Triggering an early discharge before a natural strike occurs (similar to controlled triggering);
- Capturing lightning and dissipating it away from the site to be protected.

These devices remain experimental but could open the way **to active, mobile protection** — particularly for outdoor events or temporary facilities such as festivals, remote worksites...

In April 2025, the NTT Group (Japan) successfully **triggered and guided a lightning strike using a drone**, demonstrating the potential of new active risk management approaches in complex environments not covered by traditional systems.

Smart materials and new architectures.

Research is also underway on:

- **Intelligent conductive coatings** integrated into building or vehicle envelopes (aircraft, trains, etc.);
- **Modular interception structures**, 3D-printed and capable of adapting to specific site needs, or even deploying automatically through embedded intelligence.

→ Note :

These exciting innovations **are not yet standardized** and therefore cannot currently replace devices recognized by international standards (NF C 17-102, IEC 62305...). However, they represent **fertile ground for tomorrow's solutions**, particularly in aerospace, defense, and isolated critical infrastructures.

5.3—
Overview of lightning protection standards and regulations.

Protecting an infrastructure against lightning is not only a matter of technology. It is also — and above all — a matter of **rigorous methodology, supported by technical standards validated** at national or international level. These standards ensure the reliability, reproducibility, and safety of installed protection systems.

A process based on risk assessment.

The main lightning protection standards, whether international IEC standards or national texts such as NF C 17-102, are all built on a common principle: protection must be justified by a risk analysis. This is the first step.

This approach makes it possible to evaluate:

- The level of local exposure (lightning ground flash density);
- The criticality of the structure (function, contents, human presence);
- The potential consequences of a strike.

It is this structured approach that **determines the required protection level**. This methodology is at the heart of IEC 62305-2, which introduces the **notion of tolerable risk** (RT) and defines protection levels I to IV.

Two complementary, not competing, families of standards.

Today, two main families of standards coexist — not in competition, but complementing each other:

- **International standards IEC 62305** (and their European equivalent EN), which define the design principles of conventional systems (simple rods, mesh cages, wire systems);

- **National standards dedicated to ESE** (Early Streamer Emission) lightning rods, such as **NF C 17-102 (France), UNE 21 186 (Spain)**, or technical texts adopted in more than 50 countries (Turkey, Romania, Argentina, Morocco, etc.).

Contrary to common misconceptions, there is no conflict between these frameworks. **CENELEC** has stated that ESE devices “do not fall within the scope of EN 62305”: they are therefore legitimately governed by specific national frameworks.

This is a standard situation in the normative world: **when a subject is not covered by an international standard, sovereign national standards apply.**

Adapting the standard to the project.

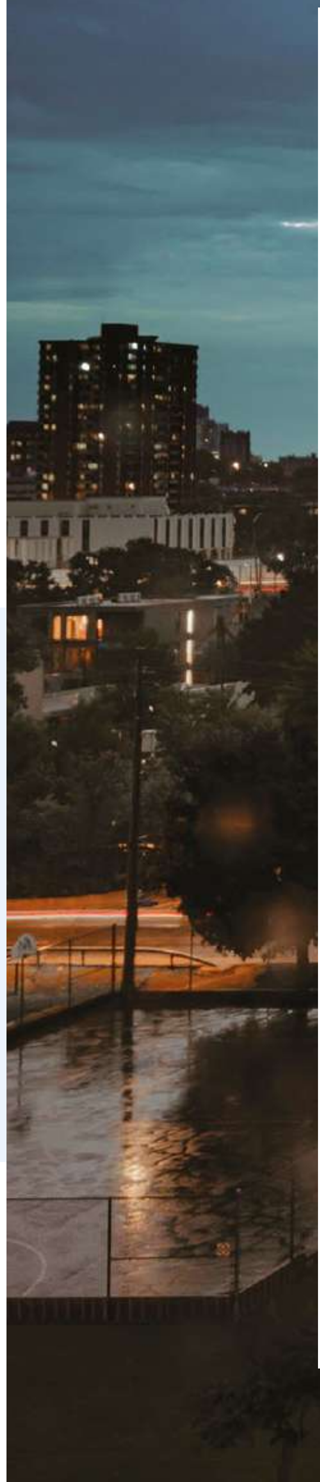
The issue is not about choosing “the best” standard, but about selecting **the most appropriate one for a given project**, depending on the country of installation, site configuration, and objectives in terms of continuity, aesthetics, or maintenance.

KEY TAKEAWAYS

- **Risk assessment is the essential starting point**, regardless of the standard chosen.

- **ESE devices are regulated by specific standards**, recognized in many countries.

- **Protection standards are multiple**, because projects are diverse.



5.4—
Choosing the right lightning protection technology: the importance of lightning risk assessments.

Selecting a lightning protection system is not simply a matter of picking equipment from a catalog. A **thorough risk assessment**—required by international standards such as IEC 62305 and NF C 17-102—is a critical first step. It determines whether protection is needed, defines the required protection level, and guides the system’s overall design. **Only after this stage can the appropriate technology be selected.**

Why is a risk assessment indispensable?

Each technology (ESE, Franklin rod, mesh cage, wire system) has its own **advantages and constraints**, which can only be effectively assessed according to:

- The characteristics of the building (height, materials, usage);
- The site configuration (urban environment, isolation, terrain);
- The local climate (keraunic level, ground flash density);
- The functional requirements (service continuity, public protection, heritage preservation…);
- And the acceptable level of risk.

The normative lightning risk assessment process and technical survey.

STEP N°1

→ Evaluation of lightning occurrence

Based on:
• **Nk** (keraunic level) = number of thunderstorm days per year;

• **Ng** (ground flash density), calculated by:

Ng = 0.04 × Nk1.25
or
Ng ≈ Nk / 10 (approximation)

STEP N°2

→ Identification of zones to be protected

Standards require an **analysis by functional zone**:

- The **structure itsef**;
- **Equipment** and contents;
- **People** (inside and outside);
- **Sensitive** environment.

STEP N°3

→ Calculation of risk (R) and comparison with tolerable risk (RT)

- If **R ≤ RT** → protection not required.
- If **R > RT** → protection measures must be implemented.

STEP N°4

→ Determination of the required protection level (LPL)

Four levels are defined, depending on exposure and potential consequences:

Level	Required efficiency	Current range (kA)	ESE rods typical protection radius (m)
I	98%	3 to 200	up to 79 m
II	95%	5 to 150	up to 86 m
III	90%	10 to 100	up to 97 m
IV	80%	16 to 100	up to 107 m

STEP N°5

→ Determination of the number and radius of air terminals

The design of an external protection system requires:

- **Determining the number of air terminals** (lightning rods or conductors);
- **Calculating their protection radius (Rp)** based on:
  - Required protection level (LPL);
  - Height of the air terminal (h);
  - Site topology;
  - Chosen method (rolling sphere, protection angle, mesh).

EXAMPLE
For an ESE lightning rod 5 m high with LPL II, the theoretical protection radius can reach 60–80 m.

Hence the importance of choosing systems compliant with standards and tested for real efficiency.

6—
FOCUS ON ESE LIGHTNING RODS: An innovative technology offering a wider protection radius with equal efficiency.

6.1—
The operating principle of ESE devices.

History of ESE: a technology with four decades of experience.

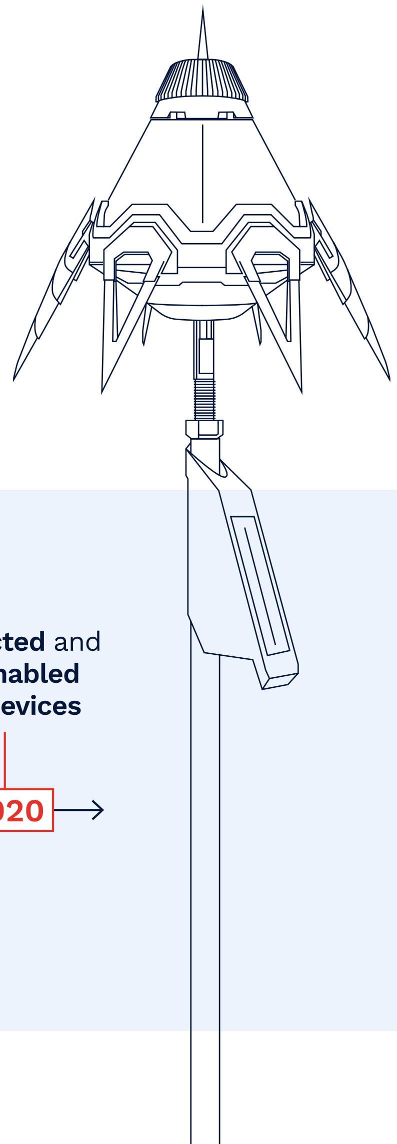
Early Streamer Emission (ESE) **lightning rods** emerged in the 1980s, in the context of **applied research** aiming to improve the risk mitigation of traditional lightning protection systems. **Their purpose: to intercept lightning discharges earlier and more efficiently**, thereby extending the protected area around a structure.

Since then, the technology has been adopted in more than 100 countries, **standardized** under several national frameworks (notably **NF C 17-102** in France, **UNE 21186** in Spain, and **NP 4426** in Portugal), and **tested experimentally in real-life conditions** in Indonesia, Brazil, and Florida.

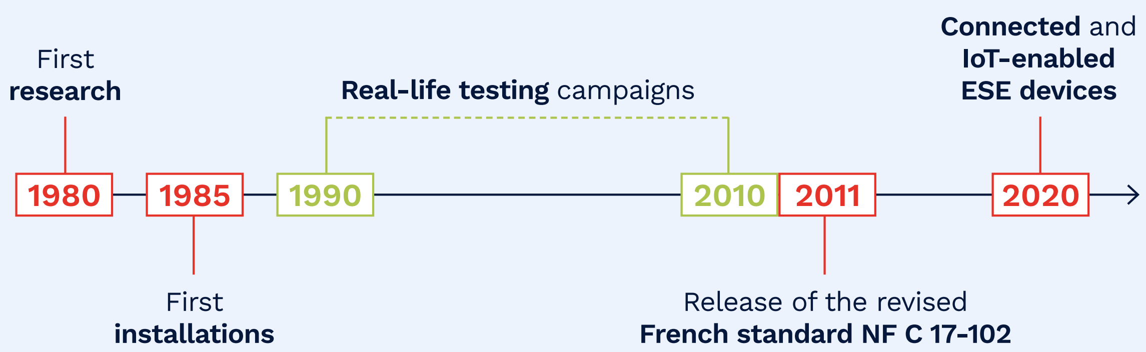
GOOD TO KNOW
The development of ESE devices was supported by scientific institutions, and their capabilities validated by high-voltage laboratory tests followed by field trials in regions with high thunderstorm activity.

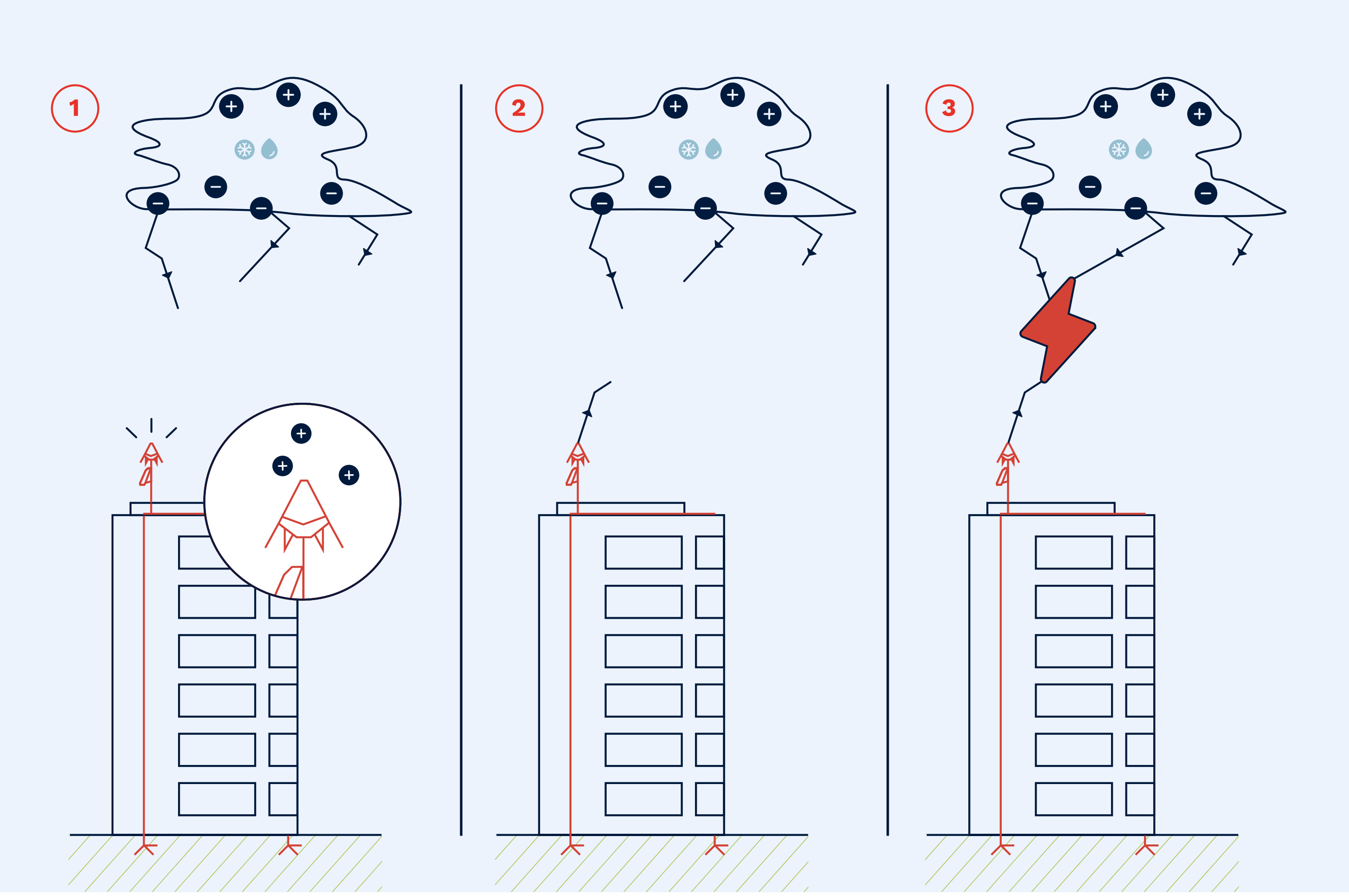
A mature, but continuously evolving, technology.

Over the decades, ESE devices have been miniaturized and optimized (durable materials, reduced maintenance). They have integrated new functions (remote monitoring, diagnostics) and have undergone scientific evaluations: high-voltage tests, impact counting, digital simulations.



The key stages in the development of ESE lightning rods.





How do ESE devices work?

The technology of the Early Streamer Emission (ESE) lightning rod relies on **lightning initiation mechanisms**. Its purpose is **to artificially promote the formation of the upward leader in order to capture lightning earlier and higher** than traditional systems.

When a thunderstorm approaches, the **atmospheric electric field** near the ground intensifies in response to the negative charge at the cloud base. This field may exceed **50–100 kV/m** close to the ground, especially atop tall structures (towers, steeples, masts…).

When this threshold is reached, natural **upward discharges** may form from sharp ground features through the **corona effect**. These upward leaders propagate toward the cloud to connect with **descending leaders**. The point of connection determines the **lightning channel** and therefore the impact point.

ESE objective: “win the race” to connection.

The ESE is designed to generate its upward leader earlier than surrounding structures. By doing so, it maximizes its chance of being the preferred strike point.

This early triggering relies on three main functions integrated into the device:

- **Release of seed electrons** at the tip, in the form of plasma, to initiate discharge earlier.
- **Space-charge evacuation**, neutralizing parasitic charges around the rod tip to maintain optimal conditions for leader initiation.
- **Active synchronization** with the evolving electric field, triggering initiation at the critical moment when the ambient field peaks, just before a strike.

A measurable time advantage.

The ESE rods specifications are often expressed as “advanced triggering time” (ΔT): the time (in microseconds) by which an ESE emits an upward leader compared to a conventional Franklin rod. Depending on the model, this ranges from 10 to 60 µs (NF C 17-102).

The greater the ΔT, the wider the protection radius. This can be explained by a simple physical principle: during a thunderstorm, lightning descends from the cloud in the form of a negative leader, while the lightning rod emits an upward leader to intercept it.

- Physically, if the ESE emits its leader earlier, it can propagate farther before meeting the descending leader.
- The interception occurs higher in the atmosphere, which widens the protection cone at ground level.
- This mechanism allows ESE devices to achieve protection radii of up to 107 meters, depending on installation height and required protection level.

Two technical approaches.

Manufacturers use two different methods:

- **Electronic triggering:** based on circuits powered by battery or by the ambient field, actively releasing the leader at the critical moment.
- **Geometric triggering:** no onboard electronics; relies on design, internal configuration, and materials to intensify the electric field locally.

6.2— The advantages of ESE lightning rods.

FOCUS ON **COST EFFICIENCY:** A decisive economic lever.

Beyond their technical engineering effectiveness, Early Streamer Emission (ESE) lightning rods offer **significant economic advantages** compared with conventional systems such as Franklin rods or meshed cages.

→ The **key economic benefit** of ESE lies in their **extended protection radius**.

A single well-positioned ESE device can **cover a large area**, significantly reducing the number of capture rods, down conductors, and grounding components required.

→ **Less material, less labor,** and therefore a substantially lower overall cost, especially on large or complex sites.

ESE devices are also based on a **simplified and therefore less expensive architecture**:

- **Fewer components** (reduced number of rods, conductors, electrodes);
- **Less specialized labor** required for installation;
- **Fewer materials,** meaning **lighter logistics** (transport, storage);

Concrete example

Comparison between a conventional system and an ESE system at a paper packaging factory in Chirols (France), subject to Protection Level II (IEC 62305 standard)
(Source: Indelec, Chirols case study, 2023. Further details available on request)

Over a 5-year horizon, **the total cost of the ESE system was more than five times lower than that of an equivalent passive protection system** — for the same level of protection (Level II, according to IEC 62305 standard).

→ **This solution not only secures assets, but also optimizes CAPEX and OPEX budgets** for lightning protection projects.

FOCUS ON **INSTALLATION:**
Simplicity, speed, safety.

ESE devices offer **significant logistical and operational advantages** during installation:

- **Fewer components, fewer connections, fewer fixing points** which results in a **faster and simpler installation**;
- Compact design enables **mounting on rooftops, dedicated masts, or existing structures**, including difficult-to-access areas (chimneys, silos, pylons, etc.);
- Reduced complexity means **lower error risk**, fewer construction delays, and easier compliance inspections (Indelec, field feedback). (Indelec, field feedback)

→ **Fewer components, less complexity.**

Use case

ESE lightning rods are particularly well suited to **isolated or exposed infrastructures:**
- **On photovoltaic fields**, ESE devices minimize panel shading — a critical factor for energy performance — while ensuring effective protection.

FOCUS ON **ENVIRONMENTAL BENEFITS.**

ESE devices also align with **sustainability and corporate responsibility policies**. Their **streamlined design** enables up to **8 times less copper consumption** compared to heavily metallic meshed cage systems. (Source: Indelec comparative data, 2023).

→ This technical choice helps **reduce the building's overall carbon footprint** by limiting the use of critical resources and emissions linked to metal extraction and processing.

ESE devices are therefore consistent with:
- **Environmental certifications** such as LEED®, HQE™, BREEAM®;
- **Low-carbon strategies**:
- **Anticipated regulatory frameworks** targeting high-carbon-intensity materials (e.g. CSRD directive, EU Green Taxonomy regulation, Eco-design directive).

This issue is further developed in section 4.3 ("Supply tensions in raw materials used for lightning protection should not lead to underinvestment").

FOCUS ON **OPEN AREAS:**
Covering more with fewer devices.

Thanks to their extended protection radius, ESE lightning rods are **particularly suited to open and large-scale environments**:
- A single ESE can protect **a radius of up to 107 meters**, depending on installation height and technical specifications;
- This drastically **reduces the number of devices needed for industrial sites**, logistics warehouses, stadiums, or outdoor parking areas.

→ **Fewer points, greater protected area.**

Use case

Golf courses are among the environments most exposed to thunderstorms due to their open, flat geography. Despite storm detectors, several serious incidents have been recorded:

- **East Lake (PGA Tour[29], 2019):** six spectators injured after a lightning strike, despite play suspension;
- **Hazeltine National (1991) and Crooked Stick (1991):** two spectators killed by lightning;
- **Tanah Merah & Laguna National (Singapore, 2000s):** fatalities despite storm warnings.

These tragedies highlight a key reality: **alerts alone are not enough**. Technical solutions such as ESE devices provide effective protection for sensitive areas (tees, greens, spectator zones). Their installation is already common in the US, Europe, and Asia.

An example of site protected is the **Boone Valley Golf Club (Missouri, USA)** (https://boonevalley.org/)

FOCUS ON **AESTHETIC BENEFITS.**

With their wide protection radius, ESE devices **reduce the number of visible elements** and **bulky rooftop structures**. This technical feature translates in practice into a **very low visual impact**.

Their compact format and ability to be mounted on dedicated masts or rooftops allow for **discreet integration**, without tangled cables or alteration of a building's silhouette.

→ **They are particularly suited to heritage and architecturally sensitive sites** (listed buildings, historic centers, museums...). Examples: Angkor Vat, Montmartre, Burj Khalifa Dubai, etc.

FOCUS ON **LATEST DEVELOPMENTS:**
Real-time control and enhanced reliability.

As risk management and business continuity requirements rise, lightning protection systems are evolving into **smart, connected solutions** offering greater **visibility into their activity and operational status**.

A NEW GENERATION of connected ESE devices.

The lightning protection market is evolving toward smarter, more connected solutions. In response to growing requirements for traceability, predictive maintenance, and resilience, several manufacturers now integrate electronic monitoring modules into their devices.

This advanced instrumentation enables risk managers, industrial operators, and specialized engineering firms to:

- Monitor the operational status of devices remotely;
- lan verification and compliance interventions more efficiently at lower cost (no requirement to reach the air terminal atop the poles…);
- Ensure continuous traceability of lightning strikes, as required by certain standards or industrial regulations (in the form of a digital logbook).

Indelec
SMART LIGHTNING SOLUTIONS

In this context, **Indelec has developed the Prevectron® 3 Connect range**, an ESE lightning rod equipped with embedded sensors and a remote communication system, enabling real-time monitoring of the device.

→ **Continuous monitoring** of the lightning rod's condition via an internal sensor;

→ **Automatic detection of lightning strikes** — even weak ones — with time-stamped recording;

→ **Secure data transmission** to a digital platform;

→ **Automatic alerts** in case of anomaly or maintenance needs.

Such solutions are fully aligned with **international trends** in **critical asset management, industrial cybersecurity, and optimization of technical operations**.

6.3—
ESE lightning rods: a widely adopted, proven, and recognized technology for 40 years.

Global adoption.

Since the 1980s, Early Streamer Emission (ESE) lightning rods have gradually established themselves as a reference solution for lightning protection in many high-exposure countries.

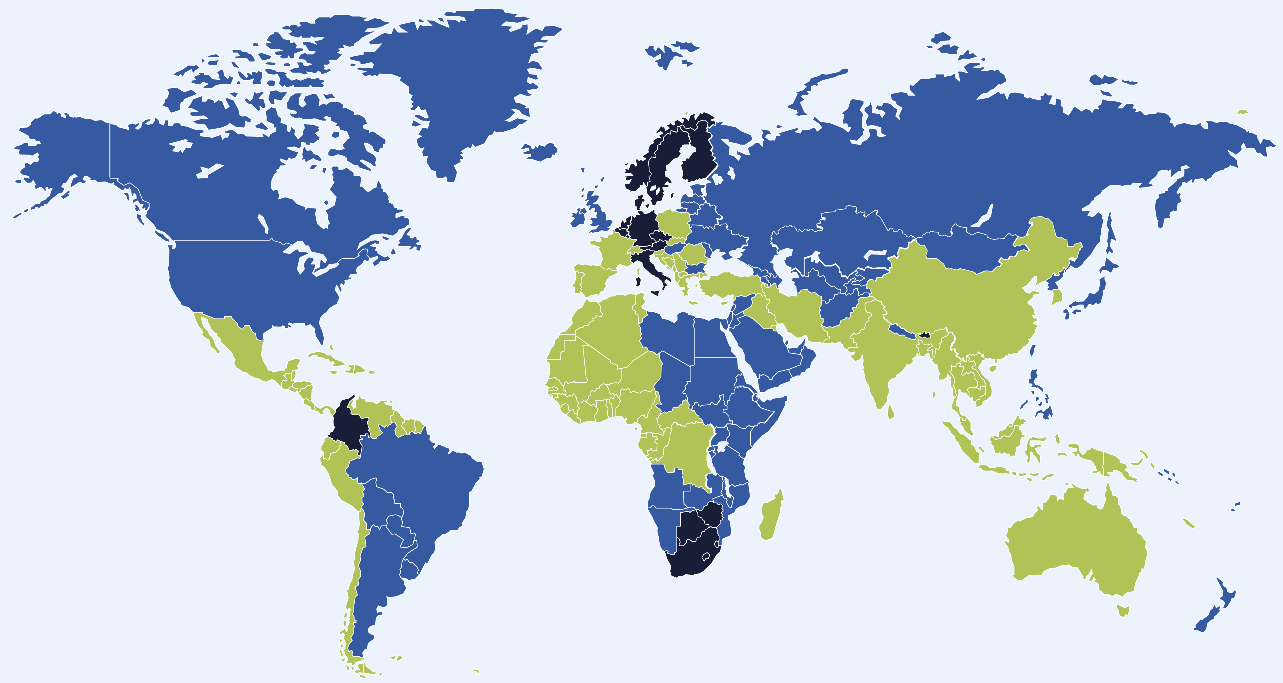
With **more than one million ESE devices installed worldwide**, according to the International Lightning Protection Association (ILPA) and GIMELEC , this technology now enjoys **confirmed global adoption**, driven by:

- **Strong penetration** in countries such as **Brazil, Mexico, Morocco, Nigeria, Congo, Thailand, Bangladesh**, and **numerous European markets** (e.g. France, Spain, Portugal, Greece);
- Geographic analysis of installations shows that **ESE devices are predominantly deployed in the world's most lightning-prone regions**. ILPA data indicates that **over 51.5% of ESE lightning rods** are installed in areas where ground flash **density (Ng) exceeds 10 strikes/km²/year** — the highest exposure zones globally, such as Brazil, Malaysia, India, and Central Africa. By comparison, Northern European countries report an Ng below 2.

Today, **ESE lightning rods are present on all continents** and are regarded as a **key component of electrical and climate resilience strategies**, particularly in regions exposed to extreme weather phenomena.

Use of ESE lightning rods worldwide:

Widely used | Used | Rarely used



Proven customer satisfaction.

One of the most significant indicators of the ESE lightning rods risk mitigation is **user satisfaction**. Two large-scale, independent studies confirm this perception:

IPSOS – MEDD / GIMELEC / INERIS Survey – June 2002[23]
→ 483 industrial sites surveyed in France

PROTECTION RATE

40%
of sites were equipped with a lightning protection system

of which
36,2%
used ESE devices

LIGHTNING STRIKE FREQUENCY

27%
of sites were struck at least once every 5 years

OVERALL SATISFACTION
(ALL TECHNOLOGIES COMBINED)

92%
satisfied users
(very or rather satisfied)

FOCUS ON ESE-EQUIPPED SITES

96%
overall satisfaction

85%
satisfied with ease of use

87%
satisfied with maintenance cost

OP Marketing Study – Gimelec D84 – June 2012[24]
→ 197 industrial sites equipped / 1,580 ESE devices analyzed

REAL LIGHTNING EXPOSURE

320
lightning strikes recorded on the analyzed sites

in
88% of cases,
no damage observed

USER SATISFACTION

93%
of users declared themselves satisfied with their ESE protection system

CONSEQUENCES

Only **5**
sites suffered material losses

2
outside the protected zone + **3**
without surge protectors

Indelec
SMART LIGHTNING SOLUTIONS

EXAMPLES OF LANDMARK SITES equipped with ESE lightning rods: Indelec project portfolio.

SECTOR	CLIENTS	LOCATION
Landmark and prestigious sites	Angkor Vat	Siam Reap, Cambodia
	Sacré Coeur Montmartre	Paris, France
	Burj Khalifa	Dubai, UEA
	National Museum of Anthropology	Mexico, Mexico
	Tower of London	London, UK

Focus Angkor Vat

→ CHALLENGE
Protecting the largest religious monument in the world, **covering 1,500 × 1,300 m** with **five towers reaching 65 m in height**.

→ SOLUTION
In close collaboration with restoration scientists, Indelec developed a **customized solution**. The lightning protection system needed to withstand discharges of several thousand amperes while remaining virtually "invisible".

Residential buildings	Sultan Palace	Nairobi, Kenya
	255 St Paul Street	Denver, USA
	Ararat Tower	Limassol, Cyprus
	Reserva Ecoville	Curitiba, Brazil
	Botanika	Hyderabad, India

SECTEUR	CLIENTS	LOCATION
Data center	OVH	Croix, France
	Kaspi Bank	Almaty, Kazakhstan
	Infosys	Bangalore, India
	Google	Thornton, USA
	Voltekko Gama	Alcochete, Portugal

Focus Data center OVH Cloud

→ CHALLENGE
Protecting a next-generation data center hosting nearly 35,000 servers in Roubaix, **ensuring maximum service continuity** in an environment highly sensitive to surges and electromagnetic fields.

→ SOLUTION
Indelec deployed **Prevectron®3 Connect lightning rods** on self-supporting masts, installed away from buildings for isolated protection. The connected devices provide real-time monitoring for OVHCloud teams. Particular attention was given to grounding quality (resistance < 5 ohms) and equipotential bonding.

Commercial buildings	The Village – Al Jawhara Mall	Jeddah, Saudi Arabia
	Arribat commercial center	Rabat, Morocco
	Monsieur Bricolage	Nis, Serbia
	Mall of Indonesia	Jakarta, Indonesia
	Mall Real Cariari	Heredia, Costa Rica

Industrial sites	Bitner Cable	Trzyciąż, Poland
	Toyota	Chachoengsao, Thailand
	Saint Gobain Brasilit	*Multi-sites*, Brazil
	Liberty Steel Plant	Galati, Romania
	ACC Giga Factory	Billy Berclau, France

SECTEUR	CLIENTS	LOCATION
Sports facilities and stadiums	**Allegiant Stadium**	Las Vegas, USA
	Stade Orange Velodrome	Marseille, France
	Franceville Stadium	Franceville, Gabon
	Sydney Cricket Stadium	More Park, Australia
	Daegu Stadium	Daegu, South Korea

Focus Allegiant Stadium : Super Bowl 2024

→ CHALLENGE
Ensuring the safety of tens of thousands of spectators and guaranteeing continuity of the most watched sporting event in the US, in a **complex architectural venue with high lightning exposure**.

→ SOLUTION
In partnership with NLP Corp, Indelec designed and deployed a **tailor-made lightning protection system** for Allegiant Stadium. The solution, **fully compliant with international standards**, combined reliability, optimal coverage, and discreet integration into the infrastructure.

Use case Prevectron3® Connect, July 2025

Water park OWA Parks & Resorts — Foley, Alabama, USA

A lightning strike hit the ESE lightning rod and was automatically recorded on indelec-connect.com on July 30, 2025, 19:59 (UTC+2) thanks to the device's **IoT features**. The lightning rod **remained fully operational** after the strike.
Context: A leisure center with **large-scale structures** and extensive **open areas** requiring protection.

Hazardous and flammable storage sites	**ZOHR Gas Field**	Mediterranean, Egypt
	Petroleum Company	Rusororo, Rwanda
	Antamina	Ancash, Peru
	Air Liquide	*Multi-sites*, France
	Korean Gas Corporation	*Multi-sites*, South Korea

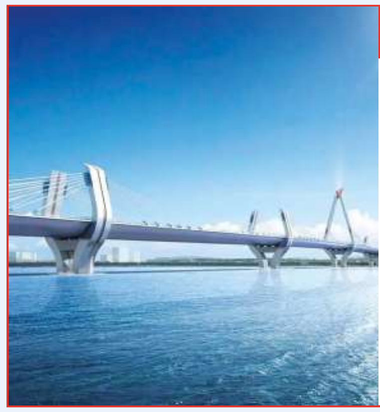
Focus ZOHR Gas Field

→ CHALLENGE
Protect the **critical infrastructures of the largest gas field in the Mediterranean**, operated by ENI in partnership with EGPC, in an environment exposed to **saline humidity** and **frequent coastal thunderstorms**.

→ SOLUTION
Installation of **Prevectron®3 S60 lightning rods with remote testing modules** by ELSEWEDY SEDCO on several site facilities. This setup ensures **easier maintenance** and **continuous monitoring**, perfectly suited to the operational constraints of a very large offshore site.

→ RESULT
A **reliable, intelligent, and easy-to-maintain** lightning protection solution that helps secure the strategic gas production of the Shourouk concession in full compliance with industrial and regulatory standards.

SECTEUR	CLIENTS	LOCATION
Transport infrastructures	**Chaban Delmas Bridge**	Bordeaux, France
	Selander Bridge	Dar Es Salam, Tanzania
	Tat Son Nhat Airport	Ho Chi Minh Ville, Vietnam
	Istanbul Sabiha Gökçem Airport	Istanbul, Türkiye
	VLI Portuário Luiz Antonio Mesquita	Santos, Brazil



Focus Selander Bridge

→ CHALLENGE
Protecting a 6.2 km **strategic infrastructure**, exposed in a coastal zone with heavy traffic (55,000 vehicles/day), featuring pylons up to 40 meters high and difficult to access for maintenance.

→ SOLUTION
Indelec conducted a full **lightning risk assessment** and delivered a tailored solution with **Prevectron®3 S60 Connect lightning rods**, enabling remote supervision. This approach ensures effective protection during the rainy season while reducing on-site maintenance constraints.

Use case Prevectron3® Connect, June 2025

Victor Attah International Airport — Akwa Ibom, Nigeria

A lightning strike hit the ESE lightning rod and was recorded on indelec-connect.com on 19/06/2025 at 19:06 (UTC+2) through its **IoT features**. The lightning rod **remained fully operational** after the strike.

Logistics platforms	**Marlog Amot Logistics Center**	Beit Shemesh, Israel
	Hala CTP logistics park	Zilina, Slovakia
	Amazon	*Multi-sites*, USA, France
	Prologis	*Multi-sites*, France
	Logitics Facilities	Suhar, Oman

Use case Prevectron3® Connect, July 2025

RATP Bus Depot — Thiais, France

A lightning strike hit the lightning rod and was recorded on indelec-connect.com on 21/07/2025 at 13:27 (UTC+2) through its **IoT features**. The lightning rod **remained fully operational** after the strike.

Event specifics are large-scale structure and ESE lightning rod installed in the middle of the roof, surrounded by metallic mass.

7—
Navigating the ESE lightning rod market.

7.1—
Counterfeits and associated risks.

A fragmented and vulnerable market.

The ESE lightning rod market today **faces dange-rous practices**:

- **Counterfeits** imitating certified products wit-hout meeting required standards or expected engineering effectiveness.
- **Non-tested products**, sold without certification — often at low cost but **highly defective** in the event of a real lightning strike.
- **Installations carried out without prior risk studies** or qualified installers.

RESULT:
Increased risks for people, buildings, and sensitive equipment, as well as for insurers, who may refuse coverage in case of non-compliant installation.

The effectiveness of an Early Streamer Emission (ESE) lightning rod relies on **controlled triggering technology**, whose **reliability depends on several essential factors**:

- **PROVEN TECHNOLOGY**: Only devices featuring advanced electronic triggering, validated both in laboratory tests and in real-world conditions, can be considered reliable;
- **EMBEDDED ELECTRONICS**: Components must withstand extreme lightning currents — a frequent failure point in counterfeits or low-end products;
- **OFFICIAL CERTIFICATIONS**: NF C 17-102:2011, UL, CE, Bureau Veritas... without these labels, sustainability and safety cannot be guaranteed;
- **MATERIALS AND MANUFACTURING**: Certified-quality metals and alloys are re-quired. Counterfeits often show insulation defects that compromise both lifespan and effectiveness.

Typology of counterfeits or non-compliant products.

Type of product	Main risks	Warning signs
Visual copies	Deceptive appearance, but non-compliant internals	No certification, inconsistent markings
Low-end products	Untested electronics, fragile materials	Abnormally low price, vague or incomplete manuals
Fake ESE (“decorative”)	No actual triggering mechanism	No triggering system, no laboratory testing
Non-certified installations	Even a good ESE loses efficiency if poorly installed	No prior risk study, no material traceability

Example of counterfeit.

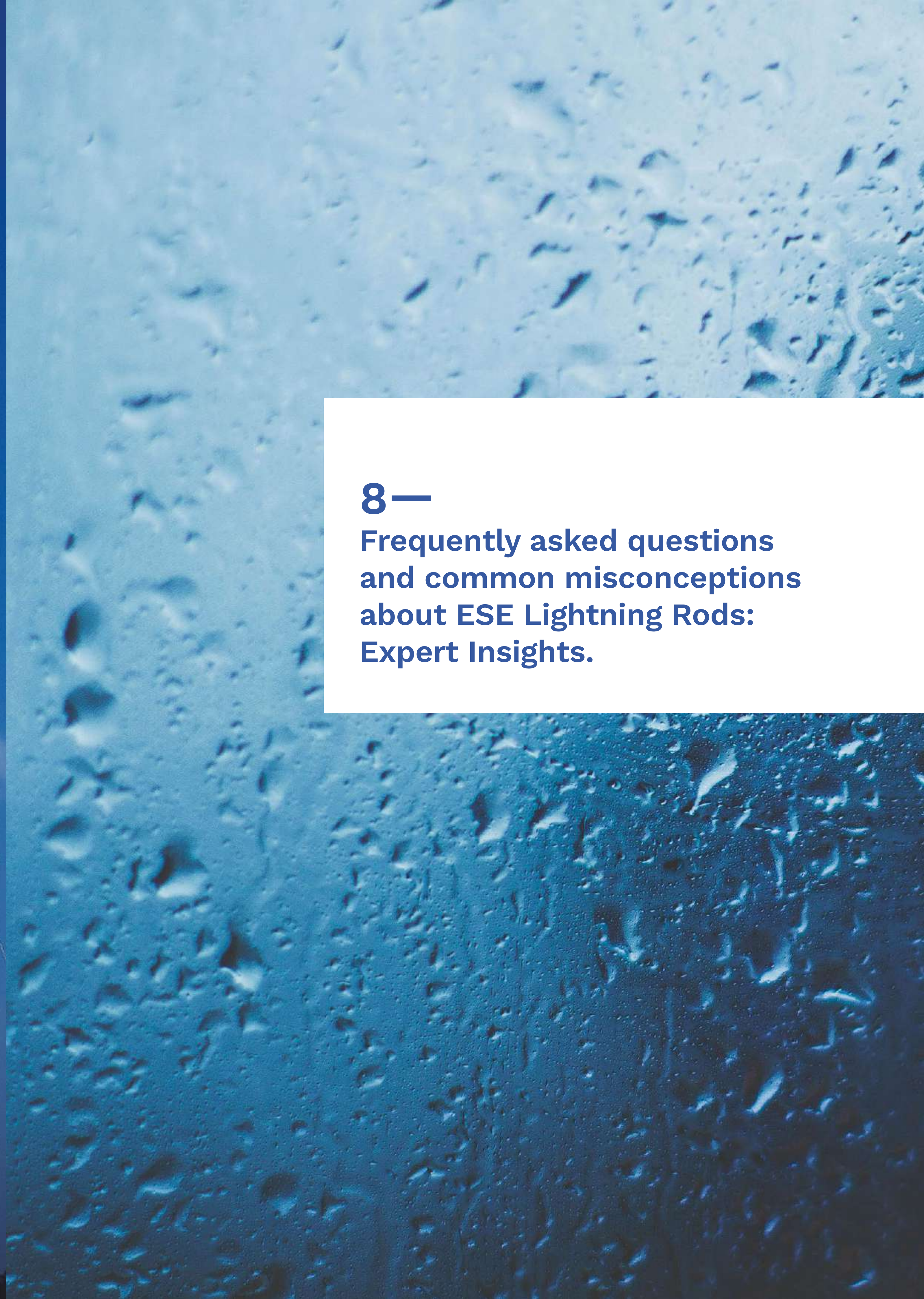
In May 2024, Chinese authorities (Dongguan PSB) **seized a batch of fake “PREVECTRON” ESE devices** → the operation led to the **arrest of five individuals** (Source: legal advice, Indelec).

RECOMMENDED BEST PRACTICES.

- Require a prior **standardized and certified risk study.**
- **Verify the product certification** and its origin.
- **Demand a detailed technical study** for the selection and positioning of ESE devices.
- **Ensure the qualification of the installer.**
- **Favor manufacturers with proven international experience.**
- Be extremely cautious with **offers priced well below market value.**

8—

Frequently asked questions and common misconceptions about ESE Lightning Rods: Expert Insights.



Expert Insights

Despite more than 40 years of existence and hundreds of thousands of units installed worldwide, Early Streamer Emission (ESE) lightning rods still raise questions. To clarify certain technical or regulatory points, **we interviewed two Indelec experts**.

They answer here the **most common questions**, based on **current standards**, **fundamental scientific principles**, and **field experience**.

Two Indelec experts to answer your questions.

Sylvain FAUVEAUX

Researcher at LiRi (Lightning Innovation & Research Institute) with over 16 years in the lightning protection industry and 5+ years in academia. He is a certified **Qualifoudre N4 Expert** & Trainer, holder of a **PhD in Electronics** (Mines Douai / University of Bordeaux I), and a **qualified Associate Professor** (Electronics).

Ulric KLUJ

Expert part of key standardization committees **(IEC TC81, CENELEC TC81X, AFNOR UF81)**.

Are ESE lightning rods compliant with standards? Do they conflict with international norms?

The design and installation of ESE lightning rods comply with various national and international lightning protection standards, which present no conflict:

- International standards (IEC 62305-2) define the methodology for lightning risk analysis;
- National standards (NF C 17-102, UNE 21 186, NP 4426, I7, etc.) define the design, installation, and testing of ESE-based lightning protection systems;
- International standards (IEC 62561 series) specify the technical characteristics and test procedures for all lightning protection system components (conductors, lightning counters, clamps, connectors, etc.).

It is now widely accepted in the technical community that:

- Specifications for lightning protection systems are fully standardized;
- Design, installation, and maintenance must follow these national and international standards;
- Local codes and regulations often provide additional requirements. For example: Portugal's Civil Protection Authority issued Technical Note24 making lightning risk analysis (and protection where required) mandatory for all buildings.

Do ESE lightning rods "attract" lightning?

The principle of an ESE lightning rod is similar to that of Franklin rods developed in the 18th century: the purpose is not to attract lightning, but to provide a preferred and safe path for the current to reach the ground and dissipate.

The difference lies in coverage: a conventional rod protects a limited zone whereas an ESE device provides a larger protection radius, meaning fewer devices are needed to protect the same building. But their role and function remain identical.

Are electromagnetic effects dangerous or disruptive?

Yes. **Lightning is hazardous not only at the direct strike point** (fusion, fire, explosion) but also **indirectly due to the electromagnetic fields it generates**. These fields are a major cause of transient overvoltages.

Therefore, an effective protection system must combine direct protection (lightning rods), **and indirect protection** (surge protective devices installed in electrical panels).

Expert Insights

What independent tests have been conducted?

As with all safety-critical equipment, ESE lightning rods undergo a combination of:

- **Laboratory tests:** Standards include annexes defining complete test protocols — environmental, physical, and electrical sequences, all performed on the same sample. Independent certification bodies can attest conformity;

- **Real-world field tests:** Given the extraordinary values of lightning (current, leader length, electric field, timing), laboratories cannot fully replicate natural strikes. Scientific platforms therefore conduct field testing in high-lightning areas (e.g., triggered lightning campaigns);

- **Statistical studies:** Large-scale surveys (e.g., IPSOS in France, ST in Malaysia) complement lab data;

- **Connected devices:** The latest generations of ESE lightning rods transmit real-time strike data, providing continuous validation of predictive models and risk reduction in real conditions.

Are ESE devices mainly installed in Europe, where lightning density is low?

False. In **Europe**, installation is largely driven by **legal or regulatory requirements**. In tropical regions with very high lightning density, protection is an absolute necessity to:

- **Save lives** (schools, sports facilities, rural areas — e.g., Bangladesh Ministry of Disaster Management program);

- **Ensure service continuity** (transport and energy infrastructures);

- **Preserve cultural heritage**;

- **Maintain industrial processes** despite climatic risks.

Can lightning energy be harvested and stored?

The idea is attractive, but technologies do not exist today:

- We **cannot yet predict precisely** where lightning will strike.
- **No technology currently** allows storage of extremely high currents delivered in milliseconds.

For now, lightning remains unexploitable as a renewable energy source.

Is lightning activity increasing?

Yes. As explained in Section 3, lightning is directly affected by climate change. Convective storms, where lightning is central, are expected to become more frequent, more intense, and more widespread.

For every +1°C warming, the atmosphere can hold ~7% more humidity — a key factor fueling storms. Climate models converge:

→ **+50 %** lightning strikes in the US by **2100**[16] ;
→ **+41 %** long-continuing-current (LCC) strikes by **2090** in some regions.

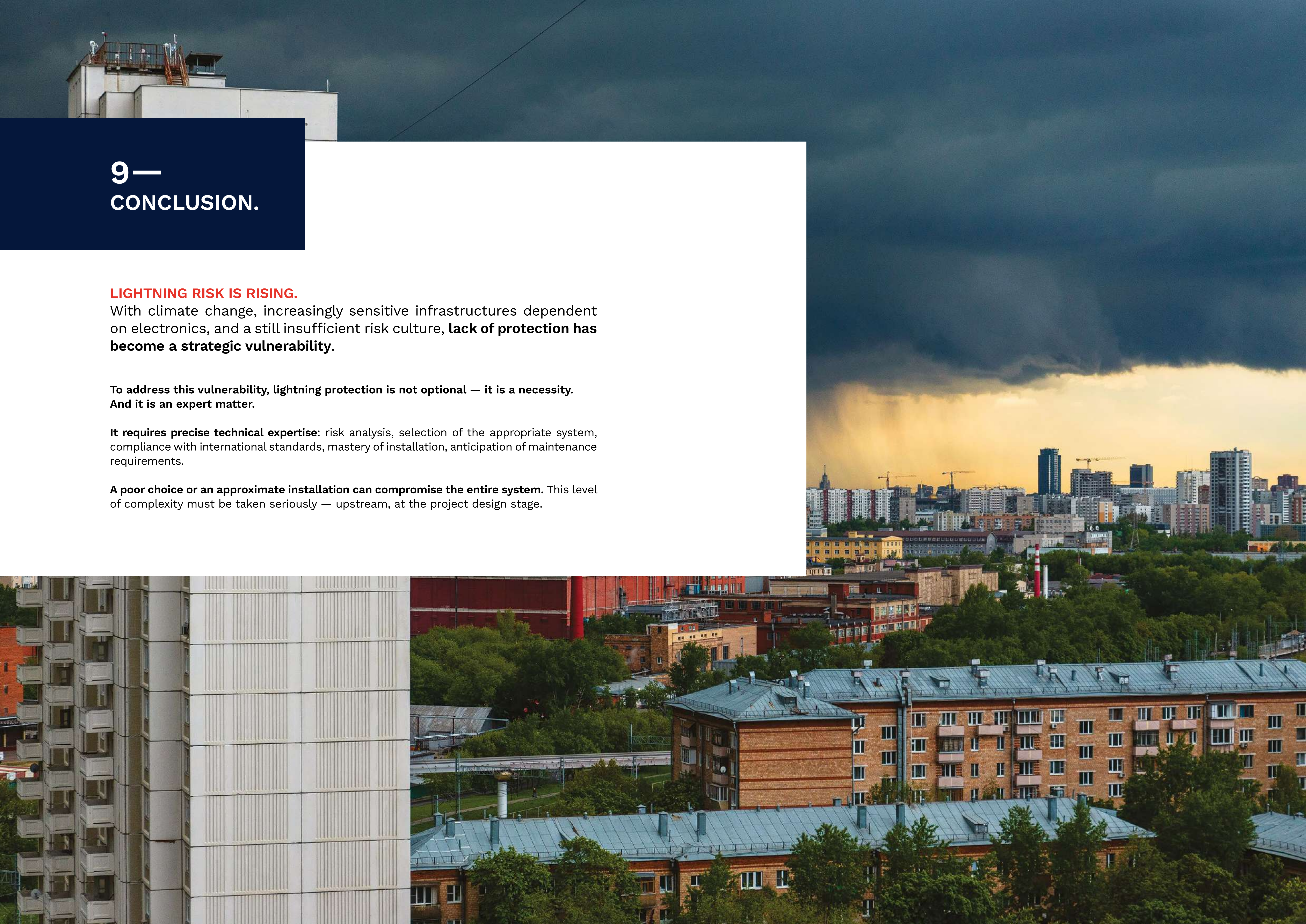
Most exposed regions are South America, Western North America, Southeast Asia and Mediterranean Europe.

Which professions are responsible for installing lightning protection systems?

Originally, both direct (rods) and indirect (surge protectors) systems were installed by electricians.

However, for more than 20 years, **the industry has become increasingly specialized**, with **dedicated training and certification programs** (e.g., UL Label, Qualifoudre) and **independent inspection services** to ensure compliance with standards and local regulations.

These specialized and certified professionals ensure installations are safe, compliant, and effective.



9—
CONCLUSION.

LIGHTNING RISK IS RISING.

With climate change, increasingly sensitive infrastructures dependent on electronics, and a still insufficient risk culture, **lack of protection has become a strategic vulnerability**.

To address this vulnerability, lightning protection is not optional — it is a necessity. And it is an expert matter.

It requires precise technical expertise: risk analysis, selection of the appropriate system, compliance with international standards, mastery of installation, anticipation of maintenance requirements.

A poor choice or an approximate installation can compromise the entire system. This level of complexity must be taken seriously — upstream, at the project design stage.

10—
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