GSMA

06

Futureproofing Connectivity

# Annexes




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November 2026

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**Acknowledgements**

This report has been developed by the GSMA with Frontier Economics.

The GSMA would like to thank members of the GSMA Climate Action Taskforce, Regulators, Network Equipment Manufacturers and Insurers whose expertise and valuable insights helped to shape this report series.

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# Futureproofing Connectivity

**This is the sixth report in a six-part series 'Futureproofing Connectivity: Climate Risk and Resilience in Telecommunications'.** This collection of research identifies weather-related risks that telecommunications networks face, the associated financial impacts of these risks and what is needed to strengthen the resilience of networks in a changing climate.

By quantifying exposure to climate risk and showcasing best practices in network resilience, the research provides guidance for operators on climate-related planning, investments and reporting. The overarching goal of the series is to align the sector more closely and help prepare telecommunications networks for the impacts of a more volatile climate.



















→ You can explore the other reports in the series here.

# Report series structure

This research is split over a six-part series 'Futureproofing Connectivity: Climate Risk and Resilience in Telecommunications'

## 01
## Executive summary and recommendations

Describes the research approach, key findings and provides practical recommendations for operators, policymakers, regulators, suppliers and investors to strengthen the resilience of telecommunications networks to the impacts of climate change.

## 02
## Weather-related risks and impacts on telecommunications networks

Identifies acute and chronic weather-related risks and associated restoration costs that can affect telecommunications networks and maps these risks to different types of network infrastructure. This includes direct risks to mobile and fixed access networks, core networks, data centres, towers, backhaul, transport links and other supporting infrastructure. It also considers the sector's exposure to indirect risks and interdependencies, such as power supply and other critical systems.

## 03
## Legal, regulatory and voluntary frameworks shaping network resilience

Assesses the resilience and adaptation obligations that telecommunications companies are expected to meet. These include telecoms-specific network resilience requirements, critical infrastructure obligations, corporate governance and risk management frameworks and climate-related reporting and disclosure frameworks.

## 04
## Assessing weather- and climate-related risks

Reviews how operators currently assess risk. It covers the tools, methods, data sources, models and internal governance arrangements they use, together with the variables they need to understand the financial impact of physical climate risks and the cost of building resilience.

## 05
## Prevention, response and recovery practices

Examines how operators respond to and manage weather-related risks in practice. This includes how resilience is embedded in network design, maintenance and renewal; the measures taken to reduce vulnerability and maintain service; how operators prepare for, respond to and recover from severe weather events; and how they manage the residual risks and financial impacts that cannot be fully prevented.

## 06
## Annexes

Explains the methodology behind the modelling used to estimate infrastructure repair and replacement costs, and estimated telecommunications outages under current and future climate conditions. The inputs, sensitivities, assumptions and limitations are detailed, so that operators might use the approach in their own climate risk assessments.

# Annex 1
# Modelling weather-related risk

## Modelling the costs of severe weather hazards

The modelling conducted for this report series has estimated the impact of climate change on telecommunications operators in the form of increases to infrastructure repair and replacement costs due to severe storms, coastal flooding and riverine flooding. The analysis estimates the total global risk of these forms of severe weather for mobile operators is **$1.7 billion per year under current climate conditions** (i.e. the expected cost of damage to mobile infrastructure) and **$3.1 billion per year under mid-century climate conditions**.

### Severe weather risks to telecommunications networks

These estimates have been developed with a modelling framework that operators can use to estimate the scale of severe weather risk for their own networks. The approach, outlined in detail below, can be adapted by operators using detailed datasets on infrastructure assets and local knowledge of weather hazards.

#### Approach to estimate the impact of severe weather events on operators' infrastructure

The approach combined global hazard datasets with information on the location of telecommunications infrastructure, as well as assumptions about asset vulnerability and the replacement costs of these assets. This is set out in Figure 1.

The analysis first identified the global risk of severe weather across different hazards and intensity levels and overlayed this with the number of telecommunications assets located within each risk band. The following figures provide an illustrative summary of this process for mapping the risk of severe weather hazards to the presence of mobile infrastructure.

Figure 2a shows the location of cell towers, as geopositioned by the OpenCellid dataset. Figure 2b then overlays global storm intensity for a 1-in-100-year storm under current climate conditions to identify the maximum wind speeds expected to be faced by each site for a storm with a 100-year return period. Figure 2c zooms in on Mexico and demonstrates the variation in wind speed intensity faced by different parts of the country and how these correspond to the location of cell sites, separately for urban and rural areas.

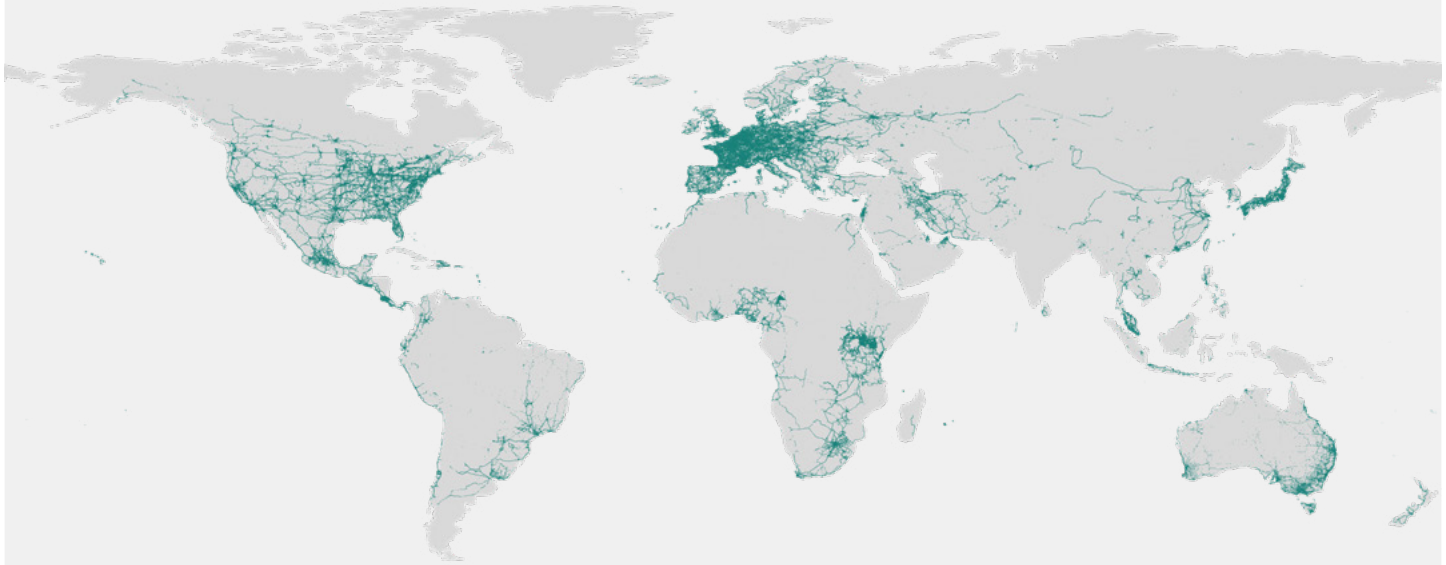
**Figure 1** **Geographic variation in the infrastructure costs associated with different severe weather events**




Source: Frontier Economics analysis of OpenCellid data and STORM data.

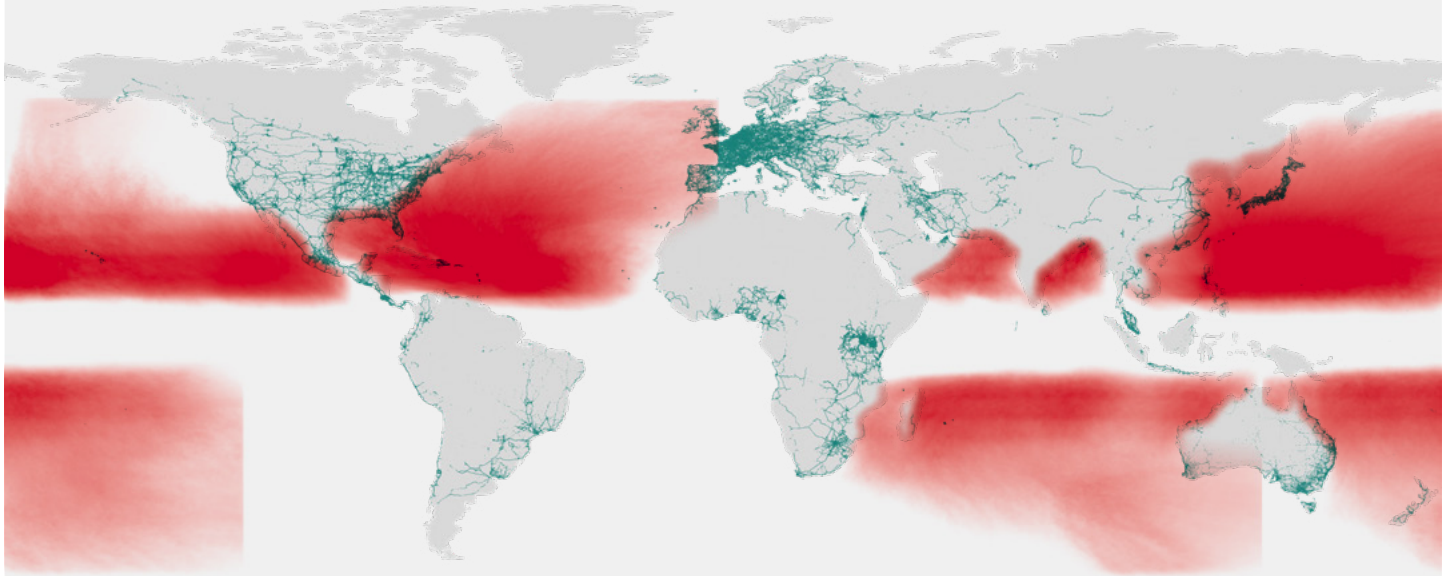


## Figure 2a Location of cell towers, global



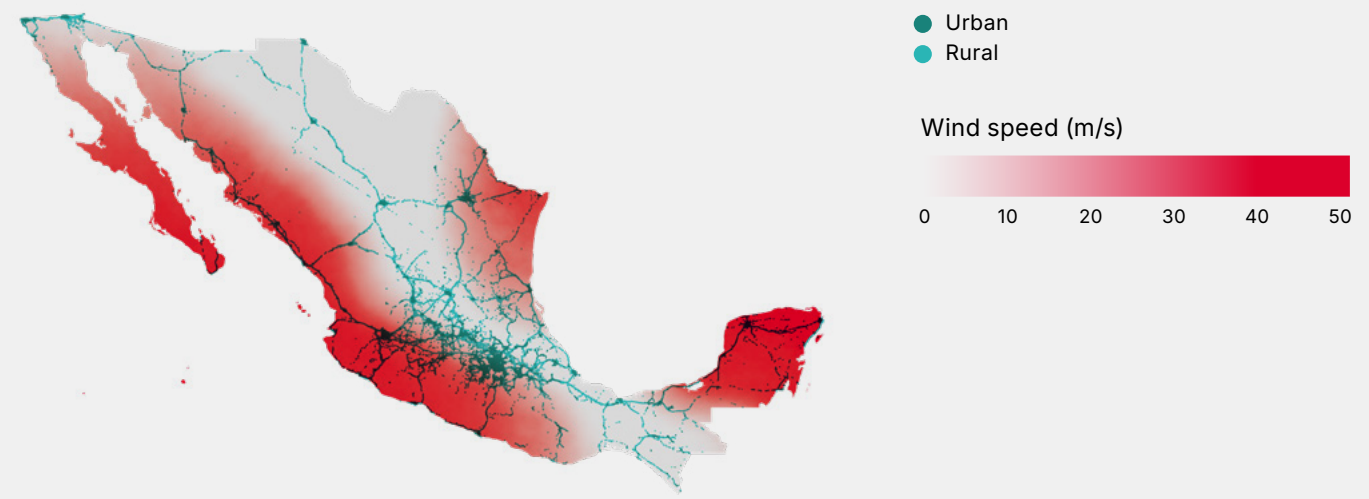
Source: Frontier Economics analysis of OpenCellid data.

## Figure 2b Location of cell towers overlaid with 1-in-100-year storm intensity, global



Source: Frontier Economics analysis of OpenCellid data and STORM data.

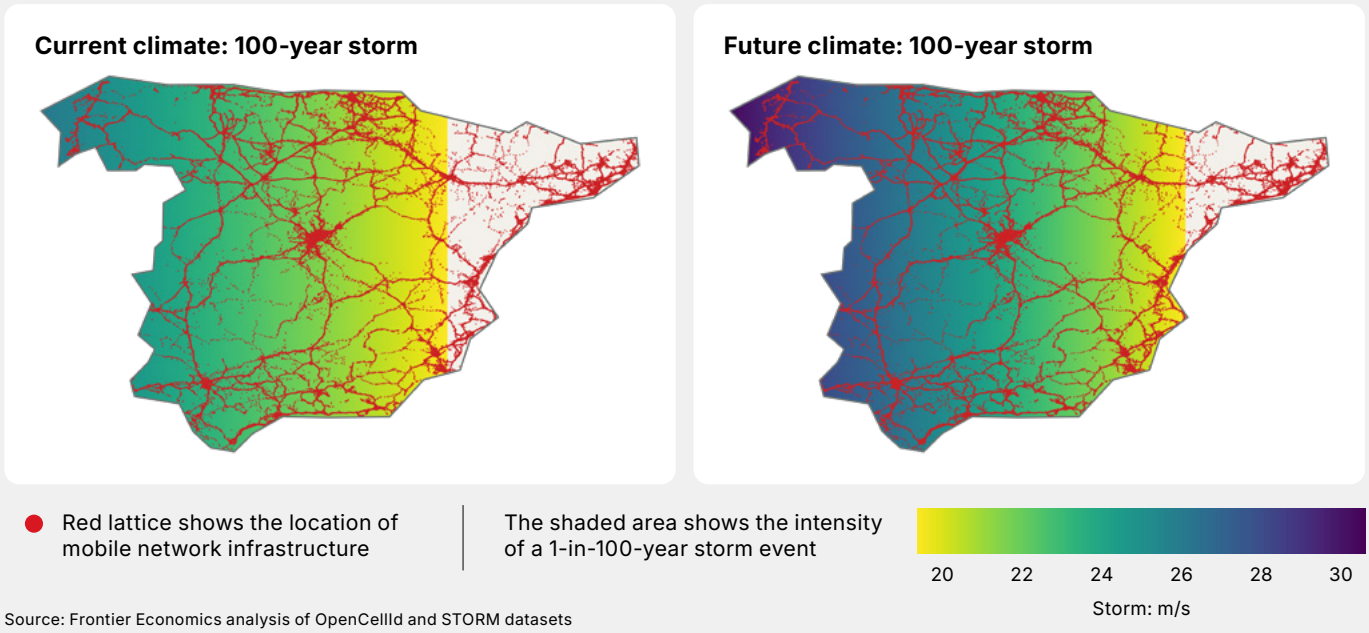
**Figure 2c** **Location of cell towers overlaid with 1-in-100-year storm intensity, Mexico, under current climate conditions**




Source: Frontier Economics analysis of OpenCellid data and STORM data.

This assessment was conducted for different time horizons. For example, Figure 3 presents the storm risk faced by mobile infrastructure in Spain under current (left) and projected mid-century (right) climate conditions. By comparing the intensity of such a severe storm under current climate conditions with those under projected mid-century climate conditions, the analysis assessed the increase in storm intensity over time as a result of climate change and the subsequent impact on network assets being exposed to more intense wind speeds.

**Figure 3** **Risk of severe weather under current and projected mid-century climate conditions, Spain**




Source: Frontier Economics analysis of OpenCellId and STORM datasets

The exposure analysis was then translated into the financial impact on operators. The modelling considered where assets are located, the severity of the hazard they face and the likely vulnerability of those assets to damage. This allowed the model to estimate the potential cost of repair, replacement or resilience measures under future climate conditions. The assessment used industry-standard fragility and vulnerability curves to estimate how the likelihood and scale of asset damage changes as hazard intensity increases.

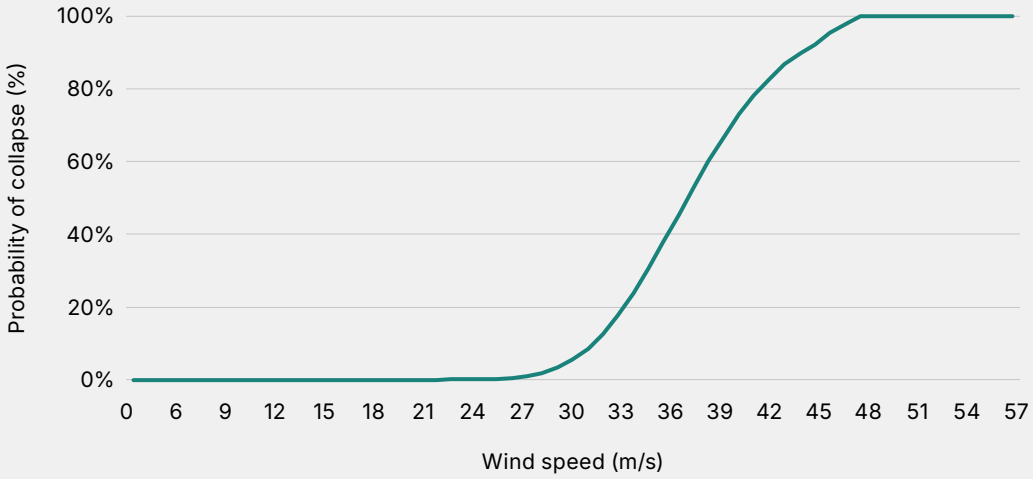
Rather than relying on a single published study, the vulnerability functions were developed using evidence from multiple engineering studies within the NHESS Physical Vulnerability Database,[1] providing a globally consistent representation of telecoms infrastructure. This database provides estimated vulnerability curves across a range of physical assets, including communications towers, electricity poles, commercial buildings and residential buildings, among others.

The vulnerability modelling distinguishes between wind and flooding because the underlying engineering relationships differ.

For storms, published fragility curves are used. Fragility curves estimate the probability that an infrastructure asset reaches a specified damage state (in this case, structural collapse) as wind speed increases. The database contains separate fragility curves for different types of communications towers.

At wind speeds below 23 m/s (51 mph), the probability of collapse is estimated to be zero. At higher wind speeds, the probability of collapse gradually rises and once wind speeds reach a critical threshold (approximately 35 m/s, or 78 mph) the probability increases sharply. This means that relatively small increases in extreme wind speed can have a material impact on expected damage costs.

**Figure 4 Industry-standard fragility curve used to assess the probability of collapse of telecoms assets, according to storm intensity**



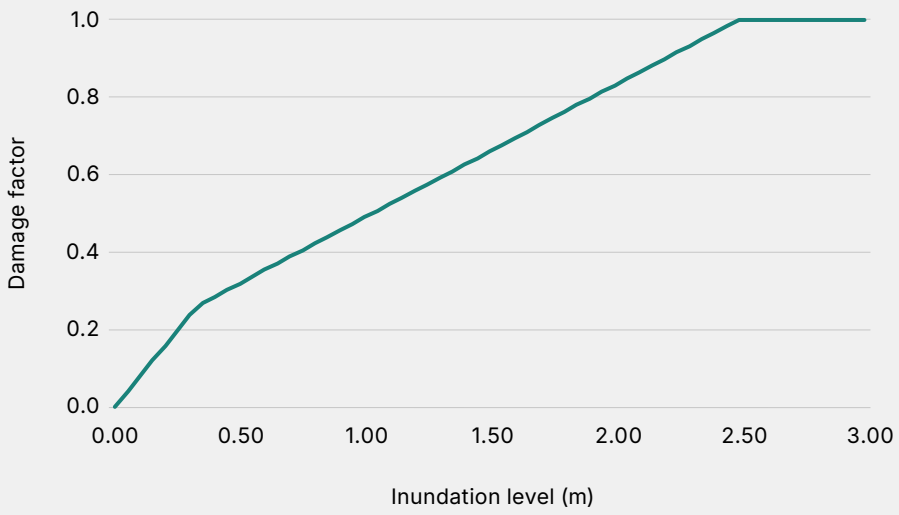

Source: Frontier Economics analysis based on fragility curves from the NHESS Critical Infrastructure Physical Vulnerability Database (Mignan et al., 2024), drawing on Gao and Wang (2018).

For flooding, published vulnerability curves are used. These estimate the mean "damage factor", which represents the expected repair cost as a proportion of the total replacement cost for a given flood depth.

As flood depth increases, the expected damage factor also rises. For example, a damage factor of 0.8 at a depth of 1.9 m implies that a telecoms tower facing a flood depth of 1.9 m is expected to sustain damage equal to 80% of its replacement cost. The damage factor reaches 1 (or full damage) at higher levels of inundation (around 2.5 m). This is used to convert the intensity of flood exposure into an estimate of financial loss.

1 Nirandjan, S. et al. (2024). "Review article: Physical vulnerability database for critical infrastructure hazard risk assessments – a systematic review and data collection". Natural Hazards and Earth System Sciences, Volume 24, Issue 12.

**Figure 5 Industry-standard vulnerability curve used to assess the vulnerability of telecoms assets to flood depth**




Source: NHESS Critical Infrastructure Physical Vulnerability Database (Mignan et al., 2024)

For both hazards, the curves were used to link the intensity of an event, such as wind speed or flood depth, to the probability or severity of infrastructure damage. These estimates were then combined with asset values and the number of exposed sites to estimate the expected cost of severe weather events.

A key limitation is that these curves do not account for remedial actions that operators may take to strengthen infrastructure, such as tower reinforcement, flood protection, relocation or improved site design. As a result, they provide a consistent baseline estimate of risk faced across countries, and can consider how this risk varies geographically, but will not be a precise estimate of the risk faced by individual operators.

As a final step, the model applied an estimated replacement cost for mobile sites to the assets at risk (taking into account the degree of risk from the fragility curves). This was based on estimates from the European Commission Bottom-Up Mobile Cost Model,[2] adjusted for regional price indices, to reflect regional variation in the typical cost of materials and labour.

## Scenario-based sensitivities

The main estimates presented in this report isolate the impact of changing climate hazards by holding the underlying telecoms network constant between current and future climate scenarios. This provides a clear estimate of the incremental financial risks associated with climate change, independent of changes in network architecture or investment decisions.

However, mobile telecommunications networks are expected to evolve considerably over the coming decades. Operators are expected to continue modernising network technologies, expanding network capacity and altering infrastructure ownership arrangements.

These developments may have a material impact on the future financial exposure of telecoms infrastructure to severe weather events. To recognise these uncertainties, the modelling framework presents some alternative scenario-based sensitivities. These scenarios follow the same modelling approach described above but explore how alternative assumptions about the evolution of mobile networks affect the estimated infrastructure damage costs.

2 European Commission. (18 December 2024). Finalisation of the mobile cost model for roaming and the delegated act on a single EU-wide mobile voice call termination.

## Migrating from legacy technologies to 5G

The modelling exercise assumed that the relative deployment of 2G/3G, 4G and 5G technologies would remain unchanged between the current and future climate scenarios.

An alternative scenario considered the continued migration from legacy technologies to 5G. Under this scenario, the representative active infrastructure composition was modified by reducing the proportion of 2G/3G equipment and increasing the proportion of 5G equipment deployed on existing telecoms sites. This scenario reflects the ongoing retirement of legacy mobile technologies and their replacement by newer technologies on the existing site portfolio.

The exercise modelled three scenarios:

- **Scenario 1:** Significant phasing out of legacy technologies. A 50% reduction in 2G/3G equipment at sites, with a corresponding increase in 5G equipment.
- **Scenario 2**: Total phasing out of legacy technologies. A 100% reduction in 2G/3G equipment at sites, with a corresponding increase in 5G equipment.
- **Scenario 3:** Total phasing out of legacy technologies and modest 4G migration. A 100% reduction in 2G/3G equipment at sites and 25% reduction in 4G equipment, with a corresponding increase in 5G equipment.

These represent indicative technology mixes that may be observed by the mid-21st century. The impact of these alternative scenarios on future annual expected infrastructure replacement costs is presented in Table 1. Note that these assumptions have no impact on expected costs under baseline climate conditions.

**Table 1 Scenario sensitivity – the impact of migration to 5G networks on the expected annual cost under projected mid-century climate conditions**

| Scenario | Storms | Coastal floods | River floods | Total |
|---|---|---|---|---|
| **No migration** | $2.37 bn | $157 m | $577 m | **$3.11 bn** |
| **Significant phasing out of legacy technologies** | $2.44 bn | $161 m | $593 m | **$3.20 bn** |
| **Total phasing out of legacy technologies** | $2.51 bn | $165 m | $608 m | **$3.29 bn** |
| **Total phasing out of legacy technologies and modest 4G migration** | $2.58 bn | $170 m | $624 m | **$3.38 bn** |

The infrastructure repair and replacement costs associated with severe weather hazards are estimated to be greater under higher migration scenarios. In particular, the total financial cost is estimated to increase from $3.1 billion under the main scenario to:

- $3.2 billion under Scenario 1 – a 2.9% increase
- $3.3 billion under Scenario 2 – a 5.7% increase
- $3.4 billion under Scenario 3 – an 8.6% increase

This is expected given that 5G equipment is comparatively more costly to repair and replace. However, it is important to note that this is only true for the physical repair and replacement cost. More generally, modern equipment (such as that used for 5G communications) is typically more resistant to other sources of damage and disrepair, such as heat. As such, this could reduce the overall cost associated with severe weather such as heat for modern 5G equipment, relative to older 2G, 3G or 4G equipment.

## Network densification in urban areas

The deployment of 5G is expected to increase not only through the replacement of existing equipment, but also through the construction of additional telecoms sites to support increasing network capacity and traffic demand, especially in urban areas.

This scenario therefore considers the impact of future network densification by increasing the number of urban 5G telecoms sites within the model. Unlike the previous scenario, which changes only the technological composition of existing sites, this scenario increases the overall telecommunications asset base exposed to severe weather hazards. The resulting estimates therefore capture both the impacts of changing climate hazards and the additional exposure associated with continued network expansion.

The exercise models two scenarios:

- **Scenario 1:** Modest network densification. A 25% increase in the number of sites with 5G equipment, in urban areas.
- **Scenario 2:** Significant network densification. A 50% increase in the number of sites with 5G equipment, in urban areas.

The impact of these alternative scenarios on future annual expected infrastructure replacement costs is presented in Table 2. Note that these assumptions have no impact on expected costs under baseline climate conditions.

As before, the infrastructure repair and replacement costs associated with severe weather hazards are estimated to be greater under more intense network densification. In particular, the total financial cost is estimated to increase from $3.1 billion under the central scenario to:

- $3.8 billion under Scenario 1 – a 21% increase
- $4.4 billion under Scenario 2 – a 42% increase

This is the combined impact of a larger proportion of more 5G sites, and more sites in general, at risk of damage or collapse.

**Table 2 Scenario sensitivity – impact of densification of urban 5G networks on the expected annual cost under projected mid-century climate conditions**

| Scenario | Storms | Coastal floods | River floods | Total |
|---|---|---|---|---|
| **No network densification** | $2.37 bn | $157 m | $577 m | **$3.11 bn** |
| **Modest network densification** | $2.89 bn | $184 m | $687 m | **$3.76 bn** |
| **Significant network densification** | $3.39 bn | $210 m | $796 m | **$4.40 bn** |

# Modelling the scale of weather-related outages

The analysis compiled a global list of telecommunications outages between 2022 and 2024 and overlays historical weather hazard data to identify which outages coincided with severe weather events.

The analysis then applied assumptions for the average number of customers affected to estimate the scale of weather-related outages.

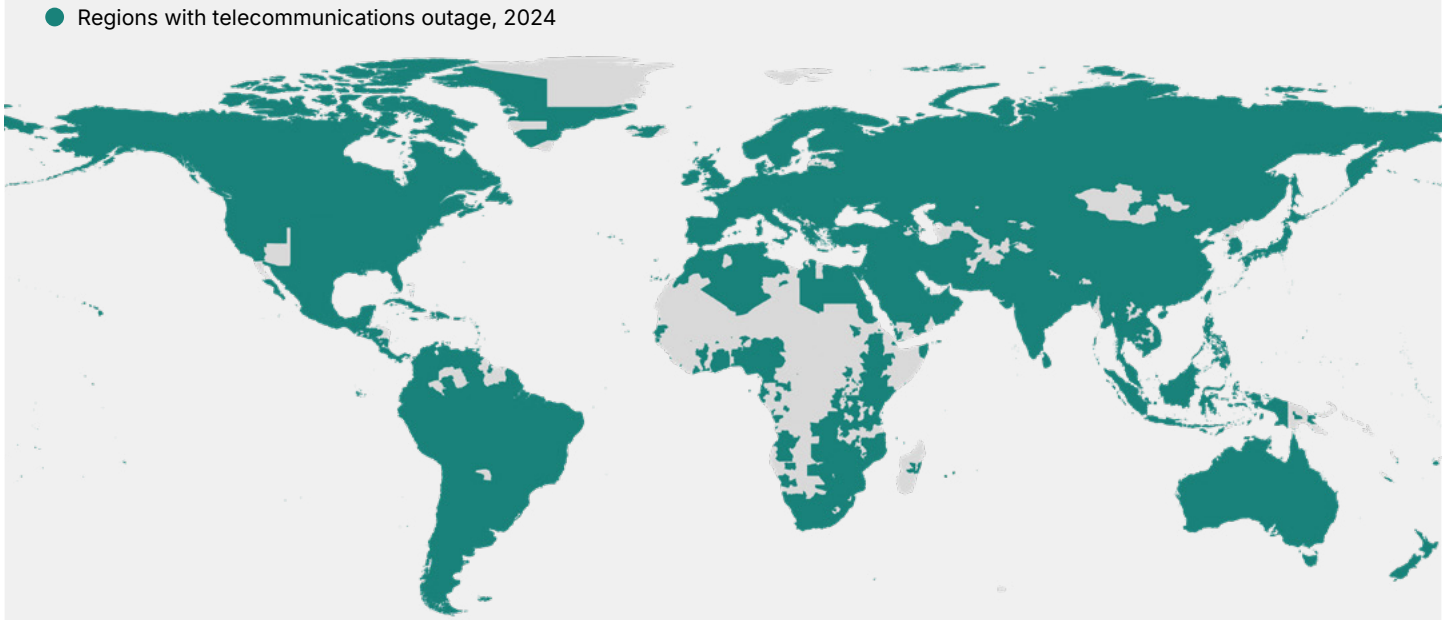
**01** Compile a list of telecommunications outages in the world over 2022-2024

**02** Overlay historic weather hazard info to identify outages that occurred during weather events

**03** Inform assumption on average number of customers affected by a typical outage

The first stage of the modelling identified potential weather-related outages. A global database of internet connectivity disruptions between 2022 and 2024 was identified. Figure 6 shows the regions that recorded a telecommunications outage in 2024 according to the Internet Outage and Detection Analysis (IODA) dataset.

**Figure 6 Global telecommunications outages, 2024**

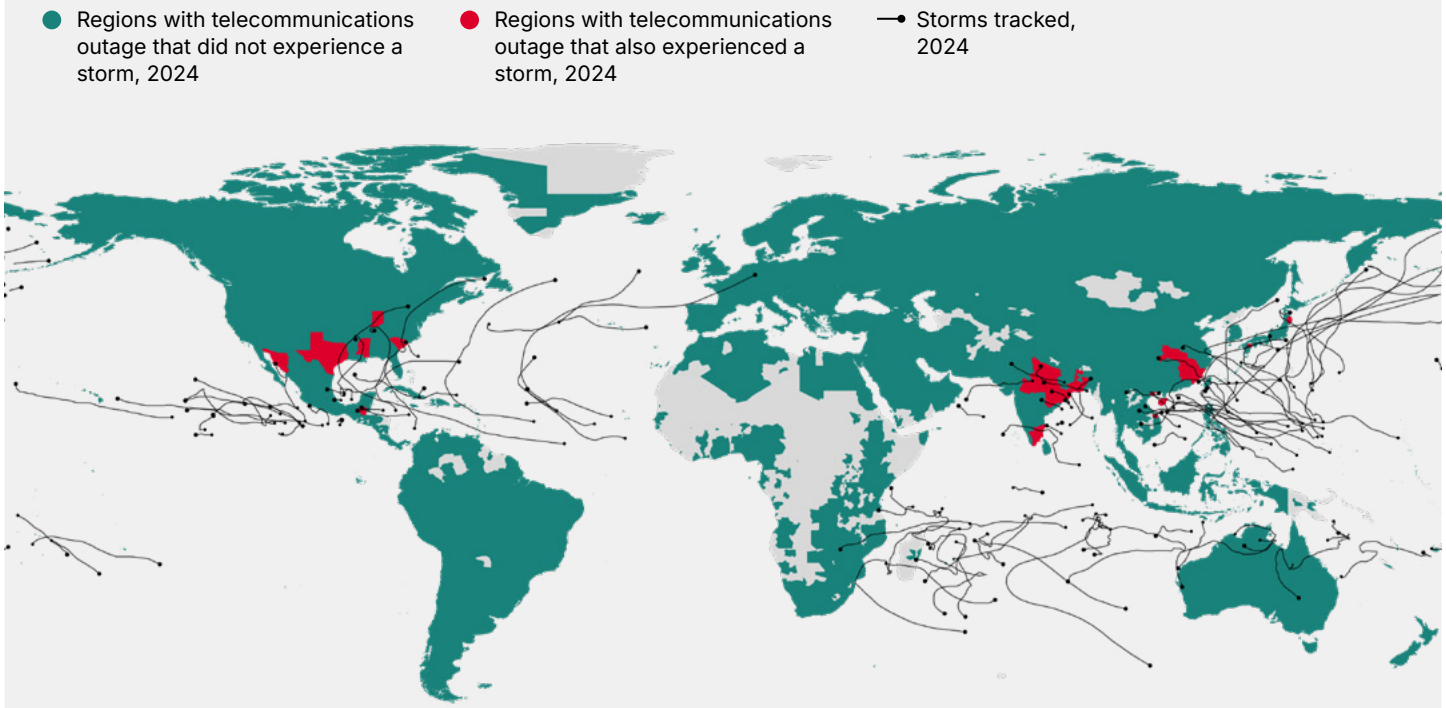



Source: Frontier Economics analysis of IODA outage data

The identification of outages was then cross-referenced with information on tropical cyclone tracks and major flood events. This identified around 450 outages across more than 50 countries that occurred at the same time as a local storm or flood. The matching process identified outages that may have been associated with severe weather, but temporal and geographic coincidence does not by itself demonstrate that the weather event caused the outage.

Figure 7 shows, for illustration, the number of regions where outages occurred at the same time and place as a storm event in 2024. The same matching was done for 2022–2024 for storms as well as coastal and riverine floods.

**Figure 7 Global telecommunications outages coinciding with storms, 2024**




Source: Frontier Economics analysis of IODA outage data and data on actual storm tracks (IBTRaCS) in 2024).

For regions affected by weather-related outages, regional population data was used to assess the number of people living in affected areas. This number was then scaled down to estimate the proportion of people living in the region expected to be affected by the weather-related outage. This estimate was based on empirical review of the scale of two hurricanes observed in 2024.

The next stage converted the identified outages into an estimate of the total number of users affected. Consistent global information on the number of users affected and the duration of individual outages was not generally available. The modelling therefore applied assumptions about the average number of customers affected by a typical event and its average duration, based on an empirical review of notable severe weather events over recent years.

Specifically, empirical evidence from Hurricane Fiona (Puerto Rico) and Hurricane Beryl (Jamaica) suggested that approximately 25–30% of telecoms customers may lose service during catastrophic island-wide hurricanes. These were compiled from published information about the impact of Hurricane Fiona from the Federal Communications Commission (FCC) in the United States[3] and operator reports on the impact of Hurricane Beryl in Jamaica.[4]

The estimates in these reports were combined with information on regional broadband penetration rates, operator market shares and population from the World Bank and Telegeography to convert these figures into a percentage of population affected.

However, these events represent some of the most severe weather-related outages for which customer-level data are publicly available and are therefore considered representative of the upper end of the severity distribution rather than a typical severe weather event. Consequently, the model adopted a lower assumption of 10% of customers affected, with sensitivity analysis spanning 5% to 25%. The upper sensitivity aligns closely with the empirical evidence from these benchmark events.

3 FCC. (18 September 2022). Communications Status Report for Areas Impacted by Hurricane Fiona.
4 Jamaica-Gleaner. (17 July 2024). "Flow reconnects more of its fixed and mobile customers".

# Annex 2
# Climate modelling – inputs and assumptions

## Future climate change pathways depend on mitigation activities

When making forecasts of future climate and weather conditions, climate scientists use multiple scenarios that define different pathways for greenhouse gas (GHG) concentration.

In AR6, the Intergovernmental Panel on Climate Change (IPCC) assesses different Shared Socioeconomic Pathways (SSPs).[5] These describe alternative futures for emissions, land use, air pollution, economic development and climate policy. They range from low-emissions pathways (SSP1–1.9), in which emissions fall rapidly, to high-emissions pathways, in which emissions remain high or continue to rise (SSP5–8.5). These are not forecasts. Instead, they provide a structured way to test how different emissions pathways could affect future temperature, sea-level rise and weather-related hazards.

Each SSP 1–5 refers to the approximate level of "radiative forcing in 2100", measured in watts per square metre (which relates to the level of GHG concentration). For example, SSP2–4.5 is a "middle of the road" socio-economic pathway with radiative forcing of approximately 4.5 W/m² by 2100.

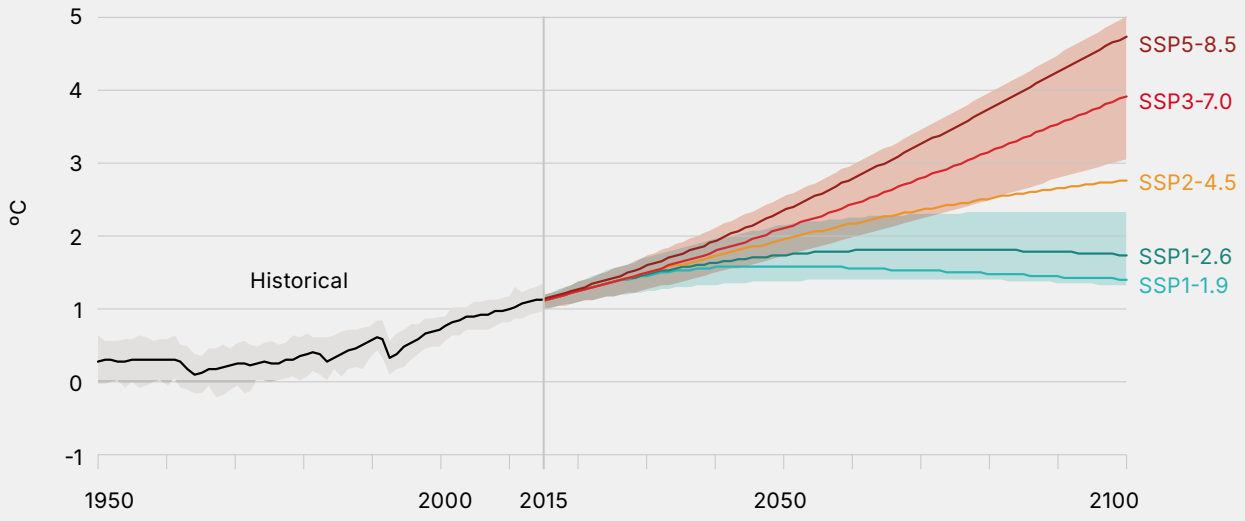
**Table 3 The Shared Socioeconomic Pathways (SSPs), including 8.5**

| SSP pathway | Emissions category | Core assumption | Approx. radiative forcing in 2100 | Global surface temperature change, 2041 to 2060 | Global surface temperature change, 2081 to 2100 |
|---|---|---|---|---|---|
| **SSP1–1.9** | Very low GHG emissions | $CO_2$ emissions decline to net zero around or after 2050, followed by net negative $CO_2$ emissions. | 1.9 W/m² | 1.6 [1.2–2.0]°C | 1.4 [1.0–1.8]°C |
| **SSP1–2.6** | Low GHG emissions | $CO_2$ emissions decline to net zero around or after 2050, followed by varying levels of net negative $CO_2$ emissions. | 2.6 W/m² | 1.7 [1.3–2.2]°C | 1.8 [1.3–2.4]°C |
| **SSP2–4.5** | Intermediate GHG emissions | $CO_2$ emissions remain around current levels until the middle of the century before declining. | 4.5 W/m² | 2.0 [1.6–2.5]°C | 2.7 [2.1–3.5]°C |
| **SSP3–7.0** | High GHG emissions | $CO_2$ emissions roughly double from current levels by 2100. | 7.0 W/m² | 2.1 [1.7–2.6]°C | 3.6 [2.8–4.6]°C |
| **SSP5–8.5** | Very high GHG emissions | $CO_2$ emissions roughly double from current levels by 2050. | 8.5 W/m² | 2.4 [1.9–3.0]°C | 4.4 [3.3–5.7]°C |

5 SSPs build on, and partly replace, the Representative Concentration Pathways, or RCPs, used in the IPCC Fifth Assessment Report. RCPs were labelled by their approximate radiative forcing level in 2100, such as RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The key difference is that RCPs primarily described different concentration and radiative forcing pathways, whereas SSPs combine climate outcomes with broader socio-economic narratives. This makes SSPs more useful for assessing adaptation and resilience because they allow analysis of both physical climate change and the wider social and economic context in which those risks occur.

Figure 8 shows how these scenarios are used to assess how different emissions trajectories would affect global temperature, sea-level rise and the frequency and severity of climate hazards.

**Figure 8 Impact of emission pathways on global surface temperatures**




Source: IPCC AR6, Figure SPM.8
Note: The ranges around the central values represent the uncertainty in the estimated historical warming response, arising from differences among climate models.

SSP5–8.5 should be treated as a high-end scenario rather than a central or business-as-usual pathway. In AR6 it remains useful for understanding the consequences of very high GHG emissions and for stress testing long-lived infrastructure against severe climate outcomes. However, its plausibility has been increasingly debated,[6] reflecting recent trends in climate policy, renewable energy costs and observed emissions.

For this reason, the results shown under SSP5–8.5 should not be interpreted as a forecast of the most likely future. In this report, SSP5–8.5 is used to illustrate an upper-end risk case. Core resilience planning should consider a range of scenarios, including intermediate and high pathways, while recognising that even lower-emissions pathways can still imply material increases in weather-related hazards over the lifetime of telecoms assets.

6 For example, a recent discussion paper that proposed several scenarios to be considered as part of AR7 suggested that the "high" scenario would be somewhat below the SSP8.5 "High emission scenario: A scenario with emissions as high as judged to be plausible, based on assuming developments that include a rollback of current mitigation policies. This scenario is expected to result in forcings below SSP5-8.5." See: Van Vuuren, D. P. et al. (2026), "The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7)". Geoscientific Model Development, 19, pp. 2627–2656.

## Datasets measuring the intensity of severe weather hazards

Severe weather datasets generally model the physical intensity of a weather hazard in a specific location. For example, they may estimate maximum wind gust, sustained wind speed, rainfall depth, flood depth, snow load, lightning density, wildfire weather conditions or extreme temperature. A common output of these datasets is a return period estimate, such as the intensity of a storm expected to be exceeded once every 10, 25, 50 or 100 years, on average. In practice, a 1-in-50-year event means an event with a 2% probability of being equalled or exceeded in any given year.

These datasets are provided by several types of organisations. Public weather and climate agencies provide observed weather records, gridded re-analysis datasets[7] and climate projections. Examples include national meteorological offices, hydrological agencies, European Centre for Medium-Range Weather Forecasts (ECMWF), Copernicus, National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA). Academic and research institutions provide event databases, regional climate models and downscaled climate projections. Commercial providers, including catastrophe-modelling firms and specialist flood, windstorm and climate-risk vendors, provide more processed hazard layers and probabilistic event sets, often designed for use by insurers, investors and infrastructure owners.

## Data limitations

Several caveats should be noted when using severe weather datasets.

First, these datasets generally measure average or probabilistic hazard conditions over a defined spatial area and time frame. They are therefore useful for identifying areas that are more or less exposed to a given hazard, but they should not be interpreted as precise forecasts of where or when individual events will occur.

Second, return period metrics such as 1-in-10, 1-in-25 or 1-in-50-year events do not mean that a storm of that intensity will occur at regular intervals, nor do they identify the exact assets that will be affected in a future event. In practice, a lower-risk area can still experience a severe event, and a higher-risk area may not experience one during the period being assessed.

Third, the spatial resolution may not provide sufficient resolution to identify highly localised conditions.

Fourth, forward-looking climate datasets are subject to uncertainty. Results can vary depending on the climate model, emissions scenario, downscaling approach, baseline period and hazard metric used.

Fifth, there are barriers to accessing some datasets. While some weather-hazard datasets are available on an open-source basis, others are only available by licence, which can be free or paid. There can also be technical barriers to accessing data. Operators may need technical skills to access data (for example, via APIs) and special equipment or services (for example, to download large datasets).

7 "Gridded datasets are discrete products created by entities such as NOAA, ECMWF, NASA, Australia Bureau of Meteorology and others. Gridded data products are developed to provide spatially and temporally consistent data coverage and can be used to supplement or replace existing ground-based observations, which can often be sporadic, irregularly spaced or have fragmented historical records. Gridded datasets are constructed using inputs including ground-based observations, satellite imagery, rainfall radar and oceanographic measurements. These are then used to run physical models of the type used in weather forecasting to create a series of "reanalysis data" interpolated to regular grids. These are available both at the ground surface and sometimes at levels through the atmosphere. Some products provide full global coverage for a range of weather variables, others may only provide regional datasets or single variables though these can be at a higher spatial resolution." Source: Speedwell Climate, "Gridded Data".

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