RISK AND RESILIENCE REPORT

National Risk Assessments of Cross-Border Risks

Kevin Kohler

Zürich, February 2023
Center for Security Studies (CSS), ETH Zürich

Available online at: css.ethz.ch/en/publications/risk-and-resilience-reports.html

Author: Kevin Kohler
Editor: Andrin Hauri
Language editing: Christine Eriksen
Layout and graphics: Miriam Dahinden-Ganzoni
Client: Federal Office for Civil Protection (FOCP)
FOCP project supervision: Stefan Brem, Head of Risk Analysis and Research Coordination
ETH-CSS project management: Andrin Hauri, Head of the Risk and Resilience Team;
Oliver Thränert, Head of Think Tank.

DOI: 10.3929/ethz-b-000592788

Content

Executive Summary

This report provides a comparative analysis of national risk assessments. Specifically, it compares the assessments made by nine European countries and Swiss Re respectively of five types of cross-border risks: electricity supply shortage, nuclear accident, pandemic, severe space weather, and volcanic outbreak. Even though the selected countries have correlated risk profiles for these hazards, the report finds noteworthy differences in their estimated likelihood and impact. For example, the likelihood of a severe nuclear accident varies by up to 10,000 times between different assessments, and for a large volcanic outbreak by up to 5,000 times.

Some of these differences can be traced back to methodological choices, such as probabilistic safety assessments versus historical frequency, the dataset used, or modelling adaptions that, for example, downgrade the severity of historical pandemics to account for modern medicine.

The report also highlights a number of general considerations for national risk assessments and cross-border risks. For example, the standard 5x5 risk matrix used in ISO 31010 and EU recommendations can introduce distortions in risk communication and priorization, such as the underestimation of risks with extreme impacts.

Acknowledgements

This report has benefited from feedback and answers to specific questions at several stages. For this, the author would like to thank Stefan Brem (Swiss Federal Office for Civil Protection), Jouni Pousi (Finnish National Emergency Supply Agency), Leendert Goijer (Dutch National Institute for Public Health and the Environment), Pontus Leisten (Swedish Civil Contingencies Agency), Eric Durand (Swiss Re), as well as Andrin Hauri (Center for Security Studies). All opinions and possible mistakes are exclusively attributed to the author.

1 Introduction

Regional and global shocks, such as the COVID-19 pandemic and its reverberations on health, social cohesion, and the economy, as well as the Russian invasion of Ukraine and its impacts on food, gas, electricity, and migration, have dominated the headlines in recent years. This has strengthened the emphasis on and demand for public risk management.

To prepare for future shocks, governments identify, analyse, and evaluate risks to prioritize preparedness and mitigation efforts. Many countries use a national risk assessment, a periodic review of collective risks, to establish a baseline of knowledge. Such assessments are encouraged, or even required, by national, regional, and global organizations, such as the EU,[1] the Organisation for Economic Co-operation and Development (OECD),[2] and the UN Sendai Framework for Disaster Risk Reduction.[3]

Coherence across national risk assessments

The national risk assessment is a relatively recent instrument that has emerged in tandem with civil protection organisations' broadening responsibilities after the Cold War. Leading countries, such as the United Kingdom, created their first national risk assessment in the late 2000s, while other countries have not yet carried out an integrated assessment of their risks. As national risk assessments are still an evolving practice, it is important to review and exchange best practice.

Efforts to strengthen the coherence and interoperability of risk assessments often focus on methodological frameworks. This includes the Global Risk Assessment Framework (GRAF) of the UN Office for Disaster Risk Reduction (UNDRR)[4] and the Recommendations for National Risk Assessment by the European Commission.[5] However, as risk analysis involves individual expert judgement, the use of the same methodological framework ("throughput coherence") does not automatically lead to congruent outputs ("output coherence").

This report focuses on a comparative analysis of national evaluations of cross-border risks, based on the assumption that the probability and intensity distribution of transnational and global hazards should have similarities within a region. Therefore, significant differences in national evaluations of cross-border risks are indicators of which countries and which hazards are worth investigating more closely in order to better understand divergences in the overall risk assessment process, from data sources to expert opinions to risk comparison frameworks.

Outline

The report first provides a brief background on national risk assessments (section 2) and the case study selection (section 3). It then compares the evaluations made by nine countries and Swiss Re respectively for five cross-border risks: electricity supply shortage (section 4), nuclear accident (section 5), pandemic (section 6), severe space weather (section 7), and volcanic outbreak (section 8). Lastly, the discussion and conclusion (section 9) summarise the identified challenges and assessment differences, and provide the author's perspective on how risk assessments could continue to evolve and strengthen.

2. Background

2.1 National Risk Assessments

A national risk assessment is "a product or process that collects information and assigns a value to risks at a strategic national level for the purpose of informing priorities, developing or comparing courses of action, and informing decision making."[6] National risk assessments usually consist of three main parts: 1) the identification of risks in a risk register; 2) the characterization and analysis of these risks in scenarios and models; and 3) the evaluation of these risks in a matrix for easy cross-comparisons and prioritization.

Types of risks: National risk assessments include either a broad range of risks ("multi-hazard") or all collective risks ("all-hazard"). Many states do not include all adversarial threats (e.g., terrorism, military conflict) and the question of what is a collective risk and what is an individual risk remains ambiguous. The ownership of the assessed risks depends on the political system in a country. It is usually dispersed across departements and authorities.

Time horizon: The horizon of a national risk assessment is usually between 1 and 10 years. It can be complemented with trend analyses of how expected changes in the next 10 to 35 years will likely influence civil protection.[7] The national risk assessment is different from risk monitoring. The assessment provides a baseline probability relevant for generic preparedness and mitigation efforts, whereas early warning networks enable advanced preparedness and mitigation hours or days ahead of a hazardous event.

Level of analysis: This report uses four geographic risk categories ordered by increasing scope: local, national, regional (affecting multiple countries), and global.[8] The focus of this report is on the national level. There are a number of reports that look at risks at a global scale – predominantly produced by the private sector and academia.[9] The UNDRR also publishes a biannual Global Assessment Report on Disaster Risk Reduction, which explores a broad spectrum of issues around disaster risk governance but is not a risk assessment.[10]

In federal states, such as Germany and Switzerland, civil protection is primarily a subnational task. This means that the Bundesländer and Cantons respectively are the operational leads, whereas the federal government has a coordinating role. For example, in Switzerland the national risk assessment is used as a starting point for many subnational risk assessments.

2.2 Risk Assessment Standards

2.2.1 UNDRR

Under the Sendai Framework for Disaster Risk Reduction, there has been a push towards establishing a common or at least interoperable terminology,[11] a disaster loss reporting framework,[12] and a risk assessment framework[13] on a global level. This push has so far had mixed success, as countries differ in their understandings of, for example, what constitutes a disaster, and disaster loss data therefore only has limited comparability.[14] This is particularly evident with regards to the reporting of deaths attributed to COVID-19 within the Sendai Framework.

2.2.2 European Union (EU)

The EU is comparatively advanced in supranational risk management due to the work of the Union Civil Protection Mechanism (UCPM).[15] Among other measures, the Mechanism obliges member and participating states to develop risk assessments at national or appropriate subnational level, and provide the European Commission with a summary every three years that focuses on key risks.[16] Based on these summaries, the Commission publishes an overview of the EU risk landscape. It lists which risks have been identified by countries and provides context, including data on disaster losses, and the methodological approaches used by countries in their respective risk assessments.[17]

The Commission has also published several non-binding guidelines relevant to risk assessments, including a guideline on risk assessments,[18] and reporting and capability assessment guidelines to help countries with the UCPM reporting duties[19]. The Joint Research Centre (JRC) of the Commission has also collected the contributions of expert teams for descriptions of risk assessment approaches specific to chosen hazards.[20] The following sections provide a brief and approximate summary of the general EU approach to risk assessment.

Risk identification: According to the European Commission[21], national risk assessments should consider at least all the hazards that: a) would on average occur once or more in 100 years (i.e., all hazards with an annual probability of 1 per cent or more), and b) for which the consequences represent significant potential impacts (i.e., >50 people affected, >100 million EUR in economic and environmental costs, and with significant or very serious political/social impact (level 4)). Less likely hazards or risk scenarios (e.g., volcanic eruptions, tsunamis) should also be considered when the likely impact exceeds a threshold of 0.6 per cent of gross national income (GNI). At least three scenarios with three or more different intensities should be included in the assessment when the likelihood of a hazard exceeding the above thresholds is more than one in ten years.

The temporal horizon of the risk identification process should generally consider risks that may appear in the immediate future (i.e., one to five years ahead). For the purpose of the EU-wide overview, it is also useful if the Member States with more advanced risk assessments look 25 to 35 years ahead to identify broad trends or emerging risks. Such foresight can also take a global perspective and identify international interdependencies.

Risk analysis: According to the European Commission,[22] the usefulness of comparing national risk assessments depends on common understanding on how scenarios are built. Of the possible risks and their varying degrees of intensity, only a limited number of scenarios can be included. National risk assessments have attempted to deal with selection limitations by referring to standards, such as 'reasonable worst case' scenarios. However, many uncertainties remain with this approach.

Risk evaluation: The 2010 Risk Assessment and Mapping Guidelines for Disaster Management by the European Commission suggest using a risk matrix with "5 or more points" per scale, and the following five classes for political/social impact: 1) limited / insignificant, 2) minor / substantial, 3) moderate / serious, 4) significant / very serious, 5) catastrophic / disastrous.[23]

This advice was repeated in the 2019 reporting guidelines, which state that "to facilitate a more comprehensive overview at EU level, Member States could preferably use a 5x5 risk matrix, if appropriate, with scale levels of impacts and probability indicated. Where possible, Member States are encouraged to assign quantitative ranges to each of the numbers from 1 to 5".[24] The guidelines also ask states to consider distinct risk matrices for human impact, economic and environmental impact, and political/social impact.

2.2.3 International Organization for Standardization (ISO)

The ISO has a group of standards focusing on risk management (31000). EU guidelines and several national methodologies explicitly refer to ISO standards. In particular, they refer to the consequence/likelihood matrix in ISO 31010.[25] In this matrix, scales can have any number of points, with three, four, or five point scales being the most common. It should extend from "the maximum credible consequence to the lowest consequence of interest". It further states that "a consequence/likelihood matrix is used to evaluate and communicate the relative magnitude of risks". It "can be used to compare risks with different types of potential consequence and has application at any level in an organization".

The standard also notes some limitations. For example, the "validity of risk ratings depend on how well the scales are developed and calibrated", and "it requires a single indicative value for consequence to be defined, whereas in many situations a range of consequence values are possible and the ranking of the risk depends on which is chosen".

2.3 Cross-Border Risks

The regional and global interconnections of national systems and supply chains have many benefits. Yet, it also creates potential for correlated and systemic risks that affect cross-border systems. The EU requirements for risk reporting explicitly include the identification of key risks with potential cross-border impacts. These are defined as:

- Impacts resulting from risks generated in a neighbouring country.
- Impacts that spill over into a neighbouring country.
- Impacts affecting two or more countries simultaneously.[26]

3 Methodology

The aim of this report is to compare national assessments of cross-border risks for countries with correlated risk profiles. While no two countries have the exact same risk profiles, comparing countries with correlated risk profiles at a minimum requires an explation when their respective impact and likelihood assessment of cross-border events differ substantially.

The cross-border risks compared for this report were chosen to include a mix of different types of hazards:

- Natural hazards: severe space weather (regional to global), volcano outbreak (regional to global).
- Technological hazards: electricity supply shortage (regional), nuclear accident (regional).
- Social hazards: pandemic (global).[27]

Given that most of these cross-border risks have a regional rather than a global scope, geographic proximity is required for countries to be compared. Therefore, only European countries were selected for this report:

- Switzerland and its neighboring countries Germany, France, Italy, and Austria, as they are of particular interest to the Swiss Federal Office for Civil Protection.
- The United Kingdom, the Netherlands, Finland, and Sweden, as they are known in Europe for good disaster risk management practices.
- Swiss Re, as it is one of the largest re-insurance companies in the world, and thus has models of many natural hazards that can serve as a cross-check for national risk assessments.

Background interviews

In addition to desk research that compared national risk assessments and individual scenarios published by the above countries and Swiss Re, the author conducted background interviews with individuals involved in these assessments. The objective of these interviews was to identify, confirm, or refute the findings discussed in the report. The interviews were semi-structured to ensure the following main points of interest were covered:

1. Did the selected countries use a specific measure of intensity or event as a reference point for a scenario?
2. Did the selected countries assign a specific annualized probability to a scenario?
3. What factors and data sources were discussed to determine the likelihood and impact of a scenario?

4 Electricity Supply Shortage

4.1 Background

An electricity supply shortage is an imbalance between electricity supply and demand due to limited production, transmission, or import capacities that lasts for several days, weeks or even months. For the duration of a shortage, electricity management measures, such as temporary shutdown of electricity-intense industries or rolling blackouts, are required to reduce consumption and avoid larger, uncontrolled blackouts.

The synchronous grid of continental Europe is the largest synchronous electrical grid in the world in terms of connected power. It stretches from Portugal to Ukraine, and from Denmark to Algeria. The EU has the explicit goal to increase the level of interconnected electricity between European countries. Switzerland's electricity grid is also highly interconnected. High interconnectivity can help mitigate local and national production shortfalls. However, it also means that there is a regional risk of an interconnected production shortfall across Europe.

Examples of electricity supply shortages include the Californian energy crisis in 2000 and 2001, Japan's energy supply shortage after the Tohoku earthquake and tsunami in 2011, the Belgian energy crisis in 2018, or the everyday reality of electricity supply shortages in countries such as South Africa. In 2022, Europe commenced a prolonged and tense period of electricity supply issues, as heatwaves reduced productivity levels of nuclear power plants, and Russian gas exports to Europe declined from around 400 million cubic meters a day at the beginning of the war, to less than 100 million cubic meters.[28] This has led to elevated electricity costs, shutdown of electricity-intense industries, and public campaigns to save energy.

Given that most of the countries examined in this report had not included an electricity supply shortage scenario in their national risk assessments, the following section lists the scenarios found for both electricity supply shortages and more short-term blackouts. Planned and unplanned blackouts can be the result of a prolonged supply shortage but they can also be caused by natural hazards, accidents, or sabotage.

4.2 Overview Electricity Supply Shortage

Case study	Risk register	Scenario description	Expected impact	Annualized probability
Austria[29]	No	2019 scenario exercise "Helios" of a **Europe-wide power shortage** and a subsequent power blackout.	-	-
Finland[30]	Yes	During winter peak consumption, about a quarter of needed power is covered through imports. If imports fail, there is a **shortage of power**, which can lead to curtailments of power use.	Strong impact on the economy and the functional capacity of the population and services.	-
Uusima (capital region)[31]	Yes	**Blackout** The main Finnish grid has collapsed due to a large-scale disruption and it takes at least 24 hours to fix the situation.	Disruptions to water supply, payments systems, street and train traffic, telecommunications and heating. More than 500 million EUR of damages.	**1 in 100** to **1 in 10**
France[32]	No	**Degraded energy supply** European trade is disrupted due to a shortage of gas.	Frequent use of back-up means of power generation and the "Ecowatt" color-alerts to call on the population to save energy	-
Germany[33]	Yes	**A prolonged region-wide blackout in Germany** Targeted simultaneous sabotage destroys numerous transformers and renders them inoperable. As a result, power is lost in large parts of Germany. After about 24 hours, those responsible on site and in the utilities central crisis management teams become aware that the power outage could last several weeks.	Each kilowatt hour lost equals costs of 8 to 16 EUR. Applied to a one-hour power outage in Germany on a workday in winter, the economic damage would be between 0.6 and 1.3 billion EUR. In a power outage lasting several weeks, impacts on other critical infrastructures and further immediate costs should be expected.	-
Italy[34]	Yes	**2003 Italy blackout**	One lesson learned of the 2003 blackout was that many people living at home depend on life-saving medical instruments that run on electricity (e.g., automatic respirators).	-
Netherlands[35]	Yes	In large parts of Europe, including in the Netherlands, the **power supply fails** because of a frequency drop in the grid. Due to complications, it takes 24 hours before the system is operational again.	The impact on organizations and citizens is high because different processes are (partly) out of order, such as public transport (train, tram, subway), medical home equipment, payment services, fuel stations, communications (fixed, mobile, internet), and shops are closed. Catastrophic impact on basic needs and disruption of daily life. Very serious economic costs.	**1 in 100** to **1 in 10*** (*1 in 20 to 1 in 2 at least once in the next 5 years)
Swiss Re	No	-	-	-

Switzerland[36]	Yes	**Electricity undersupply (-30 per cent)** Time: winter. Appeals to the population and the economy to save energy. Consumption restrictions for certain applications and quotas for large consumers for 12 weeks. Central management of controllable power plants for 12 weeks. Restrictions on cross-border energy flows, coordinated with neighboring countries for 12 weeks. Temporary grid shutdowns necessary for two weeks. Uncontrolled power outages cannot be ruled out.	Direct financial losses and costs are estimated to amount to circa 10 billion CHF. Economic performance is reduced by circa 90 billion CHF. Circa 100 fatalities and 1000 people injured.	**1 in 30**
	Yes	**Blackout due to physical damage to network infrastructure** Affected population: 0.8–1.5 million. Time: summer Duration of complete outage: 2–4 days. Regeneration period: days to weeks.	Direct damage and mitigation costs amount to a total of 230 million CHF. Economic performance is reduced by circa 1.6 billion CHF. An estimated 15 fatalities, 20 seriously injured, 60 moderately injured, and 120 slightly injured.	**1 in 30**
Sweden[37]	Yes	- (biannual threat and risk assement is classified)	Power supply has a special significance within the energy system because electricity is almost always required for the supply of all other types of energy. In addition, the supply of electricity is critical for the functioning of other activities, including electronic communications, transport, food supply, health and medical care, social care, and municipal technical services.	-
United Kingdom[38]	Yes	**Major disruption of electricity supply** to 1 million people for longer than 18 hours**.**	Disruption to essential services, such as transport, telecommunications, water, food, fuel, or finance. The severity of the disruption would depend on individual service providers' back-up power arrangements. Disruptions could lead to casualties or fatalities due to the loss of essential services, such as heating of homes during cold weather. Disruption to health care and emergency services, if power loss lasts a long time. Loss of lighting, heating, air conditioning. Disruption to businesses, for example, via lost working hours and damage to electronic equipment, potentially resulting in data loss or corruption.	**1 in 100** to **1 in 20**

4.3 Analysis

First, it should be highlighted that electricity supply shortages and blackouts are conceptually different from the other risks evaluated in this report, as they are infrastructure rather than hazard focused. The national risk assessments of most countries primarily follow the logic of hazards (e.g., storm, heatwave, sabotage) rather than the impacted critical infrastructures (e.g., water, food, communications). However, because the electricity grid is such a key critical infrastructure, it is often included. As Sweden notes, "there are many potential causes of disruption to the power supply. These include storms, torrential rain, solar storms, the breaking of a dam, and antagonistic actions. For the activities affected, the cause is rarely of much importance".[39]

Second, most countries only have scenarios for short-term disruptions of the electrical grid caused by local technical failure, rather than a persistent undersupply of electricity. In contrast, Switzerland's national risk assessment not only identifies electricity supply shortage as a risk; it is also considered the top risk in terms of annualized expected loss amongst the 44 analyzed scenarios. The Swiss assessment explicitly states that an undersupply is not only a national but also regional risk. The electricity shortage scenario is caused by a "cold wave across Europe" and "several coal power plants in Eastern Europe that are out of operation due to technical problems", and the shortage also affects "surrounding European countries".[40]

Third, Finland's most recent national risk assessment focuses on the impact of disruptions to vital societal functions without indicating a specific probability. However, its methodology guide for local risk assessments includes a scale with five categories on which the probability of events is assessed.[41] Hence, the local risk assessment of the capital region of Uusima has been included as a complement in sections 4.2 and 5.2 of this report.

Fourth, the French national risk assessment does not include blackouts or electricity supply shortages. However, the private French network operator RTE produces forecasts for every winter, which are regularly updated. Overall, this approach is closer to an early warning system than a risk assessment.

Fifth, with regards to blackouts, the likelihood assessments cover a similar span across the analysed countries, even though the duration of the outages varies between the scenarios. For the risk of an electricity supply shortage, only Switzerland provides a sufficiently detailed scenario suitable for a comparative analysis.

Sixth, insurers do not have public, comprehensive blackout or electricity supply shortage models, and generally cover blackouts based on specific hazards. Mills and Jones provide an overview of the grid disruption scenarios that are covered (or not) from an insurance perspective.[42]

5 Nuclear Accident

5.1 Background

Nuclear power plant accidents are measured on the International Nuclear Event Scale (INES), which has seven levels and is logarithmic. Levels 1 to 3 describe nuclear incidents, whereas Levels 4 to 7 describe nuclear accidents with escalating environmental discharges of radioactive substances.[43] A nuclear power plant accident has three main phases: 1) the preliminary phase, which lasts from the start of the incident until radioactivity is released into the environment; 2) the cloud phase, which lasts from the time radioactivity is released until the particle cloud has passed; and 3) the ground phase, which lasts for as long as radiation is emitted from the contaminated ground. For example, some foods from mountainous regions in Scandinavia and the UK are still subject to controls due to fallout from the Chernobyl nuclear accident in 1986.

The first nuclear power plant built for civil purpose launched in 1954. Since then, worldwide, two INES Level 7 events have occurred.[44] First, in 1986 there was the explosion and core meltdown in Unit 4 of the Chernobyl Nuclear Power Plant in the former Soviet Union. About 10 ExaBecquerel of radiation was released,[45] hundreds of thousands of people had to be evacuated, and radioactive aerosols were carried through the air for thousands of kilometers before rain washed them out of the atmosphere. While confirmed deaths are less than 100, estimates of long-term deaths due to excess cancer deaths vary considerably. WHO estimates 4,000.[46] Second, the Fukushima Daiichi Nuclear Power Plant in Japan was severely damaged by the 2011 earthquake and subsequent tsunami, resulting in a meltdown in Units 1 to 3. About 1 ExaBecquerel of radiation was released[47], about 150,000 people had to be evacuated, and about 2,000 people died due to the physical and mental stress of evacuation and disrupted healthcare.[48] Switzerland experienced a INES Level 4 event with the partial core meltdown at the Lucens Experimental Nuclear Power Plant in 1969. The consequent damage to humans and the environment was limited, as the reactor was located in a mountain tunnel.

5.2 Overview Nuclear Accident

Case study	Risk register	Scenario description	Expected impact	Annualized probability
Austria[49]	Yes	**Accident at a nuclear power plant near a border** Two scenario intensities (KKW 14a, KKW 14b).	Impact estimation: 14a: 3.5/5 14b: 4.5/5 (qualitative scale 1 to 5)	Likelihood estimation: 14a: 1.9/5 14b: 0.9/5 (qualitative scale 1 to 5)
Finland[50]	Yes	**Severe nuclear power plant accident in Finland or Finland's neighbouring areas** There are four nuclear power plant units in Finland. Neighbouring areas of Finland include the Russian Leningrad (Sosnovyi Bor) and Kola plants, and the Swedish Forsmark plant.	Direct health impacts remain low, if the protection measures work. However, significant effects on people's living conditions and the environment, as well as negative psychological and social effects. Suspension of some economic production. Finnish exports would likely require cleanliness certificates or measurements.	**1 in 100,000** to **1 in 10,000**
Uusima (capital region)[51]		A **small release of radioactive material** at the Loviisa nuclear power plant, which the wind carries west towards the large population centers of Uusimaa.	In the event of an emergency, the population is evacuated within a 5 km radius of the power plant and the Loviisa Valko district. If the situation continues to escalate, the population within 20 km of the protection zone may be evacuated.	**Lower than 1 in 1,000**
France[52]	Yes	a) **Severe accident:** Core melt down in a French 900 MWe pressurized water reactor, followed by radioactive releases, more or less controlled. Circa 0.0075 ExaBecquerel released. b) **Major accident:** Core melt down in a French 900 MWe pressurized water reactor, followed by massive aerosol releases of 1 ExaBecquerel (≈ Fukushima).	a) On-site costs 6 billion EUR; offsite radiological costs 9 billion EUR; contaminated territories 11 billion EUR; costs related to power production 44 billion EUR; image costs 47 billion EUR; total circa 120 billion EUR. b) On-site costs 8 billion EUR; offsite radiological costs 53 billion EUR; contaminated territories 110 billion EUR; costs related to power production 90 billion EUR; image costs 166 billion EUR; total circa 430 billion EUR.	-
Germany[53]	Yes	**Nuclear accident (INES Level 7) in Germany** Four scenarios: a) rural vs. urban location. b) winter vs. summer.	100 to 1,000 deaths. >1,000 – 10,000 injured/sick. Between 40,000 and 390,000 evacuated for at least one year depending on the scenario >10 per cent of all agricultural land contaminated. Numerous companies go bankrupt. The federal government is called upon to promote reconstruction programs. Recession looms.	-
Italy	No	-	-	-

Netherlands[54]	Yes	**Nuclear disaster in the Netherlands** Accident at the Borssele nuclear power station, conditions include 24 hours warning time, rain, harvest time, and large parts of or the whole country is affected. Radiation also spreads across the border.	An area of 100–1,000 km^2 becomes inaccessible for more than half a year. Decline in tourism and a significant decrease in exports of Dutch products 500 long-term fatalities due to cancer as a consequence of radiation. Very serious economic costs.	**Lower than 1 in 10,000** (*less than 1 in 2,000 at least once in the next 5 years)
		Nuclear disaster in Europe Accident at a nuclear power plant in Europe close to the Netherlands, but not just across the border, with two days warning time. Maximum release of radiation (10 x “STC-CON-1”) with wind towards the Netherlands.	An area of between 100–1,000 km^2 can become contaminated by radiation hotspots (due to rain showers). In the long run it is feasible that there may be some victims (10–100) as a consequence of exposure to radiation in hotspot areas. Agricultural measures will be taken. The airspace is closed for a period. Logistics experiences substantial delays as vehicules need to be rerouted. The financial damage for the Netherlands is very serious.	**1 in 100 million**
Swiss Re	No	-	Private insurers only cover damages from nuclear accidents up to a certain fixed amount.	-
Switzerland[55]	Yes	**Incident with severe core damage in Switzerland** Containment failure and unfiltered release of radioactivity. Iodine release: 10^{16} Bq Caesium (Rb-Cs class) release: 10^{15} Bq Noble gases release: 3.10^{19} Bq Time of release after start of accident: 9 hours. Average weather conditions.	Around 300,000 people flee or are evacuated from the affected area. In the process, accidents occur, and about 20 people are expected to die. Several dozen people suffer serious injuries. Several hundred people with moderate to light injuries. An area of several 1,000 km^2 is radioactively contaminated.	**1 in 2.5 million**
Sweden[56]	Yes	**Nuclear accident (INES Level 5) in south Sweden** Occurs without warning on a winter morning with heavy snow and biting cold. Swedish nuclear power plants have pressure-relieving accident filters designed to remove at least 99.9 per cent of long-lived radioactive substances. Such filters were not fitted at the Chernobyl or Fukushima Nuclear Power Plants. In the scenario, however, it is assumed that these filters are not working as they should.	Around 14,500 people are evacuated and cannot return for 1+ year. Approximately 290,000 hectares of arable land are affected by radioactive fallout Agricultural and forest products from the contaminated area could be subject to export restrictions or reduced demand. Total economic costs following a nuclear accident in Sweden today would probably exceed 50 billion SEK.	-
United Kingdom[57]	Yes	**Industrial accident – nuclear.**	Level D Economic impacts: 1 billion to 10 billion GBP. 20,000 people evacuated over 3 days.	**Lower than 1 in 500**

5.3 Analysis

First, it is noteworthy that all but one of the analyzed countries have a nuclear accident scenario. A nuclear accident is the only hazard for which Austria prepared two separate scenarios in its 2011 risk analysis, even though it was the first country in the world to ban nuclear power plans in 1978, and has never had an operational plant on its territory.[58] In the Netherlands, there is a notable popular worry about risk externalities imposed by a neighboring country, with their assessment stating, "there have been no major accidents affecting national security in the past years. There are, however, concerns amongst parts of the population about the safety and supervision of several Belgian nuclear power plants close to the Dutch border."[59]

Second, there are two types of likelihood estimations for nuclear accidents. Some, like in the UK assessment (lower than 1 in 500) are part of an open-ended, lowest likelihood category. Others, like the assessments in Switzerland (1 in 2.5 million), Finland (1 in 10,000 to 100,000), and the Netherlands (1 in 100 million) contain specific numbers. This makes comparison difficult. Overall, there appears to be a convergence towards very low likelihood estimations. However, there is still a clear gap between Finland and the Netherlands. Numbers that are lower than 1 in 1 million may be explained by regulatory requirements and the use of probabilistic safety assessments.

In Switzerland, the Federal Nuclear Safety Inspectorate (ENSI) is the responsible authority for the risk assessment of nuclear accidents. Nuclear power plants do not require a general licence in Switzerland if ENSI assesses the risk of an accident with a resulting dose of more than 1 Millisievert (mSv) for members of the public to be no more than 1 in 1 million per year.[60] Many countries use similar safety goals and thresholds.[61] The method used by ENSI and similar agencies in other countries for this differs from the assessment of natural hazards. Instead of a mix of historical accident frequency and human expert judgement, nuclear risk assessments use a fault tree analysis.[62] This assessment is a safety analysis that looks at the reliability of materials and redundancies. It does not take into account security threats.[63]

Third, while there is no publicly available model of nuclear accident risk by Swiss Re, the mandatory liability insurance for operators can still be used as an external coherence check. For example, one can look at the annual insurance premium paid by a specific nuclear power plant and compare it to the maximum payout in case of a nuclear accident. The Swiss nuclear power plants in Gösgen and Leibstadt are both independent corporations that list their insurance costs as part of their financial reporting. In 2021, the annual premiums were 7.244 million CHF for Gösgen[64] and 7.3 million CHF for Leibstadt[65] for a maximum payout of 1 billion CHF each.[66] This 1 to 137 ratio between premium and maximum payout is an indicator that the insurance industry likely thinks that the risk of a severe accident is higher than 1 in 2.5 million. The implied annualized likelihood for a serious accident is significantly lower than 1 in 137, as it is unknown how the insurer sees the losses distributed between small and large events, and the insurer's planned margin. Still, it is likely closer to 1 in thousands, which is closer to the Finnish assessment and historical event frequency,[67] rather than 1 in millions. Moreover, the insurer is allowed to exclude from coverage any damages caused by extraordinary natural processes or warlike events, as well as damages from terrorist violence between 500 million and 1 billion CHF.[68]

At the same time, nuclear accident risks should be contextualized. Statistically, electricity production with coal, oil, biomass, and natural gas is less safe than with nuclear energy, due to air pollution and accidents.[69] However, these forms of energy production are not included in national risk assessments, as they are geared towards events that require actions from emergency response organizations rather than slow perpetual processes.

6 Pandemic

6.1 Background

An epidemic is an infectious disease outbreak that remains limited to a geographical region (e.g., seasonal influenza). A pandemic is a worldwide outbreak of an infectious disease (e.g., COVID-19, HIV/AIDS). Throughout history, periodic outbreaks of infectious diseases have had a significant and long-lasting impact on societies. Most emerging disease outbreaks occur through a zoonotic jump, where a pathogen that affects an animal host manages to infect and spread among humans. In many cases there are intermediary animal hosts (e.g., palm civets, camels) that spread the virus from the reservoir animal host (e.g., bats). For example, HIV/AIDS, SARS-CoV-1, and MERS-CoV existed in animal reservoirs before jumping over to humans through hunting, the consumption of bushmeat, and close contact with farm animals. Other potential origins of disease outbreaks are laboratory accidents and intentional releases. Once adapted to humans, pathogens may be transmitted between humans through droplets, aerosols, direct touch, contact with contaminated objects (fomites), the fecal-oral route, or through blood and other bodily fluids. The worldwide spread of emerging infectious diseases can occur much faster today than in the past due to international airtravel.

The risk of pathogens with pandemic potential is usually assessed based on two factors: their transmissibility and their lethality. The basic reproduction number R^0 estimates on average how many people an infected person will transmit the disease to, assuming no immunity through prior infection or vaccination, and no non-pharmaceutical interventions to slow the spread of the disease. The case fatality rate (CFR) denotes the percentage of people from all confirmed infected persons that die. The infection fatality rate (IFR) denotes the percentage of all suspected infected persons based on models that die.

Historical examples of pandemics include the bubonic plague (541–549, 1331–1353, and 1855–early 20th century), and cholera (1817–1824; 1826–1837, 1846–1860, 1863–1875, 1881–1896, 1899–1923, 1961–1975). Today, public waste management, water infrastructure, and antibiotics have made the prospect of such bacterial pandemics less likely. Hence, the focus is almost exclusively on viral pandemics and influenza pandemics in particular. Historical influenza pandemics occurred in 1889–1890, 1918–1920 ("Spanish flu"), 1957–1958, 1968–1969, 1977–1979, and 2009–2010 ("swine flu"). The 1918 "Spanish flu" is the most severe influenza pandemic on record with a CFR of about four per cent, and an estimated 17.5 million deaths in 1918/19.[70] The most severe pandemic in recent history, is the currently ongoing worldwide outbreak of SARS-CoV-2. From 2020 to 2022, the COVID-19 pandemic, whose origin is still the subject of scientific debate, has caused more than 6.7 million recorded deaths,[71] about 20 million estimated deaths,[72] and has reduced the global economy by trillions of USD.[73]

6.2 Overview Pandemic

Case study	Risk register	Scenario description	Expected impact	Annualized probability
Austria[74]	Yes	**Pandemic influenza** About 30 per cent of the population infected.	36,000 hospitalizations. Impact evaluation: 4.4/5 (qualitative scale 1 to 5)	Likelihood evaluation: 3.7/5 (qualitative scale 1 to 5)
Finland[75]	Yes	**Pandemic influenza** The infection spreads easily via droplets between people, the population has no resistance against the new virus, and there is no preventive vaccine. By default, 35 per cent of the population falls ill within eight weeks (calculated with the FluSurge program).	Mild scenario: 11,480 hospitalizations, 3,450 deaths. Moderate scenario: 27,500 hospitalizations, 5,650 deaths. Severe scenario: 35,690 hospitalizations, 9,050 deaths. The social, production, and economic impacts of a pandemic are significant. Vulnerable sectors include leadership, defence, internal security, energy supply, transports, and food supply.	**1 in 40** to **1 in 10** The most recent extensive pandemic influenzas have broken out every 10–40 years, and the likelihood of a new influenza outbreak is high.
France[76]	Yes	-	Discontinuities in social life and in activities of vital importance to society and the state. Economic losses due to absenteeism. The World Bank has estimated the cost of a pandemic at 2 trillion EUR, which would be as severe as the Spanish flu. Potential public disorder, although this has very rarely been observed in past pandemics. Isolation of vulnerable people.	-
Germany[77]	Yes	**Influenza pandemic** Three main scenarios using “InfluSim” software: low: 15 per cent of population infected within eight weeks; medium: 30 per cent infected; severe: 50 per cent infected.	Medium: about 370,000 hospitalizations and 103,000 deaths in Germany. Severe: about 624,000 hospitalizations, and 171,500 deaths in Germany.	-
		SARS pandemic Hypothetical new emerging disease. Infection-fatality rate like SARS-CoV-1. Three waves.	About 78 million infections. 7.5 million deaths in Germany.	N/A
Italy[78]	Yes	**Influenza pandemic** R0 = 1.4 for moderate scenario. R0 = 1.7 for most likely scenario.	Moderate: 30,228 hospitalizations. Most likely: 102,102 hospitalizations.	Unpredictable time intervals.

Netherlands[79]	Yes	**Influenza pandemic – severe**	The number of people admitted to hospitals ranges between 40,000–50,000. The number of fatalities exceeds 10,000. Catastrophic disruption of daily life.	**1 in 100** to **1 in 10*** *5 – 50 per cent probability of an influenza pandemic in the next 5 years (unknown whether severe or mild).
Swiss Re[80]	No	**Pandemic influenza model** The lethality and transmissibility of an emerging virus are generated randomly from historically based distributions each time the model is run. The 1918 pandemic was the most severe of any of the last 13 pandemics; the model therefore assumes that 1 in 13 pandemics will be as lethal and transmissible as 1918. Swiss Re also tested 'H5N1 allowances' for more severe scenarios. These included, for example, varying the 1-in-13 weighting of the 1918 pandemic (from 1 in 20 to 1 in 3).	-	**1 in 30** (mild influenza pandemic) **1 in 200** (severe influenza pandemic) **1 in 3'000** (1918 mortality pandemic)
Switzerland[81]	Yes	**Influenza pandemic** Early warning time 1–3 months. Easy transmissibility. 25 per cent of the Swiss population infected Antiviral drugs are effective. Vaccine availability after 4 months.	40,000 people are hospitalized for a week (2 per cent of infected). 1 million people are treated as outpatients, but without hospitalization (12,5 per cent of infected). 8,000 deaths (0,4 per cent IFR). Expected direct costs of around 10 billion CHF; reduced performance of the Swiss economy of around 5 billion CHF due to lost working hours.	**1 in 55**
Sweden[82]	Yes	**Pandemic influenza** 30 per cent of the population infected.	Around 190,000 or 2 per cent of the population fall seriously ill. 8,000 to 10,000 deaths. Economic impact of about 6 billion SEK.	There is no reliable scientific estimate of when the next pandemic will occur.
United Kingdom[83]	Yes	**Pandemic**	Up to half of the population may fall ill during a flu (or flu-like) pandemic. Up to 2.5 per cent of those with symptoms could die as a result. Between 210,000 and 315,000 deaths. Significant disruptions to all sectors of society (e.g., education and businesses); about 28 billion GBP of economic losses due to absenteeism.	**1 in 100** to **1 in 20**

6.3 Analysis

First, the inclusion of biological risks in disasters risk assessments remains incomplete. If a disaster is defined as "any situation which has or may have a severe impact on people, the environment, or property, including cultural heritage",[84] biological hazards such as pandemics are clearly part of disaster risk. The Sendai Framework for Disaster Risk Reduction explicitly includes biological hazards.[85] The question of whether this should in- or exclude endemic diseases remains debatable. Excluding them seems to favor a fatalistic approach towards hazards, such as seasonal influenza. Including them would shift disaster risk reduction from the realm of emergency services towards public health authorities.

There is a broad agreement that at least pandemics, which require a whole-of-society response, should be included in national risk assessments. Yet, their inclusion in risk assessments is not fully reflected in disaster loss reporting and databases. For example, the widely used disaster loss database EM-DAT has a category for epidemics, but this only lists successfully contained disease outbreaks. It neither lists outbreaks that become a global pandemic, nor diseases that become endemic. For 2020, EM-DAT lists a total of 126 deaths from biological hazards due to outbreaks of Dengue fever, Lassa fever, and yellow fever.[86] The UK and Italy, for example, reported a total of only 110 and 20 disaster deaths, respectively, to UNDRR for 2020.[87] In contrast, Switzerland and Sweden have reported their COVID-19 deaths to UNDRR, 7,923 and 9,265 deaths respectively.[88]

Second, almost all pandemic scenarios explicitly focus on influenza pandemics. This is based on a common assumption that influenza is the most likely cause of a pandemic, and that preparations for such a pandemic can also be useful for other pandemics. The World Health Organization supports this focus through the Pandemic Influenza Preparedness framework. Germany is the only country in this report that has explicitly looked at a pandemic scenario modelled on the severity of SARS-CoV-1. Yet, even Germany only has a response plan for an influenza pandemic.

Third, the focus on influenza in terms of preparations leads to certain assumptions. For example, it is assumed that an influenza vaccine would be available quickly, reducing the length of a pandemic to a couple of months. For other viruses, the time needed to develop a vaccine may be considerably longer. The development of several vaccines against SARS-CoV-2 has been very fast, given the novelty of the virus, but still slower than the 2009 H1N1 influenza vaccine.

Fourth, the actual "reasonable worst case" scenario of a pandemic is more severe than what is used as the "reasonable worst case" in most national risk assessments. For example, the COVID-19 pandemic has already exceeded the most severe pandemic scenario in most national risk assessments, even though it "only" had a pre-vaccine infection fatality rate of about 0.6 per cent.[89] The CFR of COVID-19 peaked in April 2020 at about 7 per cent and has since fallen to about 1 per cent.[90] Worse outbreaks are reasonably possible. For example, in the last two decades, there have been successfully contained outbreaks of SARS-Cov-1 (11 per cent CFR), Middle Eastern Respiratory Syndrome (34 per cent CFR), Ebola (25–90 per cent CFR) and avian influenza (60 per cent CFR).

Fifth, in accordance with the limited severity of the focused scenario, national pandemic plans mostly have an overarching mitigation strategy that accepts that a large portion of the population will be infected.[91] However, for a very severe pandemic (e.g., German SARS scenario), a second strategic option may be desirable,[92] such as local suppression or elimination strategies with a higher commitment to first line defenses, such as border sanitary measures (e.g., quarantine hotels).

Sixth, even without worst-case scenarios, the pandemic scenarios do not fit in well to the 5x5 matrices used by many countries, as they exceed the threshold to reach the maximum impact category several times over. This is discussed in more detail in section 9.2 of this report, as a general issue for risk communication and priorization.

Seventh, despite some minor differences in the likelihood assumptions between the analyzed countries and varying severities of the scenarios, all of them seem to more or less follow the historical frequency of pandemics in the last few hundred years. The outlier in the pandemic scenario assessments is Swiss Re. Swiss Re has modelled influenza risk based on historical pandemics, but with a reduced expected impact today due to new technologies, such as antiviral therapies, vaccines, and antibiotics reducing secondary infections. While this model predicts a pandemic with an annual likelihood of 1 in 33 to 1 in 25, it assumes that a pandemic with the severity of the one in 1918 only has a likelihood of 1 in 3,000. A weakness of the Swiss Re model is that it treats the emergence of new infectious diseases as an exogenous and constant factor, and only considers technology on the response side. This may be useful to model natural zoonotic spillover risk, but it fails to account for accidental and intentional releases of pathogens. A number of factors, such as the strong proliferation of high-containment biolaboratories,[93] and the emergence of cloud labs and synthetic biology,[94] may increase the risk of non-natural pandemics.

Eigth, pandemics have a large protection gap. Due to the globally correlated risk, (re-)insurers view pandemics as "too big to insure"[95] and only cover a very small share of disaster costs, which means private sector risk assessments and transformation services may be less reliable than for other risks. The exposure of (re-)insurers to pandemics has traditionally focused on life insurance. In the case of the COVID-19 pandemic, there were also court challenges arguing that government-mandated shutdowns were covered by certain wording in business interruption insurance policies.

7 Severe Space Weather

7.1 Background

Solar storms can release radiation, high-energy particles, and clouds of magnetically charged particles, which can interfere with radio communication, satellites, and even electricity grids. Solar storms are a cyclical hazard whose frequency rises and falls with solar cycles, which last about 11 years. Solar cycles are measured in terms of observed dark spots on the Sun's surface. These sunspots are the origin of most coronal mass ejections, in which a plasma cloud of charged particles is released into the heliosphere and outer space. The peak amplitude of solar cycles varies over time. These fluctuations are not fully understood yet, but solar cycle intensity is assumed to be slightly decreasing from the peak of the Modern Maximum.[96] At the same time, civilization's exposure to space weather is increasing due to a growing dependence on vulnerable systems, such as satellites. Solar storms can be hazardous in three main ways:

- A solar radiation flare can reach Earth in less than 10 minutes. The radiation is not harmful to humans within the Earth's atmosphere, but can interfere with radio communications.
- High-energy particles, such as protons, can reach Earth within about one hour, and can interfere with or damage satellites.
- The coronal mass ejection itself reaches the Earth in about 1 to 3 days and can also interfere with the electricity grid.

Geomagnetic storms are commonly measured in terms of how much they weaken the strength of planet Earth's magnetic field. This is measured in nano-Tesla (nT) units. The most severe recorded geomagnetic storm was the Carrington Event in 1859 (-1760 nT), which made auroras visible around the globe and caused the failure of battery-powered electrical telegraph systems in Europe and North America.[97] Today, such an event would cause widespread outages of electricity grids and communications failures. Other strong geomagnetic storms were recorded in 1882, 1903 (-531 nT), 1909 (-595 nT), 1921 (-533 nT), 1946 (512 nT), 1960 (–339 nT), 1989 (–589 nT), 2000 (–301 nT), and 2003 (–383 nT). Most of them caused minor damages, such as jamming of radio broadcasting and military radio communication, and problems with electricity grids close to the North or South pole.[98]

Before the 1840s, severe space weather events did not cause damage, as there was no vulnerable electric infrastructure. However, the historical record may be extended through written accounts of unusual observations of auroras[99], which identify a storm in 1770 as at least as strong as the Carrington Event.[100] The analysis of radionucleides may help to identify even earlier superstorms.[101] Two near misses for Carrington grade events were also recorded in 1972 and 2012. Lloyds estimated that the economic cost to the United States would have been between 600 billion and 2.6 trillion USD if the 2012 coronal mass ejection had been directed towards Earth.[102]

Since 1996, solar storms are monitored by the Solar and Heliospheric Observatory satellite from NASA and the European Space Agency.

7.2 Overview Severe Space Weather

Case study	Risk register	Scenario description	Expected impact	Annualized probability
Austria	No	-	-	-
Finland[103]	Yes	a) **Major solar storm** induced disturbance in Finland. b) **Solar storm** that has the capacity to impact the entire country and multiple sectors.	a) - b) Indirect impacts on thousands of people because of shortages of electricity, heat, clean water, and telecommunications. Causes voltage fluctuations in the national grid and possible damage to transformers. Finland's national grid is relatively resilient, but problems in the neighbouring countries can also affect it via the joint Nordic power grid.	a) **1 in 11** to **1 in 5.5** b) **1 in 100**
France	No	-	-	-
Germany	No	-	-	-
Italy	No	-	-	-
Netherlands[104]	Yes	**Satellite disruption due to solar storm** Several satellites cease operation or spin out of control. Only some of the lost communication satellite capacity can be transferred to not affected satellites. GPS positioning and time signals can no longer be delivered reliably to Europe.	10 to 100 fatalities due to, for example, disruption to communication systems for emergency services, failure systems in hospitals, or traffic accidents. >1 million people affected for 2–6 days (in particular by a lack of power and food supply; <100,000 people affected for 1 month or longer. <50 billion EUR costs (primarily response and recovery), but possibly also >50 billion EUR in the event of a more serious escalation.	**1 in 1,000** to **1 in 100** Somewhat likely in 5 years.
Swiss Re[105]	Yes	**a) Carrington type solar storm** **b) Québec+ event** Storm event with an impact similar to Québec 1989 on a local grid.	a) Estimated loss: Scandinavia and the UK (28,903 million USD non-linear, 37,210 million USD linear); Germany, France, Italy, Switzerland and Austria (73,934 million USD non-linear, 95,185 million USD linear). b) Estimated loss: Austria (213 million USD), France (1.466 billion USD), Germany (1.843 billion USD), Italy (1.169 billion USD), Scandinavia (739 million USD), Switzerland (277 million USD), United Kingdom (1.203 billion USD).	**1 in 500** to **1 in 150** Carrington **1 in 11** Québec event

Switzerland[106]	Yes	**Geomagnetic superstorm** with maximum globally measured perturbation of the Earth's magnetic field of around -1600 nT. **(Carrington event)** The solar storm hits Earth in December. Storm phase triggered by three coronal mass ejections and lasts one week.	Widespread temporary failure of electronically controlled infrastructures (e. g. communication infrastructures, power supply).	**1 in 1,700**
Sweden[107]	Yes	**A powerful solar storm outbreak** The scenario plays out during a winter of heavy snowfall and cold temperatures. Major disruptions to satellite signals and total loss of short-wave radio communications that last for several hours at a time across the daylight side of the Earth.	A power outage throughout central and southern Sweden for at least three days. There may be knock-on effects to, for example, transportation, electronic communications, health and medical care, social care, and municipal technical support. Since Sweden's electricity grid is connected to other countries also affected by the same solar storm, this will have a major impact on cross-border co-operation and co-ordination. The economic impact of damaged infrastructure such as satellites, pipelines, telecommunication base stations, and railway transformers could amount to more than 50 billion SEK.	N/A
United Kingdom[108]	Yes	**"Reasonable worst case" (Carrington event**; localized disturbance of 4,000–5,000 nT min^{-1})	Level C Economic impacts: 100 million to 1 billion GBP. Electricity supply: major disruption to electricity supply to greater than 300 thousand consumers for longer than 18 hours. Disruption or loss of services reliant on satellite-enabled technologies. Temporary outages of on-board satellite electronics and possible damage to or total failure of satellites, disrupting satellite television broadcasts, and reducing the accuracy of weather forecasts. Disruption to essential services, particularly transport, retail finance, energy and communications.	**1 in 100**

7.3 Analysis

First, even though solar storms are a global hazard, countries do not have the same risk profiles. The intensity of the expected impact increases from the equator towards the geomagnetic North and South Poles, peaking at 60 to 70 degrees of geomagnetic latitude (Scandinavia and Canada). However, the risk remains elevated above 40 degrees of geomagnetic latitude (USA, almost all of Europe and Russia).[109] The southern hemisphere is far less exposed, with only Antarctica, New Zealand, and the southern tips of Australia and Argentina above 40 degrees of geomagnetic latitude.

Second, there is a gap in the likelihood assessment between Switzerland, Swiss Re and the UK. The easiest way to approach the annualized likelihood for a Carrington grade event is to take the historical record as a baseline frequency. This would indicate a frequency of about 1 in every 180 years (based on records since 1840), or about 1 in every 250 years (based on written record since circa 1500). This is roughly in line with the assessment of Swiss Re and other insurers such as Lloyds, which indicate 100 to 250 years as a reasonable range.[110] However, as mentioned above, the annualized risk level is cyclical based on the solar cycle as well as grand solar maxima and minima.

Switzerland's national risk assessment in 2015 placed the likelihood of a -1600 nT solar storm at a comparatively high: 1 in 80.[111] The 2020 assessment made a 17-fold adjustment to a comparatively low: 1 in 1,700. The reasoning behind this change was a statistical analysis by mathematicians.[112] Their study argued that the distribution of recorded solar storms from 1957 to 2017 fits a curve, which indicate that the likelihood of a future solar storm of a certain intensity decreases with the time since a similar recorded event. Their result is that the probability of a Carrington grade event is much lower than the simple historical baseline indicates.

Based on background interviews, the analyzed countries generally also have a larger span of uncertainty for the baseline probability of space weather and volcanic outbreaks than for more common natural hazards, which have a higher annualized expected loss, such as floods and earthquakes.

Third, solar storms only cause limited direct damage to the environment and humans. They mainly impact critical infrastructures, such as the electricity grid and satellite systems. Therefore, the topic could be considered from a critical infrastructure rather than a natural hazard angle. For example, the scenario toolbox of the Netherlands allows for different types of interferences and disturbances of satellite communications, which are not limited to solar storm.

Fourth, insurance coverage of damage to electrical grids caused by solar storms depends on whether the voltage fluctuations result in physical damage to a transformer.

Fifth, for additional context to the above overview, the use of the likelihoods 1 in 11 and 1–2 in 11 for solar storms of medium intensity by Swiss Re and Finland corresponds to the duration of a solar cycle. There is some divergence between Swiss Re (1 in 11) and Lloyds (1 in 50) for a Québec-level event.[113]

8 Volcano Eruption

8.1 Background

During a volcanic outbreak, molten lava and other materials, like gases, are ejected from a magma chamber beneath the Earth's surface. The intensity of volcanic eruptions is measured based on the volume of expunged material in the volcanic explosivity index (VEI), which ranges from zero to eight on a logarithmic scale. Large explosive eruptions cause damage in their vicinity through heat, toxicity, and kinetic impacts. They also release vast amounts of ash high up into the atmosphere with transnational or even global impacts. For example, the emission of a lot of sulfate aerosols into the Earth's atmosphere can temporarily lower the temperature worldwide. The sulfurdioxide-rich errruption of the Icelandic volcano Laki in 1783 (VEI 4) temporarily lowered global temperatures, causing crop failures and food shortages.

Today, another key concern is the impact of volcanic ash on aviation safety due to incidents of engine failure in aircrafts flying through ash clouds. In 2010, the eruption of the Icelandic Eyjafjalla volcano (VEI 4) caused ash clouds to spread rapidly over Europe, grounding air traffic for several days. In just over a week, more than 100,000 flights were canceled, around 10 million passengers were affected, and the industry recorded total losses of around 1.7 billion USD.[114] In addition, suppliers who rely on, or trade in, air freight were also affected. In hindsight, the initial upper limit of ash density for safe flights, which was introduced during the crisis, was set too low.[115] Since then, regulators have aimed to better define a safe upper limit of ash density which is currently set at about 4 milligram of ash per cubic meter.[116]

In Europe, there are only a few active volcanoes. The largest recorded volcanic eruption in Europe happened in Santorini, Greece (VEI 7, 1620 BCE). In Iceland, the largest recorded outbreaks are Bardarbunga (VEI 6, 1477), Eldgjá (VEI 6, 939),[117] Grímsvötn (VEI 6, 8230 BCE), Hekla (VEI 5, 5150 BCE, 4110 BCE, 2310 BCE, 1100 BCE, & 1104), Katla (VEI 5, 1262, 1625, 1721, 1755), Askja (VEI 5, 8910 BCE, 1875), and Oraefajokull (VEI 5, 1362). In Italy, the largest recorded outbreaks are Vesuvius (VEI 5, 6940 BCE, 2420 BCE, 79, 472, 1631), Etna (VEI 5, 1500 BCE, 122 BCE), and Campi Flegrei (VEI 5, 2150 BCE).[118]

8.2 Overview Volcano Eruption

Case study	Risk register	Scenario description	Expected impact	Annualized probability
Austria	No	-	-	-
Finland	No	Mentioned in description of **disruptions of food supply and disruptions of logistics**	-	-
France[119]	Yes	Describes **volcanoes in French overseas territories**, and the catastrophic eruption of Mount Pelee, Martinique on 8 May 1902, which caused about 29,000 deaths. There are no active volcanoes in metropolitan France. Volcanoes in other countries are not mentioned.	-	-
Germany	No	-	-	-
Italy[120]	Yes	**"**Subplinian" **eruption of the Vesuvius volcano** near Naples [Plinian eruption of Vesuvius in 79 CE = VEI 5].	Surrounding area may be affected by pyroclastic flows; roughly 600,000 people living in this red zone need to be evacuated; a larger area is impacted by significant fallout of ash.	- (conditional probability that 95 per cent of outbreaks in Italy are subplinian)
Netherlands	No	-	-	-
Swiss Re[121]	No	**Global volcano model** The hazard component generates a large number of potential volcanic eruption events of different intensities for 508 globally distributed volcanoes of explosive nature. The modelled intensities of volcanic eruptions range from a Volcanic Explosivity Index (VEI) of 3 to 6. Each of the modelled volcanic eruptions is assigned an individual eruption probability, which is based on its past eruption history.	The primary effects that are calculated are those on cities in the immediate vicinity of volcanoes, which includes Reykjavik (Iceland), Naples and Catania (Italy) in Europe. 10–20 billion USD in costs. A global ash fall hazard map is accessible to Swiss Re's clients in CatNet.	
Switzerland[122]	Yes	**A volcanic eruption of magnitude 6 VEI in Europe** Ash clouds rising up to 40 kilometers. The airspace of the affected country and neighboring states are closed for a total of eight days due to high ash concentrations. In the other European countries, the airspace is not closed, but flights are cancelled or diverted. Air traffic returns to normal after three weeks. Global temperature decrease in the following two to three years averaging between 0.5 and 0.7°C.	Overall, the event results in direct economic damages of 500 million CHF and indirect damage of 500 million CHF.	**1 in 70,000**

Sweden[123]	Yes	In the early summer, the **Eldgjá volcanic fissure in Iceland erupts**. Ten days after the eruption starts, a volcanic dry fog reaches Sweden [last outbreak 939 = VEI 6].	Between 30 and 99 people will die and around 2,500 people will need medical care due to concentrations of sulphur dioxide, sulphuric acid, and small solid particles. This scenario would have a major economic impact. However, due to an insufficient knowledge base in the analysis, the level of uncertainty is too high to conduct a quantitative assessment of the total costs.	Very rarely
United Kingdom[124]	Yes	**"Reasonable worst case" scenario.**	Level C Economic impacts: 100 million to 1 billion GBP.	**1 in 4** to **1 in 20**

8.3 Analysis

First, similar to nuclear accidents, countries with volcanoes tend to focus on the primary effects of an outbreak. This includes Italy, as well as the overseas territories of France. In contrast, countries that do not have their own volcanoes, such as Switzerland and the UK, primarily focus on cross-border effects of volcanic ash.

Second, most central, eastern, and south-eastern European countries do not include any volcanic scenario in their national risk assessment.[125]

Third, the only selected countries that offer concrete probabilities are Switzerland and the UK, but their assessments differ substantially (1 in 70,000 vs. 1 in 20 to 1 in 4). The historical record would indicate a baseline probability that lies somewhere between the two estimates. The record of the largest outbreaks in Europe until about 10,000 BCE show four outbreaks that reach the threshold of VEI 6. This indicates an annualized baseline probability of about 1 in 3,000 for a VEI 6+ outbreak in Europe, and about 1 in 600 for a VEI 5 outbreak. The Swiss national risk assessment uses a slightly different baseline than this report's author, with two VEI 6 outbreaks in Europe (excluding Santorini and Eldgjá). It is unclear where the additional expert adjustment comes from, but one factor may be that Switzerland adds additional criteria, such as weather conditions and corresponding air traffic restrictions. One factor that is not mentioned in the UK Risk Register, which could potentially explain the high likelihood assessment is the country's overseas territories.

Fourth, there is the possibility of very low likelihood / very high impact scenarios, such as a VEI 7+ outbreak with consequences for global temperatures and agriculture. As pointed out by one of the interviewees, recent data from ice cores indicates that the likelihood of such an event is higher than previously assumed.[126] An economic worst-case scenario could be a repetition of the Laacher Lake outbreak that happened around 11,000 BCE in the Eifel region in Germany, estimated at VEI 6.[127]

9 Discussion

9.1 Towards Output Coherence

While it is instructive to compare and exchange methodological approaches and insights for national risk assessments between countries, a strong focus on developing a common standardized methodology has three limitations.

First, there is no universal risk analysis method that is best suited for all potential hazards and critical infrastructures. In the words of the European Commission's Joint Research Centre, "different risks of different origins require very different methods of risk assessment, not only due to diversity of phenomena, but also due to different availability of data and knowledge".[128]

Second, most risk analysis methods contain human expert judgement. Due to variability in judgement between experts the same analysis framework does not guarantee the same output. As ISO 31010 explicitly states, risk matrices can be "very subjective and different people often allocate very different ratings to the same risk".[129]

Third, the use of multiple risk analysis approaches can be desirable when combined with output coherence tests. When trying to accurately date and understand the past, it is acceptable to use an overlapping set of methods,[130] and the author sees no strong reason not to allow more than one method to estimate the likelihood and impact of a future event caused by a particular hazard.[131] Convergence of risk estimates using different methods indicates less uncertainty, while divergence indicates more uncertainty.

The main alternatives to a strong focus on a standardized methodology ("throughput coherence") is to put more focus on sharing data sources ("input coherence") and on comparing the results of risk assessments ("output coherence"). There is room for improvement on both of these points. For example, the reviewed case studies do not indicate clearly whether or what historical datasets or expert surveys were used as inputs for likelihood assessments, with the notable exception of Swiss Re.[132]

Still, the focus of this report is output coherence. In particular, the outputs of national risk assessments for cross-border risks should be reasonably comparable, to highlight discrepancies and opportunities for exploring assessment processes, and to learn from each other. Using this approach, this report has identified a number of issues spanning risk identification, as well as the analysis of the likelihood, and impact of reference scenarios.

9.1.1 Risk Identification

First, there are differences in the comprehensiveness of risk registers. The UK with 36 different hazards[133] and

Switzerland with 44 hazards[134] are on the more comprehensive end, whereas countries like Austria, Germany, and Italy have identified and analyzed a narrower spectrum of collective hazards.

Second, the differences in risk identification also extend to some risks with very high annualized expected losses. Specifically, electricity supply shortage, which is identified as the top risk in the Swiss national risk assessment, is not similarly included in most other national risk assesments.

Third, risk assessments may identify hazards, failures of critical infrastructures, or in some cases trends as risks.[135]

- Hazards can impact a number of (critical) systems. Floods, wildfires, or infectious diseases are examples of hazards.

- Critical infrastructures and systems may be impacted by a number of hazards. Electricity grids, radio networks, or nuclear power plants are examples of critical infrastructures.

- Trends and critical uncertainties can impact the frequency and severity of hazards, as well as the vulnerability and exposure to them. For example, climate change, social cohesion, or geoeconomic conflict are factors that significantly influence the risk landscape.

National risk assessments are traditionally hazard-focused. However, many countries find it useful for preparedness and mitigation purposes to explicitly highlight risks to key critical infrastructures. Hence, many national risk assessments contain a pragmatic mix of hazards and critical infrastructures. Trends are usually not evaluated in terms of their expected value in national risk assessments. However, they may be analyzed in separate trends reports.[136] The Global Risks Report of the World Economic Forum, for example, provide analysis that also includes trends and critical uncertainities.[137]

Fourth, the focus on collective risks with multiple deaths per event in national risk assessments excludes the leading causes of death (cardiovascular diseases, cancer, respiratory diseases)[138] and the leading risk factors for deaths (high blood pressure, smoking, air pollution).[139] National risk assessments are effectively national disaster risk assessments, and primarily geared towards collective risks that require emergency services. While this is not a problem per se, it is important to be aware that they are not comprehensive.

Fifth, differences in risk identification as well as the exclusion of some identified risks from disaster loss reporting limit the comparability of aggregated recorded disaster impacts across countries. For example, the inclusion or exclusion of deaths from traffic accidents can shape national disaster statistics.[140] The inclusion or exclusion of biological hazards can massively change global disaster statistics (see section 6.3).

9.1.2 Likelihood Analysis

First, not all countries aim to assess the likelihood of hazards in a systematic and quantified way. Of the analyzed countries, the Netherlands, Switzerland, Sweden, and the UK have attempted to do so. Finland includes a trend assessment of the likelihood (decreasing, stable, increasing) in their national assessment, and more specific probabilities in their local assessments. Austria includes a qualitative assessment. France, Germany, and Italy avoid likelihoods altogether.

The assessment of the baseline annualized probability of many hazards is admittedly difficult. Hence, refusing to indicate a probability range for a hazard with a statement, such as "there is no reliable scientific estimate of when the next pandemic will occur"[141] may sound reasonable or even scientifically rigorous. Yet, likelihood is a fundamental aspect of risk. In its classic definition by Knight, risk is defined as likelihood times impact.[142] If it were impossible to assign any range of probability, it might be more adequate to talk about uncertainty rather than risk. Without a likelihood assessment, there can also be no annualized expected loss, making it unclear how a national risk assessment is supposed to fulfill its purpose of helping with the priorization of preparedness and mitigation efforts.

Moreover, the inability to predict something precisely does not mean that every scenario is equally (un-)likely. Indeed, the selection of a few scenarios for analysis from the infinitude of possible scenarios is not random, but includes the implicit assumption of a minimum level of plausibility. Otherwise, it might be hard to explain why countries analyze the scenario of an influenza pandemic and not that of a plague pandemic, or a terrorist attack and not an alien invasion. Hence, it is better to think in terms of levels of uncertainty.[143]

Vagueness may be a risk-averse strategy that offers less (political) attack-surface as some scenarios become reality and others not. However, overall it seems not only preferable but necessary for a national risk assessment to assign probability ranges to hazard scenarios.

Second, there are examples of significant differences in probability assessment of cross-border hazards, such as nuclear accidents, severe pandemics, severe space weather, and a large volcanic outbreak. In most of these cases, it was possible to subsequently trace back these differences to different methods or assumptions. In the nuclear scenario, the main difference appears to be between a probabilistic safety assessment that primarily looks at failure rates of parts, and an approach focusing on the historical frequency of accidents. For severe pandemics, all actors appear to start with the historical frequency, but Swiss Re also downgraded the severity of historic outbreaks based on modern medicine. For a Carrington-like solar storm most reply on historical frequency. Switzerland also uses the historical frequency but adapted to a model that assumes a decreasing probability of such an event over time.

Third, for most non-geophysical hazards, the annualized probability of an event should not be communicated as an average return period. For example, Switzerland expects a major data center outage once every 20 years, a biolab incident once every 1,000 years, and a nuclear accident once every 2.5 million years.[144] This may suggest a too long time horizon of the analysis to the reader. The Swiss report does not make an assessment of the level of nuclear accident risk beyond the next ten years, let alone 2.5 million years from now. Accordingly, return periods may also mistakenly suggest that the risk level will remain fixed for a long time. However, all technological and social risks change over time due to dynamic factors. Even the characteristics of many natural hazards are changing, for example, due to climate change. Overall, this may overemphasize decreasing risks (e.g., cold waves), and underemphasize future (e.g., AI) and emerging risks (e.g., heat waves, cyberattacks). Hence, annualized probabilities of occurence are preferably communicated without years (e.g., 1 per cent or 1 in 100).

9.1.3 Impact Analysis

First, there are differences in impact analysis, including the types of impacts considered. In general, differences in expected impact are a less reliable signal of output incoherence than differences in the hazard probability for cross-border risks. This is because vulnerability and exposure to cross-border risks are expected to vary more between the reviewed countries, due to factors such as differences in GDP, demographics, urbanization, health system capacity, or electricity grid resilience to space weather.

There are also differences in the types of impacts that countries have considered. For this reason, countries could cross-check with other countries to see if they have overlooked key factors. It seems that cross-border impacts from domestic risk sources that spill over into one or more neighbouring countries are often not considered. The impact of cross-border risks generated in one or more neighbouring countries is primarily considered if there is no risk source of the same type within the assessing country (e.g., the impact of volcano outbreaks on air travel).

Second, most countries do not have a consistent formula for how to compare different types of impact. The main exception among the analyzed countries is Switzerland, which has conversion factors that translate all forms of impact into financial damage.[145] The EU's suggestion of creating separate risk matrices per impact type[146] has not been followed by the analyzed countries, nor would it help to make different types of impacts comparable for risk prioritization.

The UK's risk assessment is a positive example in that it aims to bring these types of impacts together. However, it still has shortcomings. First, it is still unclear how to accumulate impacts across categories. Hence, a hazard that is evaluated on Level B on five impact categories, may be assessed lower than a hazard that only has one type of impact but reaches Level C. Second, the conversion rates between different types of impacts are inconsistent across event sizes because the impact levels do not scale equally across types of impacts. For example, we can compare the upper limit for loss of life and economic losses in the first four impact categories:

- Level A: 8 deaths, 10 million GBP = implied value of a statistical life 1.25 million GBP.
- Level B: 40 deaths, 100 million GBP = implied value of a statistical life 2.5 million GBP.
- Level C: 200 deaths, 1 billion GBP = implied value of a statistical life 5 million GBP.
- Level D: 1,000 deaths, 10 billion GBP = implied value of a statistical life 10 million GBP.[147]

The UK's national risk assessment mentions that the scale indicators are approximations and "should NOT be read as a set of criteria that needs to be met in order for an assessed risk to be classified at these levels."[148] Such language provides an opening for accumulated impact and a hedge against any notion of incoherence, but it also undermines the purpose of a risk assessment, or renders it more subjective.

Third, on a related note about public health, countries sometimes estimate the burden of disease or impact of an intervention in quality-adjusted life years (QALY).[149] For example, the death of a nine-year old person would lead to a loss of more QALYs than the death of a 90-year-old person due to the difference in remaining life expectancy. Such differentiation may be relevant for scenarios that disproportionally harm specific age groups. For example, in the COVID-19 pandemic the mortality rate grew exponentially with old age.[150] Statistically, older aged people are expected to have multiple co-morbidities[151] and less life expectancy than younger people. Hence, the questions of how to attribute deaths to a cause, and whether to take into account life expectancy, are relevant for pandemic scenarios. At the same time, such fine-graded distinctions remain a secondary issue compared to the general problem of correctly accounting for high impact risk in assessments (section 9.2).

Fourth, there are opportunities for more mapping of risk interlinkages. While there is a widespread acknowledgement of the need to take into account interlinkages and cascading effects for impact analyses, the operationalization is not easy.[152] It is also worth re-iterating that some of the identified risks are hazards, whereas others are failures of critical infrastructure. If both types of risks are included in an assessment, it may happen that the impacts of certain risks are counted twice in the same assessment, whereas others are not (e.g., the risk of a coldwave that can cause an electricity supply shortage, and the risk of an electricity supply shortage that can be caused by a coldwave). This is not a big problem, but it is still worth keeping in mind.

9.2 The Case against Risk Matrices

The previous section highlighted that standards are not sufficient for coherence between national risk assessments. This section goes further by arguing that risk matrices as a key standard for process coherence are not always useful and sometimes even harmful.

First, it should be noted, that the recommendations to use a 5x5 matrix are underdefined, as they are only accompanied by approximate qualitative suggestions on what the categories could be. In practice, European countries use a smorgasbord of category definitions.[153] Meaning, these categories differ substantially between countries, both in absolute terms, as well as relative to the national population or GDP. As such, 5x5 risk matrices are not sufficient for comparability

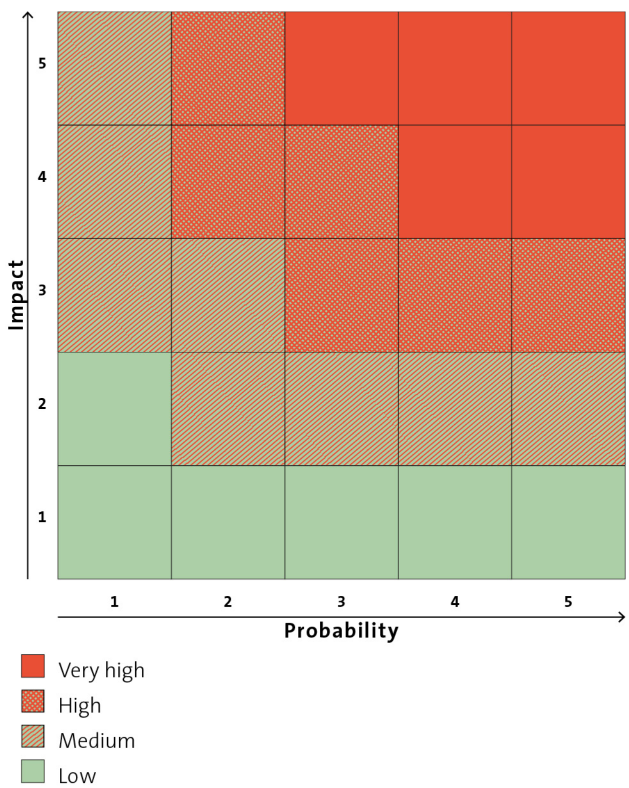


Figure 1. 5x5 Risk Matrix, adapted from EU reporting guidelines.

Second, as highlighted in section 9.1.3, some national risk matrices are also not self-consistent, as they consider different types of impacts without ensuring that these grow in lock-step along an axis.

Third, and most importantly, risk matrices can introduce distortions in risk communication and prioritization. Several authors including Cox (2008)[154] and Thomas, Bratvold, and Bickel (2014)[155] have highlighted general limitations of the use of risk matrices. These include range compression, centering bias, and category-definition bias.

However, what is most relevant in the specific context of national risk assessments is that risk matrices systematically understate extreme impact risks.

9.2.1 Extreme Impact Risks

Over longer periods of time, many if not most expected disaster deaths do not come from the aggregated impact of many "moderate" scenarios but a few "worst case" scenarios. Hence, if we care about reducing disaster deaths, we cannot exclude extreme impact risks as inconvenient outliers from our risk analyses. The outlier is the norm when it comes to historical data of disaster deaths.

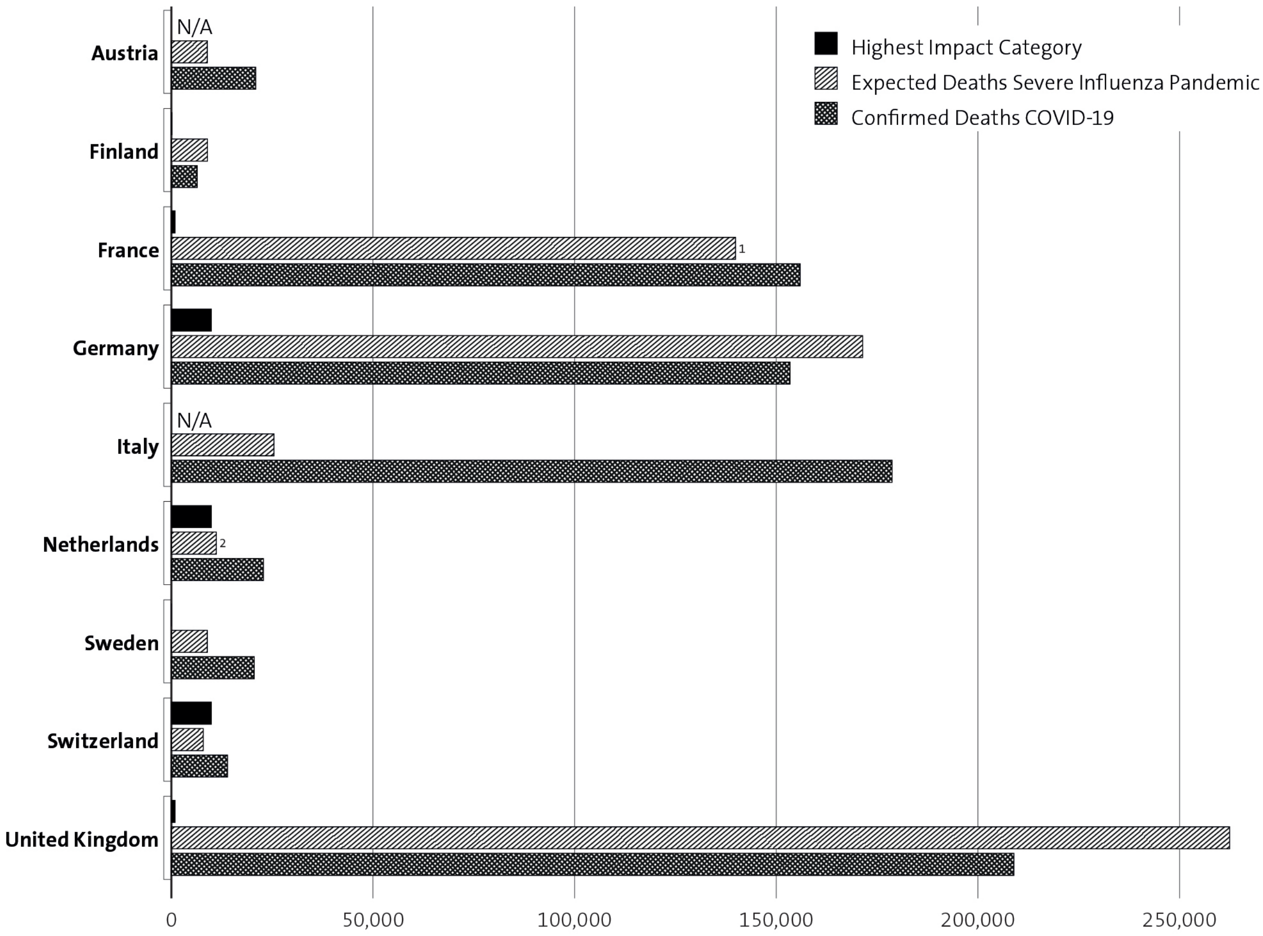
From the foundation of the UNDRR in 1999 to 2020, about 1.2 million people worldwide died due to natural hazards according to the data from EM-DAT. Of those, nearly half died in just three disaster events: The 2004 Indian Ocean earthquake and tsunami, the 2008 Myanmar cyclone, and the 2010 Haiti earthquake, each of which caused close to, or more than, 200,000 deaths. Similar patterns for disaster deaths can also be found in a number of other hazard domains and countries.

Yet, EM-DAT excludes pandemics. The World Health Organization has recorded more than 6.7 million deaths due to the COVID-19 pandemic as of January 2023.[156] As such, COVID-19 arguably was responsible for more than 80 per cent of worldwide disaster deaths since the founding of UNDRR. In fact, if we take the model of the *Economist,* the true death toll lies between 16 and 28 million people,[157] making the COVID-19 outbreak as a single megadisaster responsible for about 95 per cent of all disaster deaths in the 21st century.

Why risk matrices understate extreme risks:
Risk matrices can assign higher qualitative ratings to quantitatively smaller risks. This is because the quantitative values of estimated probabilities and impacts are reduced to a few categories. Hence a risk with "Impact 5" and "Probability 2" is assessed as a lower priority than risk with "Impact 4" and "Probability 4", even if the former has a higher annualized expected loss. The minimum values required to enter the second lowest or highest category on an axis are particularly impactful because the lowest and highest categories are often open-ended towards

very low and very high values, respectively. In practice, it is mostly low thresholds for reaching the maximum impact category that create distortions. Pandemic scenarios provide a good example of this:

- Finland expects 9,050 deaths in a severe influenza pandemic, which is 45 times higher than the 200 deaths to reach the maximum impact category.[158]
- Sweden expects 8,000 to 10,000 deaths in a pandemic influenza, which is 160 to 200 times above its maximum impact threshold (50+ deaths).[159]
- France did not project expected deaths in a influenza pandemic, but COVID-19 shows that its maximum impact category of 1,000+ deaths is inadequate[160].
- In the UK, expected deaths in the influenza scenario are 200 to 300 times higher than the maximum impact threshold (1,001+ deaths).[161]
- Germany's SARS scenario has 7.5 million expected deaths, which is 750 times higher than the maximum impact threshold (10,000+ deaths).[162]



Austria and Italy do not have public impact categories.

1. France does not project hospitalizations or deaths. 140,000 reflects the same population death rate (0.2%) as the German influenza scenario.
2. The Netherlands only projects expected hospitalizations. The deaths are calculated as 25% of expected hospitalizations, which is in line with other countries.

Figure 2. Comparison of the threshold for the highest impact category in a risk matrix and expected/confirmed deaths (as of 22 November 2022) in a pandemic.

	Expected Deaths Influenza / Threshold Max. Impact Category	Recorded Deaths COVID-19 / Threshold Max. Impact Category	Expected Deaths in Germany's SARS Scenario (9.3% of pop.) / Threshold Max. Impact Category[3]
Switzerland	0.8	1.4	81.3
Netherlands	1.1[1]	2.3	165
Germany	17.2	15.4	750
Finland	45.3	32.5	2,580
France	140[2]	156	6,280
Sweden	180	413	19,400
United Kingdom	263	209	6,260

Austria and Italy do not have public impact categories.

1. The Netherlands only projects expected hospitalizations. The deaths are calculated as 25% of expected hospitalizations, which is in line with other countries.
2. France does not project hospitalizations or deaths. 140,000 reflects the same population death rate (0.2%) as the German influenza scenario.
3. Germany is the only country with a public scenario for a SARS pandemic. The other numbers reflect the application of the same population death rate (9.3%).

Figure 3. Pandemic scenarios and COVID-19 deaths divided by the threshold for the highest impact category in national risk assessments.

The comparison of the highest impact categories in national risk assessments with the expected deaths caused by a severe influenza pandemic and the confirmed deaths by the COVID-19 pandemic in Figures 2 and 3, shows that only Switzerland[163] and the Netherlands[164] have chosen categories that roughly correspond to the size of the risk. The possibility of a more severe pandemic, such as the German SARS scenario, would not fit adequately into the impact categories of any selected country.

In short, the main advantage of the risk matrix in ISO 31010 is that it is simple and easy to use. However, for a national risk assessment, it is the author's opinion that 5x5 matrices are neither required nor particularly suitable. They reduce the output resolution of risk assessments, which can lead to significant misrepresentations of the results of a multi-hazard risk analysis. Specifically, they tend to understate the importance of very high impact risks.

9.2.2 Alternatives

There are multiple options to complement or replace a traditional risk matrix for comparative risk visualization and priorization. What these approaches have in common is that they aim to follow the golden rule of data visualization: "the representation of numbers, as physically measured on the surface of the graphic itself, should be directly proportional to the quantities represented."[165]

Scatter plot: The most simple solution is to keep a figure with likelihood and impact on the x- and y-axes, but to use a continuous scale rather than a small number of discrete categories. This avoids previously discussed threshold effects.

Bar charts: Vertical or horizontal bar charts can be an easy and effective way to compare the annualized expected loss of different hazards. Switzerland plan to use bar charts to complement its risk visualization.[166]

Treemap charts: Treemap charts in which the size of the annualized expected loss is proportional to the size of a square can be an easy and effective way to compare different hazards. For example, the MIT Observatory of Economic Complexity makes extensive use of tree map charts,[167] and Switzerland plant to use it to complement its current risk visualization.[168]

9.3 Multi-Level Risk Assessments

Whereas the previous sections have discussed issues around national risk assessments, this last section briefly discusses the vertical dimension that ranges from local, to national, to regional, to global risk assessments. Specifically, it considers the mismatch between political and risk boundaries that are typical for cross-border risks.

(Re-)use of risk assessment capacities: Local governments will often have a better understanding of their local geography, local critical infrastructure, local disaster history, local emergency response capacities, and operational learnings from disaster response than national or international actors.

At the same time, smaller local governments and countries may lack adequate risk assessment capacities to analyse regional and global risks in-depth. Does it make sense if a small local government with limited resources aims to estimate the likelihood of a severe solar storm or a global pandemic? At best, it is a duplication of efforts at higher levels. At worst, it is a duplication of efforts combined with less trustworthy results due to more limited resources and access to experts.

Providing re-usable and adaptable outputs on an international or global level is probably undervalued compared to establishing interoperable methodologies. A stronger pool of re-usable content in risk identification, risk characterization, macrotrends and their impact on hazard probability over time would facilitate the national risk assessment work in smaller and poorer countries. Assessments from a higher political level may still be adapted to the local context. For example, a pandemic risk model may account for local age structure, travel patterns, and healthcare capacity. However, it does not make sense to start at zero. This kind of interoperability and knowledge transfer already works quite well in many countries between the national and the local level. However, today, there is no readily available global disaster risk assessment on which national risk assessments could build.

Mismatch between political and risk boundaries: Ultimately, it is not just the risk assessment, but also the risk ownership that becomes misaligned with the scope of risks above the national level.

This creates a collective action problem, where countries can be incentivized to underinvest in risk reduction if a large share of the consequences are cross-border spillovers, which cannot always be internalized in a semi-anarchic international system.[169]

Countries that are affected by regional and global risks that originate outside their borders may be inclined to focus their national strategy on mitigation rather than prevention. For example, much effort is placed on preventing pandemics, as they are almost bimodal between early containment (>100,000) and the infection of a large share of the world population (1+ billion). Yet, countries spend more time and energy on national pandemic response plans than they contribute to pandemic prevention across borders.

10 Conclusion

This report has compared national risk assessments of five cross-border risks in Europe. This comparison has revealed differences in risk identification, likelihood analysis, and impact analysis.

- **Electricity supply shortage:** This regional risk has been evaluated as the biggest amongst 44 analyzed risks in Switzerland. Yet, it has not been identified as a risk in most other countries – at least until the Russian invasion of Ukraine in 2022 and its consequences for European energy security.

- **Nuclear accident:** The likelihood assessments for major accidents range from 1 in thousands to 1 in millions. The former appear to be informed more strongly by the historical record of accidents, whereas the latter is informed by probabilistic safety assessments.

- **Pandemic:** Swiss Re's model assumes a lower likelihood of a severe pandemic than most national assessments, based on downwards adjustments to the severity of historical pandemics due to modern medicine. With the exception of Germany, the most severe pandemic scenarios in national risk assessments use a CFR that is substantially lower than that of several successfully contained infectious disease outbreaks in the recent past.

- **Severe space weather:** Switzerland assigns a lower baseline probability to a Carrington-like geomagnetic storm than the UK and Swiss Re because it models the historical record with the assumption of a decreasing hazard rate.

- **Volcanic outbreaks:** There is a large difference in the likelihood estimate between the UK and Switzerland, the cause of which the author could not identify. Differences in categorizations of historical outbreaks, airspace closures, and overseas territories may be contributing factors.

Aside from such specifics, the report shows that the approach of looking for output incoherences between countries, and using these as a starting point for follow-up questions and discussions, can be fruitful. A Delphi survey could go further than this report in clarifying reasons for disagreements between experts in the assessment of cross-border risks.

Furthermore, the report has used the selected risk assessment comparisons to highlight a number of more general considerations for national risk assessments. These include:

- **Risk identification:** There remains ambiguity over what should be included in a national risk assessment. Should the focus be on hazards, infrastructures, or trends? What qualifies as a collective risk and what as an individual risk?

- **Risk matrix:** The standard 5x5 matrix used in ISO 31010 and EU recommendations can introduce distortions in risk communication and priorization. Specifically, the qualitative assessment in a matrix does not have to correspond to the quantitative assessment of annualized expected loss. This effect can lead to the underestimation of risks with extreme impacts, such as a pandemic.

- **Level of analysis:** Cross-border risks might be better analyzed and managed if there was more risk assessment capacity and risk ownership on regional and global levels.

This list of general issues is not comprehensive and this report cannot answer all questions that are raised within it. However, it has hopefully provided an overview, a few concrete suggestions for improvements, and a useful impetus for further discussions and developments of national risk assessment practices and procedures.

11 Bibliography

1 European Parliament and Council of the European Union. (2013). *Decision No 1313/2013/EU on a Union Civil Protection Mechanism.* eur-lex.europa.eu, Art. 6; European Commission. (2019). *Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU*. eur-lex.europa.eu

2 OECD. (2014). *Recommendation of the Council on the Governance of Critical Risks*. oecd.org, p. 5.

3 United Nations General Assembly. (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. preventionweb.net Target G-5, p. 9; United Nations General Assembly. (2015). *69/283: Sendai Framework for Disaster Risk Reduction 2015–2030*. un.org Priority 1: Understanding Disaster Risk, p. 9ff.

4 United Nations Office for Disaster Risk Reduction. (n.d.). *Global Risk Assessment Framework (GRAF)*. preventionweb.net

5 European Commission. (2021). *Recommendations for National Risk Assessment for Disaster Risk Management in EU*. op.europa.eu.

6 OECD. (2014). *Recommendation of the Council on the Governance of Critical Risks*. oecd.org, p. 3.

7 e.g. Hauri, A., Kohler, K., Roth, F., Käser, M., Prior, T. & Scharte B. (2020). *Trend Analysis Civil Protection 2030* (Zurich: CSS/ETH).

8 This reflects the terminology of the Emerging Risks Working Group of the OECD High-Level Risk Forum.

9 World Economic Forum. (2023). *The Global Risks Report 2023.* weforum.org; Swiss Re Institute. (2022). *sigma: Resilience Index 2022*. swissre.com; Cambridge Centre for Risk Studies. (2019). *Cambridge Global Risk Outlook 2020*. jbs.cam.ac.uk

10 United Nations Office for Disaster Risk Reduction. (2022). *Global Assessment Report on Disaster Risk Reduction*. undrr.org

11 UN General Assembly. (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. preventionweb.net

12 UNDRR. (2023). *Measuring Implementation of the Sendai Framework*. sendaimonitor.undrr.org

13 United Nations Office for Disaster Risk Reduction. (n.d.). *Global Risk Assessment Framework (GRAF)*. preventionweb.net

14 Kohler, K., Hauri, A., Roth, F. Prior, T. & Scharte B. (2020). *Monitoring and Reporting under the Sendai Framework for Disaster Risk Reduction* (Zurich: CSS/ETH), p. 18f.

15 Eriksen, C., Hauri, A. & Thiel, J. (2021). *An Evaluation of Switzerland becoming a Participating State of the European Union Civil Protection Mechanism* (Zurich: CSS/ETH), p. 19–26.

16 European Parliament and the Council of the European Union. (2013). *Decision No 1313/2013/EU on a Union Civil Protection Mechanism*. eur-lex.europa.eu, Art. 6; European Parliament and the Council of the European Union. (2019). *Decision (EU) 2019/420 amending Decision No 1313/2013/EU on a Union Civil Protection Mechanism*. eur-lex.europa.eu, Art. 6.

17 European Commission. (2017). *Overview of natural and man-made disaster risks the European Union may face*. data.europa.eu; European Commission. (2021). *Overview of natural and man-made disaster risks the European Union may face*. data.europa.eu

18 European Commission. (2010). *Risk Assessment and Mapping Guidelines for Disaster Management.* ec.europa.eu

19 European Comission. (2015). *Risk Management Capability Assessment Guidelines*. eur-lex.europa.eu

20 European Commission. (2019). *Recommendations for National Risk Assessment for Disaster Risk Management in EU: Version 0*. data.europa.eu; European Commission. (2021). *Recommendations for National Risk Assessment for Disaster Risk Management in EU: Version 1*. drmkc.jrc.ec.europa.eu

21 European Commission. (2010). *Risk Assessment and Mapping Guidelines for Disaster Management.* ec.europa.eu, p. 24.

22 European Commission. (2010). *Risk Assessment and Mapping Guidelines for Disaster Management*. ec.europa.eu, p. 21f.

23 European Commission. (2010). *Risk Assessment and Mapping Guidelines for Disaster Management*. ec.europa.eu, p. 19.

24 European Commission. (2019). *Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU*. eur-lex.europa.eu, p. 19f.

25 ISO (2017). B.9.3 Consequence/likelihood matrix (risk matrix or heat map). In: *Draft International Standard IEC/DIS 31010: Risk Management – Risk assessment techniques,* p. 98–101.

26 European Commission. (2019). *Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU*. eur-lex.europa.eu, p. 27.

27 The classification into these three categories corresponds with the categorization by the Swiss Federal Office for Civil Protection.

28 Bloomberg. (2022). *How Nord Stream Became So Important in Europe's Gas War*. bloomberg.com

29 Bundesministerium für Inneres. (2019). *Krisenübung „Helios"- Experten ziehen Bilanz*. bmi.gv.at

30 Ministry of the Interior. (2019). *National Risk Assessment 2018.* julkaisut.valtioneuvosto.fi

31 Uudenmaan alueellisen riskiarvion työryhmä. (2018). *Uudenmaan alueellinen riskiarvio 2018*. intermin.fi, p. 47–52.

32 RTE. (2022). *Perspectives pour le système électrique pour l'automne et l'hiver 2022-2023*. assets.rte-france.com

33 Büro für Technikfolgenabschätzung beim Deutschen Bundestag. (2010). *Gefährdung und Verletzbarkeit moderner Gesellschaften – am Beispiel eines großräumigen Ausfalls der Stromversorgung.* tab-beim-bundestag.de, p. 63; Bundesamt für Bevölkerungsschutz. (2019). *Stromausfall.* bbk.bund.de

34 Dolce M., Miozzo A., Di Bucci D., Alessandrini L., Bastia S., Bertuccioli P. Bilotta D., Ciolli S., De Siervo G., Fabi D., Madeo L., Panunzi E., Silvestri V. (2020). *La protezione civile in Italia.* protezionecivile.gov.it, p. 185f.

35 The National Network of Safety and Security Analysts. (2019). *National Risk Assessment*. english.nctv.nl, p. 31ff.

36 Federal Office for Civil Protection. (2020). *Strommangellage*. babs.admin.ch; Federal Office for Civil Protection. (2020). *Stromausfall*. babs.admin.ch

37 Swedish Civil Contingencies Agency. (2015). *A summary of risk areas and scenario analyses 2012–2015*. msb.se

38 HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk

39 Swedish Civil Contingencies Agency. (2015). *A summary of risk areas and scenario analyses 2012–2015*. msb.se, p.17.

40 Federal Office for Civil Protection. (2020). *Strommangellage*. babs.admin.ch, p. 6.

41 Ministry of the Interior. (2022). *Alueellisten riskiarvioiden menetelmäohje*. julkaisut.valtioneuvosto.fi, p. 14.

42 Mills, E., & Jones, R. B. (2016). An insurance perspective on US electric grid disruption costs. *The Geneva Papers on Risk and Insurance-Issues and Practice,* 41(4), 555–586, p. 558.

43 International Atomic Energy Agency. (n.d.). *International Nuclear and Radiological Event Scale (INES)*. iaea.org

44 Number of less severe events since the launch of the first nuclear power plant: 5 x INES Level 4, 2 x INES Level 5, 1 x INES Level 6.

45 Nuclear Energy Agency (2002). *Chernobyl: Assessment of Radiological and Health Impacts*. oecd-nea.org, p. 35.

46 Ritchie, H. (2017). *What was the death toll from Chernobyl and Fukushima?* ourworldindata.org

47 Tokyo Electric Power Company Holdings. (2012). *The Estimated Amount of Radioactive Materials Released into the Air and the Ocean Caused by Fukushima Daiichi Nuclear Power Station Accident Due to the Tohoku-Chihou-Taiheiyou-Oki Earthquake*. tepco.co.jp

48 Ritchie, H. (2017). *What was the death toll from Chernobyl and Fukushima?* ourworldindata.org

49 Bundesministerium für Inneres. (2014). *Krisen- und Katastrophenmanagement: Broschüren und Downloads: Risikoanalyse*. bmi.gv.at

50 Ministry of the Interior. (2019). *National Risk Assessment 2018.* julkaisut.valtioneuvosto.fi, p. 66ff; Ministry of the Interior. (2016). *National Risk Assessment 2015.* julkaisut.valtioneuvosto.fi, p. 33.

51 Uudenmaan alueellisen riskiarvion työryhmä. (2018). *Uudenmaan alueellinen riskiarvio 2018*. intermin.fi, p. 52–55.

52 Secrétariat général de la Défense et de la Sécurité nationale. (2014). *National Response Plan: Major Nuclear or Radiological Accidents*. gouvernement.fr; Pascucci-Cahen, L. & Patrick, M. (2013). *The cost of nuclear accidents*. oecd-nea.org

53 Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (2021). Risikoanalyse „Freisetzung radioaktiver Stoffe aus einem Kernkraftwerk". In *10 Jahre Risikoanalyse im Bevölkerungsschutz Bund*. bbk.bund.de, p. 45–51.

54 The National Network of Safety and Security Analysts. (2016). *National Risk Profile 2016*. rivm.nl, p. 71–79.

55 Federal Office for Civil Protection. (2020). *KKW-Unfall*. babs.admin.ch

56 Swedish Civil Contingencies Agency. (2015). *A summary of risk areas and scenario analyses 2012–2015*. msb.se

57 HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk

58 Nationalrat. (1978). *676. Bundesgesetz vom 15. Dezember 1978 über das Verbot der Nutzung der Kernspaltung für die Energieversorgung in Österreich*. ris.bka.gv.at

59 The National Network of Safety and Security Analysts. (2019). *National Risk Assessment*. english.nctv.nl, p. 14.

60 Federal Council. (2005). *Nuclear Energy Ordinance*. fedlex.admin.ch, Art. 22.

61 Bengtsson, L., Holmberg, J., Rossi, J., Knochenhauer, M. (2010). *Probabilistic Safety Goals for Nuclear Power Plants*. stralsakerhetsmyndigheten.se, p. 24, 26, 32 and 33.

62 Federal Office for Civil Protection. (2020). *National Risk Analysis Methodology*. babs.admin.ch, p. 15.

63 ENSI. (2019). *Probabilistic Safety Analysis (PSA): Quality and Scope*. ensi.ch, p. 1.

64 Kernkraftwerk Gösgen. (2022). *Geschäftsbericht 2021*. kkg.ch, p. 36.

65 Kernkraftwerk Leibstadt. (2022). *Geschäftsbericht 2021*. kkl.ch, p. 20.

66 Swiss Federal Council. (1983). *Kernenergiehaftpflichtverordnung (KHV) vom 5. Dezember 1983*. fedlex.admin.ch, Art. 3.

67 Wheatley, S., Sovacool, B., & Sornette, D. (2017). *Of disasters and dragon kings: a statistical analysis of nuclear power incidents and accidents.* Risk Analysis, 37(1), 99–115.

68 Swiss Federal Council. (1983). *Kernenergiehaftpflichtverordnung (KHV) vom 5. Dezember 1983*. fedlex.admin.ch, Art. 4.

69 Ritchie, H. (2022). What are the safest and cleanest sources of energy? ourworldindata.org

70 Spreeuwenberg, P., Kroneman, M., & Paget, J. (2018). Reassessing the Global Mortality Burden of the 1918 Influenza Pandemic. *American Journal of Epidemiology,* 187(12), 2561–2567.

71 World Health Organization. (2023). *WHO Coronavirus (COVID-19) Dashboard*. covid19.who.int

72 The Economist. (2023). *The pandemic's true death toll.* economist.com

73 For the CFR of COVID-19, see: Abou Ghayada, R., Lee, KH, Han, YJ, et al. (2022). The global case fatality rate of coronavirus disease 2019 by continents and national income: a meta-analysis. *Journal of Medical Virology,* 94, 2402–2413.

74 Bundesministerium für Gesundheit und Frauen. (2006). *Influenza Pandemieplan: Strategie für Österreich (3. Auflage).* graz.at; Bundesministerium für Inneres. (2014). *Krisen- und Katastrophenmanagement: Broschüren und Downloads: Risikoanalyse*. bmi.gv.at

75 Sosiaali- ja terveysministeriön (2012). *Kansallinen varautumissuunnitelma influenssapandemiaa varten*. julkari.fi

76 Secrétariat général de la Défense et de la Sécurité nationale. (2011). *Plan national de prévention et de lutte «Pandémie grippale»*. gouvernement.fr

77 Influenza Pandemic: The most recent German Influenza Pandemic plan (2017) does not communicate any scenarios with specific numbers. These numbers are from the 2007 version: Robert Koch-Institut. (2007). *Nationaler Pandemieplan*. edoc.rki.de; SARS Pandemic: Deutscher Bundestag. (2013). Risikoanalyse «Pandemie durch Virus Modi-SARS». In: *Bericht zur Risikoanalyse im Bevölkerungsschutz 2012*. dserver.bundestag.de, p. 5f; Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (2021). Risikoanalyse „Pandemie durch Virus Modi-SARS" (Bundestagsbericht 2012). In: *10 Jahre Risikoanalyse im Bevölkerungsschutz Bund*. bbk.bund.de, p. 27–31.

78 Ministero della Salute. (2021). *Piano strategico-operativo nazionale di preparazione e risposta a una pandemia influenzale (PanFlu) 2021-2023*. salute.gov.it

79 The National Network of Safety and Security Analysts. (2019). *National Risk Assessment*. english.nctv.nl

80 Woolnough, K., Kramer, S., Ivanovic, B., & Busenhart, J. (Eds.) (2007). *Pandemic influenza: A 21st century model for mortality shocks*. Swiss Reinsurance Company.

81 Federal Office for Civil Protection. (2020). *Influenza-Pandemie*. babs.admin.ch

82 Swedish Civil Contingencies Agency. (2015). Infectious Diseases. In: *A summary of risk areas and scenario analyses 2012–2015*. msb.se, p. 48–55.

83 Department of Health. (2011). *UK Influenza Pandemic Preparedness Strategy 2011*. assets.publishing.service.gov.uk;
HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk

84 European Commission. (2021). *Overview of natural and man-made disaster risks the European Union may face: 2020 edition.* op.europa.eu, p. 13.

85 United Nations General Assembly. (2015). *69/283: Sendai Framework for Disaster Risk Reduction 2015–2030*. un.org, Art. 15.

86 Centre for Research on the Epidemiology of Disasters. (2023) *EM-DAT*. public.emdat.be

87 UNDRR. (2023). *United Kingdom of Great Britain and Northern Ireland: A-2a: Number of deaths attributed to disasters.* sendaimonitor.undrr.org; UNDRR. (2023). *italy: A-2a: Number of deaths attributed to disasters.* sendaimonitor.undrr.org

88 UNDRR. (2023). *Switzerland: A-2a: Number of deaths attributed to disasters.* sendaimonitor.undrr.org; UNDRR. (2023). *Sweden: A-2a: Number of deaths attributed to disasters.* sendaimonitor.undrr.org

89 Meyerowitz-Katz, G., & Merone, L. (2020). A systematic review and meta-analysis of published research data on COVID-19 infection fatality rates. *International Journal of Infectious Diseases,* 101, 138–148.

90 Ritchie, Hannah, Edouard Mathieu, Lucas Rodés-Guirao, Cameron Appel, Charlie Giattino, Esteban Ortiz-Ospina, Joe Hasell, Bobbie Macdonald, Diana Beltekian and Max Roser. (2023). *Mortality Risk of COVID-19*. ourworldindata.org

91 see e.g. Federal Office of Public Health. (2018). *Swiss Influenza Pandemic Plan*. bag.admin.ch, p. 15.

92 Wenger, A., Hauri, A., Kohler, K., Scharte, B. & Thiel, J. (2020). *Schweizer Krisenmanagement: Die Coronavirus-Pandemie als fachliche und politische Lernchance*. In: B. Zogg & O. Thränert (Eds.) Bulletin 2020 zur Schweizerischen Sicherheitspolitik (Zurich: CSS/ETH), p. 107.

93 Peters, A. (2018). The global proliferation of high-containment biological laboratories: understanding the phenomenon and its implications. *Rev Sci Tech,* 37(3), 857–883.

94 Dunlap, G. & Pauwels, E. (2017). *The Intelligent and Connected Bio-Labs of the Future: Promise and Peril in the Fourth Industrial Revolution*. wilsoncenter.org; Esvelt, K. (2022). *Delay, Detect, Defend: Preparing for a Future in which Thousands Can Release New Pandemics*. dam.gcsp.ch

95 German Insurance Association (GDV). (2020). *Green paper: Supporting the economy to better cope with the consequences of future pandemic events*. gdv.de; National Association of Mutual Insurance Companies (NAMIC). (2020). *Insurance Trades Unveil Federal Pandemic Solution*. namic.org

96 Petrovay, K. (2020). Solar cycle prediction. *Living Reviews in Solar Physics,* 17(1), 1–93.

97 NASA. (2014). *Near Miss: The Solar Superstorm of July 2012*. Science.nasa.gov; Lakhina, G., Alex, S., Tsurutani, B., & Gonzalez, W. (2004). *Research Records of Geomagnetic Storm*. Proceedings of the International Astronomical Union, 2004(IAUS226), 3–15.

98 Guillon, S., Toner, P., Gibson, L., & Boteler, D. (2016). A colorful blackout: The havoc caused by auroral electrojet generated magnetic field variations in 1989. *IEEE Power and Energy Magazine,* 14(6), 59–71.

99 Knipp, D. J., Bernstein, V., Wahl, K., & Hayakawa, H. (2021). Timelines as a tool for learning about space weather storms. *Journal of Space Weather and Space Climate,* 11, 29.

100 Hayakawa, H. et al. (2017). Long-lasting extreme magnetic storm activities in 1770 found in historical documents. *The Astrophysical Journal Letters,* 850(2), L31.

101 O'hare, P., et al. (2019). Multiradionuclide evidence for an extreme solar proton event around 2,610 BP (~ 660 BC). *Proceedings of the National Academy of Sciences,* 116(13), 5961–5966.

102 Lloyds. (2013). *Solar Storm Risk to the North American Electric Grid*. assets.lloyds.com, p. 4.

103 Ministry of the Interior. (2016). *National Risk Assessment 2015.* julkaisut.valtioneuvosto.fi, p. 34f; Ministry of the Interior. (2019). *National Risk Assessment 2018.* julkaisut.valtioneuvosto.fi

104 The National Network of Safety and Security Analysts. (2016). *National Risk Profile 2016*. rivm.nl, p. 99f.

105 Swiss Re. (2016). *Solar Storm: How to calculate insured/reinsured losses?* swissre.com, p. 12, 17 and 20.

106 Federal Office for Civil Protection. (2020). *Sonnensturm*. babs.admin.ch

107 Swedish Civil Contingencies Agency. (2015). Solar Storm. In: *A summary of risk areas and scenario analyses 2012–2015*. msb.se, p. 57–61.

108 HM Government. (2020). *National Risk Register*. assets.publishing.service.gov.uk; Royal Academy of Engineering. (2013). *Extreme space weather: impacts on engineered systems and infrastructure*. raeng.org.uk, p. 19; Hapgood, M., et. al. (2021). Development of space weather reasonable worst-case scenarios for the UK national risk assessment. Space Weather, 19(4).

109 Cambridge Centre for Risk Studies. (2016). *Helios Solar Storm Scenario*. jbs.cam.ac.uk, p. 11.

110 Lloyds. (2013). *Solar Storm Risk to the North American Electric Grid*. assets.lloyds.com, p. 8.

111 Federal Office for Civil Protection. (2015). *Katastrophen und Notlagen Schweiz Technischer Risikobericht 2015*. babs.admin.ch, p. 22 and 27.

112 Moriña, D., Serra, I., Puig, P., & Corral, Á. (2019). Probability estimation of a Carrington-like geomagnetic storm. *Scientific reports,* 9(1), 1–9.

113 Lloyds. (2013). *Solar Storm Risk to the North American Electric Grid*. assets.lloyds.com, p. 8.

114 Bisignani, G. (2010). *The eruption of Eyjafjallajökull was a wake-up call for change.* airlines.iata.org

115 Alexander, D. (2013). Volcanic ash in the atmosphere and risks for civil aviation: a study in European crisis management. International *Journal of Disaster Risk Science,* 4(1), 9–19.

116 UK Civil Aviation Authority. (2022). *Managing ash in UK airspace*. caa.co.uk

117 This outbreak is listed as VEI 4 in the Volcanoes of the World dataset, but may qualify as VEI 6. Oppenheimer, C., et al. (2018). The Eldgjá eruption: timing, long-range impacts and influence on the Christianisation of Iceland. *Climatic Change,* 147(3), 369–381.

118 Smithsonian Institution. (2022). *Volcanoes of the World, v. 4.11.2*. volcano.si.edu

119 Gouvernement de la République française. (n.d.). *Éruption Volcanique*. gouvernement.fr

120 Dolce M., Miozzo A., Di Bucci D., Alessandrini L., Bastia S., Bertuccioli P. Bilotta D., Ciolli S., De Siervo G., Fabi D., Madeo L., Panunzi E., Silvestri V. (2020). *La protezione civile in Italia.* protezionecivile.gov.it, p. 96, 98f.

121 Swiss Re. (2017). *The destructive power of volcanic ash fall*. swissre.com

122 Federal Office for Civil Protection. (2020). *Vulkanausbruch im Ausland*. babs.admin.ch

123 Swedish Civil Contingencies Agency. (2015). Earthquake and volcanic eruption. In: *A summary of risk areas and scenario analyses 2012–2015*. msb.se, p. 27–34.

124 HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk

125 European Commission. (2021). *Overview of natural and man-made disaster risks the European Union may face*. data.europa.eu, p. 108.

126 Cassidy, M., & Mani, L. (2022). *Huge volcanic eruptions: Time to prepare*. nature.com

127 Leder, J., Wenzel, F., Daniell, J. E., & Gottschämmer, E. (2017). Loss of residential buildings in the event of a re-awakening of the Laacher See Volcano (Germany). *Journal of Volcanology and Geothermal Research,* 337, 111–123.

128 Joint Research Centre. (2021). *Recommendations for National Risk Assessment for Disaster Risk Management in EU*. publications.jrc.ec.europa.eu, p. 14.

129 ISO (2017). B.9.3.5 Strengths and limitations. In: *Draft International Standard IEC/DIS 31010: Risk Management – Risk assessment techniques,* p. 101.

130 e.g. Bradley, R. (2015). Dating Methods I. In: *Paleoclimatology* (3rd ed.). sciencedirect.com, p. 56.

131 For a broad overview over methods to approach the future see Kohler, K. (2021). *Strategic Foresight: Knowledge, Tools, and Methods for the Future* (Zurich: CSS/ETH).

132 See Swiss Re. (2007). *Pandemic influenza: A 21st century model for mortality shocks*. media.swissre.com p. 25–29; Swiss Re. (2017). *The destructive power of volcanic ash fall*. swissre.com, p. 6.

133 HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk, p. 9.

134 Federal Office for Civil Protection. (2020). *National Risk Analysis Report*. babs.admin.ch, p. 30.

135 e.g., Bundesamt für Bevölkerungsschutz. (2019). *Stromausfall.* bbk.bund.de, p. 25.

136 e.g., Hauri, A., Kohler, K., Roth, F., Käser, M., Prior, T. & Scharte B. (2020). *Trend Analysis Civil Protection 2030* (Zurich: CSS/ETH).

137 World Economic Forum. (2023). *The Global Risks Report 2023*. weforum.org

138 Ritchie, H., Spooner, F., Roser, M. (2019). *Causes of Death*. ourworldindata.org

139 Ibid.

140 Kohler, K., Hauri, A., Roth, F. Prior, T. & Scharte B. (2020). *Monitoring and Reporting under the Sendai Framework for Disaster Risk Reduction* (Zurich: CSS/ETH), p. 18.

141 Swedish Civil Contingencies Agency. (2015). *A summary of risk areas and scenario analyses 2012–2015*. msb.se, p. 54.

142 Knight, Frank. H. (1921). *Risk, Uncertainty and Profit.* Boston, MA: Houghton Mifflin.

143 Walker, W., Lempert, R. & Kwakkel, J. (2013). Deep Uncertainty. In: S. Gass & M. Fu (Eds.) Encyclopedia of Operations Research and Management Science. Boston, MA: Springer.

144 Federal Office for Civil Protection. (2020). *National Risk Analysis Report*, p. 19 and 34.

145 Federal Office for Civil Protection. (2020). *National Risk Analysis Methodology*. babs.admin.ch, p. 18.

146 European Commission. (2019). *Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU*. eur-lex.europa.eu, p. 20.

147 HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk, p. 10.

148 Ibid.

149 Whitehead, S. J., & Ali, S. (2010). Health outcomes in economic evaluation: the QALY and utilities. *British medical bulletin,* 96(1), 5–21.

150 Centers for Disease Control and Prevention. (2022). *Risk for COVID-19 Infection, Hospitalization, and Death By Age Group*. cdc.gov

151 Barnett, K., Mercer, S. W., Norbury, M., Watt, G., Wyke, S., & Guthrie, B. (2012). Epidemiology of multimorbidity and implications for health care, research, and medical education: a cross-sectional study. *The Lancet,* 380(9836), 37–43.

152 For such a mapping see e.g. Federal Office for Civil Protection. (2010). *Schlussbericht Kritikalität der Teilsektoren: Programm Schutz Kritischer Infrastrukturen.* babs.admin.ch

153 European Commission. (2017). *Overview of natural and man-made disaster risks the European Union may face*. data.europa.eu, p. 71–80.

154 Cox, L. A. (2008). What's wrong with risk matrices?. *Risk Analysis,* 28(2), 497–512.

155 Thomas, P., Bratvold, R. B., & Bickel, E. (2014). The risk of using risk matrices. *SPE Economics & Management,* 6(02), 56–66.

156 World Health Organization. (2022). *WHO Coronavirus (COVID-19) Dashboard*. covid19.who.int

157 Economist. (2022). *The pandemic's true death toll*. economist.com

158 OECD. (2017). *National Risk Assessments: A Cross Country Perspective*. read.oecd-ilibrary.org, p.128.

159 OECD. (2017). *National Risk Assessments: A Cross Country Perspective*. read.oecd-ilibrary.org, p.247.

160 Direction générale de la prévention des risques. (2018). *Rapport 2015-2017 du délégue aux risques majeurs.* ecologie.gouv.fr, p. 62.

161 HM Government. (2020). *National Risk Register.* assets.publishing.service.gov.uk, p. 10.

162 Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (2021). *10 Jahre Risikoanalyse im Bevölkerungsschutz Bund*. bbk.bund.de, p. 30.

163 Federal Office for Civil Protection. (2020). *National Risk Analysis Methodology*. babs.admin.ch, p. 19.

164 The National Network of Safety and Security Analysts. (2019). *National Risk Assessment*. english.nctv.nl, p. 20.

165 Tufte E. R. (1983). The visual display of quantitative information. Cheshire, CT: Graphics Press.

166 Forthcoming publication by the Swiss Federal Office for Civil Protection.

167 Observatory of Economic Complexity. (2022). *The best place to explore trade data.* oec.world

168 Forthcoming publication by the Swiss Federal Office for Civil Protection.

169 See e.g., Cornes, R., & Sandler, T. (1996). *The theory of externalities, public goods, and club goods*. Cambridge University Press.; Barrett, S. (2007). *Why cooperate?: The incentive to supply global public goods*. Oxford University Press.