Centre on Regulation in Europe

BUILDING RESILIENCE IN EUROPE'S ENERGY SYSTEM

REPORT

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ACER	Agency for the Cooperation of Energy Regulators
ASIDI	Average System Interruption Duration Index
CAIDI	Customer Average Interruption Duration Index
CBA	Cost-Benefit Analysis
CE	Continental Europe
CHPs	Combined Heat and Power
DORA	Digital Operational Resilience Act
DRR	Disaster Risk Reduction
DSOs	Distribution System Operators
ENTSOE	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FSRUs	Floating Storage and Regasification Units
GWh	Gigawatt hours
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
KV	Kilowatt
LNG	Liquefied Natural Gas
MS	Member State
NDP	Network Development Plan
NECPs	National Energy and Climate Plans
NERC	North American Electric Reliability Corporation
NIS 2	Network and Information Systems Directive
PPs	Plans and Programmes
RES	Renewable Energy Sources
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SEA	Strategic Environmental Assessment
SoS	Security of Supply
TEN-E	Trans-European Networks for Energy Regulation
TSOs	Transmission System Operators
TYNDP	Ten Year Development Plan
VoLL	Value of Lost Load

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EXECUTIVE SUMMARY

Extreme climatic events are increasing both in terms of frequency and scale, causing serious damage to **physical assets** such as gas and electricity transport infrastructure. More extreme weather conditions also affect the **availability of intermittent renewable energy sources** such as wind and solar, and the **volatility of energy demand**. Additionally, Europe's electricity and gas sectors are becoming more interdependent as the continent moves towards its 2050 net zero goals, creating efficiencies but new vulnerabilities resulting from **system integration**.

Thus, a robust and ***resilient*** energy system that can withstand, adapt, and recover quickly when hit by climate-related hazards is clearly of the essence in Europe's energy transition. It is therefore urgent to ask **how EU law and regulation can support and create incentives for a more resilient infrastructure**.

This report illustrates the consequences of climate-change related hazards through **concrete case studies** of electricity and gas networks hit by disasters like wildfires, storms and extreme cold.

Diverging approaches by national regulatory authorities show that there is **no consensus on the need to intervene through regulation/legislative changes to reinforce the role of operators** in resilience building. This report argues in favour of a **targeted regulatory approach at EU level**, around the principles and measures described below.

The approach to resilience in EU energy legislation is often limited to specific aspects of the quality of energy supply. A more **comprehensive and integrated approach** must be promoted. Our **proposal for the definition of resilience,** inspired by the one contained in the **Critical Entities Resilience Directive,** is: '*an entity's ability to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover from a disruptive event*'.

EU energy legislation addresses specific sides of resilience in a targeted manner, e.g., grid planning and system operational management and technical performance. This is already a good start, but **resilience must be better integrated and defined as a mandatory assessment requirement creating strong incentives to invest** in order to limit additional costs in case of major disruptions. This requires having a **broader assessment scope** (e.g., including flexibility) and a **longer-term perspective**.

A key task for grid operators will remain to **identify and assess risks** that will form the basis for investment plans and decisions. A particular challenge here is to **define criteria and metrics** that will reflect disruptions of varying scale and in a longer timeframe (network plan as basis for investment decisions).

In addition to planning, emergency preparedness, restoration, and technical performance, resilience building must be better integrated at the level of **market design**, with a **close interaction between grid operators** and other actors contributing to resilience, such as **providers of flexibility, ancillary and balancing services**.

The energy system has become more decentralised, with a higher share of intermittent renewable energy sources. This put an additional burden on grid operators when managing the grid, while final customers (both wholesale and households) are increasingly responsive to prices. **Flexibility must be further promoted and taken into account in resilience planning, notably at the level of the grid**, and **operators must be encouraged to map the potential for flexibility**.

Cost-benefit Analysis (CBA) rules may be considered when it comes to investments in regulated networks like distribution and transmission power networks. **Benefits of resilience-motivated investments tend to be much more difficult to measure than the costs.** However, if the benefits are not properly accounted for in the analysis, then investments with a primary focus of improving resilience may yield a negative CBA balance and be automatically ruled out.

Network operators will not enter into the related expenses if they are not compensated, e.g., through user tariffs. However, in regulated natural monopolies such as electricity and gas transmission and distribution such investments need to be justified by the resulting benefits. This brings up the **question of the role of regulators, and the methodologies the latter use** to both monitor operators' assessment and investments, but also in terms of guidance as to the prioritisation of investments. In reality, **resilience will be one among other criteria that spread between short-term to long-term investment frames**. A separate but related matter is the question of cost recovery for these investments (including through tariffs).
Multicriteria approaches using several resilience metrics may represent a way forward. However, it needs to be clear how resilience is considered in regulatory decision-making.

Some national regulators are developing approaches to evaluate or to incentivise resilience. In the **UK**, **DSOs** are required to include **resilience aspects in their business plans**. In **Italy**, DSOs are required to **publish CBA-supported plans** for defending networks against climate-related hazards. In **Australia**, the regulator has indicated that resilience-related investments would be allowed. Also in **Italy, a new risk-based methodology** has been approved for improving the resilience of the electricity transmission grid. Generally, **legal changes have generally not been required**. A **changed approach by the regulator** and the **commitment of network operators has been sufficient**.
California has adopted a **different approach** for improving resilience against wildfires, which takes **ownership and financial structure of US utilities into consideration**. In this case, **legal changes were required**.

Due to the increased nature of **coupling** between the gas and electricity sectors, **new gas and electricity resilience metrics may be needed that reflect increasing inter-dependence** and feedback between the two sectors and **how one sector can support resilience of the other sector**.

Monetising the benefits of resilience measures is **important to establish a basis for regulatory decisions on network development plans, but also difficult.** Research is ongoing in this area and consensus has yet to be achieved. The research has, however, already shown **how the monetisation of resilience could be approached**:

- The **system under consideration is modelled**, including a model of the vulnerability (fragility) of individual components to identified threats.
- The **impact of extreme event(s) under consideration on a resilience metric**, such as the trajectory of lost load, is compared with and without investment.
- The **physical metric is monetised using appropriate valuation of losing load**.
- **Expected benefits are computed** by multiplying benefits with the probability of occurrence of identified hazards.

The **Value of Lost Load (VoLL) will be a very important component of any approach to monetising resilience**. Estimates for VoLL do exist in the context of traditional reliability studies. Such estimates are, however, restricted to the direct impact of the loss of electricity or gas supply, usually for a relatively short duration. Unplanned, large-scale, and long-lasting disruptions of supply services may have a more serious impact. **Research in this area is urgently needed for proper valuation of resilience benefits.**

Another challenge is the estimation of hazard probabilities. The degree of increase of extreme events will depend on the climate scenario. **A risk-based approach may therefore be appropriate.** This would entail **analysing different scenarios for the evolution of the likelihood of climate hazards and would ideally take the statistical distribution of these hazards through time into consideration**.

There are **different ways of bringing the required investments about**, e.g., through **economic incentives or command and control**. To some extent, resilience expenditures **may overlap and replace other costs incurred to improve reliability and security of supply against 'ordinary' events**. **Costs will, however, almost certainly increase** if the quality and reliability of energy supply Europe is accustomed to is to be maintained. These costs **may be thought of as insurance against the greater damage that would ensue in the absence of action**.

Finally, despite improved resilience of energy infrastructure, there will occur extreme events that may seriously damage infrastructure and entail high costs. **Insurance funds such as those established in California may be a good solution to share such costs unless markets fill the gap** and offer insurance for these kinds of events. This policy does, however, need further study on whether it actually makes the system more resilient, since insurance in general introduces both adverse selection and moral hazard.

1. INTRODUCTION

´Resilience´ has appeared as a new paradigm applying across many sectors and infrastructures, including energy. It can be defined as the ability of a system to overcome extreme events with minimum disruptions and with a rapid restoration or adaptation phase. In the context of ecological sciences, resilience has been defined as the ability of a natural system to resist and undergo changes without losing its core structure and function.[1] In the energy context, 'resilience' has notably been defined as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event".[2]

This report focuses on the resilience of energy infrastructure to climate-change-related hazards for a good reason: extreme events are increasing both in terms of frequency and scale, causing serious damage to critical infrastructures and physical assets, such as gas and electricity transport infrastructure. Sometimes these events cumulate with other crises (e.g., health, economic, political, war, cybercrime). Unfortunately, this development is set to continue and become even more acute: according to the IPCC, temperatures will rise faster in Europe than average global temperatures.[3] Weather extremes will also increase. With fewer cold spells and frost days, Europe will experience more heat waves. While winter precipitation will increase in Northern Europe, the opposite is projected for summers in the Mediterranean, extending to northward regions. Except for the Mediterranean, extreme precipitation and pluvial flooding are predicted at global warming levels exceeding 1.5°C. The sea level will rise in Europe, except for the Baltic Sea, and extreme sea levels will become more frequent and intense. Concurrent with rising temperatures, glaciers, and permafrost will decline, potentially leading to an increased frequency of rockslides and rock avalanches.

While Europe has experienced an increased incidence of climate-related hazards in recent decades (see, e.g., Figure 1), the IPCC projections for Europe would indicate a further increase in the frequency of such threats and their intensity. The impact will depend on the success of efforts to reduce greenhouse gas emissions, but even if global warming can be limited to 1.5°C it will be significant. Higher levels of warming would entail even higher impacts. Thus, the frequency of extreme temperature events – which lead to an increased risk of wildfires but can also affect underground power lines – will likely increase by fifty percent relative to the current level and more than fourfold from levels experienced without warming; heavy precipitation over land will likely occur fifteen percent more often than experienced currently and would be fifty per cent more likely than before the present global warming level of 1°C.

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[1] C.S. Holling, Resilience and stability of ecological systems, Annual Review of Ecology and Systematics (1973) 4: 1-23; C Folke, SR Carpenter, B Walker et al (2010), Resilience thinking: integrating resilience, adaptability and transformability, Ecology and Society 15(4).

[2] Grid Reliability & Resilience Pricing Grid Resilience in Regional Transmission Organizations & Independent System Operators, 162 F.E.R.C. para. 61,012, p.3

[3] Regional fact sheet – Europe, Sixth Assessment Report, IPCC, https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Europe.pdf

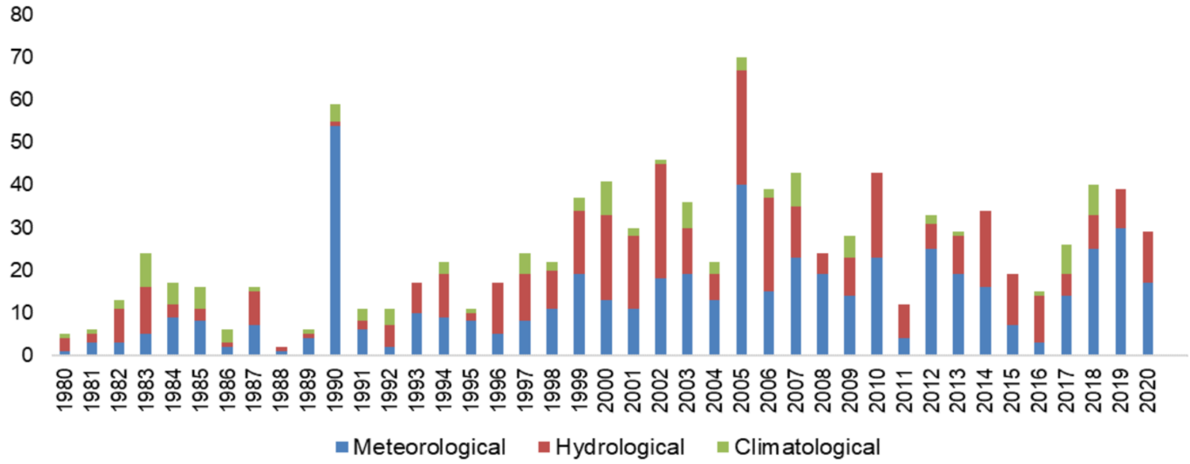

Figure 1. Number of weather- and climate-related events in the EU, by disaster subgroup, 1980-2020[4]

Source: European Commission, based on The Emergency Events Database (EMDAT; CRED, UCLouvain)

Concurrent with the climatic changes – already experienced and projected – Europe has set itself the ambitious goal of becoming climate neutral by 2050. An intermediate goal is to reduce emissions by at least 55% by 2030 compared to 1990. As a part of this goal, the European Commission has proposed that the share of energy generation from renewable sources will double over a decade, viz., rising from 20% to 40% in 2030.

Further, in response to Russia's military invasion of Ukraine, the European Commission[5] adopted the REPowerEU plan, which contains short- and medium-term policy targets aiming to phase out fossil fuel imports from Russia well before 2030 and increase the EU-wide renewable target from 32% to 45% by 2030. The REPowerEU plan consists of the following policy areas and changes:

1. Increase in energy efficiency in the buildings and industrial sector. In particular, encouraging behavioural change, installing heat pumps in buildings, and further electrifying energy consumption in the industry.

2. Fuel diversification by importing gas from LNG and non-Russian pipeline gas supply sources, encouraging domestic production of biomethane and renewable hydrogen.

3. The higher renewable target of at least 45% requires policies to support the quicker roll-out of wind and solar energy.

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[4] Figure from Gagliardi, N., Arévalo, P., & Pamies-Sumner, S. (2022). The Fiscal Impact of Extreme Weather and Climate Events: Evidence for EU Countries. Publications Office of the European Union.

[5] "REPowerEU Plan", Brussels, 18.05.2022, COM(2022) 230 final.
Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

These policy objectives require considerable investments in green energy generation and a solid and efficient transmission infrastructure that allows energy to flow reliably between European countries and regions. Intermittent renewable energy sources like wind and solar also pose challenges to the stability of the power system due to the difficulty of predicting flows in the grid.

In most scenarios, reaching carbon neutrality requires a power system that will rely on carbon-free generation and a high level of direct electrification of final energy services demand, such as space heating and road transport. Therefore, the impact of extreme weather conditions impacts not just the availability of wind and solar but also the volatility of energy demand.

Sector integration – linking different types of energy carriers – is also crucial in EU energy strategy. In particular, as Europe moves towards carbon neutrality by 2050, the electricity and gas sectors will be more integrated via end-use technologies (e.g., hybrid heat pumps) and emerging low-carbon technologies (e.g., hydrogen production from water electrolysis)[6]. The aim is to efficiently support the transition to a more efficient, low-carbon energy system. But the drive towards more efficiency also creates new vulnerabilities and failures in one system – e.g., electricity or gas supply – that may spread to other systems. Thus, robust infrastructure is critical for ensuring a reliable energy supply, given the increasing coupling of the two energy sectors and more frequent and volatile low-carbon energy production and demand patterns.

The focus of this paper is on the regulatory regime for gas and electricity operators. In particular, it looks into whether the regulation of operators' investment strategy and operation practices needs to be reconsidered, taking resilience aspects into consideration.[7] Energy infrastructure operators – not least transmission system operators in the electricity and gas sectors – are facing a significant challenge: the drive towards a cleaner energy system requires more and better system services due to a rapid rise in renewables and increased sector integration; at the same time, increasing frequency and intensity of climate-related hazards demands a system that is more robust and can withstand, adapt and recover quickly when hit by such shocks. Resilient infrastructure is clearly of the essence in the transition towards a greener Europe. It is highly relevant and timely to ask how EU law and regulation can support and create incentives for a more resilient infrastructure.

Ensuring and building resilience requires structural adaptations. Investments are vital and urgent to increase the resilience of the energy sector, and so is the adaptation of operational practices to the ´new normal´ of extreme events. This is especially relevant in the context of accelerating climate change, the war in Ukraine, the energy crisis, and increasing sector-coupling between gas and electricity.

[6] Pollitt, M.G. and Chyong, C.K., 2021. Modelling net zero and sector coupling: lessons for European Policy makers. Economics of Energy and Environmental Policy, 10(2), pp.25-40.

[7] Disruptions to the service capacity of other infrastructure, e.g., roads and IT/telecommunications, may affect the resilience of energy infrastructure. Such issues are identified where appropriate but not analysed in detail.

The next section of the paper defines resilience in general, as well as its application in energy systems. Section 3 outlines and draws lessons from several case studies of recent extreme events in electricity as well as gas grid management. Section 4 reviews how resilience is addressed in EU laws and regulation. Section 5 discusses the role of network operators (electricity and gas) in enhancing resilience and mitigating risks. Section 6 considers some of the hurdles in current EU regulation for enhancing resilience, gives examples of emerging national initiatives in this area, and discusses promising research developments aimed at measuring and valuing resilience. Section 7 concludes and gives policy recommendations.

2. DEFINING RESILIENCE IN ENERGY SYSTEMS

The concept of 'resilience' has gained increased recognition in a broad range of disciplines since the 2000s. Policy and regulation also increasingly refer to resilience as a general objective, but often fall short of defining it. The legislation also starts referring to resilience or the need to be more resilient, both at national, EU and international level. When it comes to energy, very few laws refer to 'resilience' as an objective of regulatory intervention. However, several legal acts refer to concepts like 'reliability', 'adequacy of supply', 'security of supply' or 'restoration'. By contrast, policy documents contain several references to the concept of resilience. This calls for reviewing the definition of resilience, its precise meaning and how it translates into the energy infrastructure regulatory context.

The general definition of resilience is reviewed below (2.1), before assessing which understanding it could have in the context of energy system and energy infrastructures (2.2) and which factors affect natural gas and electricity systems resilience (2.3).

2.1 General definition of resilience

The noun 'resilience' comes from the Latin verb *resilire*, meaning to 'recoil' or 'to rebound', and was used in the 1600s with the meaning 'springing back'. In the 1800s-1900s, it took on a more technical understanding and is associated to the qualities of materials and equipment to resist shocks.[8] In social science, where 'resilience' is a well-established concept, it has been defined as 'a system's capacity to absorb disturbance and still remain within the same state or domain'. Authors like C.S. Holling have played a central role in theorising the concept in the context of ecological sciences.[9] They establish that resilience is the ability of a natural system to resist and undergo changes without losing its core structure and function. Other sub-distinctions are made such as between ´engineering resilience´ – as the ability of a system to return to the pre-disturbance state[10] –, and ´social-ecological resilience´ – as the capacity of an ecosystem to respond and adapt to disruptions.[11]

Resilience is therefore more than merely resistance[12] to a shock. It shows the ability of a system to deal with change and continue to develop. The process of resilience is not linear, but more like a spiral, including a transformative phase. It can be preventive (pre-disaster), but could also follow a disaster, rebounding from it to use the window of opportunity created to introduce resilience, as captured by the term 'Build Back Better' (BBB).[13] As summarised by the Stockholm Resilience Centre: "Resilience is the capacity of a system, be it an individual, a forest, a city or an economy, to deal with change and

[8] D.E. Alexander, Resilience and disaster risk reduction: an etymological journey, Nat. Hazards Earth Syst. Sci., (2013)13, pp. 2707–2716.
[9] C.S. Holling, Resilience and stability of ecological systems, Annual Review of Ecology and Systematics (1973) 4: 1-23; C. Folke, SR. Carpenter, B Walker et al (2010), Resilience thinking: integrating resilience, adaptability and transformability, Ecology and Society 15(4).
[10] Lance H. Gunderson, 'Ecological Resilience—In Theory and Application' Annual Review of Ecology and Systematics 2000 31:1, 425-439.
[11] C.S. Holling, (n5).
[12] Resistance is defined by Holling as 'The capacity of the ecosystem to absorb disturbances and remain largely unchanged'.
[13] The Build Back Better (BBB) term has been recognised by the United Nations Sendai Framework for Disaster Risk Reduction (2015-2030) as a key global priority for action for both pre- and post-disaster planning and implementation. See Priority 4: 'Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction'.

continue to develop. It is about how humans and nature can use shocks and disturbances like a financial crisis or climate change to spur renewal and innovative thinking."[14] This development dimension of resilience is not a synonym of growth, although it could be associated with a growing process for the community or territory encompassed.[15] To align with sustainability goals, this development dimension of resilience should be associated with the management of ecosystems. Those are some of the interlinkages captured by the notion of social-ecological resilience.[16]

From this general working definition, it is already apparent that 'resilience' is a multi-faceted topic. Engaging with it will require a wide range of assets, resources, actors, and authorities to be involved. In the legal and regulatory context, a multisectoral approach is needed. Cross-sectoral risks and interdependencies must be heeded. Such an engagement will require thinking both in terms of local, regional, and global ecosystem approaches. It will also require a common understanding and taxonomy of the defined types of hazards, threats, and risks to be addressed and the likelihood of their occurrence. In this exercise, a comparison with related concepts, such as disaster risk reduction (DRR) is useful. Further, engagement with the resilience imperative in the legal and regulatory context requires consideration of a wide range of legal and regulatory mechanisms and careful assessment of rights and obligations associated with them. The different understandings of resilience lead to divergent approaches to disaster preparedness and recovery.

Legal scholars have advanced a first working definition of resilience in legal context as being: "the ability of our social-ecological ecosystems[17] to resist and adapt to disruptions, and to pursue sustainable development and equity in an inclusive and nature-based manner".[18] This definition can also be used for further guidance in the development of the EU regulatory framework.

2.2 Energy system and energy infrastructure resilience

Dealing with resilience in the context of energy infrastructure makes the definition of disruption and the response to it more specific.[19] The approach tends to be limited to 'engineering resilience' where the focus is on the performance of the system, with multiple components and interconnections, some of them being defined as 'critical infrastructures'. The risk is of being too restrictive in the approach, and missing interlinkages with the other ecosystems. By focusing on the resilience of energy infrastructures we acknowledge this limitation but want also to make the analysis more specific to the sector, and thus contribute to regulatory improvement.

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[14] Stockholm Resilience Centre, What is Resilience, available at https://www.stockholmresilience.org/research/research-news/2015-02-19-what-is-resilience.html

[15] The suitability of concepts like 'sustainable development' or 'green growth' is often criticised in the literature on resilience.

[16] W.N. Adger, Social and ecological resilience: are they related? Progress in Human Geography 24(3), pp. 347-64.

[17] Be it a group of individuals, a natural ecosystem, a city, an infrastructure, a country, a sector or an economy.

[18] C. Banet, H. Mostert, L. Paddock, M. Montoya and I. del Guayo, Conclusion - Managing disruption and reinventing the future: resilience as requirement for legal frameworks, in C. Banet et al (eds.), Resilience in Energy, Infrastructure, and Natural Resources Law: Examining Legal Pathways for Sustainability in Times of Disruption (Oxford UP, 2022), Chapter 22, p.361.

[19] BJ. Jess, H. Heinrichs and W. Kuckshinrichs, 'Adapting the theory of resilience to energy systems: a review and outlook", Energy, Sustainability and Society 9, 2019.

In the energy context, 'resilience' has notably been defined as ¨the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb*,* adapt to, and/or rapidly recover from such an event¨.[20] It is often addressed in terms of 'energy security', 'security of supply' or 'resource adequacy'. 'Reliability' and 'operational flexibility' are also useful reference concepts that all address the elements of resilience. The manner these concepts relate to the regulatory model for network operators is analysed in Section 4.

As defined above, building resilience is a process and operators, as regulated entities, need to receive the right signals to invest in it. Today, resilience, as a steering objective, is reflected only to a limited extent in the regulatory model for operators. This has been revealed by several recent incidents in Europe and abroad, as reviewed in Section 3. Notably, the definition of clear and adequate incentives for operators to invest in grid maintenance and reliability measures has been identified as an important tool in risk avoidance. The risk of damages due to lack of grid maintenance has increased in the past decade, with wildfires as one example cause. It raises questions relating to the economic regulatory model for system operators, with the undermining risk of liability for neglect in case of damage, both for operators and public authorities.[21] It also raises the fundamental question of whether 'resilience' should be monetised as part of this economic regulatory model or left apart as a separate regulatory objective. Shortfalls also have enormous consequences for the whole society. The risk is particularly acute at the distribution level. In liberalised markets, some grid companies are small, publicly owned, single-purpose companies, and this economic situation may limit their investment capacity.

As a first example, one can look at the extent to which energy modelling tools are taking resilience into account as a parameter. Indeed, as energy modelling serves as a basis for making energy planning decisions, it will be crucial that resilience is considered in those models too. In practice, ensuring resilience is often seen and calculated in terms of costs for utilities in these models (e.g., the price of replacing or repairing a power line after a storm), which represents a barrier to its implementation and financing. A change of approach and method is also required in this domain. Researchers at the US National Renewable Energy Laboratory (NREL) have already developed a methodology for quantifying the benefits of resilience to energy systems (i.e., quantifying resilience metrics).[22]

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[20] Grid Reliability & Resilience Pricing Grid Resilience in Regional Transmission Organizations & In-dependent System Operators, 162 F.E.R.C. para. 61,012, p.3. Also in the United States, another similar definition of resilience in the energy context is given in Presidential Policy Directive 21 (PPD-21) on Critical Infrastructure Security and Resilience (2013) as meaning: 'the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents'.

[21] C. Banet and A. S. Brunt, Regulating high voltage power lines: electromagnetic fields and safety, in Martha M. Roggenkamp, Kars J. de Graaf and Ruven C. Fleming (eds.), Energy Law, Climate Change and the Environment, Elgar Encyclopedia of Environmental Law series, (Edward Elgar, 2021), Chapter IX.52, pp. 621-632. Indeed, public authorities may not be protected from litigation risks when lack of action and duty of care can be claimed.

[22] K. Anderson et al*.*, Integrating the Value of Electricity Resilience in Energy Planning and Operations Decisions, in IEEE Systems Journal, vol. 15, no. 1, pp. 204-214, March 2021; C. Murphy et al, Adapting Existing Energy Planning, Simulation, and Operational Models for Resilience Analysis, Technical Report NREL/TP-6A20-74241, 2020.

How to better factor in resilience in regulatory models for energy network operators is the central question investigated in our project.

2.3 Gas vs. electricity resilience

In the context of climate change, the resilience of the natural gas and electricity systems can be affected differently due to various factors.

Natural gas system resilience:

- Vulnerability to extreme weather events (e.g., sudden drop in air temperature resulting in huge increase in demand for space heating or hurricane disrupting offshore gas production facilities) that can increase demand and disrupt supply and delivery infrastructure.
- Because Europe is part of global gas markets, its dependence on a limited number of suppliers, transportation routes and storage facilities which can increase the risk of supply disruptions due to war and geopolitical tensions.
- Leakage of methane, a potent greenhouse gas, during production and transportation, which can negatively impact the environment (e.g., explosion of the Nord Stream offshore gas pipeline, or the U.S. Aliso Canyon gas leak).

Electricity system resilience:

- Vulnerability to extreme weather events (e.g., hurricanes, droughts, heat waves) that can impact power generation (e.g., reduce hydro power generation, increase demand for cooling) and transmission and distribution networks (e.g., due to wildfire).
- Dependence on centralised generation and transmission infrastructure, which can be vulnerable to cascade failure and cause widespread outages.
- Increasing integration of renewable energy sources, such as wind and solar, which can be intermittent and weather-dependent, and require additional investments in grid infrastructure and storage solutions to increase resilience.

While both systems have distinct risks (gas is more prone to geopolitical risks while electricity is more prone to nature-based and climate-related risks), with the advent of new low-carbon energy technologies and vectors (e.g., low-carbon hydrogen from water electrolysis or gas steam methane reformation) both gas and electricity will become more integrated or sector-coupled. As noted in Chyong et al., (2021[23]), for Europe to reach net-zero climate target, European gas and electricity systems will be more integrated (e.g., via hydrogen production and hybrid heat pumps). Hence, climate-related risks that are more specific to the electricity sector propagate to the gas system and vice-versa. Overall, it is worth noting that European primary energy consumption peaked in 2006 and has since then fallen at an average rate of 0.8% p.a. Thus, the declining energy demand and

[23] Chyong, C. K., Pollitt, M., Reiner, D., Li, C., Aggarwal, D., & Ly, R. (2021). Electricity and Gas Coupling in a Decarbonised Economy. Brussels: Centre on Regulation in Europe.

investments in infrastructure to support the growth in the early 2000s have helped improve the operation of the energy market and its resilience.

3. LESSONS LEARNED FROM RECENT MAJOR EXTREME EVENTS AND EFFECTS ON GRID MANAGEMENT

Case selection

Six cases are outlined below: three relating to electricity and three to natural gas. One of the natural gas cases (Texas 2021 Freeze) also deals with the coupling of gas and electricity. Our focus is on cases related to 'sudden' nature-based events or to those that can be classified as *force majeure* that could impact operations of electricity and natural gas systems.

3.1 Electricity cases

The first electricity case is related to transmission system operations (TSOs) and the separation of the European system. This incident was a consequence of a wildfire in the South of France and resulted in Iberia being separated from the rest of Europe. The second and third cases concern distribution system operations (DSOs). The former was the consequence of storms in the Australian state of Victoria, the latter concerns wildfires in California and the related bankruptcy of PG&E.

Case 1: Continental Europe Synchronous Area Separation on 24 July 2021[24]

On 24 July 2021, a severe wildfire broke out near Moux, in the South of France, in an area where two 400 kV transmission lines, connecting France and Spain, passed through. While intense firefighting efforts were mobilised, there was a lack of communication between the firefighting services and RTE, the French TSO. RTE was not informed of the fire – even if requesting the outage of lines to allow an intervention is covered by an agreement between RTE and the French Fire Department – therefore it did not respond to it in a timely manner in the operation of its system or in coordination with other TSOs, notably REE and REN (the Spanish and Portuguese TSOs, respectively).

Due to the impact of the fire, there was a cascade of trips on several transmission power system elements connecting France and the Iberian Peninsula, starting with the faults on the two lines directly impacted by the fire. The result was that the Continental Europe (CE) Synchronous area was divided into two areas, with the Iberian Peninsula being separated from the rest of the CE power system for approximately one hour. No major damage occurred to the power system, but there was considerable load shedding and disconnection of generation. In particular, a significant amount of distributed RES generation was disconnected.

This incident originated in a major wildfire but became serious due to a failure of communication from the firefighting services to the TSO. There were no faults in system operation or planning and both system protection and defence plans worked as they were supposed to. The tripping and

[24] This section is based on ENTSO-E (2022). Continental Europe Synchronous Area Separation on 24 July 2021, ICS Investigation Expert Panel, Final Report, 25 March 2022.

disconnection of RES generation, in part due to non-compliance by RES generators with EU network codes on voltage and frequency limits does, however, appear to have exacerbated the situation and acted against system stability. Indeed, a key recommendation of the expert panel investigating the incident was that stakeholders should "work together to ensure that the mandatory security requirements are implemented and monitored for their compliance".[25]

In other words, behind the system separation lies a climate-change-related disaster – the wildfire – near power system infrastructure. The latter was confounded by a failure of communication and a destabilisation of the system due to a large share of distributed RES generation.

A rise in wildfire risk – and, more generally, environmental risks related to climate change – was observed and acknowledged by the expert panel, which also adopted the key recommendation that TSOs should "continuously develop and improve their environmental risk identification and mitigation processes to be prepared for a potential increase in their occurrence due to the effects of climate change".[26]

Even if this incident became acute due to communication failure, this case offers potential lessons on the resilience consequences of the combination of a rise in climate-related hazards and an increasing share of distributed RES generation. Both would appear to tend towards a less resilient system.

Case 2: June and October 2021 Storms in Victoria, Australia[27]

In June 2021, the Australian state of Victoria was hit by a severe storm which had a major adverse impact across the state, causing widespread damage to property, felling trees, downing power lines, causing road closures, and damaging critical infrastructure. Electric power outages were extensive: at peak, almost 300,000 customers had no power and, three days later, almost a quarter of those were still off supply. A little over four months later, in October 2021, another storm swept over the state with an even larger immediate impact: at peak, over half a million customers lost power. In both cases, thousands of customers were still off the electric grid a week after the storms.

The power outages had serious consequences. Telecommunications – in some cases, all phone and internet communication were lost – water treatment facilities, health services and supermarkets were affected. People found themselves without "power and the ability to heat their homes, in some cases customers were also without water and sewerage services, communications and other services that are dependent on the power supply".[28] Information was hard to provide to customers due to

[25] ENTSO-E (2022 p. 122.
[26] ENTSO-E (n18).
[27] This section is based on Electricity Distribution Network Resilience Review Expert Panel (2022), Final Recommendations Report – the Expert Panel was established by the Victorian Government after the June 2021 storm – and Emergency Management Victoria (2022), Community Report: June 2021 Extreme Weather Event, May.
[28] Electricity Distribution Network Resilience Review Expert Panel (n23) p.46.

interrupted telecommunications which exacerbated problems and caused frustration among the affected customers.

The consequences of the extreme weather events in Victoria illustrate the fundamental importance of electricity distribution networks for customers. These events also offer potential lessons on how to improve the resilience of such critical infrastructure. The reviews initiated by the Victorian Government as well as the regulatory response are of particular interest for this study. We shall return to both in Section 6.

Case 3: PG&E and Wildfires in California

Wildfires have wreaked havoc on California in recent years, destroying homes and other property, taking lives, and forcing thousands to evacuate their homes every year. Some of these fires have been caused by power lines, e.g., by sparks from faulty lines and by sparks emitted when trees fell on power lines. PG&E is a major investor-owned and publicly traded utility in California, providing natural gas and electricity to over five million households. In January 2019, facing tens of billions of dollars of potential liabilities, after a series of wildfires in 2019 and over the previous years, caused by or related to PG&E power equipment, the utility declared pre-emptive bankruptcy.[29]

PG&E emerged from bankruptcy in 2020 in time to join a new $21 billion wildfire insurance fund established by the state of California. Wildfires have, however, continued in California, and in April 2022 the company agreed to pay $55 million in penalties and costs related to fires in 2021 and 2019.

The case of PG&E has been dubbed the ´first climate change bankruptcy´.[30] The reason is its connection to wildfires which have increased massively in California. There is interplay, however, with company incentives to cut costs and PG&E has been accused of lack of maintenance of its power lines leading to failures, which have caused major wildfires.[31] Thus, climate change plays a role, but company behaviour also seems to be a contributing factor.

The case of PG&E is a very complex one but offers potential lessons on the importance of the regulatory environment and the role of incentives for resilient power networks. The regulatory and legislative response in California as well as the response of the company are also of interest for this study. We shall return to those issues in Section 6.

[29] According to California law, utilities are held liable for damages caused by wildfires ignited by their equipment, even if the company is not negligent in its operations; this is so-called *inverse condemnation*. Thus, the damage caused by a fire started when a tree falls on a power line is the liability of the utility. See John MacWilliams, Sarah La Monica and James Kobus (2019). PG&E: Market and Policy Perspectives on the First Climate Change Bankruptcy, Columbia School of International and Public Affairs, Center on Global Energy Policy.

[30] E.g., The Wall Street Journal (2019). PG&E: The First Climate-Change Bankruptcy, Probably Not the Last, 18 January. https://www.wsj.com/articles/pg-e-wildfires-and-the-first-climate-change-bankruptcy-11547820006, accessed on 20 November 2022.

[31] E.g., New York Times (2019). How PG&E Ignored Fire Risks in Favor of Profits, 18 March 2019. https://www.nytimes.com/interactive/2019/03/18/business/pge-california-wildfires.html accessed on 20 November 2022.

3.2 Natural gas cases

Considering the issues raised in previous sections, this section focuses on three case studies – one teasing out the impact of sudden drop in air temperature on requirements for gas to heat homes and hence capability of the gas system to deliver ´instantaneous´ energy needs. The second case study sheds light on the impacts of (rather limited compared to a low-carbon energy system envisaged in Chyong et al., 2021) sector coupling between gas and electricity and how this coupling affects system resilience considering climate-related risks. The last case study looks at a *force majeure* event – an explosion at a regional gas hub in Central Europe (Baumgarten, Austria) in 2017. The explosion affected gas deliveries to Italy, Germany and Slovenia for one day, highlighting the interconnectedness of the European gas system.

Case 4: ´The Beast from the East´ (24 February 2018 – 3 March 2018)

A change in the Jetstream led to cold air drawn from Siberia bringing snow and freezing weather to the UK and Northwest Europe between 24 February and 3 March 2018. The event was dubbed ´Beast from the East´, which pushed the U.K. gas system close to a stress condition. It resulted in low gas deliveries from offshore gas fields, Norway, and the Continent coupled with low levels of gas in UK storage sites and extremely high gas demand for space heating.

The case study highlights the challenge of ensuring that the gas supply system, in particular the distribution system, is resilient against a sudden cold snap for a country predominantly relying on gas for space and water heating. For example, the peak hour gas demand in the UK at the distribution level (i.e., mostly for domestic usage) during the event (1 March) reached 214 GW (at 18:00), which is four times higher than the electricity peak demand (53 GW on the same day and time). Not only the peak hour demand was high, the ´Beast from the East´ event highlights the challenge for a resilient gas system to supply the fuel for domestic heating in a northern country during a three-hour period in the morning – from 05:00 to 08:00. On that day, the three-hour gas demand requirement in the morning reached some 116 GWh, which is 7 times higher than the highest three-hour electricity demand requirement observed in the U.K. This difference highlights that the resilience of the gas system is about maintaining flow to deliver energy in consecutive peak hours, while in electricity, resilience is about peak capacity.

The event led National Grid (the UK’s gas system operator) to issue a *Gas Deficit Warning (GDW)*, which was issued for the first time since 2008. The warning was meant to indicate that the gas supply system would most likely be in ´imbalance´. The objective of this warning was to send a request to shippers to voluntarily turn up their supply or reduce their demand in order to boost line-pack inventory, should the system operator recognise a risk to the end-of-day gas balance after a supply or demand shock. However, the media portrayed this warning as the UK would be running out of gas. This, according to National Grid, led to unnecessary ´overreaction´ from market participants, resulting in very high intraday gas spot prices (500p/therm[32]). According to the UK's energy regulator, Ofgem (2019[33]), "National Grid are of the opinion that the term GDW was taken out of context by some market observers, fuelling a sense of panic that was unwarranted." One conclusion from this case is the way we communicate about the potential impact of a crisis situation and therefore proportionate cost of ensuring resilience. For example, after the event both market participants and the regulator agreed to change the wording of this warning from *Gas Deficit Warning* to *Gas Balancing* (National Grid, 2019[34]). The system operator argued that the switch in wording of the warning would mean shippers could respond more efficiently reducing the need for the system operator to intervene in the market as residual balancer.

Before this Arctic storm, in December 2017, a major offshore production platform was shut down, leading to the loss of about 12% of the UK national winter daily demand. Despite this, supply from interconnectors, Norway and mainland Europe and other sources supported the network, and the system remained stable.[35]

The UK gas case study shows that even though majority of the network is inherently resilient to climate events, outages caused by poor planning and maintenance can cause disruptions on the network. It should also be noted that even though there were gas supply challenges, a diverse source of electricity generation ensured that electricity outages were minimal. However, while gas infrastructure is more resilient to climate risks, operation of the network involves the potential of pipeline explosions be it sub-sea or at processing stations. This additional safety risk brings along an additional level of technical and reliability standards that are absent in electricity networks.

Case 5: Texas 2021 Freeze – a case of gas and electricity coupling

This event, its causes and consequences, are now well-documented[36]. This section focuses on regulatory and policy changes resulting from this event. We focus on the lessons learned and how they relate to the discussion around sector coupling in Europe.

Following the 2021 winter storm, Federal Energy Regulatory Commission (FERC) approved enhanced reliability standards proposed by the North American Electric Reliability Corporation (NERC) to keep power plants in operation and prevent cascading outages during severe climate conditions. However, as the electricity and gas networks are becoming increasingly interconnected it raised the question of who will pay for the enhanced resiliency measures, electricity or gas customers. Should the networks be decoupled and evaluated as standalone entities, or should a combined approach be taken when addressing the cost of resiliency measures?

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[32] Ofgem (2019). Uniform Network Code (UNC)685: Amendment of the UNC term 'Gas Deficit Warning' to 'Gas Balancing Notification'. Available here: https://www.ofgem.gov.uk/sites/default/files/docs/2019/07/unc685_d.pdf
[33] Ofgem (2019). Uniform Network Code (UNC)685: Amendment of the UNC term 'Gas Deficit Warning' to 'Gas Balancing Notification'. Available here: https://www.ofgem.gov.uk/sites/default/files/docs/2019/07/unc685_d.pdf
[34] https://datacommunity.nationalgridgas.com/key-documents/gas-deficit-warning-and-margins-notice-changes/
[35] https://www.gov.uk/government/publications/uk-national-risk-assessment-on-security-of-gas-supply-2018
[36] Busby, et al., Cascading risks: Understanding the 2021 winter blackout in Texas

One approach that has been discussed is to identify interdependencies on the network and encourage information sharing between the two systems. Information is critical, and its absence has been a common theme in cascading failures caused by infrastructure dependencies. Both system operators, gas and electricity, must have sufficient information concerning their current operating conditions and the various risks they each face to properly evaluate resiliency/contingency actions. This would improve coordination during severe climate events and lead to quicker response times, lowering outage frequency and duration.[37]

For example, during the Uri 2021 storm, electricity operators cut power to gas processing facilities to reduce the demand and avoid a system collapse. This, however, led to reducing the gas supply to the few power plants that could still operate during the storm. Better coordination between gas suppliers and the Electric Reliability Council of Texas (ERCOT) would have identified gas distribution infrastructure as a critical load and excluded it from load-shedding activities. This would have allowed continued gas network operation, helping keep some plants in operation and homes heated.[38]

Given that this is a shared benefit between electricity and gas networks, the cost of investment should be recovered by customers of each network. Therefore, Energy regulators should provide incentives to invest in resilience and weatherisation by quantifying such investment's social cost and benefits. A government grant and investments by utilities should facilitate the communication infrastructure investment necessary to address this issue. A barrier to this, however, may be the sensitivity of the information shared as utilities and concerns over data security.[39]

An argument can be made that electricity customers should cover most of the increased cost of resiliency against these low-probability, high-impact events since electricity networks, stand-alone, are more prone to failures during these events than gas networks. The electricity network is principally above ground and covers large portions of the state, whereas gas infrastructure is mainly underground. Should each system be stand-alone, the failure rate for gas networks is considerably lower than for electricity networks[40]. Most of the gas infrastructure is inherently resilient to extreme climate events, given that most of its network is underground. Overall, the cost of increasing resilience in a coupled gas and electricity system depends on the customer mix of each network.

[37] Public Utility Commission of Texas - 2022 Weather Emergency Preparedness Report . PUCT. (n.d.). Retrieved March 1, 2023, from https://interchange.puc.texas.gov/Documents/53385_788_1241589.PDF ;
SoCalGas - Case Studies of Multi-Sectoral Resilience to Natural Disasters. (n.d.). Retrieved March 1, 2023, from https://www.socalgas.com/1443742022576/SoCalGas-Case-Studies.pdf ;
[38] SoCalGas - Case Studies of Multi-Sectoral Resilience to Natural Disasters. (n.d.). Retrieved 1 March 2023, from https://www.socalgas.com/1443742022576/SoCalGas-Case-Studies.pdf
[39] UK Climate Change Risk Assessment Report. (n.d.). Retrieved 3 March 2023, from https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Chapter-2.pdf
[40] https://www.gti.energy/wp-content/uploads/2018/11/Assessment-of-Natural-Gas-Electric-Distribution-Service-Reliability-TopicalReport-Jul2018.pdf

The main insight from this case study is that there is a need for binding crisis coordination plan between gas and electricity TSOs and that they should jointly assess and prepare for risks and identify those that have ´cascading´ effect (disruption in a part of the supply chain in one system cascade to another system and vice versa). Further, this joint crisis plan could be prepared under an oversight from the national regulator. A compounding factor that exacerbated the Texas 2021 event and the resultant electricity load curtailment was coupling between gas and electricity via gas compressor stations, which were fuelled by electricity and hence reinforced the blackout in the electricity sector, due to low pressure in pipelines carrying gas to the power stations.[41] Another regulatory and policy aspect that emerges from this case study (and others that resulted in load curtailment) is a ´order´ of disconnection in case resilience plans fail to protect system integrity and partial and controlled load shedding is inevitable. In the Texas 2021 case it was the failure to identify gas compressor stations as a 'critical' electric load.[42]

Overall, the ERCOT case study shows that the highly intertwined nature of the electricity and gas sector requires thorough planning and risk assessment to ensure the system's resiliency. Careful coordination and information sharing between gas providers and utilities in the integrated electricity-gas system can mitigate the impact of climate related disasters and quicken the system recovery. A curtailment priority order should be established to keep key gas processing facilities on-line for as long as possible with adequate backup power supply available if they are required to be disconnected from the grid.

Case 6: Explosion at Baumgarten affecting deliveries of Russian gas to Italy (12 December 2017)

On 12 December 2017, at 9 in the morning an explosion occurred on the Gas Connect Austria (GCA) grounds of the Baumgarten Natural Gas Station (Austria). The explosion led to a serious fire, which was contained to a few small fires. The plant was shut down in a controlled manner and was offline for one day. The explosion killed one person and injured 21 others. Gas transit through Austria to the south and southeast regions was affected and GCA notified neighbouring pipeline operators, so that measures can be introduced in a timely manner. This prompted Italy to declare a state of emergency as flows from the strategic site were cut off for most of the day.

In May 2022, the regional court in Korneuburg found four employees at the Baumgarten gas station guilty of negligence over the gas explosion; they were given 10-month prison sentences. According to the prosecutors[43], the incident took place just one day after the installation of the new filtering facility, which prosecutors say had not been reinstalled correctly. Further, the subcontractor also failed to remove a device for filtering moisture in gas pipelines at another site in Austria.

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[41] Busby et al., 2021

[42] This failure to make use of existing critical load assessments is also true of the August 9th 2019 blackouts in the UK, where Newcastle Airport had failed to register itself as critical infrastructure

[43] https://www.euronews.com/2022/05/18/four-employees-sentenced-over-deadly-2017-gas-explosion-in-austria

This case study highlights that, while the nature of risks to the interruption of services provided by gas infrastructure could be different (here it is the explosion in Austria that led to a halt in supplies affecting neighbouring markets – e.g., Italy – compared to rather isolated nature of risks and impacts in the UK and the Texas cases) their impact could be felt in other parts of a highly interconnected system.

Focusing on infrastructure and supply security standard, as defined by the EU Regulation 2017/1938, this case raises a question: should we have N-2 or N-3 or indeed N-1 with regard to the entire EU and/or across both gas and electricity as the two systems become more coupled? The more recent issues related to the war in Ukraine and the EU decision to reduce European reliance on Russian gas by 2027 (RePowerEU plan) make this question even more relevant.

4. RESILIENCE OF ENERGY NETWORKS IN EU ENERGY LAW AND REGULATION

This section starts by mapping the existing and proposed EU legislation that defines requirements in relation to resilience building in the energy sector (Section 4.1). Based on this mapping, a more detailed analysis of the most relevant pieces of legislation previously identified is performed (Section 4.2). As for the rest of the report, the focus is on grid operators' regulation.

4.1 Mapping of relevant legislation

4.1.1 The European Climate Law

For a large part, the EU climate legislation approaches the objective of resilience from a climate adaptation perspective, in line with the provisions of the Paris Agreement and the objective of enhancing adaptive capacity, improving climate resilience and reducing vulnerability to climate change.[44] This is clearly reflected in the European Climate Law, which requires the relevant Union institutions and the Member States to ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change.[45]

4.1.2 SEA Directive and EIA Directive

Under international and EU law, the elaboration of plans and programmes (PPs) is subject to Strategic Environmental Assessment (SEA) requirements. The international framework is set by the 2003 UNECE Protocol on Strategic Environmental Assessment to the Espoo Convention on Environmental Impact Assessment in a Transboundary Context (SEA Protocol). Directive 2001/42/EC (SEA Directive) implements the SEA Protocol into EU legislation, and follows its wording closely.[46] PPs prepared for energy fall explicitly under the scope of both the SEA Protocol and the SEA Directive, and will therefore require an assessment of 'any effect on the environment, including human health, flora, fauna, biodiversity, soil, climate, air, water, landscape, natural sites, material assets, cultural heritage and the interaction among these factors'.[47] Although resilience is not mentioned explicitly, many of the effects to be assessed before the adoption of PPs within energy will affect resilience. It is notable that National Energy and Climate Plans (NECPs) will be considered as PPs.

4.1.3 Governance of the Energy Union Regulation

[44] Paris Agreement to the UN Framework Convention on Climate Change (UNFCCC), Article 2(1) (b) and Article 7.
[45] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), Art. 5(1).
[46] Directive 2001/42/EC of 27 June 2001 of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment (EIA Directive).
[47] Ibid, Art. 2.7.

The EU Governance Regulation refers explicitly to the resilience of the regional and national energy systems and links it to the energy security dimension of the Energy Union. In their plan, Member States must define national objectives to address constrained or interrupted supply of energy sources, ensuring the diversification of energy sources and supply from third countries, energy system flexibility, notably through the deployment of domestic energy sources, demand response and energy storage, and the use of cross-border capacity.[48]

4.1.4 Electricity and Gas market legislation

EU electricity and gas legislation refers to a series of precise concepts and defines requirements that cover parts of the broader objective of resilience. In few circumstances, 'resilience' is explicitly mentioned, without being defined.

'Reliability' is a requirement often mentioned in energy legislation, associated with additional planning duties for operators, such as for power outage planning coordination.[49] 'Power quality' and 'frequency restoration' after deviation are also relevant legislative requirements.[50] Under EU law, the electricity TSOs must include, in their network development plan, measures able to guarantee the 'adequacy of the system and the security of supply', to avoid unnecessary system expansion and to anticipate consumption and cross-border trade.[51] At distribution level, the network development plans are expected to support the integration of renewable energy generation plans, facilitate the development of energy storage, demand response and the electrification of the transport sector, as well as provide adequate information to system users on anticipated expansions or upgrades.[52] At EU level, the Europe-wide ´Ten Year Development Plan (TYNDP)´ elaborated by ENTSO-E must include the modelling of the integrated network, scenario development and 'an assessment of the resilience of the system'.[53] Similar wording is used in the Gas Regulation for the TYNDP, elaborated by ENTSO-G.[54] The concept of 'resilience' is not further defined in the Electricity and Gas legislation.

The different network development plans play a paramount importance in assessing risks of lack of resilience, and the need for resilience-related investments. In accordance with legal requirements and guidance by regulators, operators' assessments are based on methodologies that increasingly refer to resilience, even explicitly. 'Climate resilience' is sometimes referred to in assessment methodologies, but 'resilience' is the most used concept for network operability. For example, the 2020 TYNDP, developed by ENTSOG (European Network of Transmission System Operators for Gas), lists 'climate

[48] Governance Regulation, Art. 4 (c)(1), Annex I – Mandatory template, 2.3 – Dimension energy security.
[49] E.g., the Electricity Regulation art. 37.1 (f) carrying out regional outage planning coordination in accordance with the procedures and methodologies set out in the system operation guideline adopted on the basis of Article 18(5) of Regulation (EC) No 714/2009, Annex I to the Regulation.
[50] See notably: Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing, and Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration.
[51] Electricity Directive, Art. 51.1. and 51.3. The Gas Directive uses a similar wording, Art. 22.1.
[52] Electricity Directive, Recital (61), Art. 32(3)
[53] Electricity Regulation, Art. 48.1.
[54] Gas Regulation, Art. 8.10.

stress' as one of the three types of stressful events to take into account to assess the resilience of the European gas system, next to supply route disruptions and infrastructure disruptions. Climate stress refers here to variation in temperatures that impacts demand and the operability of the network.[55]

Several network codes, guidelines and terms and conditions (TCMs) deal with specific aspects of resilience,[56] but mostly from an energy system perspective, based on market-based solutions. This is reflected by the role played by the system operators in terms of balancing,[57] or the manner to manage 'capacity adequacy'.

The newly revised TEN-E Regulation refers to the need for upgrading the Union's energy infrastructure in order to prevent technical failure and increase its resilience.[58] The types of threats covered are both natural and man-made, therefore covering a broader scope than other EU energy legislation. The TEN-E Regulation also refers to the European critical infrastructures directive 2002/114/EC that is currently under revision.

4.1.5 EU financial support regulation, investment criteria and related standards

It is notable that the EU legislation on climate and energy financing already refers to resilience as an assessment criterion for awarding funding. In the following paragraphs, the most relevant financing instruments are identified and the manner they define resilience as an assessment criteria is commented.

Under the ´Multiannual Financial Framework (MFF)',[59] the relevant programmes must perform a screening of the projects (climate vulnerability and risk assessment) where resilience to the potential adverse impacts of climate change is one of the assessment criteria. The assessment will measure to which extent the costs of ensuring climate resilience is integrated in the cost-benefit analysis. Despite the increase in knowledge base, the European Commission recognises that there are still some knowledge gaps as to how to assess these costs, including for infrastructure resilience. Increasing the climate resilience of infrastructure through projects funded by the European Regional Development Fund (ERDF) or the Cohesion Fund have been prioritised.

In this assessment work, standards focusing on resilience indicators have been developed, including in the context of energy infrastructures. The CEN CENELEC Coordination Group on Climate Change Adaptation (ACC CG) and the related Technical Committees responsible for the energy sector have

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[55] 2020 TYNDP ENTSOG, 29.
[56] See footnote 38.
[57] See for example, Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration.
[58] Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, Recital (10).
[59] Council Regulation (EU, Euratom) 2020/2093 of 17 December 2020 laying down the multiannual financial framework for the years 2021 to 2027.

been updating infrastructural standards. The use of standards forms part of the implementation of the EU Strategy on Adaptation to Climate Change that identified standards as an effective instrument for improving climate resilience of infrastructures across Europe. Energy infrastructures are among the four priority sectors identified in the EU Strategy in this area.[60]

Financing provided under the ERDF and the Cohesion Fund aims to promote climate change adaptation, disaster risk prevention, and resilience, taking into account eco-system-based approaches. As part of the Taxonomy Regulation, the possible negative effects of economic activity on the resilience of ecosystems may conduct to classify it as significantly harming the environmental objectives.[61] Finally, the Recovery and Resilience Facility aims explicitly at fostering resilience.

In more loose terms, the Temporary Crisis and Transition Framework adopted in March 2023, refers to the need to ensure the 'resilience of future EU low-carbon energy system', as well as the 'security and resilience of the internal market', as a justification for providing aid to undertakings severely affected by the crisis, and that for example will require solvency support.[62] Such financial support in the structural resilience of the energy system in a low-carbon scenario is to be distinguished from financial support to undertakings negatively affected by market risks related to non-nature-based events (e.g., price increase spurred by the war in Ukraine).

4.1.6 Risk Preparedness Regulation

Regulation (EU) 2019/941 deals with risk preparedness measures in the electricity sector.[63] It lays down rules for cooperation between Member States with a view to preventing, preparing for and managing electricity crises.[64] An electricity crisis is defined as 'a present or imminent situation in which there is a significant electricity shortage, as determined by the Member States and described in their risk-preparedness plans, or in which it is impossible to supply electricity to customers'[65]. The situations are broad and include the results of natural disasters and extreme weather conditions.[66] The designated national competent authority must ensure that all relevant risks relating to the security of electricity supply are assessed in line with the Directive and the requirements on resource adequacy of the Electricity Directive (including resource adequacy assessment). TSOs and DSOs, among others, will be associated with this task. 'Rare and extreme natural hazards' are included in the methodology, which is to be elaborated by ENTSO-E and submitted to ACER, for the purpose of identifying regional

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[60] CEN-CENELEC, Tailored guidance for standardization technical committees: how to include adaptation to climate change (ACC) in European infrastructure standards, March 2022.
https://boss.cen.eu/media/BOSS%20CEN/ref/climate_adpatation_in_standards_guidance.pdf
[61] Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment (Taxonomy Regulation), Art. 17(1)(f)(i).
[62] Communication from the Commission, Temporary Crisis and Transition Framework for State Aid measures to support the economy following the agresssion against Ukraine by Russia, 2023/C 101/03), 17 March 2023.
[63] Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC.
[64] Ibid, Art. 1.
[65] Ibid. Art. 2(9).
[66] Ibid, Recitals (2), (14), Art. 5.

electricity crisis scenarios.[67] TSOs and DSOs will be central actors in the implementation of the measures identified in the risk-preparedness plans.

4.1.7 Resilience of Critical Entities Directive (CER)

The Commission put forward a proposal for a directive on the resilience of critical entities in December 2020. The Directive was adopted in December 2022.The CER Directive replaces the Directive on the identification and designation of European critical infrastructure, Directive 2008/114/EC.
Several EU pieces of legislation applicable to energy companies and system operators contain obligations to strengthen resilience to other types of threats than nature-based disruptions. These include resilience to cybersecurity attacks, under for example the Cybersecurity Act[68], the proposal for a Digital Operational Resilience Act (DORA) and the proposal for a Directive on measures for a high common level of cybersecurity across the EU (NIS 2). These acts will be relevant for trading and transporting energy but address other types of risks than nature-based ones. They will therefore not be covered in this report.

4.2 Detailed analysis of the most relevant EU legislative requirements

The following sections analyse the content of the most relevant EU legislative requirements related to the role of system operators in resilience building. They assess the types of requirements (e.g., planning, assessment, investment), their legal nature (encouragement or obligation), and the extent of the requested cooperation between grid operators.

4.2.1 Criteria for the elaboration of Network Development Plans for TSOs and DSOs under the Electricity legislation

Pursuant to the Electricity Directive, TSOs shall submit a national ten year Network Development Plan (NDP) to the regulatory authority at least every two years.[69] The NDP shall describe the measures aimed to guarantee the ’adequacy of the system’ and security of supply’.[70] There is no explicit definition whether "security of supply” encompass the resilience to extreme climate events. In addition, the loss of electricity transmission assets - and consequently of transmission capacity - due to nature-based events may also originate local adequacy concerns when it is no longer possible to supply demand in a local area due to reduced availability of transmission capacity.

[67] Ibid, Art. 5(2)(a).
[68] Regulation (EU) 2019/881 of the European Parliament and of the Council of 17 April 2019 on ENISA (the European Union Agency for Cybersecurity) and on information and communications technology cybersecurity certification and repealing Regulation (EU) No 526/2013 (Cybersecurity Act).
[69] Electricity Directive, Art. 51.
[70] Electricity Directive, Art. 51(1).

When elaborating the plans, TSOs must take into account the potential for the use of demand, response, energy storage facilities or other resources as alternatives to system expansion. They must also take into account prospects in terms of consumption, trade with other countries and investment plans for Union-wide and regional networks.[71] The national regulatory authority shall assess the consistency of the NDP will the Union-wide TYNDP. Investments necessary to implement the NDPs must be ensured, either by the TSO or, in case the latter does not execute them, by the regulatory authority.[72] In conclusion, resilience to nature-based disruption to the energy system will be partially addressed as forming part of system adequacy and security of supply, but is not singled out and not explicitly mentioned.

Pursuant to the Electricity Directive (Article 31), the DSO shall be responsible for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity, for operating, maintaining and developing under economic conditions a secure, reliable and efficient electricity distribution system in its area with due regard for the environment and energy efficiency. Security and reliability of electricity supply are therefore set as key tasks of European DSOs, but, again, without an explicit reference to resilience against extreme events.

Under the Electricity Directive, the DSOs have the obligation to publish at least every two years a network development plan that they shall submit to the regulatory authority.[73] The network development plan shall provide transparency on the medium and long-term flexibility services needed and shall set out the planned investments for the next five-to-ten years, with particular emphasis on the main distribution infrastructure which is required in order to connect new generation capacity and new loads. While not explicitly mentioned in Article 32, the planned investments are expected to include investments for security/reliability reasons, due to the key tasks set out in Article 31.

In addition, this emphasis is put on the integration of new capacity and flexibility, notably in terms of demand response, energy efficiency, energy storage and other alternative to system expansion. In that context, an increased focus on flexibility contributes to resilience building.[74] This is also emphasised by a White Paper on flexibility for resilience ordered by the European Commission.[75] However, there is little basis in the EU legislation to weigh in resilience to more frequent and extreme nature-based disruption into the development plans forming the basis of system operators' grid investments. The criteria used today in network grid planning do not necessarily reflect the scale of the upcoming disruption. This raises the question of the need to adjust metrics to both large-scale and long-term signals.

[71] Electricity Directive, Art. 51(3).
[72] Electricity Directive, Art. 51(7).
[73] Electricity Directive, Art. 32(3).
[74] See already conclusions in that sense: J. Cochran, et al, "Flexibility in 21st Century Power Systems", National Renewable Energy Laboratory, 2014.
[75] Flexibility for Resilience. How can flexibility support power grid resilience? ETIS SNET (2022) https://smart-networks-energy-transition.ec.europa.eu/system/files/2022-06/MJ0722296ENN.en_.pdf

4.2.2 Criteria for the elaboration of the Union-wide Ten Year Network Development Plan by ENTSO-E and ENTSO-G

The Electricity Regulation (Article 30(1)(b)) requires ENTSO-E to elaborate the Ten Year Network Development Plan (TYNDP) that is a legally non-binding document Pursuant to Article 48 of the Regulation. The TYNDP shall include 'the modelling of the integrated network, scenario development and an assessment of the resilience of the system'. Resilience is therefore explicitly mentioned as a criterion for elaboration of the TYNDP. This has influence on the investment decisions to be taken, and that shall be consistent with the plan. Grid investment planning is a crucial initial step for ensuring that the energy system will have sufficient resilience. This is often operationalised by the application of criteria linked to flexibility or adequacy. This can be seen as a first step in the operationalisation of the objective of resilience in EU grid regulation.

ACER is to be involved in the elaboration procedure, providing an opinion and assessing the consistency between the national TYNDPs and the Union-wide TYNDP. In case of inconsistencies, it has the legal obligation to recommend amending the plans. There is however little guidance as to how to interpret the concept of "resilience" in the Regulation itself. In its Opinion on the methodology aspects of the ENTSO-E drafting of Union-wide TYNDP, ACER is not either providing indications as to how to interpret this criterion.[76] There is not either reference to resilience in ACER's assessment of the first draft Union-wide TYNDP after the entry into force of the 2019 Electricity Directive, which reveals that resilience is not yet a criterion actively applied by ACER in its review of TYNDP or methodologies for it.[77]

4.2.3 Criteria for the elaboration of regional outage planning coordination

Pursuant to Electricity Regulation (Article 37.1 (f)), the regional coordination centre shall carry out so-called 'regional outage planning coordination' in accordance with the procedures and methodologies set out in the system operation guideline (SOGL)[78] adopted on the basis of Article 18(5) of Regulation (EC) No 714/2009. Each regional security coordinator shall perform regional operational security analyses taking into account the information provided by the relevant TSOs in order to detect any outage planning incompatibility. Based on this assessment, the coordinator shall provide a list of detected outage planning incompatibilities and of the solutions it proposes to solve those outage planning incompatibilities (Art. 80(4), SOGL). The TSOs are themselves obliged to take into account the results of the assessment provided by the regional security coordinator.

[76] Opinion No 03/2021 of the European Union Agency for the Cooperation of Energy Regulatory of 3 May 2021 on the methodological aspects of the ENTSO-E draft Ten-Year Network Development Plan 2020 (TYNDP).
[77] Opinion No 04/2021 of the European Union Agency for the Cooperation of Energy Regulators of 3 May 2021 on the electricity projects in the draft ENTSO-E Ten Year Development Plan 2020.
[78] Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (SOGL).

4.2.4 Network codes requirements related to electricity balancing and emergency and restoration

Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing (EBGL), and Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration (E&R network code) also contain relevant requirements for the resilience building.

Balancing refers to the set of actions and processes that TSOs can apply on all timelines in order to ensure the maintenance of system frequency within a predefined stability range.[79] Balancing is key to the delivery of electricity to final consumers. The integration of flexibility, demand response or energy storage in the procurement of balancing services, as foreseen in SOGL, strengthens grid resilience.

The E&R network code, building on the requirements in SOGL, defines requirements and processes for addressing electricity emergency situations and restoration. SOGL identifies different critical system states, ranging from: normal state, alert state, emergency state, blackout state and restoration. This indicates a resilience circle process. SOGL also defines requirements and principles to ensure that the conditions for maintaining operational security are met. Pursuant to the E&R network code, each TSO 'should' establish a 'system defence plan' (Art. 11-22) and a 'restoration plan' (Art. 23-25) that follow a three-step process: a design phase for the plan; an implementation phase, where the necessary measures are implemented; an activation phase, where the measures identified in the plan are actively used. This process shows again that planning by system operators is a crucial part of resilience building, where the definition of risk situations and mitigation measures are key.

4.2.5 Methodology criteria for "rare and extreme natural hazards" as part of regional electricity crisis scenarios

ENTSO-E is required to elaborate the methodology for identifying the most relevant regional electricity crisis scenarios "and to submit it to ACER, pursuant to Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector (Article 5). The methodology must take into account, among others, the risk of 'rare and extreme natural hazards' (Art. 5(2)(a)).

4.2.6 Regulation of critical entities under the directive on resilience of critical entities

Pursuant to the Directive on the resilience of critical entities (Critical Entities Resilience Directive)[80], several energy assets will be defined as 'critical entities', meaning entities providing essential services that are crucial for the maintenance of vital societal functions, economic activities, public health and

[79] SOGL, Art. 2.

[80] Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC.

safety, and the environment. Such entities must be identified by all Member States (Member State Risk Assessment) and will be subject to a series of obligations aimed at enhancing their resilience and ability to provide services in the internal market.

The directive requires Member States to identify and develop measure helping the resilience of critical entities, following a risk-based approach (critical entity risk assessment). The later focuses on the entities most relevant for the performance of vital societal functions or economic activities. In order to ensure such a targeted approach, each Member State should carry out, within a harmonised framework, an assessment of the relevant natural and man-made risks, including those of a cross-sectoral or cross-border nature, that could affect the provision of essential services, including accidents, natural disasters, public health emergencies such as pandemics and hybrid threats or other antagonistic threats (e.g., terrorist attacks).

Based on the results from this assessment and the information provided by Member States, the critical entities must take appropriate and proportionate technical, security and organisational measures to ensure their resilience and have in place a ‘resilience plan’.

On their side, critical entities are encouraged (‘should’) to have a comprehensive understanding of the relevant risks to which they are exposed and a duty to analyse those risks. To that end, they should carry out risk assessments whenever necessary (‘critical entity risk assessment’). Specific provisions apply to critical entities of European significance.

The directive provides for a legal definition of resilience, meaning 'a critical entity’s ability to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover from an incident’ (Art. 2).

5. TSOS' AND DSOS' ROLE IN ENHANCING RESILIENCE AND MITIGATING RISKS

5.1 Electricity

TSOs and DSOs are responsible for the reliable transmission and distribution of electricity to customers. It follows that they must play a key role in maintaining and improving resilience of electricity networks to climate-related hazards. It is clear from the cases in Chapter 3 how susceptible above-ground power lines – both at transmission and distribution level – are to hazards such as wildfires. The frequencies of extreme weather-related events to infrastructure are expected to increase in the coming years and decades.

Concurrent with the increased frequency of climate-related hazards, the share of intermittent renewables generation (RES) has been on the rise and is set to increase even further in the coming years. This is already posing challenges for TSOs who must manage power flows that are less predictable than those in a system with mostly conventional generation. The increased share of RES, and the path to a low-carbon power system, poses many challenges such as increasing loop flows and significant re-dispatching and countertrading needs to correct market outcomes. These challenges will only increase. This project does not focus on the RES and the related market design issues.[81] A consequence of this development is, however, that the system may be less stable than before and more vulnerable to shocks. This is certainly relevant for the resilience of the power system. Questions also arise regarding whether established rules of operation such as the N-1 rule, currently the European norm on transmission system operation, are sufficiently robust to hold up to the transformation to a low-carbon system combined with increased risk of extreme climate-related hazards, where it is common to see N-2 or N-3 situations arise.[82]

How can resilient practices by TSOs and DSOs mitigate the risk of disasters and the consequences of extreme events? There are many possible options for this. A non-exhaustive list would probably include:

- Moving from Run-to-Failure Management to Preventive Maintenance.
- Exploiting the opportunities of digitalisation.
- Improving cross-sector coordination and system integration/sector coupling.
- New investment metrics, benchmarking, and standards.

TSOs and DSOs can no doubt move in the direction of resilient practice within the existing regulatory environment; there are low-hanging fruit to be picked. Better protocols as regards communication

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[81] Although market design should take resilience of the power system into consideration.

[82] The N-1 rule stipulates that any single contingency should not endanger the power system; see Articles 34 and 35 of Commission Regulation (EU) 2017/1485 of 2 August 2017 Establishing a Guideline On electricity transmission System Operation.

with authorities such as firefighting services are a good example of this (cf. Case 1 above). Network operators are, however, subject to regulation which may limit their room for manoeuvre. Thus, operators, regulators, and legislative bodies must work together to improve the regulatory framework in terms of resilience.

5.2 Natural gas

Irrespective of plans to increase resilience, the role of gas network operators is to ensure uninterrupted services of transporting gas from anywhere in their respective network areas to end-use customers at minimal cost. Currently, Regulation (EU) 2017/1938 on security of gas supply[83] defines two security of supply standards that are used to assess how each EU Member State (MS)'s gas network would be impacted by the loss of its largest piece of gas infrastructure:

1. ´An infrastructure standard´, incorporating the so-called N-1 criterion, which determines the percentage of gas demand that could be met on a day of exceptionally high gas demand in the event of the loss of MS' largest single piece of gas infrastructure.
2. ´A supply standard´ which stipulates that MS must be capable of supplying gas to meet the needs of protected customers for 30 days, in the event of disruption to the single largest piece of gas infrastructure under average winter conditions.

Thus, under the current regulation, a key goal of gas network operators is to ensure that all the required actions are taken to secure an uninterrupted supply of gas throughout the EU, especially to protected customers. The regulation stipulates that all such measures should be cost-effective and taken in a way that does not distort gas markets. The regulation defines three crisis levels:

1. 'Early warning' where there is concrete, serious, and reliable information that an event will significantly deteriorate the gas supply situation.
2. 'Alert' level where a disruption of gas supply, which results in significant deterioration of the gas supply situation, occurs but the market is still able to manage that disruption without the need to resort to non-market-based measures.
3. 'Emergency' level where all relevant market-based measures have been implemented but the gas supply is insufficient to meet the remaining gas demand so that non-market-based measures have to be additionally introduced with a view, in particular, to safeguarding gas supplies to protected customers[84].

[83] Regulation (Eu) 2017/1938 of the European Parliament and of the Council of 25 October 2017 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010.

[84] Protected customer' means a household customer who is connected to a gas distribution network and, in addition, where the Member State concerned so decides, may also mean one or more of the following, provided that enterprises or services as referred to in points (a) and (b) do not, jointly, represent more than 20 % of the total annual final gas consumption in that Member State: (a) a small or medium-sized enterprise, provided that it is connected to a gas distribution network; (b) an essential social service, provided that it is connected to a gas distribution or transmission network.

Importantly, the Regulation (Article 8) requires each MS to establish preventive action plans and emergency plans which must be updated every four years, unless circumstances require updates that are more frequent. All EU MS submitted their preventive action plans and emergency plans in 2019-20 for the European Commission (EC) to review[85].

Note that different MS may have somewhat different treatment of gas demand in the power generation sector and this treatment depends on the role of gas in the power sector (in particular if it is used in Combined Heat and Power (CHPs) to produce heat, as a primary fuel) emergency plans.

In most cases, gas markets continue to function as business as usual under the 'early warning' stage. In the UK, there are four stages in its emergency plan which correspond to the last two stages stipulated in the SoS regulation (alert and emergency levels) and the 'early warning' stage of the SoS regulation is entirely ignored in the UK emergency plan[86].

Market-based and non-market-based measures in national gas emergency plans (where those are mentioned explicitly in the plans) may be summarised as follows:

[85] These plans are available here: https://energy.ec.europa.eu/topics/energy-security/secure-gas-supplies/commissions-opinions-preventive-action-plans-and-emergency-plans-submitted-eu-countries-2019_en

[86] 'Alert' level corresponds to stage 1 (potential) see: https://energy.ec.europa.eu/system/files/2019-11/2019.11.07-national_emergency_plan_2019_0.pdf

Supply side	Demand side
'Alert' level: market-based measures	
Increased indigenous production (from renewable and exhaustible resources) and use of line-pack	Fuel switching
Use of commercial gas storage	Use of interruptible contracts
Maximise imports from LNG and pipeline sources	Voluntary load shedding
Coordinated dispatching by TSO	
'Emergency' level: non-market-based measures	
Increase use of line-pack to maximum possible without violating network integrity and safety of operations	Instruction to shed flow to interconnected markets
Instruction to maximise supplies from gas production and storage facilities (if gas in storage is part of strategic stock), including from LNG storage	Instruction to reduce gas demand for the gas-fired power generation sector and use of electricity not generated by gas
Request for activation of the cooperation and solidarity measures by other MS	Instruction to switch fuel and usage of secondary fuel stock
LNG cargo diversions through contractual options	Instruction related to heat load in public buildings
	Instruction to final consumers to reduce gas consumption and switch off industrial customers
	Definition of new temperature and/or schedule thresholds for domestic heating sector, supplied with gas

Table 1: Market and non-market-based measures to cope with a gas security of supply event: a summary of Member States emergency plans

It may be noted that, in accordance with the approach set out in EU Regulation 2017/193818, the N-1 assessment does not consider the potential for drawing line-pack gas stored in the gas transmission network to supply additional gas when there is a supply shortfall. Nevertheless, that use of line-pack is considered by some member states (e.g., Germany) as market-based measures while by others as non-market-based measures (e.g., Republic of Ireland). As evident in Table 1, most measures in the emergency plans are of a demand side nature.

6. REGULATORY PATHWAYS TO FOSTER RESILIENCE

6.1 Hurdles in the legal and regulatory environment

The EU energy legislation does address several sides of resilience in a targeted and efficient manner. However, the approach is often limited to specific aspects of resilience, focusing on energy system performance (adequacy, security of supply, reliability, frequency stability), while a more holistic approach should be promoted. On the background of energy system integration and the interrelated consequences of nature-based disruptions on energy production and transport assets, a more integrated approach to resilience building is required.

While the regulatory approach should be more holistic and comprehensive, the specificities of the different energy carriers and of the different energy production types must be acknowledged. Gas and electricity transport assets are impacted differently by natural disasters. Similarly, offshore wind energy production, distributed RES generation, nuclear power plants and hydropower plants are not subject to weather stress conditions in the same manner.

The EU legislation defines precise requirements for grid operators in terms of grid planning. Grid planning should be used as an essential requirement for assessing the need for building resilience of the energy system, not least because it serves as the basis for making related investments. The list of assessment criteria for grid planning and underlying methodologies and metrics must better reflect all components of resilience building, both short-term and long-term.

A central question in terms of regulatory approach is to know whether ‘resilience’ should be part of the economic regulatory model for operators (with economic incentives to invest in it) or whether it should not be monetised and therefore regulated as a separate issue.

6.2 Cost-Benefit Analysis as a vehicle for improved resilience

Cost-Benefit Analysis (CBA) rules are crucial when it comes to investments in regulated networks like distribution and transmission networks: the CBA of an investment project is in essence a framework weighing costs related to a certain investment against the benefits. If the benefits of resilience investments are not properly accounted for in the analysis, then investments with a primary focus of improving resilience will yield a negative CBA balance. If decisions are made on that basis, they will be automatically ruled out.

For electricity, the relevant European-level documents in this area are the ´ENTSO-E CBA Guideline for Cost-Benefit Analysis of Grid Development Projects´ and the ´Ten-Year Development Plan Implementation Guidelines´. The most recent version of the former document dates from 2021 and the latter from 2022. While security of supply is an important variable in these guidelines, resilience as such is hardly mentioned: the CBA Guideline only mentions resilience once in the entire document and this is to state that "High Impact Low Probability events, such as 'disaster and climate resilience'" are difficult to monetise since "multiplying low probabilities and very high consequences [has] little meaning" (p. 143).[87] While this text should not be taken out of context – which is that of explaining why multi-criteria analysis is favoured by ENTSO-E – it illustrates the risk that resilience benefits are not properly taken into consideration when it comes to evaluation of investment projects.

It should be noted here that security of supply and reliability indicators are likely to improve because of resilience investments. Indeed, there is a close relationship between reliability and resilience since resilience may be considered an input that contributes to the achievement of reliable service (AER, 2022). It is, however, by no means clear that resilience benefits will be fully accounted for in CBA when only reliability or security of supply measures are included.

Preventative maintenance and sophisticated planning tools – see e.g., the section on developments in Italy below – are clearly also important to enhance resilience. These, as well as strategies on holding of spares and protocols on sharing of engineering staff across regions, are key and will support rapid recovery from shocks which should be a priority. Introducing economic incentives, e.g., by compensating customers for being off supply, would strongly incentivise quick recovery. However, regulation needs to be sufficiently flexible to allow for such strategies and achieve an optimal balance between resilience and reliability benefits and the associated costs.

As related to natural gas project appraisals, Regulation (EU) No. 347/2013 (TEN-E)[88] tasks ENTSOG with developing a methodology for cost-benefit analysis (CBA) to support the Projects of Common Interest (PCI) selection process.

In 2018, ENTSOG developed its 2nd CBA methodology (gas CBA)[89] in which the term "resilience" was used twice, and various types of risks are considered. In particular, the gas CBA explicitly accounts for climatic and supply stresses and monetise the benefits from avoided demand curtailment arising from these 'stress' conditions. Therefore, 'resilience' of the gas system is understood in this context. In particular, as noted in the gas CBA (p.46)[90] "In addition to assessing demand curtailment risks, the remaining flexibility assesses how resilient to climatic stress a country is. The remaining flexibility aims

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[87] A new draft version (no. 4) of the ENTSO-E CBA was out for public consultation until 15 February 2023, https://consultations.entsoe.eu/system-development/methodology-for-a-energy-system-wide-cost-benefit/. The new draft CBA follows the revised TEN-E Regulation (EU) 2022/869, including the requirements for the content of the methodology for the system-wide CBA. The document does not, however, mention resilience as such.

[88] TEN-E is a European Parliament and Council regulation that provides guidelines for trans-European energy infrastructure. The regulation aims to facilitate investment in energy infrastructure to achieve the European Union's energy and climate policy objectives. It establishes a process for identifying PCIs), projects deemed significant for Europe which will receive benefits such as streamlined permitting procedures and cross-border cost allocation. It defines 12 European energy priority corridors, which are regions that have been identified as being of particular importance for energy infrastructure investment. The regulation also establishes Regional Groups, which are responsible for assessing candidate projects for PCI status in their respective regions, and play a crucial role in determining which projects will receive the benefits associated with being designated as a PCI.

[89] https://entsog.eu/methodologies-and-modelling#consistent-and-interlinked-electricity-and-gas-model

[90] https://www.entsog.eu/sites/default/files/2019-03/1.%20ADAPTED_2nd%20CBA%20Methodology_Main%20document_EC%20APPROVED.pdf

at capturing the extra supply flexibility a country can access through its infrastructure.*"* This remaining flexibility is measured by the increase in demand that can be accommodated before an infrastructure or supply limitation is reached. This indicator is calculated independently for each area and considers stressful situations such as extreme weather conditions and supply or infrastructure constraints. The calculation of this indicator helps to identify areas where investment in energy infrastructure may be necessary to ensure the continued reliable operation of the European gas system. The higher the value (expressed as a percentage of demand for a given area), the better the resilience[91].

Thus, the gas CBA methodology does explicitly acknowledge gas system resilience, not just in terms of traditional security of supply definition such as disruption of the largest infrastructure or 1-in-N demand conditions, but a combination of ´stress´ events, of which climatic stress conditions are assessed both independently (1-in-N) but also jointly with N-1 type of risk events. Thus, a variety of risks are assessed, and resilience of the system is monetised against these risks.

Gas CBA methodology went further and in May 2021, together with ENTSO-E, the document entitled ´ENTSOG and ENTSO-E Interlinked Model investigation, screening, and dual assessment´[92] was produced, recognising the increasing nature of sector coupling between gas and electricity sectors in Europe as the region undergoes complete decarbonisation. Again, the term "resilience" was used at least twice and both in the context and understanding as per the 2nd gas CBA methodology document. That is, resilience is expressed as 'Curtailment Rate Indicator (CR)', which measures the resilience of the European gas system (in terms of demand curtailment) to cope with various stressful events (climatic stress and supply route and infrastructure disruptions). This sector coupling trend means that as we decarbonise our energy system and potentially electrify heat load with variable renewables, the effects of climatic variability on electricity and hence on the gas system will magnify and increase considerably. While the gas CBA does explicitly mention probability of climatic stress events (p.43 of the gas CBA document[93]) (be it 1-in-20 or 1-in-50)[94] on gas demand, and hence straightforward monetisation of gas infrastructure resilience in this regard, other risks such as politically motivated actions to shut down a supply route (e.g., the ongoing war in Ukraine caused Russia to shut down gas flows to Europe via a number of pipelines) and especially the ones propagating from sector coupling with the electricity sector (e.g., wildfire, see discussion at the end of Section 2) are problematic to monetise as there is little basis to calculate risk and systematic definition of probabilities.

It is important to note that the TEN-E Regulation 347/2013 was repealed by Regulation 2022/869 (the revised "TEN-E Regulation"), in force since June 2022. The revised TEN-E Regulation sets guidelines for the development of trans-European energy infrastructure to support the EU's climate and energy

[91] p.46 of the gas CBA document.
[92] https://entsog.eu/sites/default/files/2021-05/ILM%20Investigation%20Document.pdf
[93] https://www.entsog.eu/sites/default/files/2019-03/1.%20ADAPTED_2nd%20CBA%20Methodology_Main%20document_EC%20APPROVED.pdf
[94] 1-in-20 or 1-in-50 is a gas infrastructure supply standard requiring gas network operators to factor in network capability to withhold extreme weather conditions occuring one in twenty years (or one in fifty years).

targets and objectives. The regulation includes new investment categories such as energy storage, CO_2 networks, and smart electricity and gas grids. The new TEN-E does not require anymore a gas CBA methodology and instead requires the Commission to ensure the development of harmonised cost-benefit analysis (CBA) methodologies for candidate projects in these categories, and the methodologies will be developed in a transparent manner through consultations with Member States and stakeholders. The TEN-E Regulation also includes hydrogen transport and storage infrastructure in its scope, but the deadline for the development of a final hydrogen CBA methodology does not align with the timeline for the first Union list of PCI/PMI. As a result, the Commission has tasked the JRC to develop a draft hydrogen CBA methodology to bridge the gap between the first PCI/PMI process and the ENTSOG methodology.

6.3 Current national initiatives

Beyond European regulation, the national level is important. Interestingly, there are already emerging examples of a changed approach in this area where resilience considerations are considered.

There exist examples of initiatives aiming at improved electricity system resilience. Below, we briefly describe four such initiatives. Three of those concern the regulation of distribution networks and originate from the UK, Australia, and Italy. Concrete examples in the realm of transmission system operation are harder to find, but we outline one such initiative in Italy.

United Kingdom - Ofgem

In the UK, Ofgem has recently made it a requirement for electricity distribution network operators to include resilience aspects into their business plans.[95] Several dimensions of resilience are considered:

- Asset resilience
- Workforce resilience
- Cyber resilience
- Physical security
- Climate resilience

As regards asset resilience, companies' business plans must give estimates of asset health, criticality, and replacement priorities. Physical security involves requirements associated with assets deemed as Critical National Infrastructure. Business plans must include a climate resilience strategy, outlining how DSOs will respond to the impacts of climate change on their networks over the long term. In particular, DSOs are required to identify how they aim to ensure their networks remain resilient to the impacts and risks of climate change.

[95] Ofgem (2021). RIIO-ED2 Business Plan Guidance, September, https://www.ofgem.gov.uk/publications/riio-ed2-business-plan-guidance accessed on 21 November 2022.

Italy - ARERA

Following on extreme snow events in Central Italy, which caused prolonged disconnection of over 100,000 customers, institutional stakeholders took steps towards the introduction of resilience in the regulatory framework.[96] ARERA, the Italian utilities regulator, introduced an incentive-based regulation aimed at increasing the resilience of electricity distribution networks and made it a requirement for electricity DSOs to provide prioritised three-year plans for resilience investments each year, concerning two aspects: a) the design of a network able to withstand extreme events, and, b) the ability of the system to restore its standard operation after such events. Each year DSOs are required to publish a three-year plan for defending their networks against risk factors such as ice sleeves on cables due to snow or wind, heatwaves, flooding and fallen trees due to snow.[97] A cost-benefit analysis must be provided for each project, following ARERA guidelines.[98] There are penalties for DSOs which identified a resilience-related project and do not implement that project within 12 months after the planned commissioning date.

Australia - AER

In Australia, following the 2021 storms the Victorian government established an Expert Panel to perform a regulatory review with a focus "on the distributors' obligation to: improve distribution network preparedness for, and response to, prolonged power outages arising from storms and other extreme weather events strengthen community resilience to prolonged power outages."
The Panel's final report[99] contains numerous and quite detailed recommendations for immediate, medium-term, and longer-term reform for improving network resilience.

The main recommendation for the long term is that "… national legislative framework should be amended to drive distributor investments in resilience in the longer-term"[100] and that the regulatory framework should be amended with this purpose. The Australian Energy Regulator (AER), for its part, has issued a short note on key issues regarding resilience expenditures of DSOs.[101] The AER finds that the regulatory framework is sufficiently flexible to allow for resilience expenditures. Conditions for allowing such expenditures are also outlined: *inter alia*, they need to be causally linked to expected increase in extreme weather events and shown to be required to maintain service levels in the most efficient way.

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[96] See Eurelectric (2022). The Coming Storm – Building Electricity Resilience to Extreme Weather, position paper/report (p.25). https://www.eurelectric.org/publications/the-coming-storm-building-electricity-resilience-to-extreme-weather-full-study/ accessed on 18 January 2023.

[97] ARERA (2022). Annual Report to ACER and the EC, https://arera.it/allegati/relaz_ann/22/AnnualReport2022.pdf, accessed on 22 November 2022.

[98] For further background and details see Lo Schiavo, L., Villa, F., & Turconi, C. (2019). Regulatory incentives for improving the resilience of electricity distribution grids in Italy, CIRED conference proceedings,
https ://www.cired-repository.org/handle/20.500.12455/760?show=full accessed on 1 February 2023

[99] Electricity Distribution Network Resilience Review Expert Panel (2022), Final Recommendations Report.

[100] Electricity Distribution Network Resilience Review Expert Panel (n66).

[101] Australian Energy Regulator (2022). Network Resilience: A Note on Key Issues, April.

Italy – Terna/RSE

All the above examples relate to DSOs. It is to some extent understandable that the first steps as regards moving towards improved resilience are taken at the distribution level; homes and other customers are directly connected to the distribution network and feel the impact of failures immediately and sometimes with great force and serious consequences. However, it is also important to consider resilience of transmission networks. In Italy, starting in 2017, Terna (the Italian electricity TSO) and RSE (an Italian company centred on the development of research activities in the energy sector) have developed a new risk-based methodology for improving resilience of the power grid, that received in 2022 a positive verification by ARERA (the Italian National Regulatory Authority).[102]

Resilience measures include preventive action (aimed at increasing network meshing realising new power lines), recovery actions (aimed at reducing line restoration time following power outage), mitigation actions (aimed to contain risks on the electrical system and reduce damages), and monitoring interventions (to foresee critical weather events which could have an adverse impact on the grid with the use of innovative technological solutions).

The new methodology is characterised by the following 3 key elements:

- Development of climate scenarios allows the identification of areas most exposed to the effects of severe weather events of different nature, associating with them the relative probability of climate hazards. The approach is scalable and replicable.
- An engineering approach for estimating the vulnerability of different components of electrical overhead lines to direct and indirect stresses caused by severe weather events by determining specific vulnerability curves defined by using real technical and orographic parameters.
- A probabilistic N-k approach for analysing multiple and simultaneous outages due to weather events in order to quantify the probability of occurrence of such multiple contingencies and assess their impact (in terms of Expected Energy Not supplied) on the portion of the power system exposed to the severe weather event.[103]

California

A new law has been enacted in response to wildfire disasters in California.[104]It addresses the increased financial risks facing major utilities (such as PG&E) resulting from climate change. The legislation is intended to mitigate the risk of wildfires as well as specifying how costs of future damages are to be distributed. Utilities are required to invest a total of $5 billion in safety measures such as more frequent power line inspections and better vegetation management. A wildfire safety advisory board has been established to advise the California Public Utility Commission (CPUC) as well as reviewing

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[102] Terna (2021). Tackling Climate Change: Terna, RSE, ARERA Take Action to Support the Resilience of the Electricity System, May 5, accessed on 22 November 2022. ARERA's role was to provide a positive verification to the TERNA-RSE methodology. This was by ARERA decision 9/2022, https://www.arera.it/it/docs/22/009-22.htm.

[103] For further details see https://www.terna.it/it/sistema-elettrico/codici-rete/codice-rete-italiano; A.76 "Allegato A.76 – Metodologia per il calcolo dell'incremento della resilienza della Rete di Trasmissione Nazionale".

[104] John MacWilliams et al. (2019) n. 25.

utilities' implementation of safety requirements and wildfire mitigation plans intended to reduce the probability of future catastrophic wildfires. Moreover, a $21 billion insurance fund, the California Wildfire Fund, has been established to enable utilities to stay liquid and provide essential services when facing large disasters. A CPUC-issued safety certificate is a prerequisite for accessing the insurance fund for recovery of costs related to wildfires.

The new Californian law is set to strengthen regulatory and corporate resilience expertise and climate planning requirements. It also defines utilities' financial exposure to wildfire risk and reduces investor uncertainty, making it easier for utilities to access market funding.

6.4 Measuring and monetising resilience

Clearly, resilience is an important attribute of energy systems and making these systems more resilient, i.e., improving their capability to withstand extreme events and to recover quickly from such events, is extremely important. As always, there are trade-offs between costs and benefits of resilience interventions of various kinds. While the costs of investments, preventative maintenance etc. are rather easy to measure, the benefits of improved resilience are not as well understood.

In Section 2.1, resilience was defined as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event". This definition includes several important elements which make it challenging to quantify the degree to which a system is resilient to disruptive events. However, good metrics for measuring resilience are essential: without such metrics, resilience aspects are likely to be underestimated and inadequately incentivised. In particular, the ability to recover from shocks may not be taken sufficiently well into account. But how should the resilience of a power system be quantified?

In recent years, concurrent with the emergence of resilience as an essential attribute of energy infrastructure, there has been considerable research in this area. Several approaches to measuring resilience have been proposed.[105] Most methods for measuring resilience have in common the so-called 'resilience trapezoid' (or some variation thereof) shown in Figure 1, which is a stylised but helpful way of showing the response of an energy system to a disruptive event. The figure illustrates the ability of the system to *withstand, absorb, restore,* and *adapt* to a disruptive event. In principle, these different dimensions of resilience could be measured and included in resilience metrics.[106] Importantly, a metric (or metrics) should consider how significant a disruption in power and gas

[105] See, e.g., Roege, P. E., Collier, Z. A., Mancillas, J., McDonagh, J. A., & Linkov, I. (2014). Metrics for energy resilience. Energy Policy, 72, 249-256; Willis, H. H., & Loa, K. (2015). Measuring the resilience of energy distribution systems. RAND Corporation: Santa Monica, CA, USA, 38; Panteli, M., Mancarella, P., Trakas, D. N., Kyriakides, E., & Hatziargyriou, N. D. (2017). Metrics and quantification of operational and infrastructure resilience in power systems. IEEE Transactions on Power Systems, 32(6), 4732-4742; Vugrin, E. D., Castillo, A. R., & Silva-Monroy, C. A. (2017). Resilience Metrics for the Electric Power System: A Performance-Based Approach (No. SAND2017-1493). Sandia National Lab.(SNL-NM), Albuquerque, NM.

[106] Or resilience *matrix* as in Roege et al. (2014) (n. X).

systems performance due to a high-impact event is likely to be, how the system adapts to the shock, and how quickly it can recover and return to regular operation.

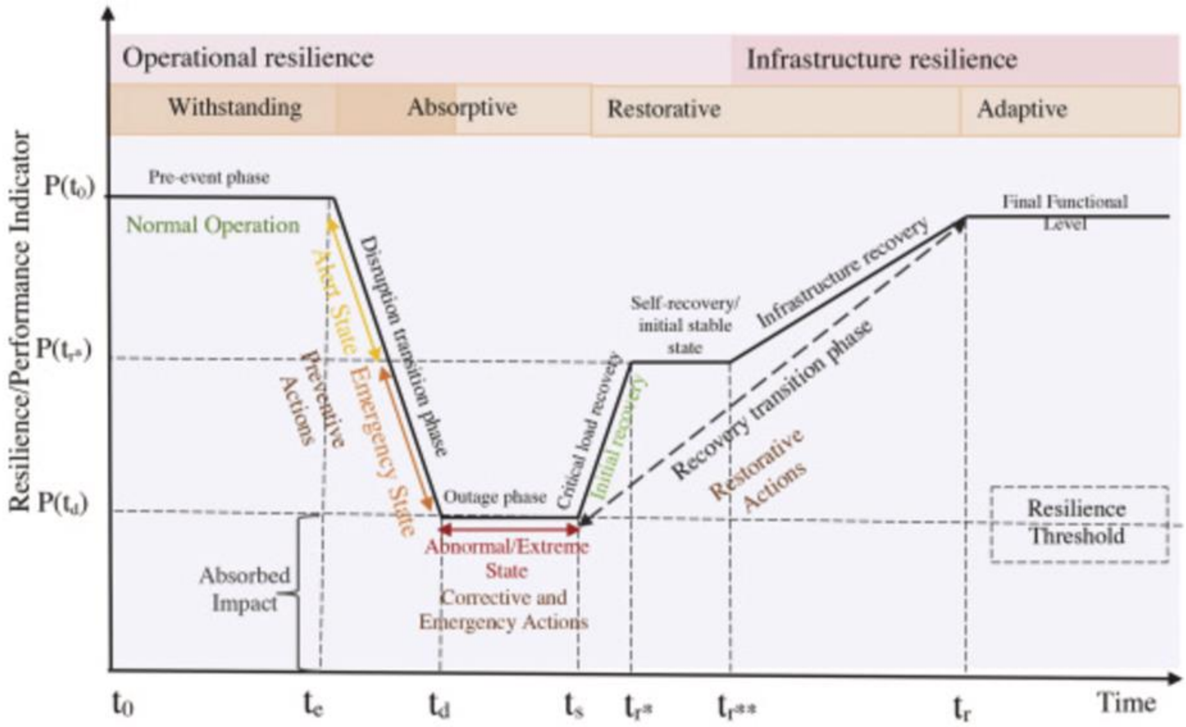

Figure 2. The resilience trapezoid associated with an event[107]

6.4.1 Resilience and reliability in the electricity market

It is relevant to consider resilience in conjunction with 'reliability' of the power supply. However, while resilience and reliability are related concepts, there are important differences. For example, due to its multidimensionality, resilience is more challenging to quantify than reliability. CBA guidelines tend to use reliability metrics such as the System Average Interruption Duration Index (SAIDI) as well as the System Average Interruption Frequency Index (SAIFI) combined with estimates of Value of Lost Load (VoLL) (or in case of gas, using Cost of Disruption of Gas Supply, CoDG[108]) for measuring reliability and monetising benefits. There is no similar consensus yet on metrics for measuring resilience. Moreover, the reliability metrics are aimed at short-term events and small-scale impacts. In contrast, a metric measuring and/or monetising resilience must consider the low probability but high impact and long-

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[107] Figure from A. Umunnakwe, H. Huang, K. Oikonomou, K.R. Davis (2021). Quantitative analysis of power systems resilience: Standardization, categorizations, and challenges, Renewable and Sustainable Energy Reviews, Volume 149, 111252.

[108] https://documents.acer.europa.eu/en/Gas/Infrastructure_development/Pages/Study-on-the-estimation-of-the-Cost-of-Disruption-of-Gas-Supply-(CoDG)-in-Europe.aspx

duration aspects of extreme events.[109] Thus, current reliability metrics are not sufficient for the analysis of investments that aim at improving resilience to large-scale disruptions.[110] A different approach is required for resilience.

A strand of the discussion around resilience revolves around current regulatory benchmarks such as the N-1 criterion. The context is that network failures during extreme weather events are often clustered and, hence, a more stringent benchmark, e.g., N-2 or N-3, may be perceived to be the best preventative measure. The picture is, however, more complicated than that: case studies in recent research indicate that making the network 'smarter' and more robust to, e.g., storms, is even more important than increasing the redundancy in a power system.[111] All resilience options need to be considered.

A comprehensive review of proposed resilience metrics is beyond the scope of this paper,[112] and we restrict attention to two important contributions to the literature which may indicate a way forward on resilience metrics.

Vugrin et al.[113] propose a 'performance-based' approach (as opposed to 'attribute-based', referring to more qualitative metrics) for measuring the resilience of a power system. A performance-based metric is designed to draw together quantitative data that describe infrastructure performance in the event of specified disruptions. Such metrics help measure potential benefits and costs associated with investments and other actions to strengthen resilience and are appropriate for cost-benefit analyses.

Based on the framework of the Resilience Analysis Process, which starts with the definition of resilience goals, Vugrin et al. recommend that the resilience of a power system to hazards be measured in terms of the consequences that will result when the hazards occur. Estimating consequences should include relevant uncertainties and be given a statistical representation, e.g., showing expected consequence, maximum consequence, the probability that the consequence exceeds some acceptable level, etc. Examples of consequence categories include customer hours of outages – critical and non-critical – time to recovery, and costs of damages and recovery. They illustrate their approach with a case study of the superstorm Sandy, which struck the northeastern United States in October 2012.

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[109] See A. Stankovic and K. Tomsovic (2018). The definition and quantification of resilience, IEEE PES Industry Technical Support Task Force, Tech. Rep. PES-TR65.

[110] See National Association of Regulatory Utility Commissioners (2016). Resilience in Regulated Utilities, and National Association of Regulatory Utility Commissioners (2016). Resilience for Black Sky Days.

[111] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson and P. Mancarella, "Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures," in IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3747-3757, Sept. 2017.

[112] For recent comprehensive reviews see, e.g., N. Bhusal, M. Abdelmalak, M. Kamruzzaman and M. Benidris (2020). Power System Resilience: Current Practices, Challenges, and Future Directions, in IEEE Access, vol. 8, pp. 18064-18086, and Umunnakwe et al. (2021) (n X).

[113] Vugrin et al. extend the framework proposed in J.P. Watson, R. Guttromson, C. Silva-Monroy, et al. (2015). Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States, Technical Report SAND2014-18019, Sandia National Laboratories.

Panteli et al. (2017) propose an approach for modelling and quantifying power systems resilience based on fragility modelling of individual components and the transmission system as a whole. Their model is built for mapping the real-time impact of severe weather and involves optimal power flow estimation and stochastic simulation, allowing assessment of the impact of, e.g., a storm moving across a transmission network. The approach is illustrated by a case study of a severe storm moving across the British transmission network. Different interventions are quantified regarding improvement in resilience indices such as Expected Energy Not Supplied, Loss of Load Frequency, generation capacity going offline, and number of transmission lines going offline.[114] Their approach can be generalised to other types of hazards but requires that fragility models to those hazards exist as well as repair times for each component of the model.

6.4.2 Reliability and resilience of the European gas markets

In contrast to electricity networks, gas infrastructure presents more acutely severe risks and as a result, technical standards and supply quality metrics have been established by EU Agencies (European Committee for Standardization (CEN), ENTSOG and technical associations within each Member State) and are followed by gas operators in the continent. Any interruption in the transportation, distribution and consumption of gas presents physical danger and potentially fatal hazards to stakeholders.

Similar to voltage levels on the electric grid, pipeline pressure levels give a key insight into the operational quality levels of the gas network and influence the selection of components and the operational decision making. Pressure regulating stations are vital network components that adjust gas pipeline pressure to a variety of levels for transport along the network. Germany has the longest gas network in the EU with 550,000 km of pipelines across the country with pressure regulating stations adjusting pressure levels from 100mbar to upwards of 1bar allowing safe transportation to customers and interconnection with neighbouring countries. Gas operators maintain keen oversight on pressure levels with strict regulations in place on the allowable deviations of pipeline pressure.

Storage facilities also play a critical role in providing system resiliency during high impact climate events and reliable access to stored gas has proven to be the difference maker when demand is at its highest. The 2018 arctic blast caused huge spike in gas demand (see our case study on 2018 'The Beast from the East'), resulting in a tightening of supply at a time it was most needed. Majority of the participating countries (GB, FR, DE, AT) have a variety of storage infrastructure ranging from salt caverns, depleted gas fields and aquifers. Pre Ukraine-war, regulation of storage however is not as widespread with only 10 countries having some sort of governmental oversight over the deposits and withdrawals from these facilities[115]. Regulation may be in the form of price control on withdrawals and deposits with a revenue-cap model or may be involve a mandate for increasing output to the

[114] Expected Energy Not Supplied is the expected amount of energy not being served to consumers during the period considered, due to system capacity shortages or unexpected outages of assets; Loss of Load Frequency refers to the number of loss of load events within the interval

[115] CEER, 2022.

network during gas crises. However, since the war in Ukraine, the EC imposed storage filling obligation for all EU Member States until at least 2026.

The security of supply is also improved by LNG infrastructure allowing EU countries to source gas from the global market. LNG provides the region with competitive supplies of natural gas and plays a vital role in improving the integration and price discovery of the global gas market. LNG infrastructure is used in most coastal EU countries. LNG facilities may be either in-land and with access to a port or compactly installed on a floating vessel. These units are FSRUs (Floating Storage and Regasification Units) and allow for access to LNG infrastructure with minimal construction costs.

The focus for operators is on service quality (pressure levels) and the number of interruptions experienced at the terminals of a network user. Network operators seek to optimise the continuity of performance by minimising the number of outages that occur and their duration. However, the most prudent parameter throughout the supply chain is safety; any interruption of supply can correspond to elevated danger levels. Although many of the gas metrics we shall discuss have been adapted from the electricity sector, the key difference is in the availability of widespread storage and safety measures.

The presence of leaks directly indicates the technical quality of the network is a tell-tale sign of improper installation and maintenance practices as gas leaks into the atmosphere.

An incident occurs in every operational system and may lead to disruptions but is not necessarily a precursor to an interruption. Accidents on the other hand are incidents formed because of the categorical failures in the safety standards and occur when gas is ignited, and external damage is inflicted. Of the few countries that reported on the topic, a common definition used was ‘an unwanted (uncontrolled or unintended) release of gas caused by the failure of a component in the network.’

Similar to the electricity sector, continuity of supply is monitored on both the transmission and distribution networks, through a number of key metrics such as System Average Interruption Duration Index (SAIDI), ASIDI, System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index (CAIDI) among others. However, they should not be interpreted in the same way as those for electricity. Continuity of supply is not the primary issue influencing decision-making of gas network operators due to the high availability of storage in gas grids and the extreme technical standards associated with their operation. However, unlike the electricity sector, the number of interruptions is considerably lower, primarily because a single gas interruption along the network can result in severe damage, keeping operators on edge and always proactively monitoring the network. Another difference in the reduced incidents is because most of the gas network is underground and is less vulnerable to external influences than overhead power lines. It should be noted that outages on the gas network are considerably longer to rectify. Each country has a different method of defining these metrics with weightings typically affecting how they report the events.

SAIDI is the System Average Interruption Duration Index and is used to track the total duration of an interruption on the system and is defined ratio of the sum of all customer interruption durations to the total number of customers served. Often measured in hours, many operators track this metric over the course of the year for both planned and unplanned outages.

The issue however lies in how the metric defined for each operator. Customer identification, the definition of an interruption and the portion of the network (distribution or transmission) the metric is applied to differs from operator to operator. For example, Germany defines the metric as the ratio of the total outage duration for all customers affected to the total number of customers, whereas Slovakia defines it as the ratio of interruption duration of supply points in the distribution network to the total number of supply points.

This varying definition and application areas of the metric complicates the efforts to benchmark quality of supply in the region. The best way for suitable benchmarking across EU member states is to harmonise the definition of these metrics for each system operator such that operational reliability can be compared.

The UK, Germany and the Netherlands track both aspects of the metric with France as one of the notable exceptions. Austria only focuses on the unplanned outages in its calculation. It should also be noted that the metric would also capture certain force majeure incidents (such as explosions, see our case study on Baumgarten gas explosion) skewing the data considerably.

Different gas quality can segment markets and limit interconnection capability, reducing the resilience of the gas network. For example, the high- and low-calorific gas areas in Northwest Europe. The interchangeability of gas is limited by its chemical composition, causing market segmentation across the continent. The sub-regional market of Germany, France, France, Belgium, and the Netherlands (NL) operate gases of both higher (H-gas) and lower (L-gas) heating values. L-gas, primarily from Groningen fields in NL, is transported across borders to neighbouring countries for use in industries. Germany consumes both H-gas and L-gas and, due to their differing calorific content, requires separate transmission networks across the region. Public outcry over the dangers of earthquakes in the Groningen region, in addition to the NL net-zero ambitions, has led to the policy initiatives to completely retire its gas fields by 2030.

Thus, gas quality ranges on a variety of metrics, and national gas regulators are currently tracking many of the key ones. Excessively high levels of sulphur can lead to corrosion on the network and must be reported. Regulators should seek to impose a consistent definition of the Wobbe Index as it key for safety and a more integrated gas standard across the continent. The interoperability and quality standardization issue will become even more critical as Europe ramps up the hydrogen market (e.g., hydrogen blending and/or conversation of parts of the existing gas networks to carry hydrogen).

To conclude, as with the electricity sector, the gas network also has a variety of security of supply and reliability metrics. It is recommended that more countries across the region implement many of these continuity of supply metrics to ensure suitable comparisons and more clearer benchmarking on gas supply quality. Exposed pipelines leading into cities should be weatherised to prevent the potential of freezing and bursting. This will reduce safety hazards and ensure continuity of supply in periods of elevated demand. Odorisation should also be mandated across all member countries to improve the risk management across the network. Sufficient and diverse sources of gas should be available when it is needed. LNG infrastructure however long it may take to be constructed is a vital component of the gas network as it virtually guarantees the security of supply, as shown by the current gas crisis caused by the war in Ukraine. EU energy policy should be structured towards incentivising participation in this sector. While these metrics, as in the electricity supply sector, are focused on reliability of gas supply, they do not consider resilience explicitly. New metrics focusing explicitly on resilience and increasing sector-coupling between gas and electricity will be needed as Europe decarbonises its energy system.

6.4.3 Monetisation

High-impact, low-probability events such as severe storms, wildfires, etc. have traditionally been considered difficult to monetise – cf. the earlier cited remark from the ENTSO-E CBA guidelines – although in some cases this may be possible, cf. the recent Italian DSO regulation on resilience. Multicriteria approaches using scenarios involving high-impact, low-probability events and several resilience metrics may indeed represent a way forward, as advocated by ENTSO-E. However, if a multicriteria approach is adopted, it needs to be clear how resilience is considered in regulatory decision-making: the risk is that non-monetised metrics are not placed on an equal footing with the "bottom line" results of CBA analyses and, hence, resilience investments will not be adequately incentivised. It follows that finding a good approach to monetising resilience benefits and weighing them against costs in CBA analyses is essential.

In principle, reliability indices can be combined with estimates of the Value of Lost Load (VoLL) for electricity and for gas, using 'Cost of Disruption of Gas Supply' (CoDG[116]) for monetising benefits of resilience investments, given the occurrence of an extreme storm or similar event. In scenario analysis, this would represent a step in the right direction by monetising damages of high-impact events such as storms or floods. To be incorporated in CBA analyses, however, a further step is required: to calculate expected benefits and weigh against investment costs and other resilience measures, 'probabilities of occurrence' also need to be modelled. Moreover, VoLL estimates need to be appropriate for resilience analysis: In reliability analysis, VoLL is often presented as a single parameter,

[116] https://documents.acer.europa.eu/en/Gas/Infrastructure_development/Pages/Study-on-the-estimation-of-the-Cost-of-Disruption-of-Gas-Supply-(CoDG)-in-Europe.aspx

whereas in reality, it will vary between customer types, time of day and season, duration of the outage, etc.[117]

Duration-dependent customer-damage functions – based on VoLL estimates – can be used to estimate the monetary cost of high-impact events. This is proposed and illustrated by Anderson et al. (2019). However, conventional measures of VoLL are unlikely to capture the full costs of high-impact; low-probability events such as the storms in Victoria (cf. Section 3.1). The traditional measures are restricted to the direct impact of the loss of electricity, usually for a relatively short duration. Unplanned, large-scale, and long-lasting blackouts, which can impact and propagate to other critical infrastructures, have a more serious impact on the lives and welfare of people and the operation of businesses. In the events, we are considering, apart from lights and computers turning off for a limited time as well as electricity-powered heating and cooling shutting down, most modern service facilities – including critical services such as hospitals, health care centres, fire stations, police stations as well as less essential services like shops, gas stations, etc. – will be unable to operate; the internet and telecommunications are disabled; after a while, food in refrigerators and freezers will go bad. Such costs will increase with increased electrification – extended loss of power will, e.g., disable the entire car fleet when it is fully electrified – and energy sector integration. A customer damage function in such scenarios would include the direct cost of lost electricity supply to homes and businesses and the indirect cost of losing access to other services and infrastructures likely to be affected.

A way of taking the different nature of high-impact low-probability events into account would be to assign higher values to mass loss events. Thus, if a whole community is off supply for a period this is more serious than an isolated incident. Also, long duration events might come with rising values of customer minutes lost. This would reinforce societal concern to prevent systemic events.

Given the appropriate VoLL estimates – duration dependent and taking direct as well as indirect costs into account – the approach of Anderson et al. (2019) could be combined with models like those in Panteli et al. (2017) to monetise the impact of large-scale disruptive events. Given estimates for probabilities of occurrence the expected benefits of resilience investments and interventions – damages and costs avoided due to the resilience measures – could then be incorporated in CBA analyses.

[117] For a recent review of the economics of VoLL see, e.g., Gorman, W. (2022). The quest to quantify the value of lost load: A critical review of the economics of power outages. *The Electricity Journal*, *35*(8), 107187.

7. CONCLUDING DISCUSSION AND POLICY RECOMMENDATIONS

Extreme events are increasing both in terms of frequency and scale, causing serious damage to critical infrastructures and physical assets, such as gas and electricity transport infrastructure. IPCC projections for Europe indicate a further increase in the frequency of such threats and their intensity. The impact will depend on the success of efforts to reduce greenhouse gas emissions, but even in the unlikely event that global warming could be limited to 1.5°C, it will be significant. Higher levels of warming would entail even higher impacts.

Increasing frequency and intensity of climate-related hazards demands a system that is more robust and is *resilient*: it can **withstand, adapt, and recover quickly when hit by such shocks.** Simultaneously, the drive towards a cleaner energy system, a rapid rise in renewables and increased sector integration has led to a **system that is less stable and more volatile than before** and more vulnerable to shocks. This calls for **more and better energy-network system services**. Resilient infrastructure is clearly of the essence in the energy transition in Europe. It is therefore urgent to ask how EU law and regulation can support and create incentives for a more resilient infrastructure.

Case studies

In this report, case studies of electricity and gas networks hit by disasters like wildfires, storms and extreme cold, illustrate the consequences of climate-change related hazards in a concrete way. The electricity cases illustrate the resilience consequences of a rise in climate-related hazards and an **increased share of distributed RES generation**, the fundamental importance of well-functioning electricity networks for modern life, and the importance of the regulatory environment. The gas case studies highlight that climate-related risks (such as 1-in-20 or 1-in-50 gas demand scenarios) are explicitly considered because **gas demand (at least in the northern hemisphere) is largely driven by weather conditions** (e.g., temperature).

Defining resilience in regulation

Diverging approaches by national regulatory authorities shows that there is **no consensus on the need to intervene through regulation/legislative changes to reinforce the role of operators** in resilience building (ex: Australia, Italy, etc.). The question is therefore to know whether EU intervention is opportune, and if yes, which regulatory and legislative approach should be adopted at EU level. This report argues in favour of a **targeted regulatory approach at EU level**, around the principles and measures described below.

The approach to resilience in EU energy legislation is often limited to specific aspects of the quality of energy supply such as: adequacy, security of supply, reliability, frequency and pressure stability, and operational security. A more **comprehensive and integrated approach** must be promoted. This starts by having a clear definition of resilience in context and as a common steering objective. The **Critical Entities Resilience Directive** contains a definition of resilience that is appropriate and can be used as a useful blueprint with few adjustments. Our **proposal for the definition of resilience** is: '*an entity's ability to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover from a disruptive event*'.

EU energy legislation addresses specific sides of resilience in a targeted manner. A first area where resilience is referred to is **grid planning**, with specific assessment requirements for regulators as part of the network development plans. This puts grid operators in the forefront. This is already a good start, but **resilience must be better integrated and defined as a mandatory assessment requirement creating strong incentives to invest** in order to limit additional costs in case of major disruptions This requires to have a **broader assessment scope** (e.g. including flexibility) and **longer term perspective**. One question raised in the report is whether modelling systems have the right metrics for reflecting resilience needs. A key task for grid operators will remain to **identify and assess risks** that will form the basis for investment plans and decisions. A particular challenge here is to **define criteria and metrics** that will reflect disruptions of varying scale and in longer timeframe (network plan as basis for investment decisions). A second area where resilience is referred to in the energy legislation is as part **of system operational management and technical performance**. This is crucial to system resilience, but the approach should be broadened in order to anticipate the scale of disruptions.

In addition to planning, emergency preparedness, restoration, and technical performance, resilience building must be better integrated at the level of **market design**, with a **close interaction between grid operators** and other actors contributing to resilience, such as **providers of flexibility, ancillary and balancing services**.

Promoting and accounting for flexibility

The energy system has become more decentralised, with a higher share of intermittent renewable energy sources. European countries have set ambitious targets for new generation capacity within offshore wind, which raises questions as to the management of grid stability and balancing management. This put an additional burden on grid operators when managing the grid. On their side, final customers (both wholesale and households) are increasingly responsive to prices. In that context, the use of flexibility will contribute to energy system resilience. **Flexibility must be further promoted and taken into account in resilience planning, notably at the level of the grid**. **Operators must be encouraged to map the potential for flexibility**.

Incentivising investment in resilience

CBA rules may be considered when it comes to investments in regulated networks like distribution and transmission power networks. **Benefits of resilience-motivated investments tend to be much more difficult to measure than the costs.** However, if the benefits are not properly accounted for in the analysis, then investments with a primary focus of improving resilience may yield a negative CBA balance. If decisions are made on that basis, they will be automatically ruled out.

Incentivising resilience investments and interventions is clearly very important: network operators will not enter into the related expenses if they are not compensated, e.g., through user tariffs. However, in regulated natural monopolies such as electricity and gas transmission and distribution such investments need to be justified by the resulting benefits. Grids being regulated entities, brings up the **question of the role of regulators, and the methodologies the latter use** to both monitor operators' assessment and investments, but also in terms of guidance as to the prioritisation of investments. In reality, **resilience will be one among other criteria that spread between short-term to long-term investment frames**. A separate but related matter is the question of cost recovery for these investments (including through tariffs).
Multicriteria approaches using several resilience metrics may represent a way forward. However, if a multicriteria approach is adopted, it needs to be clear how resilience is considered in regulatory decision-making.

Novel approaches to building resilience

Some national regulators are developing approaches to evaluate or to incentivise resilience. In the **UK**, **DSOs** are required to include **resilience aspects in their business plans**. In **Italy**, DSOs are required to **publish CBA-supported plans** for defending networks against climate-related hazards. In **Australia**, the regulator has indicated that resilience-related investments would be allowed, given a causal link to an increase in extreme weather events. Also in **Italy, a new risk-based methodology** has been approved for improving the resilience of the electricity transmission grid. Interestingly, in the only EU case (Italy) the **provisions of the Electricity Directive were adequate** and, more generally, **legal changes have generally not been required**. A **changed approach by the regulator**, considering resilience-related investment as one aspect of network companies' development plans, and the **commitment of network operators has been sufficient**.

California has adopted a **different approach** for improving resilience against wildfires, which takes **ownership and financial structure of US utilities into consideration**. The approach there relies on required expenditures on safety measures by utilities as well as a monitoring body as a gatekeeper for utilities' access to a wildfire insurance fund; access to the fund is contingent on having undertaken adequate safety measures. In the case of California, **legal changes were required**.

Impact of increasing gas-electricity coupling

High-impact, low-probability events such as severe storms or wildfires have traditionally been considered **difficult to monetise** and have not been accounted for in documents such as the ENTSO-E CBA Guidelines. The concept of resilience is used more explicitly when it comes to gas supply. In particular, the gas CBA explicitly accounts for climatic and supply stress conditions and monetise the benefits from avoided demand curtailment arising from these stress conditions.

Due to the increased nature of **coupling** between the gas and electricity sectors, **new gas and electricity resilience metrics may be needed that reflect increasing inter-dependence** and feedback between the two sectors and **how one sector can support resilience of the other sector**. For example, how gas and hydrogen storage can mitigate risks of dunkelflaute (cold, cloudy and calm days) as the electricity sector increasingly relies on variable renewable energy.

This sector coupling trend means that as we decarbonise our energy system and potentially electrify heat load with variable renewables, the **effects of climatic variability on electricity and hence on the gas system will magnify and increase considerably**. While the gas CBA guidelines do explicitly mention the probability of climatic stress events on gas demand, and hence straightforward monetisation of gas infrastructure resilience in this regard, **other risks** such as **politically motivated** actions to shut down a supply route and especially the ones propagating from sector coupling with the electricity sector (e.g., wildfire) are **problematic to monetise as there is little basis to calculate risk and systematic definition of probabilities.**

Monetising resilience

The report raises the question on whether resilience should be monetised or not. Monetising the benefits of resilience measures is **important to establish a basis for regulatory decisions on network development plans, but also difficult.** Research is ongoing in this area and consensus has yet to be achieved. The research has, however, already shown **how the monetisation of resilience could be approached**:

- The **system under consideration is modelled**, including a model of the vulnerability (fragility) of individual components to identified threats.
- The **impact of extreme event(s) under consideration on a resilience metric**, such as the trajectory of lost load, is compared with and without investment.
- The **physical metric is monetised using appropriate valuation of losing load**.
- **Expected benefits are computed** by multiplying benefits with the probability of occurrence of identified hazards.

The **Value of Lost Load (VoLL) will be a very important component of any approach to monetising resilience**. Estimates for VoLL do exist in the context of traditional reliability studies. Such estimates are, however, restricted to the direct impact of the loss of electricity or gas supply, usually for a relatively short duration. Unplanned, large-scale, and long-lasting disruptions of supply services, which can impact and propagate to other critical infrastructures, may have a more serious impact on the lives and welfare of people and the operation of businesses than the events considered in reliability studies. **Research in this area is urgently needed for proper valuation of resilience benefits.**

Another challenge is the estimation of hazard probabilities. Moreover, in many cases the probability of the extreme events involved – e.g., drought and wildfires in Southern Europe – is predicted to increase from current levels over the typical lifetime of the investments considered. The degree of increase will depend on the climate scenario. **A risk-based approach may therefore be appropriate.** This would entail **analysing different scenarios for the evolution of the likelihood of climate hazards and would ideally take the statistical distribution of these hazards through time into consideration**.

In essence, investing in improved resilience of energy infrastructure is just one aspect of the process of adapting to and mitigating climate change. To some extent the expenditures involved **may overlap and replace other costs incurred to improve reliability and security of supply against 'ordinary' events**. **Costs will, however, almost certainly increase** if the quality and reliability of energy supply Europe is accustomed to is to be maintained. These costs **may be thought of as insurance against the greater damages that would ensue in the absence of action**, i.e., if the consequences of climate change for extreme weather events were to be ignored and only responded to on an *ex-post* basis, after disasters have occurred. There are **different ways of bringing the required investments about**, e.g., through **economic incentives or command and control**. In regulated sectors cost recovery of investments usually takes place through tariffs. Finally, despite improved resilience of energy infrastructure, there will occur extreme events that may seriously damage infrastructure and entail high costs. **Insurance funds such as that established in California may be a good solution to share such costs, unless markets fill the gap** and offer insurance for these kinds of events. This policy does, however, need further study on whether it actually makes the system more resilient, since insurance in general introduces both adverse selection and moral hazard.

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