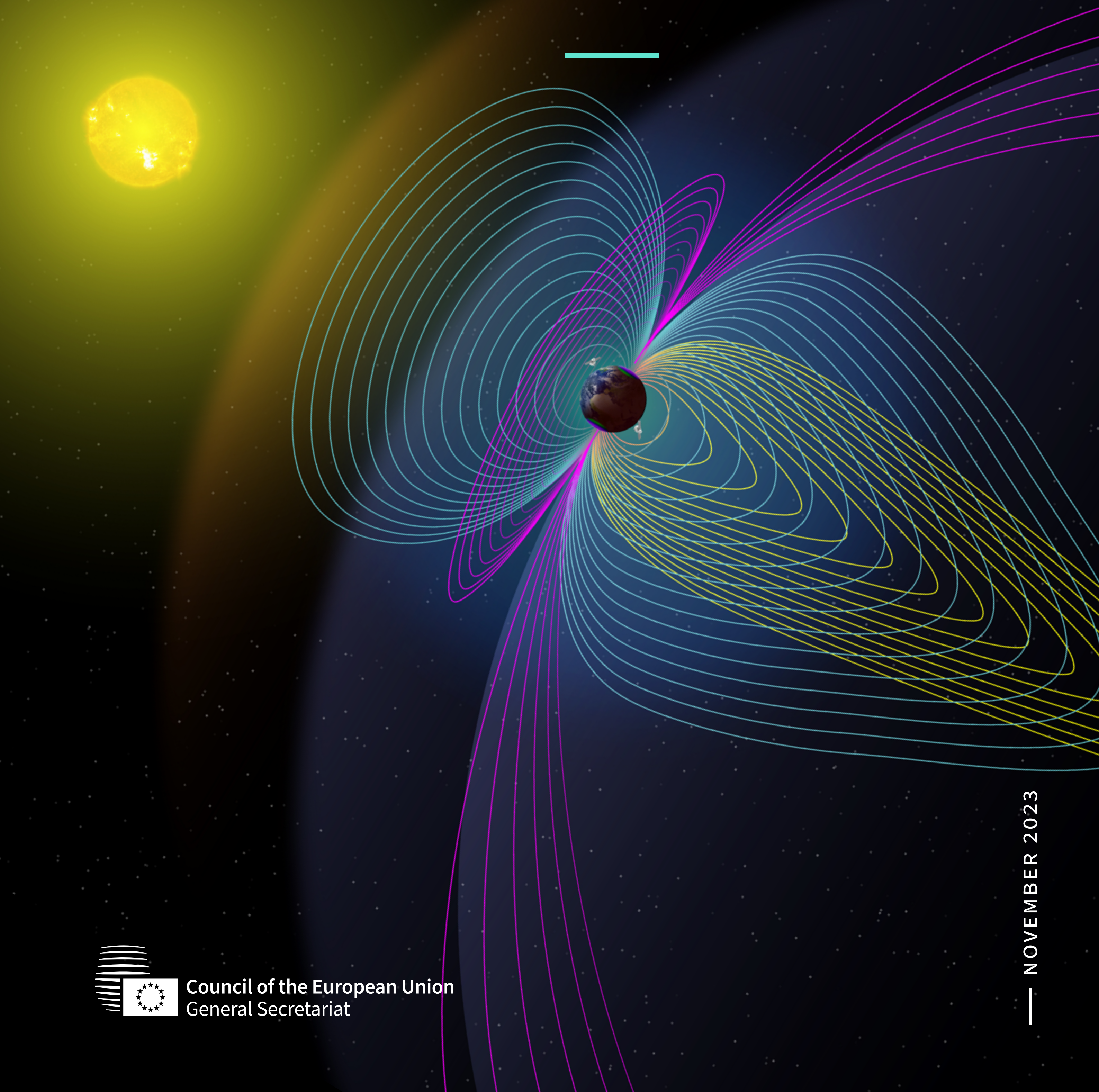
ART —— Analysis and Research Team

RESEARCH PAPER

Solar storms: a new challenge on the horizon?



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Council of the European Union
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Introduction

When the most powerful solar storm on record, also known as the Carrington event, caused widespread telegraph outages and even fires across North America and Europe in 1859, electrification was still in its infancy. Since that extraordinary event, various **geomagnetic storms**, although less intense, **have left their mark across the globe**.
The heavy reliance of modern society on technology, which continues to expand exponentially, leaves us highly vulnerable to the consequences of a major solar storm. Such an event could disrupt the lives of millions and cause very extensive damage. This could include direct and widespread damage to vital infrastructure, including power grids, digital communication networks, and satellite systems.

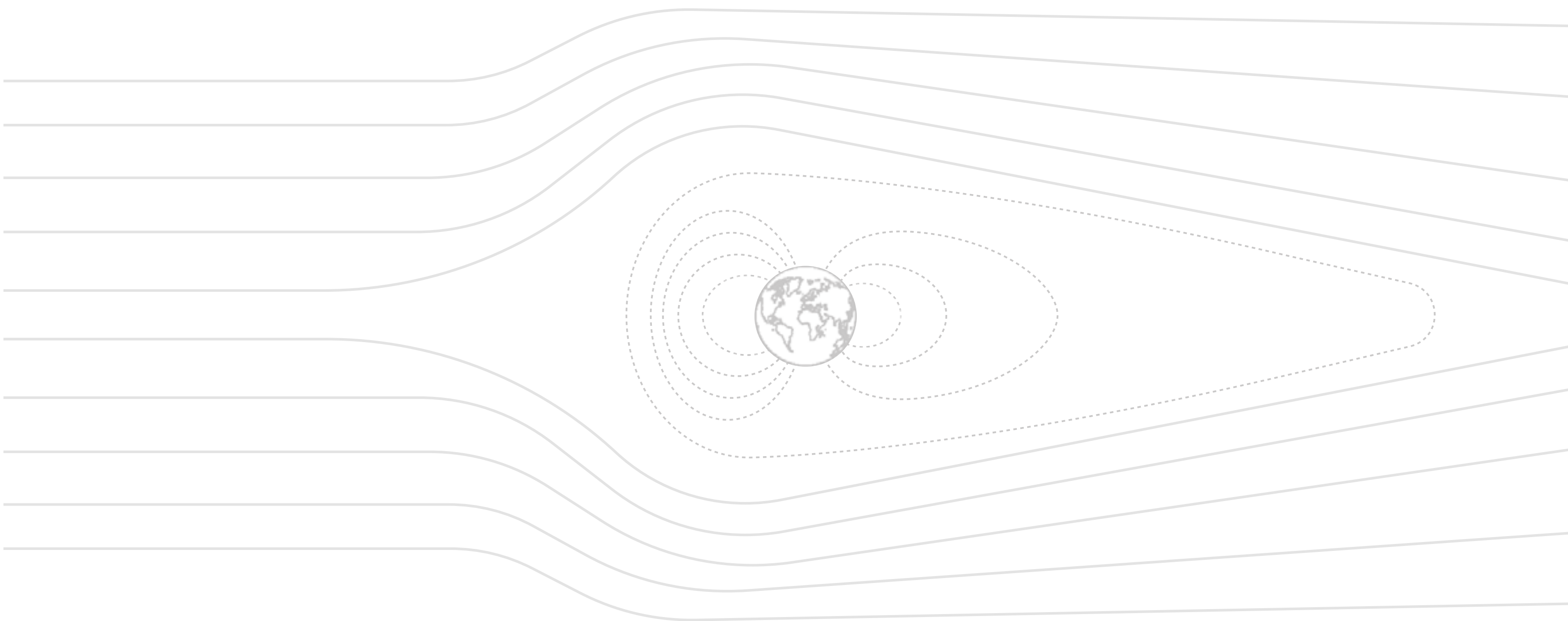
Although strong solar storms are rare events, **the question is** not whether they will occur, but rather **when the next one will take place**. Determining the frequency of extreme space weather events is extremely difficult, yet various estimates suggest that relatively strong events happen about every 50 years, and anything between 150 to 500 years for extreme storms such as the Carrington event[1]. Whilst the future behaviour of the sun remains difficult to predict, the 11-year solar cycle, with its solar peaks, is a useful factor in helping predict solar weather events. The next **solar peak** is expected **in 2025**. Historical data suggests that solar storms are increasingly likely during this period, even if the probability of more extreme events remains an open question[2].

This paper seeks to highlight the **importance of understanding and preparing for a severe space weather event**. The first part will provide a brief explanation of what constitutes a solar storm, its historical impact, and the main risk factors involved. The second part will explore the potential consequences of an extreme solar event in today's world. It will focus both on those sectors which are most immediately susceptible, as well as the potential cascading effects over the short to medium term, including the economic, social and political consequences.

In the final section, the note will suggest measures to enhance preparedness and mitigate the effects of solar storms. These measures will highlight the vital role of the EU and the need for more high-level discussion and policy development to protect our technology-dependent civilisation from the impacts of space weather events.

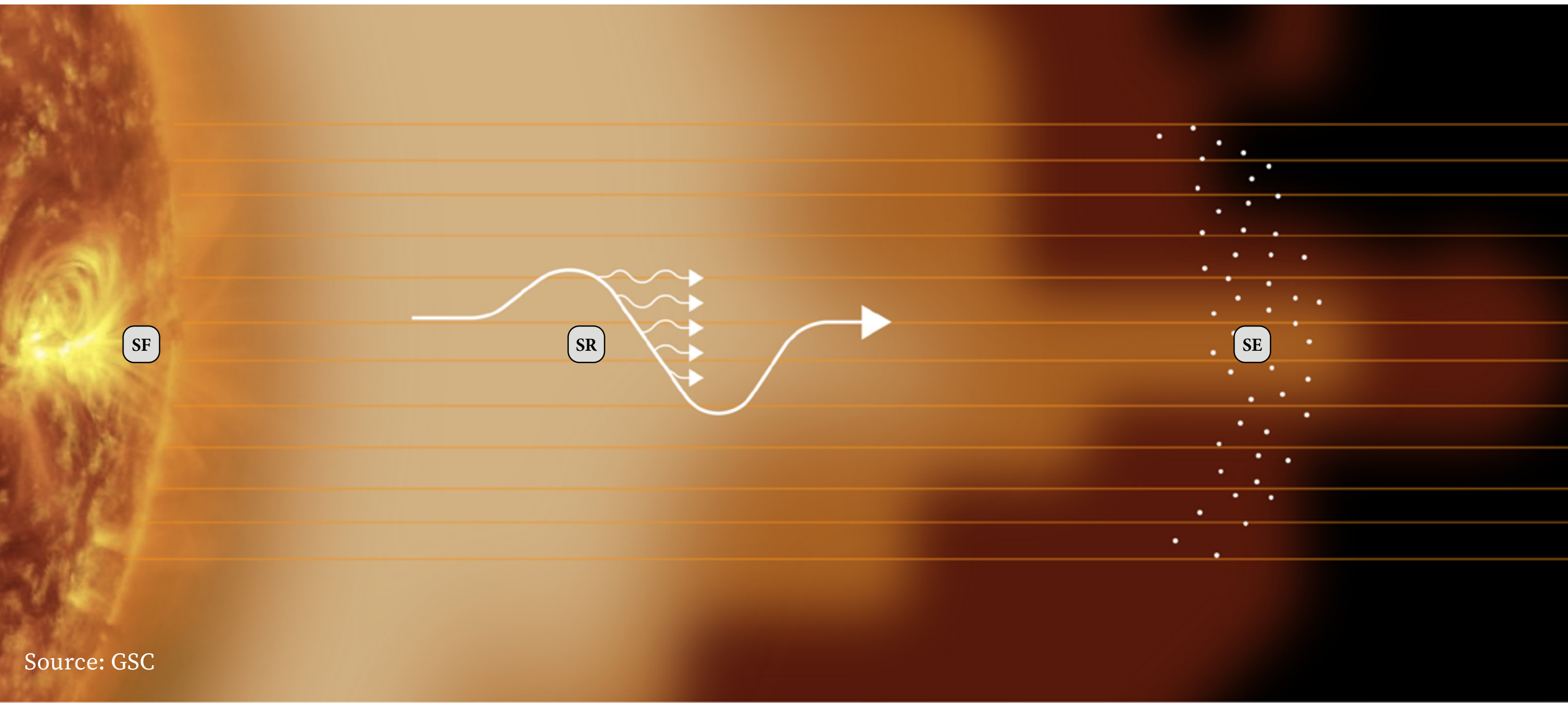
Understanding space weather

Space weather is a term used to describe a range of **phenomena associated with fluctuations in the Sun's activity**. Like its terrestrial counterpart, space weather typically unfolds without significant disruptive consequences. Nevertheless, in some cases strong solar activity can have a direct impact on the performance of a range of technologies and can influence Earth's critical infrastructure, as shown by past events *(see pp.4-5)*.



Severe space weather[3]

Examples of weather	SF Solar Flares	SR Solar Radio Bursts
Time to reach Earth	8 minutes	8 minutes
What is it?	Explosive releases of electromagnetic radiation from the Sun's atmosphere.	The intense solar radio emission related to a solar flare.
Technological threats	They can cause radio blackouts of High Frequency (HF) communications used by aircraft on the sunlit hemisphere.	They can be a threat to Global navigation satellite system (GNSS) service performance in the hemisphere facing the sun.



Source: GSC

Historical events

Previous space weather events can provide helpful insights into the likely threat they might present to modern technologies across various sectors.

August-September 1859

Carrington event

The most severe space weather event on record. There were two huge auroral events, visible as far south as Cuba and Hawaii. Although electricity was in its infancy, the storm caused **widespread telegraph outages across the world**. In July 2012, the Earth narrowly avoided a Carrington-scale event[4].

May 1921

New York Railroad superstorm

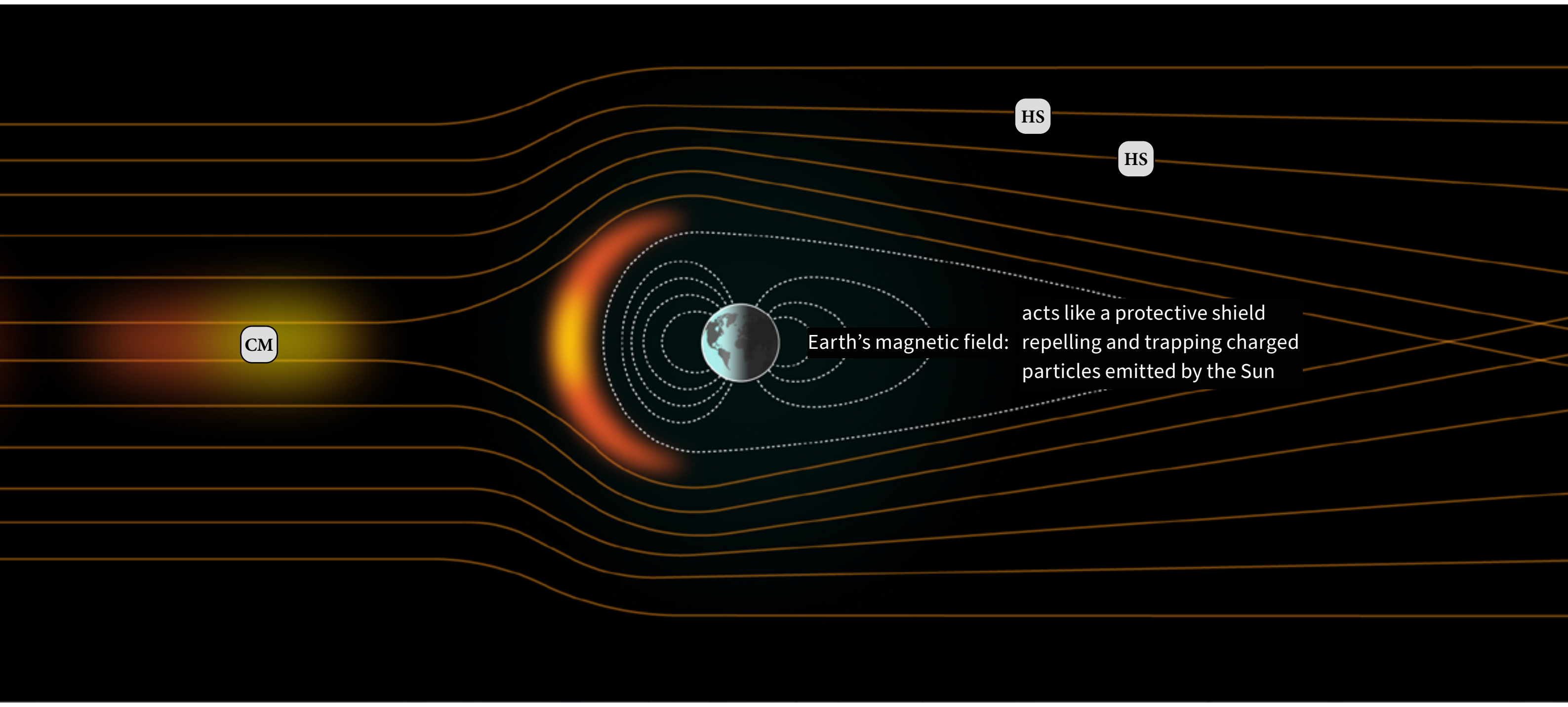
The largest geomagnetic storm of 20th century, know as the New York Railroad superstorm, had a considerable impact on the **telegraph and railroad systems in** the area of **New York City**, causing also extensive damage across the globe[5].

August 1972

Series of solar storms

A series of solar storms caused large **electric and communication-grid disturbances** through large portions of the US mid-West, as well as satellite disruptions. The storm also caused the accidental **detonation of** numerous US **naval mines** near Haiphong, North Vietnam[6].

SE Solar Energetic Particles	CM Coronal Mass Ejections	HS High speed solar wind streams
12-15 minutes	1-4 days (fastest known transit time: 15 hours)	1-3 days
They are emitted from the Sun in the form of electrons, protons and ions.	Plasma ejections from the Sun's corona, carrying with it a magnetic field.	Streams of plasma that flow out of regions of the Sun where its magnetic field connects out to interplanetary space.
They can damage satellites, such as GNSS, communication satellites and Earth monitoring satellites, as well being the driver of atmospheric radiation storms.	These storms induce electric fields in the Earth that drive disruptive electric currents into ground-based conductors including the power network. Geomagnetic storms can also disturb the ionosphere disrupting the operation of HF communications, GNSS, and satellite communications.	When a HSS passes over the Earth, it exposes many important satellites to a much harsher radiation environment and puts them at risk of damage. The impact can persist for several hours to a few days. Similar radiation risks can arise from CMEs but are usually of shorter duration.



March 1989

North-America storm

A geomagnetic storm caused a **nine-hour outage of Hydro-Québec's electricity transmission system**, during the Canadian winter, causing an estimated $6 billion in damage[7]. The event also triggered over 200 grid problems at various locations across the US.

October 2003

Halloween storms

During Halloween storms, magnetic field fluctuations were particularly strong over Northern Europe, with **Sweden experiencing a one-hour-long power outage** affecting 50,000 people. The storm temporarily disrupted satellite and communication services[8] and **aircraft were advised to avoid high altitudes near the polar regions**. At the same time, twelve **transformers in South Africa were disabled** and had to be replaced.

September 2017

Solar storm

A storm **affected radio frequency and satellite communication systems** around the world, including Europe[9]. Civil airliners were re-routed to avoid air space regions with an increased risk of radiation.

February 2022

Starlink incident

SpaceX lost 40 of 49 Starlink newly launched satellites because of a solar storm[10]. The incident is believed to constitute the largest loss of satellites as a result of a single geomagnetic event.

Risk factors

In the past, solar storms have demonstrated their capacity to affect different regions of the Earth. Yet, the **threat** posed by space weather has **increased due to a combination of physical and technological risk factors** (*see illustration p.7*).

Magnetic latitude

The risk of strong magnetic field fluctuations depends strongly on the geomagnetic latitude. The **threats** presented by solar storms are **greater at high latitudes** (areas associated with visible aurora) **than middle latitudes**. Nevertheless, during extreme storms the impact can also be felt at lower latitudes, as was the case in South Africa in 2003. Major solar events are therefore normally limited in the extent of their impact, and in the case of Europe could affect some Member States and not others.

Ground conductivity

Ground conductivity can influence the intensity of solar storms. This is the case for a region which extends roughly from France to Hungary, and covers Northern Italy, where it has been shown that there is a higher average geoelectric field due to low ground conductivity. In the case of the 1989 Quebec blackout, the **geology of the area** also played a decisive role[11].

Coast effect

Coastal regions experience an enhancement in the surface electric field due to the **high conductivity of the seawater**. Seawater carries additional electrical charge, and shore-based transformers provide a path for the current to flow[12].

Technological characteristics

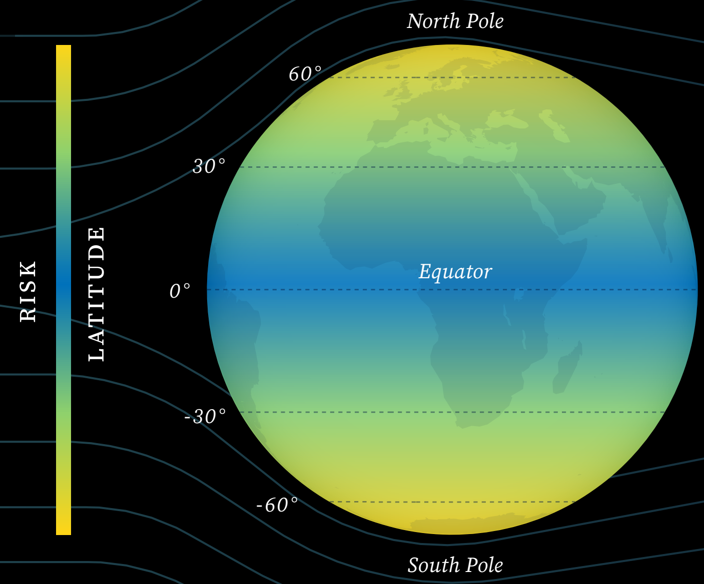
The risk associated with solar storms is linked to the characteristics of the transmission lines. The electrical current carried by a line increases over distance, which means that the **overall risk increases where there are long cables, such as submarine networks**. In recent decades, vulnerability to solar storms has grown because of the increasing use of transmission lines with very high voltages[13]. Another risk factor is **aging infrastructure**, which is at risk of structural damage and possibly collapse as a result of even moderate solar events. Communication **satellites are also among the systems at highest risk** due to direct exposure to highly charged particles in Coronal Mass Ejections. Threats include damage to electronic components, particularly in low earth orbit systems such as Starlink[14].

Despite the infrequent occurrence of solar storms, **the heavy reliance of our societies on electrical and digital technology means** that the disruption to energy supplies **could have serious consequences**. But the extent of such disruption is unknown, not least because there has been no major solar storm since the advent of extensive electrification, digitalisation, and the space age. However the impact is likely to be very significant, and is likely to grow in the future as the twin transitions lead to a **rapid expansion in electrification**, with some forecasting a **tripling of global power consumption by 2050**[15].

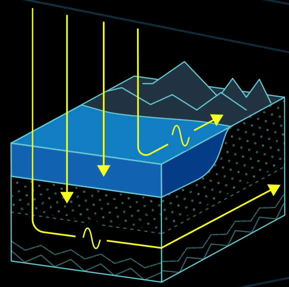
Risk factors

I. PHYSICAL

High latitudes
Threats are greater at higher latitudes but can also affect lower latitudes.

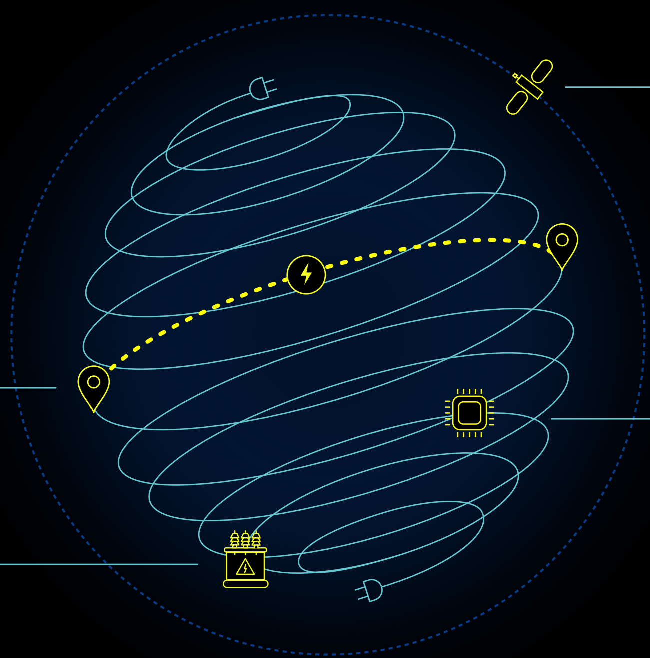


Ground conductivity
Geology can enhance the average geoelectric field.



Coast effect
High conductivity of seawater enhances the surface electric field in coastal regions.

II. TECHNOLOGICAL



Long transmission lines
Longer cables carry higher voltages, increasing their vulnerability to solar storms.

Satellites
Their electronic components are severely exposed to highly charged particles in CMEs.

Ageing infrastructure
Deteriorated infrastructure can collapse without prior notice.

Reliance on technology
Extensive electrification and digitalisation make us highly vulnerable to energy disruptions.

Source: GSC

Risks and consequences of an extreme solar storm today

A Carrington-scale event today would have severe consequences for our societies. It has been estimated that, in the US alone, 20 to 40 million people could be without electricity for a period of between 16 days and 1-2 years[16]. Some studies looking at the UK have estimated that **it could take weeks, and possibly months, to repair damage** to the UK power grid system from an extreme geomagnetic storm[17]. The worldwide losses due to an extreme magnetic storm would be between $7bn and $42bn per day[18].

Whilst it is difficult to assess the impact of such an event based on storms which occurred when electrification was much less developed, some studies and national strategies have tried to identify the likely main critical infrastructure disruptions. These are reflected in the table below.

Main immediate impacts

Space	Solar storms can directly damage satellites by impacting their electronic components or by influencing their position. This can lead to malfunctions, data corruption, and permanent damages (including the loss of satellites), with severe consequences for space-based systems, including GPS, satellite communication networks and banking operations.
Energy	Solar storms pose significant risks to the energy sector. They can disrupt the high voltage power grid, potentially leading to widespread blackouts, as well as fuel distribution systems.
Digital	Geomagnetic disturbances can interfere with communication networks, disrupting cell phones, landlines, and internet connectivity. Submarine cables are at high risk of induced currents during these events (99% of internet data flows through cables laid on the seabed[19]).
Transport	Airspace closures might disrupt air travel, while maritime safety is compromised due to the loss of navigation aids signals such as GPS and AIS. This can force port maritime traffic towers to close access to ports. In addition, road traffic congestion could occur as traffic lights cease functioning, resulting in chaotic conditions. A strong solar storm would also affect electric vehicles, as well as railway infrastructure.
Health	Solar storms could disrupt the storage of medicines and processes requiring refrigeration. Medical devices and equipment relying on electrical power and communication systems may face challenges. Solar storms also potentially expose humans, especially those at high altitudes, to increased radiation levels, posing health risks.
Food supply chain	Energy disruptions can affect refrigeration systems crucial for keeping food cold throughout the entire supply chain, from production and processing to distribution and retail.
Water distribution systems	Solar storms can disrupt water supply systems that rely on essential components such as pumps, valves, and sensors. Wastewater treatment systems, dependent on electricity for their operation, would also be affected.

Main impacts of extreme solar space events on Earth

TECHNOLOGICAL IMPACTS

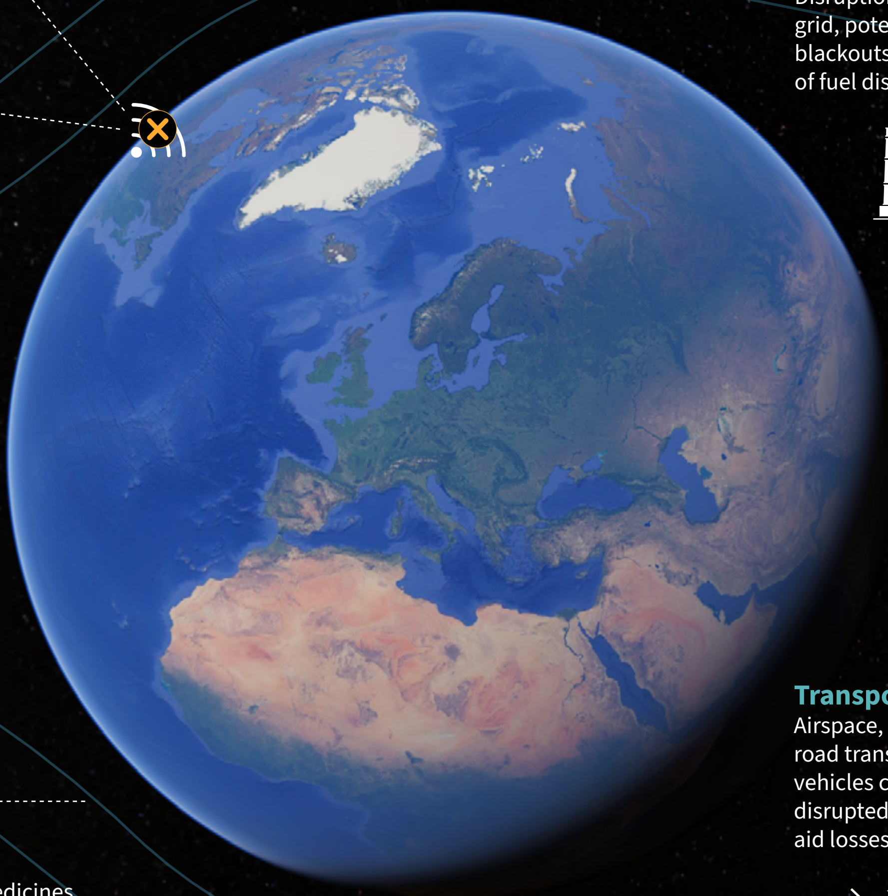
Space
Satellite damage that can disrupt GPS, communication networks and banking operations.

Digital
Disruption of cell phone, landline and internet connectivity networks.

ECONOMIC IMPACTS

Finances
Banking payment system shutdowns which could cause global financial market disarray.

Energy
Disruption of high voltage power grid, potential widespread blackouts, disruptions of fuel distribution systems.



Transport
Airspace, maritime transport, road transport and electric vehicles could be severely disrupted, also due to navigation aid losses (GPS/AIS).

SOCIETAL IMPACTS

Health
Medical equipment and medicines could be at risk due to storage failure and power grid breakdown.

Food and water supply
Refrigeration and water supply disruption that could paralyze food supply systems.

Source: GSC

Possible cascading consequences over the short to medium term

The ramifications of a Carrington-scale solar event go well beyond the most obvious and immediate disruption. They could set in motion a **complex chain reaction of short to medium term consequences** that could have a profound effect on many aspects of our daily lives. Despite some similarities with other known natural disasters, **this phenomenon has several characteristics which make it unique**. Unlike earthquakes or volcanic eruptions, whose effects are relatively localised, **a solar storm could hit** several different regions of the world, including some but not necessarily all **EU Member States**. Solar storms cannot be compared to conventional extreme weather events, whose impacts, although significant, tend to follow more predictable patterns. They are also very different from global emergencies such as the COVID pandemic which affected the entire world in a relatively uniform manner. What sets a solar storm apart is also its potential to **strike at multiple levels**, disrupting everything from vital satellite systems to submarines networks. Moreover, the **limited number of historical records** adds to the challenges of understanding and preparing for these events.

In the short to medium term, the economic repercussions of a Carrington-scale solar storm would be felt first when technologies which are integral to our daily lives start to fail. For instance, financial payment systems could be blocked, with credit cards no longer usable as transactions rely on satellite systems. This could lead to significant **disruptions in financial transactions**, creating major challenges for the integrity of the banking system[20]. Simultaneously, stock markets could experience turmoil, with temporary shutdowns[21] leading to **market instability**. The solar storm would also impact on the supply chain, which could extend across various sectors, including agriculture, food supplies, and water distribution systems. **Transport networks**, including air, sea, and land routes, **would face significant difficulties**. Air traffic control systems could experience malfunctions, and electric vehicles might cease to operate and recharge effectively. Overall, these factors could generate **substantial economic disruption, hitting growth** and putting strains on financial systems as countries struggle to repair damaged systems.

The aftermath of a solar storm would lead to a **series of social challenges**. Prolonged disruptions could trigger a temporary dislocation of population from the most severely affected areas. **Among the most vulnerable would be the older generations**, who would have to face the consequences of failing heating and cooling systems. This could result in an increase in weather-related health issues and place additional **strain on healthcare access**, which might in turn be more difficult to access due to technology failure. To address some of these challenges, authorities might need to establish distribution centres for essential supplies. Measures to prevent black-market activities might be needed, with the deployment of the police or even the military to address possible looting and a **surge in crime**. The collective impact of these socio-economic challenges raises the **potential for social unrest**.

In the wake of a solar storm, **security concerns will loom large**, necessitating for instance immediate action to avert incidents at nuclear plants[22]. The implications extend to external security, affecting weapon systems[23] and military strategic communications, potentially deteriorating the ability of the military to respond to opportunistic actions by state or non-state actors[24]. Extremist groups might take the opportunity to exploit vulnerabilities and further destabilise the situation. The disruption to communication systems and the difficulties of authorities to cope with a wide range of cascading effects could lead to a **surge in disinformation**, fuelled by the blame game and a proliferation of conspiracy theories.

The magnitude of the crisis could **strain governments' ability to respond effectively**. Faced with limited resources, prioritising support, especially in restoring power supplies, would constitute a significant challenge. **Tensions and divisions** may emerge, at both the national and European level, as the **question of solidarity comes to the fore**. Solar storms can have a prolonged duration, occurring in successive waves. That means they might initially strike a region thousands of kilometres away but can hit closer to home in the subsequent days. For this reason, national authorities might be reluctant to lend critical plant such as spare transformers out of concern that they might need them themselves.

Moreover, **disputes over the cost of transnational damage** could exacerbate existing tensions between countries with different financial resources at their disposal.

The crisis could lead to a **temporary set-back for the twin transition**, with the risk of a return to fossil fuels as a short-term remedy. However, over the medium to long term, individuals and entities might opt to invest in independent technologies such as solar panels, disconnected from the vulnerable general grid. Amidst these multifaceted challenges, **the issue of responsibility for dealing with the consequences would inevitably arise**, particularly over the role of the European Union.

Both the main immediate impacts and the possible cascading consequences over the short to medium term are reflected on page 9.

Conclusion

Not all the consequences described above are of course likely to materialise in the case of a major solar storm. Much would depend on the scale and magnitude of such an event. However, an effective response requires **coordinated national and international policy action**. To address this challenge effectively, a comprehensive approach is crucial, encompassing three phases: understanding and predicting the event, preparing for and preventing its potential consequences, and responding to and recovering from its impact on critical infrastructure[25].

Phase 1 Understand and predict

An increased understanding of extreme space weather and its complex repercussions **is essential** to mitigate the impact of a major event. This necessitates **close collaboration among governments, academic institutions, and the private sector**[26]. Enhancing accessibility and sharing of information among stakeholders and the public sector is crucial for raising awareness and facilitating citizens' preparedness. Strengthening the **capacity for observing and forecasting** space weather is key, as it can provide advanced warnings and timely alerts, enabling essential services to respond promptly and protect key infrastructure.

Current forecasting capabilities have limitations depending on the nature of the solar event. Solar flares, while easier to detect, provide only a brief opportunity to react as they travel at the speed of light. Coronal Mass Ejections, which take up to four days to reach Earth, pose challenges in determining their direction, speed, and width with current satellite imagery. Certainty over the magnitude of the most severe events can only be determined with around 10-20 minutes notice[27]. Innovative approaches involving artificial intelligence are being explored to facilitate earlier assessment[28].

Phase 2 Prepare and prevent

Given the current unpredictable nature of solar storms, **strengthening the resilience of critical infrastructure is vital**. This involves conducting vulnerability assessments of critical infrastructure[29], followed by measures to ensure the robustness of vulnerable components and systems. This process includes measures such as gradually replacing existing high-voltage transformers with more resilient designs capable of withstanding excessive surges of current. Securing an **increased availability of spare transformer parts** is also crucial to ensuring rapid replacement and repair in the event of severe damage given the lengthy periods required to produce new transformers[30]. **Drawing lessons from past events**, such as the grid collapse in 1989 in Canada, where measures such as adjusting control relays and installing series capacitors in transmission lines were implemented[31], can offer valuable insights into how to enhance resilience against future occurrences. All these measures involve **significant costs**, but they would help mitigate potentially much higher expenses that would arise in the event of a severe solar storm.

Phase 3 Respond and recover

Preventive measures, while significant, will not entirely avert the effects of an extreme solar event. It is therefore important to have **comprehensive contingency plans**[32] **for responding to and recovering from such an event**. While existing response plans for other natural emergencies can provide a useful basis, the unique characteristics of space weather events calls for additional specific measures. **Close international cooperation** will be crucial in facilitating a coordinated response and the rehabilitation of cross-border infrastructure. Ensuring robust emergency communication channels is of utmost importance given the likelihood of disruption to existing telecommunication systems.

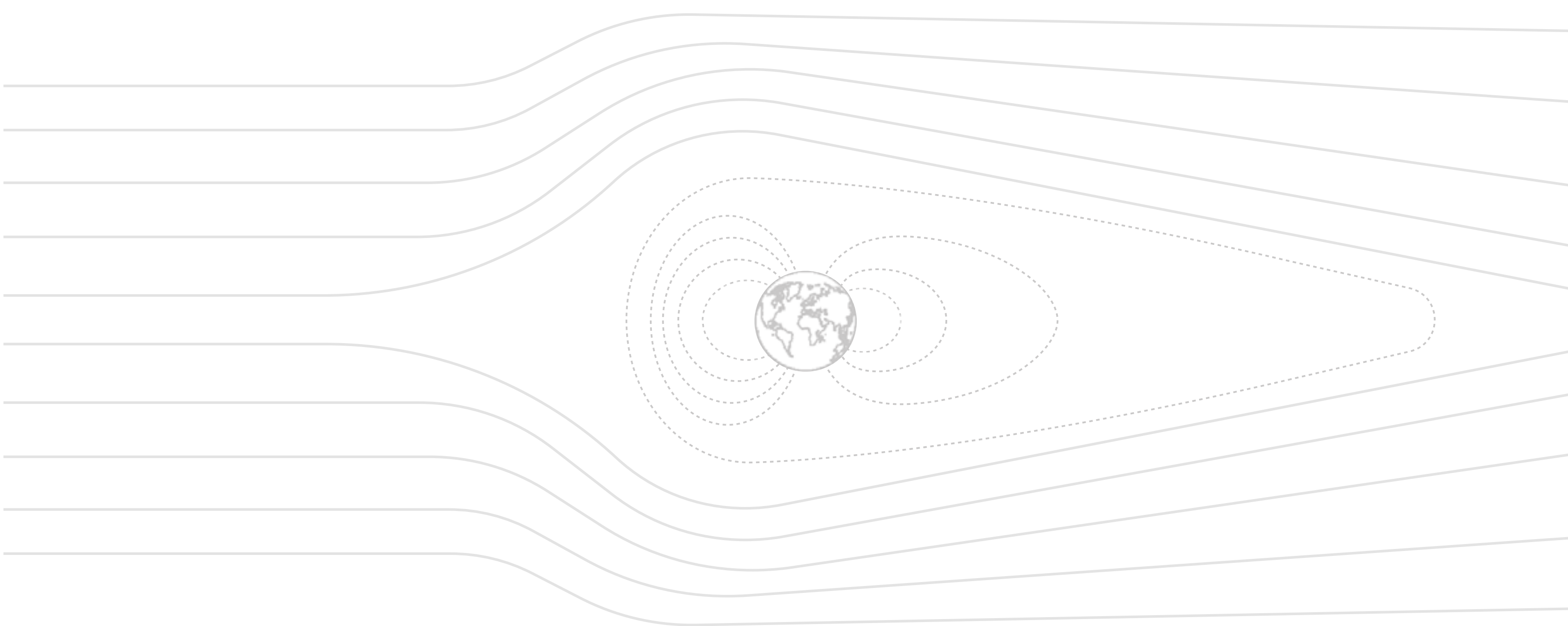
The **establishment of specific procedures** would help mitigate the impact. For instance, with improved forecasting capabilities, operators could put satellites into ‘safe mode’ by temporarily shutting down some systems to reduce their vulnerability. A rapid suspension of maintenance work on power grids could enhance network connectivity and help disperse induced currents. To ensure a timely response, the organisation of **transnational preparedness exercises** and simulations could further improve cooperation and raise awareness among local responders, national authorities and private companies.

Questions for further reflection at EU level

- What steps might the European Union take to further improve the **understanding** and prediction of solar storms, and ensure timely and accurate alerts to Member States?

- How might the EU support the protection of critical infrastructure needed for the **green transition**, including electrification, from severe solar events and further assist national authorities in developing resilience strategies as part of safeguarding key sectors?

- In the event of a severe solar storm impacting critical infrastructure in multiple Member States, the EU has various sectorial mechanisms at its disposal as well as the Integrated Political Crisis Response (IPCR)[33] arrangements at strategic level. Are there any **gaps in the existing toolbox** that the EU should address to facilitate a coordinated response and support the efficient recovery efforts of Member States?



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