



Position paper

**Resilience and
preparedness in Europe's
energy transition:
the role of low-carbon
energy R&I**

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About EERA

The European Energy Research Alliance (EERA) is the association of European public research centres and universities active in energy research. EERA pursues the mission of catalysing Europe's low-carbon energy research to shape science-based policies and advance world-class innovation. Bringing together more than 250 organisations from over 30 countries, EERA is Europe's largest community of its kind. EERA coordinates its research activities through 18 Joint Programmes and is a key player in the European Union's Strategic Energy Technology (SET) Plan.

ISBN: 9782931174111

Citation: EERA, 2025, Resilience and preparedness in Europe's energy transition: the role of low-carbon energy R&I

Available for download: www.eera-set.eu

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Date: December 2025

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Table of contents

List of abbreviations and acronyms	3
List of figures	3
Introduction: context and purpose	4
Defining resilience and preparedness: a systems perspective and its application to energy systems	7
General conceptual foundations	7
Systems perspective	7
Application to energy systems	10
Resilience and preparedness in energy systems: vulnerabilities, interdependencies and low-carbon energy R&I priorities for action	12
First cluster: Geopolitical and systemic governance challenges	12
Challenge #1: Geopolitical dependencies and supply chain risks	12
Challenge #2: Public governance and coordination gaps	13
Second cluster: Physical and digital infrastructure vulnerabilities	14
Challenge #3: Cascading effects and systemic interdependencies	14
Challenge #4: Infrastructure vulnerabilities	14
Challenge #5: Cybersecurity threats and hybrid risks	15
Third cluster: Societal and climate dynamics	16
Challenge #6: Climate-driven stressors	16
Challenge #7: Societal dynamics and demand-side vulnerabilities	18
Challenge #8: Misinformation and public trust	18
Policy recommendations	20
Strategic direction and governance – Setting the course	20
Technological and infrastructure resilience – Providing the means	21
Societal and operational preparedness – Empowering the actors	21
Conclusion	23

List of abbreviations and acronyms

Abbreviation	Full Term
EERA	European Energy Research Alliance
EU	European Union
NATO	North Atlantic Treaty Organization
TSO	Transmission System Operator
CRMs	Critical Raw Materials
ICT	Information and Communication Technology
HVDC	High-Voltage Direct Current
SET Plan	Strategic Energy Technology Plan
R&I	Research and Innovation
AI	Artificial Intelligence

List of figures

Figure 1: Venn diagram of the intersecting domains of resilience and preparedness. Source: University of Vaasa.

Figure 2: "The risk pyramid". Source: SINTEF/NTNU report – Towards an Energy-Secure and Resilient Society

Figure 3: Bow tie model for risk, vulnerability and resilience, and related concepts. Source: SINTEF/NTNU report – Towards an Energy-Secure and Resilient Society,

Figures 4 & 5: Modelling as a tool for designing climate-resilient infrastructure: illustrative scenarios. Source: Forschungszentrum Jülich.

Introduction: context and purpose

Europe faces **increasingly complex and interconnected risks**, ranging from climate change and cyberattacks to geopolitical instability and systemic shocks. These challenges are reshaping both European and global socio-economic systems, placing **resilience and preparedness at the centre of policy discussions as essential concepts for managing uncertainty effectively**.

Resilience can be broadly understood as the **capacity of a system to withstand, adapt to and recover from shocks while maintaining essential functions and thriving amid complexity and change¹**, whereas **preparedness** involves the **ability to anticipate risks, plan strategically and coordinate effective responses across all levels of governance and society to minimise the impact of crises²**. A clear understanding and consistent application of these concepts are key to building **adaptive and robust systems of all kinds**, including, of course, **energy systems** – understood as the **entire socio-technical framework of energy production, distribution and consumption**.

Resilience and preparedness in energy systems go beyond traditional notions of energy security, as they not only address supply risk management but also encompass the **ability of energy systems to anticipate, adapt to and recover from complex, interconnected and often unpredictable disruptions**. This makes it essential to combine **adaptive capabilities, institutional foresight and proactive planning with a readiness to respond when urgent action is required**.

One way to understand the practical implications of resilience and preparedness in energy systems is to consider their **relationship with the three main goals of many countries' energy policies: energy security, affordability and access, and environmental sustainability**. A successful resilience and preparedness strategy can help to shield consumers from shocks, safeguarding affordability and access, while supporting the transition to more sustainable and low-emission energy sources and enabling energy systems to withstand and adapt to climate impacts. This approach reinforces environmental sustainability. Resilience and preparedness thus provide a **unifying perspective**, ensuring that **these policy goals are**

¹ Council of the European Union, How the EU responds to crises and builds resilience, available at: <https://www.consilium.europa.eu/en/policies/eu-crisis-response-resilience/>

² European External Action Service, Preparedness Union Strategy: reinforcing Europe's resilience, available at: https://www.eeas.europa.eu/eeas/preparedness-union-strategy_en

addressed as an integrated system-level problem rather than as separate challenges.

Building on this perspective, **the need for a coherent and forward-looking approach becomes even more evident in the context of the energy transition, where low-carbon energy technologies, digital infrastructure and new interdependencies** present both opportunities and risks. In this context, strengthening resilience and preparedness will require a **combination of short-, medium- and long-term research and innovation (R&I) efforts to develop adaptive technologies, enhance system flexibility, improve operational readiness, reduce strategic dependencies and address the social dimension** of the transition.

At EU policy level, resilience and preparedness have gained renewed prominence in recent years, particularly during the **COVID-19 pandemic** and in the **aftermath of Russia's invasion of Ukraine**. Both events exposed vulnerabilities and tested Europe's capacity to respond to systemic shocks on a scale rarely seen since the end of World War II. More recently, **Spain and Portugal experienced a total power blackout in April 2025³**, leaving mainland Portugal and much of peninsular Spain without electricity for around ten hours – and in some areas for considerably longer – further underscoring the importance of strengthening Europe's ability to anticipate, withstand and **swiftly respond** to such disruptions.

EU policies such as the **REPowerEU Plan⁴ (2022)**, the **EU directive on the resilience of critical entities (2022)⁵**, the **European Economic Security Strategy (2023)⁶**, the **Niinistö report (2024)⁷**, the **European Preparedness Union Strategy (2025)⁸**, and latest **Strategic Foresight Report (2025)⁹** all reflect efforts to adapt quickly to a shifting landscape. Each policy highlights different dimensions of preparedness and resilience in energy, economic and societal systems. Influential reports by **Mario Draghi on the future of European competitiveness¹⁰** and **Enrico Letta on the European Single Market¹¹** further emphasise these concepts: in particular, Draghi stresses the need to “prepare for a radically different world” by **combining resilience with bold investment in transformative technologies**, while Letta highlights that “strategic autonomy and competitiveness go hand in hand”, calling for **collective action to reduce vulnerabilities and strengthen preparedness**. At an international level, **NATO's approach to societal resilience and civil preparedness¹²** offers useful parallels, highlighting the need for robust governance, public-private cooperation and the protection of critical infrastructure that is essential to modern economies.

Against this backdrop, this paper explores **the impact of the concepts of resilience and preparedness on energy systems and the role of low-carbon energy research and innovation in strengthening these two dimensions within this**

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- 3 Grid Incident in Spain and Portugal on 28 April 2025, ICS Investigation Expert Panel, Factual Report, 3 October 2025 - https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2025/entso-e_incident_report_ES-PT_April_2025_06.pdf
 - 4 REPowerEU Plan, 18 May 2025: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0230>
 - 5 EU Directive on the resilience of critical entities, 14 December 2022 - <https://eur-lex.europa.eu/eli/dir/2022/2557/oj>
 - 6 EU Communication on European Economic Security Strategy, 20 June 2023 - <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023JC0020>
 - 7 Safer together: A path towards a fully prepared Union - https://commission.europa.eu/topics/defence/safer-together-path-towards-fully-prepared-union_en
 - 8 European Preparedness Union Strategy - <https://webgate.ec.europa.eu/circabc-ewpp/d/d/workspace/SpacesStore/b81316ab-a513-49a1-b520-b6a6e0de6986/file.bin>
 - 9 https://commission.europa.eu/strategy-and-policy/strategic-foresight/2025-strategic-foresight-report_en
 - 10 Mario Draghi report on the future of European competitiveness: https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en?filename=The%20future%20of%20European%20competitiveness%20_%20A%20competitiveness%20strategy%20for%20Europe.pdf
 - 11 Enrico Letta: Much More than a Market - <https://www.consilium.europa.eu/media/ny3j24sm/much-more-than-a-market-report-by-enrico-letta.pdf>
 - 12 https://www.nato.int/cps/en/natohq/topics_132722.htm

framework. The analysis will distil a **set of priorities indicating where low-carbon energy R&I should best be directed to address the challenges identified.** On this basis, **operational policy recommendations will be derived to position EERA within the evolving European policy agenda on this topic.** The ultimate goal is to support Europe in advancing competitiveness, climate neutrality and strategic autonomy in a coherent and effective manner.

Defining resilience and preparedness: a systems perspective and its application to energy systems

GENERAL CONCEPTUAL FOUNDATIONS

The concepts of resilience and preparedness have evolved over the past few decades, emerging from a variety of academic and technical fields. **Resilience** originated in the 1970s within ecological science, where it was initially used to describe a **system's ability to absorb disturbances and reorganise while maintaining essential functions**¹³. Over time, it has expanded into a **multi-dimensional concept applied across social, technical and institutional systems, emphasising not only recovery, but also adaptation, transformation and the capacity to thrive amid adversity**.¹⁴ By contrast, **preparedness grew from its roots in disaster management and civil protection to become a comprehensive, proactive approach**¹⁵. It involves **anticipating risks, planning strategically and coordinating effective responses across**

all levels of governance and society to minimise the impact of crises. Together, these concepts lay the groundwork for **adaptive and robust societies and systems**, enabling them to maintain core functions under stress, manage uncertainty and emerge stronger from disruptions¹⁶.

SYSTEMS PERSPECTIVE

A **systems perspective** is essential for understanding **how resilience and preparedness operate across interconnected domains**. Complex systems – such as those governing economies, ecosystems and societies – are composed of interdependent components whose behaviour cannot be understood in isolation. **Disturbances in one area can propagate rapidly through others, producing cascading effects that challenge traditional, sector-specific approaches to risk**

¹³ United Nations Office for Disaster Risk Reduction (UNDRR), *Sendai Framework Terminology*, 2017, <https://www.undrr.org/terminology/resilience>

¹⁴ Patel SS, Rogers MB, Amlôt R, Rubin GJ. «What Do We Mean by 'Community Resilience'? A Systematic Literature Review.» PLoS Currents Disasters: <https://currents.plos.org/disasters/article/what-do-we-mean-by-community-resilience-a-systematic-literature-review-of-how-it-is-defined-in-the-literature/>

¹⁵ NHS England, *Emergency Preparedness, Resilience and Response Framework*, 2022, <https://www.england.nhs.uk/publication/nhs-emergency-preparedness-resilience-and-response-framework/>

¹⁶ European External Action Service, "Preparedness Union Strategy", 2025, https://www.eeas.europa.eu/eeas/preparedness-union-strategy_en

management. From this perspective, **resilience and preparedness are emergent properties of the system as a whole**, shaped by the **interactions, feedback loops and adaptive capacities that connect its parts**, rather than static attributes of individual components.

FIGURE 1:

Source: Vaasa University



The Venn diagram above illustrates this interconnectedness by integrating four domains: comprehensive security, economic resilience, civic resilience and preparedness through innovation and technology. Each domain contributes distinct yet complementary capacities –from strategic foresight and civil preparedness to supply chain management and technological innovation. **Resilience does not emerge within**

any single sphere, but rather at the intersections between them, where feedback loops and shared vulnerabilities are most evident. For instance, cybersecurity is not merely a technological concern; it also affects economic stability and civic trust. Similarly, strategic preparedness depends not only on emergency planning but also on innovation, governance and behavioural adaptation.

FIGURE 2:

"The risk pyramid". Source: SINTEF/NTNU report – Towards an Energy-Secure and Resilient Society, <https://hdl.handle.net/11250/5274718>

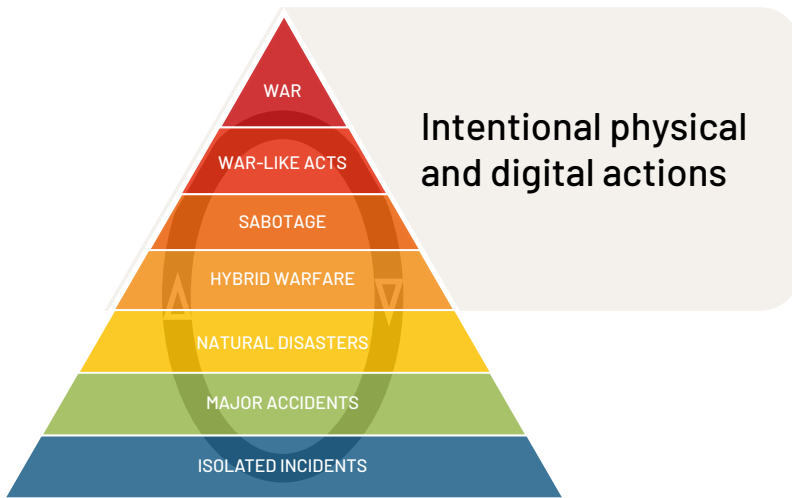
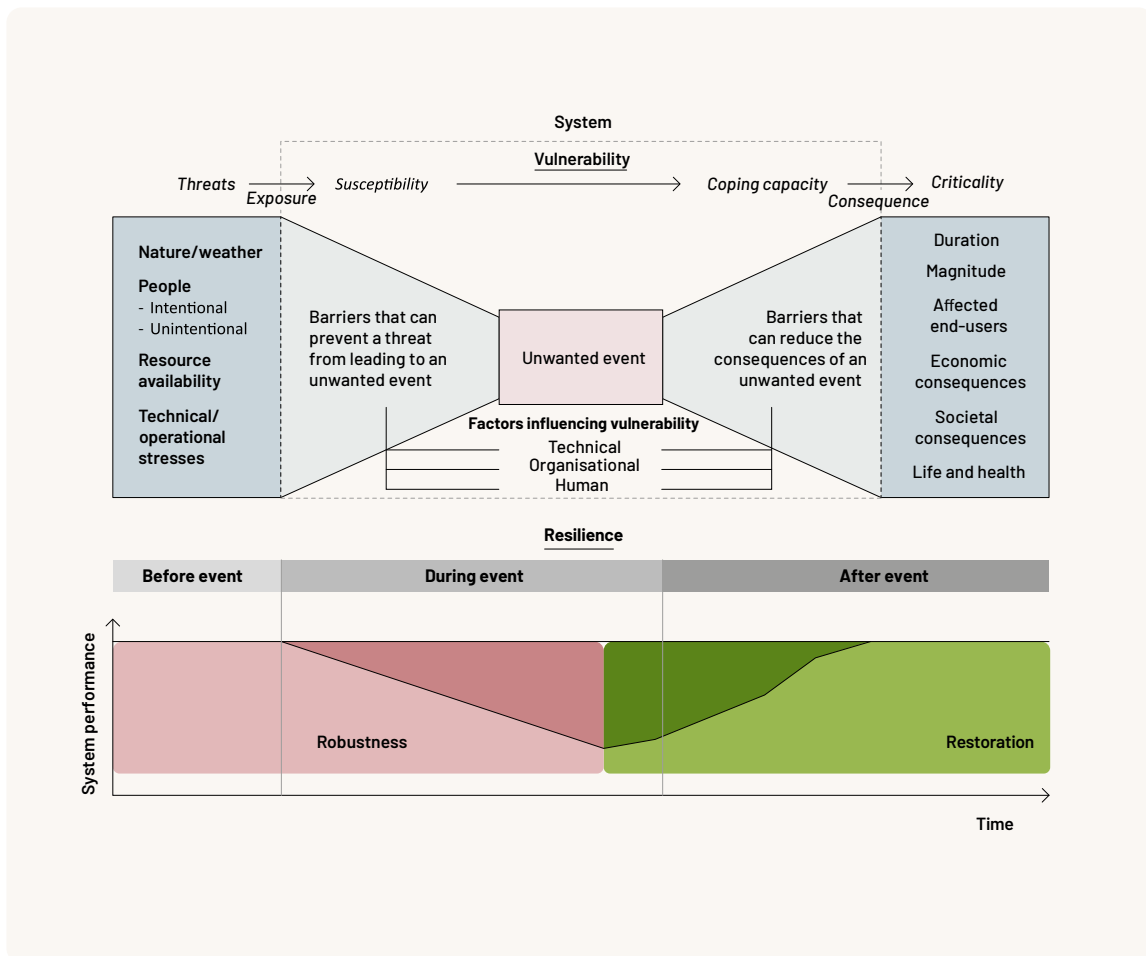


FIGURE 3:

Bow tie model for risk, vulnerability and resilience, and related concepts. Source: SINTEF/NTNU report – Towards an Energy-Secure and Resilient Society, <https://hdl.handle.net/11250/5274718>



To translate this systems thinking into practice, two analytical tools can be combined. The **risk pyramid** illustrates the hierarchy of risks – from frequent, low-impact events at the base to rare, high-impact shocks at the apex – highlighting the need for differentiated management strategies. The **bow tie model**, in turn, shows the causal relationships between threats, unwanted events, and their consequences, linking preventive and mitigative measures within a single framework. For example, an unwanted event, such as an energy shortage or component failure, may stem from either accidental faults or deliberate interference. The model helps identify the barriers that can prevent such events and the safeguards that can limit their impact when they occur.

Within this framework, resilience can be understood as the capacity of a system to absorb shocks, maintain essential functions and adapt to changing conditions, ultimately emerging stronger than before. **Rather than simply returning to its pre-crisis state, a resilient system evolves by learning from disruption, turning crises into opportunities for renewal and innovation.** Preparedness, in turn, strengthens anticipation and response capacities across the different layers of the risk pyramid, ensuring that systems can act swiftly and coherently when exposed to shocks.

Seen through this lens, resilience is not a static goal but a dynamic capability – the ability to transform risks into drivers of progress. Preparedness serves as the operational bridge that translates foresight into action through anticipatory measures, investments and governance mechanisms. Essentially, a systems perspective shifts the focus from managing individual risks to enhancing the overall readiness, adaptability and long-term sustainability of systems.

APPLICATION TO ENERGY SYSTEMS

Building on a general, systems-level understanding of resilience and preparedness, these concepts can be applied to energy systems as complex

socio-technical networks encompassing the full spectrum of production, transmission, distribution, storage and consumption. In this context, **resilience reflects the capacity of energy systems to absorb shocks, withstand stress and maintain essential functions when disruptions occur, as well as their ability to recover effectively.** Preparedness complements resilience by **enabling anticipatory action through risk assessment, scenario planning and readiness measures, ensuring that infrastructure, governance and operational processes can respond proactively to potential crises.** It also encompasses the ability of actors to **anticipate production and consumption patterns, monitor critical assets in real time, and use advanced digital tools, including AI, to improve situational awareness and facilitate timely decision-making.**

A systems perspective highlights the fact that resilience and preparedness are not confined to individual components, but arise from the **dynamic interaction** between operational reliability, market mechanisms, technological innovation and societal engagement. As Med-TSO¹⁷ highlighted, enhancing grid resilience requires, for example, robust interdisciplinary strategies and sustained collaboration among transmission system operators in order to adapt and mitigate climate-related threats, thereby ensuring the continued reliability and stability of the power infrastructure under increasingly volatile climatic conditions.

Energy systems must be able to withstand both acute shocks, such as extreme weather events, and **longer-term phenomena**, such as prolonged droughts or extended periods of low wind and solar output (known as *Dunkelflaute*¹⁸), as well as **smaller-scale disruptions** caused by congestion. In this context, grid resilience is a central issue in the new energy and climate scenario, as noted by Italian TSO Terna¹⁹. Strengthening the resilience of the electricity system is one of the primary challenges of the clean energy transition.

¹⁷ <https://med-tso.org/wp-content/uploads/2024/10/Proceedings-of-the-workshop-Resilient-grids-in-the-mediterranean.pdf>

¹⁸ <https://en.wikipedia.org/wiki/Dunkelflaute>

¹⁹ <https://www.terna.it/en/electric-system/terna-role/resilience>

Maintaining service continuity requires robust physical infrastructure and digital control systems, as well as socio-economic mechanisms such as energy hubs and community-based initiatives. **Anticipatory planning, in turn, demands coordination efforts across regulatory, technological and social domains.** Resilience and preparedness can be assessed using **indicators** such as recovery time after disruptions, the ability to restore operations following blackouts, system redundancies, and other metrics that capture robustness and adaptive capacity.

Applying these concepts emphasises the **importance of considering multiple dimensions** – technical, economic and societal – **simultaneously**, ensuring that resilience and preparedness are embedded throughout the energy system rather than being treated in isolation. Energy systems also differ across countries, reflecting variations in existing physical infrastructure, historical development paths and selected strategies for the future. These differences shape both vulnerabilities and opportunities for enhancing energy resilience and preparedness.

Resilience and preparedness in energy systems: vulnerabilities, interdependencies and low-carbon energy R&I priorities for action

Building on the literature reviewed in earlier sections, this section explores the key challenges that the energy system must address in order to enhance its resilience and preparedness. It also examines how low-carbon energy research and innovation can effectively contribute to tackling these challenges.

FIRST CLUSTER: GEOPOLITICAL AND SYSTEMIC GOVERNANCE CHALLENGES



CHALLENGE #1: GEOPOLITICAL DEPENDENCIES AND SUPPLY CHAIN RISKS

Framing the issue

Shifting global power dynamics and intensifying trade tensions – including evolving tariff

and export policies – introduce considerable uncertainty for Europe's energy systems. These challenges threaten their resilience and preparedness. These dynamics affect the availability of fuels, technologies and critical components across networks. The clean energy transition, which is integral to the EU's path to climate neutrality by 2050, is particularly sensitive to the **supply of critical raw materials (CRMs) and strategic technologies**. In this respect, Europe relies on a **limited number of external suppliers** for key low-carbon energy components and infrastructure²⁰. Furthermore, **supply constraints, export restrictions and extended lead times for equipment** can expose the energy system to geopolitical and operational vulnerabilities. Such **concentrated dependencies**, including reliance on foreign manufacturing capacity, intensify Europe's risk profile and underscore the interconnected nature of these challenges. This calls for greater anticipation, flexibility and innovation across the energy value chain.

²⁰ European Commission – Critical Raw Materials Act

Low-carbon energy R&I priorities

To mitigate these risks effectively, low-carbon energy R&I should primarily focus on:

- **Material substitution and circularity:** develop alternative materials, advanced recycling methods and circular economy approaches for low-carbon energy technologies, from laboratory to near-commercial scale.
- **Domestic manufacturing innovation:** advance scalable European production processes to strengthen technological autonomy and reduce import dependency across low-carbon energy systems.
- **Resilient supply chain strategies:** explore pathways towards “resilience through independence” and “resilience through diversified interdependence”, integrating these concepts into technology design and deployment.
- **Supply chain scenario modelling:** develop analytical tools to anticipate, quantify and simulate potential disruptions in order to guide investment priorities and strategic planning.
- **Adaptive system designs:** engineer energy infrastructure capable of maintaining flexible operation and functionality, even under partial supply constraints.
- **Innovative cooperative mechanisms:** design new models for stockpiling, joint procurement and coordinated risk management of critical materials and components.



CHALLENGE #2: PUBLIC GOVERNANCE AND COORDINATION GAPS

Framing the issue

Fragmented governance structures and uneven coordination between EU, national and regional levels can hinder timely and coherent responses to energy system crises²¹ and disruptions, such as supply interruptions, infrastructure failures or cyber-incidents. **Differences in emergency planning, storage management and regulatory implementation** risk undermining system-wide

resilience and the continuity of essential energy services. The **absence of common standards** and **limited cross-border information exchange** further weaken adaptability and responsiveness. Bridging these public governance gaps is therefore essential to ensure that resilience and preparedness are embedded not only in technology and infrastructure, but also in the institutional and decision-making processes that underpin Europe's clean energy transition.

Low-carbon energy R&I priorities

To strengthen coordination and overcome institutional fragmentation, low-carbon energy R&I should focus on the following priorities:

- **Research into governance models:** analyse and design evidence-based frameworks to improve coordination across energy infrastructure, governance levels and research systems.
- **Living labs for coupled renewable systems:** develop living labs that connect different renewable energy producers, particularly in rural and decentralised contexts, to explore how diversified generation and local coordination can enhance system resilience during supply shortages or low-generation periods.
- **Standardised resilience assessment framework:** develop, test and validate a common methodology to assess and benchmark the resilience of low-carbon energy systems and R&I activities across Europe.
- **Cross-border contingency simulation:** create integrated modelling and simulation tools to test coordinated emergency responses between countries and transmission system operators, drawing on R&I data and digital infrastructure.
- **Data-sharing platforms:** prototype secure, interoperable data-sharing systems and digital twins to enhance real-time coordination and situational awareness of critical low-carbon energy assets.
- **Participatory R&I methods:** develop innovative R&I approaches to involve citizens, local authorities and industry in the design of resilience and preparedness measures for energy systems.

²¹ European Court of Auditors - Preparedness and governance gaps

- **Institutional stress-testing tools:** design and pilot stress-testing methodologies to evaluate the capacity of institutions and governance frameworks to manage energy crises and ensure the continuity of essential services.
- **Governance of cross-border infrastructure:** examine governance models that support research-driven innovation, investment and operation of cross-border, low-carbon energy infrastructure, ensuring consistency between European and national frameworks.

SECOND CLUSTER: PHYSICAL AND DIGITAL INFRASTRUCTURE VULNERABILITIES



CHALLENGE #3: CASCADING EFFECTS AND SYSTEMIC INTERDEPENDENCIES

Framing the issue

Energy systems are embedded within broader socio-technical networks, which include transport, ICT, healthcare and industry²². Failures in one domain can cascade into others, amplifying the impact. The Iberian blackout in April 2025²³ illustrated how a power system blackout can disrupt multiple sectors simultaneously. The ongoing electrification of transport, heating and industrial processes will further intensify these interdependencies, increasing the potential for systemic failures and making anticipatory planning more challenging.

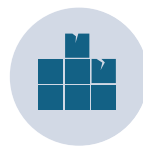
Low-carbon energy R&I priorities

Low-carbon energy R&I can enhance system foresight and adaptive capacity through:

- **Integrated system modelling:** develop and apply system models and simulation tools to analyse interdependencies and cascading effects under extreme conditions, explicitly capturing the interactions between electricity,

gas, hydrogen, heat and maritime systems.

- **Digital twins and predictive analytics:** implement real-time digital replicas of energy systems to anticipate vulnerabilities, test mitigation strategies and support predictive operation. This includes enhanced contingency analysis tools and offline angular stability assessment of power systems.
- **Decentralised and resilient architectures:** expand research into energy communities, microgrids and distributed low-carbon generation. These systems should be capable of autonomous operation during crises and enable the automatic prioritisation of energy consumption across critical industrial hubs, essential services and selected private loads as part of coordinated response mechanisms.
- **Further development of risk and vulnerability analyses:** strengthen analytical methods to identify complex and multifaceted threats, including intentional actions such as cyber-attacks and sabotage. This requires interdisciplinary approaches that integrate technical, digital and organisational aspects, and address the effects of these threats cascading across different energy carriers, while also applying to both land-based and offshore systems.
- **Interoperability standards:** advance harmonised technical protocols to reduce systemic fragility and enable coordinated responses across sectors.



CHALLENGE #4: INFRASTRUCTURE VULNERABILITIES

Framing the issue

The **rapid deployment of infrastructure**, particularly to integrate low-carbon energy sources, introduces new potential points of failure. Off-shore and subsea systems, for example, are still at risk from **extreme weather, accidents and deliberate disruption**. At the same time, the **growing electrification of end uses and the large-scale**

²² European Commission - Critical infrastructure and cybersecurity

²³ ENTSO-E - Iberian Peninsula blackout report April 2025

integration of variable renewable capacity into ageing distribution networks further intensify system vulnerability. **Sector coupling across electricity, heat and hydrogen networks adds to the operational complexity**, while **interdependencies with critical infrastructure**, such as communications and transport, increase the risk of cascading failures. The **accelerated pace of development** compounds these challenges, as **risk assessments quickly become outdated**, making it difficult to ensure that mitigation measures remain effective in such a rapidly evolving environment.

Low-carbon energy R&I priorities

To address these challenges, low-carbon energy R&I should concentrate on the following priorities:

- **Resilient design and protective technologies:** develop advanced materials, construction methods and safeguarding measures for energy assets.
- **System configuration optimisation:** research the optimal combination of centralised and distributed low-carbon generation and storage networks in order to balance efficiency, redundancy and system robustness.
- **System repair and configuration capabilities:** build both operational and strategic capacities and capabilities to repair, replace and reconfigure.
- **Multi-vector integration, control and automation:** advance technologies that enable the coupling of electricity, heat and hydrogen in order to maintain stability under stress, and make control systems more robust to ensure continued operation under severe conditions.
- **Monitoring and predictive maintenance:** deploy sensor-based and automated systems to detect anomalies, anticipate failures and improve response and mitigation through enhanced situational awareness.
- **Cross-border infrastructure research:** expand modelling and deployment approaches to enhance controllability.
- **Component-level resilience:** address vulnerabilities across energy system components through targeted design research.
- **Techno-economic feasibility studies:** integrate operational, economic and regulatory dimen-

sions into R&I on the design, investment and operation of resilient infrastructure.

- **Operational resilience:** improve dispatcher training and coordination with asset management with respect to the awareness of changes in critical infrastructure.
- **Advance HVDC grid-forming control strategies** to enable HVDC systems to play a pivotal role in preventing cascading failures and providing dynamic support for overall system stability.
- **Enhance AI-based decision support systems** for the operation of energy system control rooms, exploiting real-time data to allow operators to proactively anticipate disruptions, rapidly diagnose outages and optimise restoration strategies when the system is under stress.
- **Multilevel surveillance and detection systems:** strengthen real-time situational awareness by integrating satellite, aerial, surface and subsea sensor networks supported by AI-driven analytics.



CHALLENGE #5: CYBERSECURITY THREATS AND HYBRID RISKS

Framing the issue

Digitalisation and the use of advanced AI tools in energy systems enhance efficiency but also expose low-carbon energy infrastructure to cyber-attacks and hybrid threats that combine digital intrusion, physical sabotage and disinformation. Automated control systems that manage renewable generation, smart grids and interconnected hydrogen networks are particularly vulnerable, with potentially significant economic, operational and societal consequences.

Low-carbon energy R&I priorities

Low-carbon energy R&I can help counter these threats by developing advanced tools, methods and governance approaches to anticipate, detect and mitigate hybrid risks across digital and physical infrastructure. This can be achieved through:

- **Cyber resilience:** develop multi-layered cybersecurity architectures across all energy system assets.

- **Hybrid threat detection:** create AI-driven tools capable of identifying simultaneous cyber-physical risks.
- **Secure communication protocols:** strengthen cross-border data integrity for energy operations.
- **Stakeholder capacity research:** design training methodologies to enable an effective response to hybrid threats.
- **System-wide simulation methodologies:** develop stress-test frameworks to evaluate vulnerabilities under hybrid attack scenarios.
- **AI-based anomaly detection and defence architectures:** advance algorithms for detecting irregularities in grid communications, enhance simulation tools for cyber-physical attack scenarios and design layered defence systems to protect both digital and physical assets.

THIRD CLUSTER: SOCIETAL AND CLIMATE DYNAMICS



CHALLENGE #6: CLIMATE-DRIVEN STRESSORS

Framing the issue

Climate change poses a systemic threat to energy systems, impacting them through heatwaves, droughts, floods, storms, wildfires and other extreme events²⁴. For instance, variable hydro-power availability, nuclear constraints due to high river temperatures, and extreme weather events can disrupt electricity networks. Due to their dense infrastructure and role as energy hubs, cities can be particularly vulnerable and are increasingly becoming testbeds for resilience solutions.

Low-carbon energy R&I priorities

To address these climate-driven vulnerabilities, R&I must focus on strengthening the resilience of energy systems across the entire value chain, from infrastructure design and system operation to predictive management and emergency response. Key priorities include:

- **Climate-resilient infrastructure design:** engineer assets capable of withstanding extreme weather across all energy vectors.
- **Energy storage and flexibility solutions:** advance energy storage, demand-side flexibility, flexible industrial processes and hybrid solutions to stabilise generation and system operation under climate stress.
- **Nature-based solutions:** integrate urban greening, wetlands and natural buffers to mitigate peak loads and support system resilience.
- **Advanced forecasting and planning:** improve predictive models of weather-energy interactions for anticipatory management.
- **Integration of monitoring systems:** deploy remote sensing and AI-based data processing to automatically turn raw data into actionable intelligence. These advanced systems should enhance early warning mechanisms, strengthen real-time risk detection and support swift emergency response and decision-making in the face of natural disasters such as wildfires and floods.

²⁴ IPCC - Sixth Assessment Report, Working Group II

FIGURE 4 AND 5:

Modelling is an important tool for designing future climate-resilient infrastructure. This graphic illustrates how a hydrogen backbone could make European energy infrastructure more resilient in the event of a dark lull weather phenomenon. (Source: Forschungszentrum Jülich)

FIGURE 4

Hydrogen Flows During Dark Lulls in Northwestern Europe

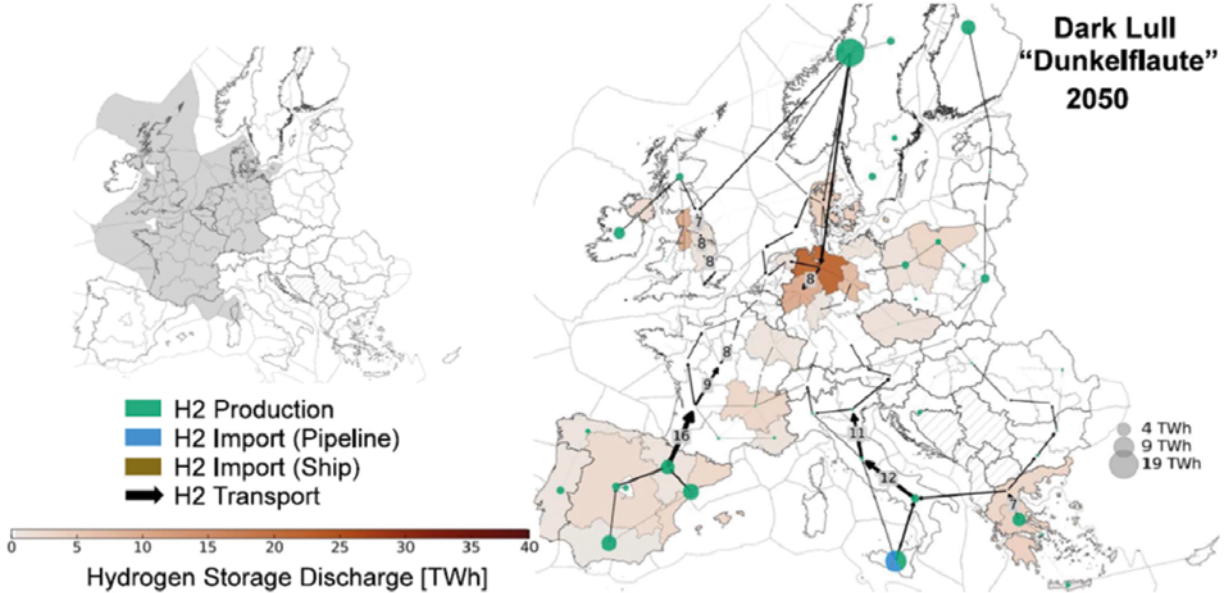
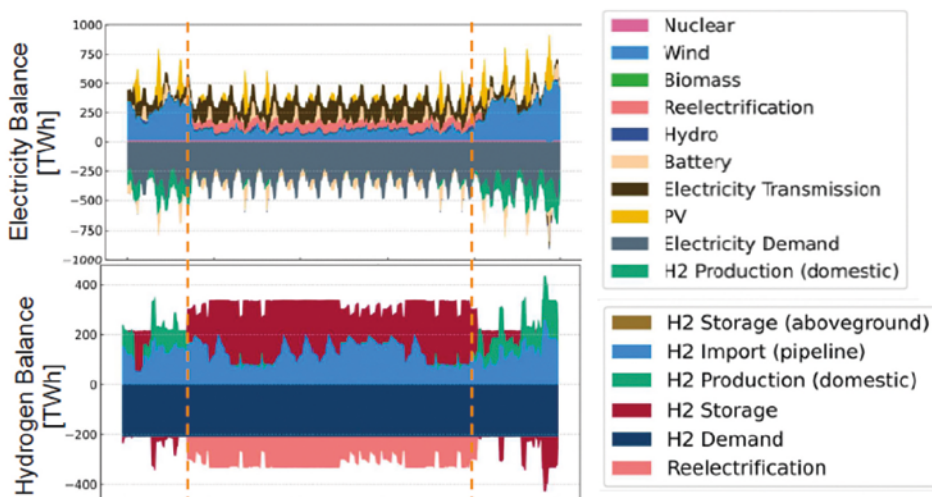


FIGURE 5

Flexibility Options to Ensure Security of Supply





CHALLENGE #7: SOCIETAL DYNAMICS AND DEMAND-SIDE VULNERABILITIES

Framing the issue

Societal dynamics play a decisive role in shaping how energy systems experience and manage demand-side vulnerabilities. **Variations in consumption patterns, perceptions of energy risk and the capacity of communities and institutions to adjust demand** determine how effectively low-carbon systems can respond to stress. These dynamics are particularly evident during periods of low renewable energy production, supply disruption or financial volatility in energy markets, when shifts in behaviour and expectations can either stabilise or further strain the system. The experience of the winter of 2022–2023²⁵, when coordinated demand reductions helped balance supply across Europe, demonstrated the importance of societal responsiveness as a component of energy resilience. However, it also exposed the limits of behavioural flexibility and the uneven capacity of different groups to adapt, revealing the social dimension of vulnerability within energy systems.

Low-carbon energy R&I priorities

To mitigate these vulnerabilities, low-carbon energy research and innovation should combine social understanding with technological and regulatory progress to foster responsive, fair and resilient energy systems. This entails action in several areas, including:

- **Behavioural and social research:** investigate consumption patterns and social behaviours to enhance energy flexibility and system responsiveness.
- **Demand-side innovation and community engagement:** pilot programmes that encourage participatory approaches to energy use, including urban and regional initiatives.
- **Market-based flexibility models:** develop dynamic pricing, demand-response contracts

and smart grid tools that are tailored to societal uptake.

- **Regulatory design and incentive structures:** explore frameworks that encourage energy-efficient practices while accounting for social equity.
- **Technological and digital solutions for consumers:** advance smart systems and adaptive management tools to support behavioural shifts.
- **Societal readiness and inclusivity integration:** ensure that R&I approaches embed equity and inclusivity to enable the practical deployment of demand-side solutions.
- **Energy sufficiency and demand reduction potential:** investigate R&I approaches that assess the potential for reducing overall energy demand and its contribution to system resilience, while complementing efficiency and flexibility measures.
- **Targeted financial support mechanisms:** develop data-driven approaches to help governments and regulators design effective and equitable support schemes for households and businesses most in need, avoiding broad, unsustainable subsidies during energy price shocks.



CHALLENGE #8: MISINFORMATION AND PUBLIC TRUST

Framing the issue

Misinformation and declining public trust represent growing challenges for the effectiveness and resilience of societies and economies, and consequently for energy systems. **Inaccurate or misleading narratives** about technologies, system risks or policy objectives can undermine confidence in institutions and hinder coordinated responses. The **increasing digitalisation of communication channels**, combined with **polarised debates and information overload**, makes it harder to distinguish between evidence-based knowledge and speculation. These dynamics

²⁵ <https://eur-lex.europa.eu/EN/legal-content/summary/coordinated-demand-reduction-measures-for-gas.html>

threaten the legitimacy of energy and climate policies, reducing the willingness of citizens and stakeholders to engage in collective efforts. The challenge, therefore, lies in safeguarding the credibility of scientific knowledge and institutional communication in an environment characterised by fast-changing information flows and social polarisation. Without trust, societies become more vulnerable to disinformation shocks and less prepared to manage technological and systemic change.

fostering critical thinking, evidence-based decision-making and adaptive learning to reinforce resilience and preparedness throughout the energy transition.

Low-carbon energy R&I priorities

To mitigate these vulnerabilities, low-carbon energy research and innovation should support approaches that strengthen public trust, improve transparency and enhance the ability of individuals and institutions to navigate complex information environments. Key priorities include:

- **Behavioural and social research:** study the drivers of energy-related misinformation and public perception in order to inform communication strategies and engagement practices.
- **Transparent and adaptive communication tools:** develop digital platforms and AI-supported systems that provide citizens with accurate, real-time information to enhance trust and understanding.
- **Participatory R&I approaches:** co-design resilience and preparedness solutions with communities to strengthen societal buy-in and responsiveness.
- **Education and awareness initiatives:** integrate energy literacy programmes addressing low-carbon technologies, energy efficiency and crisis preparedness.
- **Monitoring and early-warning systems for misinformation:** implement tools to rapidly detect misinformation trends and enable proactive interventions.
- **Strengthening social trust and acceptance:** design R&I actions that enhance public trust, transparency and dialogue between citizens, energy providers and policymakers.
- **Knowledge and capacity development:** move beyond awareness by equipping individuals, communities and institutions with the ability to interpret information, assess risks and make informed choices. Direct R&I efforts towards

Policy recommendations

Building on the analysis above, the following policy recommendations outline how low-carbon energy R&I can strengthen Europe's resilience and preparedness, while advancing the EU's overarching policy goals of competitiveness, climate neutrality and strategic autonomy.

In this respect, resilience and preparedness should no longer be regarded as defensive or reactive goals, but as strategic opportunities to reinforce innovation capacity, technological lead-

ership and societal trust in the energy transition. This requires a paradigm shift: efficiency alone is no longer sufficient; it must be complemented by redundancy, adaptability and foresight. Resilience and preparedness must therefore be recognised as key measures of system performance and policy success. The recommendations are organised under three interrelated dimensions – strategic and governance; technological and infrastructural; and societal and operational – reflecting the systemic nature of the challenge.



Strategic direction and governance – Setting the course

- 1. Reframe energy security through a systems lens**, broadening its scope beyond supply continuity to encompass resilience and preparedness as drivers of competitiveness, strategic autonomy and climate neutrality.
- 2. Position low-carbon energy R&I as a strategic enabler of resilience and preparedness**, ensuring that research priorities, funding instruments and policy frameworks converge around this goal.
- 3. Institutionalise anticipatory governance** by integrating foresight, scenario analysis, stress-testing and risk assessment into policy and investment planning at EU and national levels.
- 4. Ensure alignment across EU policy and funding frameworks** – including the forthcoming Multiannual Financial Framework, Framework Programme 10, the European Competitiveness Fund, the European Research Area Act and the revised SET Plan – so that resilience and preparedness objectives guide long-term priorities and investment choices.

5. **Set up a SET Plan coordination tool for resilience and preparedness** – for example, a **cross-cutting Task Force** or a **dedicated Implementation Working Group** – to support structured cooperation, anticipate vulnerabilities and enhance preparedness across the energy system.
6. **Strengthen EU-level coordination, data collection and systemic risk monitoring** – for example, through a **European Resilience Observatory embedded in EU foresight mechanisms** – to provide sustained intelligence for strategic policy learning.



Technological and infrastructure resilience – Providing the means

1. **Adopt a systems-based approach to low-carbon energy R&I**, integrating technical, institutional and operational dimensions in order to identify cross-sectoral interdependencies and cascading risks.
2. **Accelerate resilience-oriented innovation and deployment** through targeted funding, de-risking tools and procurement mechanisms that scale technologies enabling redundancy, adaptability and rapid restoration.
3. **Strengthen cyber-physical and infrastructure security** by supporting cross-disciplinary R&I on multi-layered cybersecurity, hybrid threat detection and system-wide stress testing.
4. **Secure critical supply chains and reinforce European manufacturing capacity** by prioritising the substitution of materials, the adoption of circular practices and the domestic production of strategic components, thereby reducing external dependencies.
5. **Leverage digitalisation for anticipatory operation** by deploying digital twins, AI-based analytics and predictive control systems to improve situational awareness and accelerate recovery.
6. **Promote interoperability and integration** by advancing common standards and protocols across electricity, heat, gas and hydrogen networks to ensure coordination and reduce systemic vulnerability.



Societal and operational preparedness – Empowering the actors

1. **Embed “preparedness by design” in regulations and project development**, ensuring that redundancy, diversification and adaptability are built in from the outset.
2. **Strengthen local and societal readiness** by supporting participatory pilot projects, community energy schemes and targeted training programmes. These efforts aim to safeguard essential services and ensure rapid recovery during disruptions.
3. **Promote demand-side resilience** by combining behavioural research with fair incentive schemes and regulatory frameworks that enhance flexibility and ensure equitable participation and burden-sharing.
4. **Strengthen public trust and counter misinformation** by investing in energy literacy, transparent and consistent communication, and participatory governance, thereby reinforcing the social legitimacy of resilience and

preparedness measures.

- 5. Foster international cooperation on resilience and preparedness research** by forming partnerships with like-minded countries, regions and global institutions to share data, foresight tools and coordinated responses to systemic shocks.



Conclusion

Resilience and preparedness must become foundational principles of Europe's energy transition. These principles must be embedded in governance, enabled by technology and sustained by societal trust. Low-carbon energy R&I is the strategic lever to achieve this transformation, turning vulnerability into innovation, and uncertainty into opportunity. By taking coherent, anticipatory and inclusive action, Europe can strengthen its competitiveness, autonomy and ability to thrive in an era defined by systemic change.

