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REGULATION AND STANDARDS FOR A RESILIENT EUROPEAN ENERGY SYSTEM

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1. INTRODUCTION

The occurrence of extreme nature-based events is causing serious damage to critical infrastructures and physical assets, such as gas and electricity transport infrastructure. Those extreme events are increasing both in terms of frequency and scale, and sometimes cumulate with other crises (e.g., health, economic, political, war, cybercriminality).

´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]

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.

This issue paper represents the first step of a broader research project on infrastructure resilience. The focus of the project 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.[3] This short paper identifies the main issues and shortcomings in current regulation, and starts identifying regulatory pathways for fostering resilience of the energy system through the regulation of operators' role. Detailed analysis will be performed in a longer paper, based on the results of this first step.

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. Finally, Section 6 considers some of the hurdles in current EU regulation

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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] 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.

for enhancing resilience, gives examples of emerging national initiatives in this area, and discusses promising research developments aimed at measuring and valuing resilience.

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 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).

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.[4] 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.[5] 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[6] –, and ´social-ecological resilience´ – as the capacity of an ecosystem to respond and adapt to disruptions.[7]

Resilience is therefore more than merely resistance[8] 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).[9] 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 continue to develop. It is about how humans and nature can use shocks and disturbances like a

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[4] D.E. Alexander, Resilience and disaster risk reduction: an etymological journey, Nat. Hazards Earth Syst. Sci., (2013)13, pp. 2707–2716.

[5] 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).

[6] Lance H. Gunderson, 'Ecological Resilience—In Theory and Application' Annual Review of Ecology and Systematics 2000 31:1, 425-439.

[7] C.S. Holling, (n5).

[8] Resistance is defined by Holling as 'The capacity of the ecosystem to absorb disturbances and remain largely unchanged'.

[9] 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'.

financial crisis or climate change to spur renewal and innovative thinking."[10] 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.[11] 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.[12]

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[13] to resist and adapt to disruptions, and to pursue sustainable development and equity in an inclusive and nature-based manner".[14] 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, with the risk 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.

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,

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

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

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

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

[14] 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.

absorb, adapt to, and/or rapidly recover from such an event¨.[15] 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 question 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.[16] 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 have also 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).[17]

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

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[15] 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'.

[16] 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.

[17] 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.

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[18]), 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 propagates to the gas system and vice-versa.

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[18] 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.

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

Case selection

Seven cases are outlined below: four 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

Two of the electricity cases are related to transmission system operations (TSOs) and the separation of the European system. The former case was a consequence of a wildfire in the South of France and resulted in Iberia being separated from the rest of Europe. The latter was the result of unexpected flows and overload at a Croatian substation and resulted in the separation of Continental Europe: South-East vs. North-West. The third and fourth 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[19]

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, 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

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[19] 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.

system protection and defence plans worked as they were supposed to. The tripping and disconnection of RES generation, in part due to non-compliance with EU network codes, 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".

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".[20]

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: The Separation of the Continental Europe Power System on 8 January 2021[21]

On 8 January 2021, a power-network substation in Croatia (Ernestinovo) experienced flows – from South-East to North-West Europe – more than those forecasted in network models and eventually tripped due to the overload. This subsequently triggered a cascade of trips of transmission network elements, resulting in a separation of the Continental Europe Synchronous Area into two areas (the North-West area and the South-East area).

There was no climate-related disaster behind this incident. Moreover, neither generation inadequacy nor large deviations from forecasted renewables generation contributed to the overload. In fact, both conventional and renewables generation were in line with scheduled production. Rather, this event seems to have occurred because of a combination of inaccuracies in operational security analysis and tight reliability margins that could not cope with the deviations from predicted flows.[22] As it turned out, the consequences were not severe: TSOs reacted quickly to stabilise the system and the two areas were resynchronised after approximately one hour. Overall, this event had limited impact on electricity supply with only a small number of private and industrial customers losing power.

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[20] ENTSO-E (n18).

[21] This section is based on ENTSO-E (2021). Continental Europe Synchronous Area Separation on 08 January 2021, ICS Investigation Expert Panel, Final Report, 15 July.

[22] The report on the incident (ENTSO-E, 2021) does not identify what caused the deviation from predicted flows.

Shocks of this nature are likely to increase in the future due to rising shares of RES generation and more extreme natural hazards.[23] This case offers potential lessons on how the system can be made more resilient to the increase in risk.

Case 3: June and October 2021 Storms in Victoria, Australia[24]

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 powerlines, 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 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".[25] Information was hard to provide to customers due to 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 4: 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

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[23] On this issue see Eurelectric (2022). The Coming Storm: Building electricity resilience to extreme weather. https://resilience.eurelectric.org, accessed on 12 December 2022.

[24] 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.

[25] Electricity Distribution Network Resilience Review Expert Panel (n23) p.46.

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.[26]

PG&E emerged from bankruptcy in 2020 in time to join a new $20 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´.[27] The reason is its connection to wildfires which have increased massively in California. There is an 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.[28] 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.

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 5: ´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

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[26] 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.

[27] 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.

[28] 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.

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 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 GWh (at 18:00), which is four times higher than the electricity peak demand (53 GWh 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.

The event led National Grid (the UK's gas system operator) to issue a *Gas Deficit Warning*, 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, which resulted in very high intraday gas spot prices (500p/therm). According to the UK's energy regulator, Ofgem (2019[29]), *"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 immediate 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 Notification* (National Grid, 2019[30]). 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.

Case 6: Texas 2021 Freeze – a case of gas and electricity coupling

This event is now well-documented (see e.g., Busby, et al., 2021[31]). We will summarise, based on public information and published academic papers, the main causes of the blackout in Texas in 2021 and will focus on regulatory and policy changes resulting from this event. We will focus on the lessons learned and how they relate to the discussion around sector coupling in Europe.

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[29] 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

[30] https://datacommunity.nationalgridgas.com/key-documents/gas-deficit-warning-and-margins-notice-changes/

[31] Cascading risks: Understanding the 2021 winter blackout in Texas

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. For example, Busby et al., (2021) noted that "The natural gas system relies on electricity, and the electrical system relies on gas. Thus, constrained gas limits the ability to generate electricity and constrained electricity limits the ability to supply gas which in turn further limits the ability to generate power in a vicious circle."

We will focus on the discussion around investments in the ´insurance´ against low probability but high impact events (a winter freeze in Texas is a very low probability but high impact event) in the Texas context and draw lessons for the EU. Another regulatory and policy aspect that emerges from this case study (and others which resulted in load curtailment) is an ´order´ of disconnection in case resilience plans fail to protect system integrity and partial and controlled load shedding is inevitable. The Texas 2021 case raises the issue of equity and fairness when planning for such load shedding – some households which were part of the same feeder, such as a hospital, received energy services, while households across the street did not have the services for the entire duration of load shedding.

Case 7: 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 of this year, 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[32], 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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[32] https://www.euronews.com/2022/05/18/four-employees-sentenced-over-deadly-2017-gas-explosion-in-austria

This case study will highlight 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.

We will focus on infrastructure and supply security standard, as defined by the EU Regulation 2017/1938. The objective is to understand if anything else could be done in terms of regulations and policies to support the resilience of gas infrastructure. 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 task even more relevant.

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

This section provides a mapping of the existing and proposed EU legislation that is directly relevant to the definition of requirements in relation to resilience building in the energy sector. The full report of this study will use the results from this mapping and offer a detailed analysis of the most relevant pieces of legislation identified below.

4.1 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.[33] 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.[34]

4.2 SEA Directive and EIA Directive

Under international and EU law, the elaboration of plans and programmes (PPs) will be 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) transposes the SEA Protocol into EU legislation, and follows its wording closely.**[35]** 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'.**[36]** 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.

4.3 Governance of the Energy Union Regulation

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

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[33] Paris Agreement to the UN Framework Convention on Climate Change (UNFCCC), Article 2(1) (b) and Article 7.

[34] 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).

[35] 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).

[36] Ibid, Art. 2.7.

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.[37]

4.4 Electricity and Gas market legislation

‘Reliability’ is a requirement often mentioned in energy legislation, associated with additional planning duties for operators, such as power outage planning coordination.[38] ’Power quality‘ and ‘frequency restoration’ after deviation are also relevant legislative requirements.[39] 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.[40] 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.[41] At EU-wide level, the ´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’.[42] A similar wording is used in the Gas Regulation for the TYNDP, elaborated by ENTSOG.[43] Resilience is not further defined in the Electricity and Gas Regulations.

Interestingly, the different network development plans provide for detailed regulation of resilience, where operators receive a series of precise duties and assessment methodologies 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, lists ‘climate 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.[44]

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[37] Governance Regulation, Art. 4 (c)(1), Annex I – Mandatory template, 2.3 – Dimension energy security.

[38] 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.

[39] 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.

[40] Electricity Directive, Art. 51.1. and 51.3. The Gas Directive uses a similar wording, Art. 22.1.

[41] Electricity Directive, Recital (61), Art. 32(3)

[42] Electricity Regulation, Art. 48.1.

[43] Gas Regulation, Art. 8.10.

[44] 2020 TYNDP ENTSOG, 29.

Several network codes and guidelines deal with some specific elements of resilience,[45] but mostly from an energy system perspective, based on market-based solutions. This is reflected by the role played by the system operator in terms of balancing,[46] or the manner to manage 'capacity adequacy'.

The newly revised TEN-E Regulation refers to the need of upgrading the Union's energy infrastructure in order to prevent technical failure and to increase its resilience.[47] The types of threats covered are both natural and man-made, therefore covering a broader scope than other energy legislation. The TEN-E Regulation also refers to the European critical infrastructures directive 2002/114/EC that is currently under revision.

4.5 EU financial support regulation, investment criteria and related standards

Interestingly, 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 defined.

Under the ´Multiannual Financial Framework (MFF)´,[48] 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 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 for that work.[49]

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[45] See footnote 38.

[46] See for example, Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration.

[47] 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).

[48] Council Regulation (EU, Euratom) 2020/2093 of 17 December 2020 laying down the multiannual financial framework for the years 2021 to 2027.

[49] 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

Financing under the ERDF and the Cohesion Fund aims to promoting 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 an economic activity on the resilience of ecosystems may conduct to classify it as significantly harming the environmental objectives.[50] Finally, the Recovery and Resilience Facility explicitly aims at fostering resilience.

4.6 Risk Preparedness Regulation

Regulation (EU) 2019/941 deals with risk preparedness measures in the electricity sector.[51] It lays down rules for cooperation between Member States with a view to preventing, preparing for and managing electricity crises.[52] 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'[53]. The situations are broad and include the results of natural disaster and extreme weather conditions.[54] The designated national competent authority must ensure that all relevant risks relating to 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 DSO, among others, will be associated to 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 electricity crisis scenarios.[55] TSOs and DSOs will be central actors in the implementation of the measures identified in the risk-preparedness plans.

4.7 Proposed regulation: Resilience of Critical Entities Directive (CER)

The Commission put forward a proposal for a directive on the resilience of critical entities in December 2020. Once adopted, the CER Directive will replace the currently applicable Directive on the identification and designation of European critical infrastructure, Directive 2008/114/EC. Under the proposal, 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 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

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[50] 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).

[51] 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.

[52] Ibid, Art. 1.

[53] Ibid. Art. 2(9).

[54] Ibid, Recitals (2), (14), Art. 5.

[55] Ibid, Art. 5(2)(a).

resilience[56] and ability to provide services in the internal market.[57] They will notably be obliged to perform a risk assessment (critical entity risk assessment)[58] that must account for all the relevant natural and man-made risks which could lead to an incident, including those of a cross-sectoral or cross-border nature, accidents, natural disasters, public health emergencies and hybrid threats and other antagonistic threats. 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'.[59] Specific provisions apply to critical entities of European significance.[60]

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 notably resilience to cybersecurity attacks, under for example the Cybersecurity Act[61], 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 the study.

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[56] Based on the draft Directive adopted by the Council (8 December 2022), resilience means 'a critical entity's ability to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover from an incident' (draft Article 2(4)). https://www.consilium.europa.eu/en/press/press-releases/2022/12/08/eu-resilience-council-adopts-a-directive-to-strengthen-the-resilience-of-critical-entities/

[57] Draft Directive, Art. 1(1), based on the text adopted by the Council on 8 December 2022.

[58] Ibid. Draft Directive, Art. 12.

[59] Ibid. Draft Directive, Art. 13.

[60] Ibid. Draft Directive, Chapter IV.

[61] 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).

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 frequency 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, pose 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.[62] 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.[63]

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

[63] 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 is 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[64] 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[65].

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[64] 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.

[65] 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[66].

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[67].

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:

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[66] 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

[67] '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

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

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

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 online-pack 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 IMPROVE RESILIENCE FRAMEWORKS

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, distributed RES generation, nuclear power plants and hydropower plants are not subject to weather stress conditions in the same manner.

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 power 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 and 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).[68] 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 as a result 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. 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)[69] tasks ENTSOG (European Network of Transmission System Operators for Gas) 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)[70] in which the term "resilience" was used twice and various types of risks are taken into account. In particular, the gas CBA explicitly accounts for climatic and supply stresses and monetise the benefits from avoided demand curtailment arising from these "stresses" conditions. Therefore, "resilience" of the gas system is understood in this context. In particular, as noted in the gas CBA (p.46)[71] *"In addition to assessing demand curtailment risks, the remaining flexibility assesses how resilient to climatic stress a country is. The remaining flexibility aims 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 takes into account stressful situations such as extreme weather conditions and supply or infrastructure constraints. The calculation of this indicator helps to identify areas where investment

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[68] 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.

[69] 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.

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

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

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 (p.46 of the gas CBA document).

Thus, the gas CBA methodology does explicitly acknowledge gas system resilience, not just in terms of traditional security of supply definition such a 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´[72] 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 decarbonize 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 mentions probability of climatic stress events (p.43 of the gas CBA document[73]) (be it 1-in-20 or 1-in-50) 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 targets and objectives. The regulation includes new investment categories such as energy storage, CO2 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 harmonized 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

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[72] https://entsog.eu/sites/default/files/2021-05/ILM%20Investigation%20Document.pdf
[73] https://www.entsog.eu/sites/default/files/2019-03/1.%20ADAPTED_2nd%20CBA%20Methodology_Main%20document_EC%20APPROVED.pdf

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.[74] 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.

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.[75] ARERA, the Italian utilities regulator, introduced an incentive-based

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

[75] 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.

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.[76] A cost-benefit analysis must be provided for each project, following ARERA guidelines.[77]

Australia - AER

In Australia, following on the 2021 storms the Victorian government established an Expert Panel to perform a regulatory review with 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[78] 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"[79] 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.[80] 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.

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

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

[77] 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.

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

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

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

sector) have developed a new risk-based methodology for improving resilience of the power grid.[81] 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) 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 changed approach is applied in real time system management as well as in the planning stage.

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.[82]

California

A new law has been enacted in response to wildfire disasters in California.[83]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 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.

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[81] 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.

[82] 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".

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

6.4 Can improved resilience be achieved within the current regulatory framework or are changes needed?

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.

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[84]) for measuring reliability and monetising benefits. However, these measures are aimed at short-term events and small-scale impacts while a metric measuring and/or monetising resilience needs to consider the low probability, but high impact and long duration aspects of extreme weather events. The consequence is that operators may not be adequately incentivised to improve resilience. In particular, the ability to recover from shocks may not be taken sufficiently well into account.

Good metrics for measuring resilience are extremely important: without such metrics, resilience aspects are likely to be underestimated and inadequately incentivised. However, High Impact Low Probability events are 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 several indicators, where some may not be monetised, may represent a way forward. But then it needs to be clear how resilience is considered in regulatory decision making. This is currently an active research area and several new resilience metrics have been proposed.[85] Yet there is no consensus on what metrics to use or how to monetise resilience. There are, however, encouraging developments in this area, such as the proposed valuation method in Anderson et al. (2021, n17) which incorporates duration-dependent customer damage functions into planning and operation models to value (monetise) resilience. This approach seems promising, although further research is required before this or other proposed resilience metrics are included in regulation.

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[84] 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

[85] See, e.g., 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; 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.

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