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RESILIENCE TO PRICE SHOCKS IN COUPLED GAS-ELECTRICITY MARKETS

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Executive Summary

The 2021-2023 European energy crisis confirmed that, in liberalised energy systems, severe stress is often mediated less through formal administrative rationing than through extreme prices, demand adjustment, and targeted emergency measures. Physical balance was largely preserved, but not costlessly: acute price spikes induced demand destruction in energy-intensive activity, intensified distributional pressures, and required exceptional interventions to stabilise expectations and sustain system functioning. This experience, reinforced by the European Commission's subsequent fitness check, underscores the need to treat the security of supply and price containment as closely related in practice but analytically distinct objectives.

This paper develops the concept of energy price resilience as a distinct element of energy resilience in coupled gas-electricity markets operating under marginal pricing. Price resilience concerns the upper tail of outcomes – magnitude, persistence, and recovery dynamics of extreme wholesale price episodes – rather than price stability in normal conditions or the elimination of scarcity pricing. The framework adapts the resilience trapezoid to price-based systems. It clarifies a critical distinction: ex post retail/fiscal protection can be essential for welfare and macro-stabilisation, but it does not, by itself, reduce wholesale exposure or the structural amplification channels that generate tail-price outcomes.

The stress-test modelling results point to a small set of mechanisms that drive price spikes. Correlated cold-weather conditions raise heating demand and increase power-sector gas burn when renewable output is weak, strengthening gas-to-power pass-through. LNG acts as the primary marginal buffer in stress years, while incremental pipeline flexibility is limited. Price responses are nonlinear and asymmetric – tight conditions produce much larger increases than loose conditions produce decreases – so average prices are a poor guide to resilience. Finally, flexibility and deliverability constraints are spatially uneven: internal network bottlenecks can keep some regions in short supply even when EU-wide capacity appears comfortable.

Energy price resilience as a portfolio problem. Instruments that matter are those that (i) reduce the probability that joint constraints bind (preparedness and deliverability), (ii) provide buffers and short-run flexibility when they do bind (storage governance, power-sector flexibility, demand response), (iii) shorten persistence once stress eases (credible, rule-bound emergency frameworks and operational coordination), and (iv) reduce structural exposure over time (risk allocation through contracting, diversification, and investment in flexibility consistent with decarbonisation).

A practical next step: introducing an Energy Price Resilience (EPR) metric

Improving price resilience is ultimately about combining several policy tools. But policymakers need a clear starting point – particularly as the Commission prepares to revise the EU's energy security framework. A practical and immediate step would be to introduce an Energy Price Resilience (EPR) metric and embed it in existing risk assessments and infrastructure planning processes.

Our analysis shows why current adequacy tests are not sufficient on their own. Today's security assessments focus largely on whether infrastructure can meet demand on a statistically defined peak day, or whether generation capacity appears adequate under a range of conditions. These tests remain important, but they do not fully capture how extreme price episodes emerge in a highly interconnected gas-electricity system.

Recent experience has shown that price stress often builds over several days or weeks. It is shaped by combinations of factors: low renewable output, cold weather, limited hydro or nuclear availability, and dependence on global LNG markets. At the same time, the power sector increasingly relies on gas during periods of low wind and solar generation. Network congestion can bind in particular regions even when overall import capacity appears sufficient. In these conditions, the question is not only whether supply can physically reach consumers, but how exposed the system is to sharp and prolonged price spikes.

The proposed EPR metric builds on existing rules rather than replacing them. It starts from the current gas N-1 standard under Regulation (EU) 2017/1938 and electricity adequacy assessments under Regulation (EU) 2019/943. It then extends these frameworks in three ways.

First, it refines how peak gas demand is assessed by explicitly taking account of electricity residual load during stress conditions, rather than treating gas and electricity risks separately. Second, it recognises that physical adequacy alone does not guarantee price stability. Systems that rely heavily on spot-indexed procurement or global LNG markets are more vulnerable when global markets are tight. The EPR, therefore, incorporates exposure to concentrated and tight global LNG supply. Third, it ensures that electricity adequacy is assessed under the same stress conditions, recognising that power-sector scarcity can reinforce gas demand and amplify both gas and electricity prices.

The framework can also be applied to prolonged low-renewable periods – sometimes referred to as "Dunkelflaute" events – where stress persists over several consecutive days (or even weeks). In such cases, resilience depends not only on capacity margins but on whether sufficient energy can be sustained over time, taking account of storage levels and feasible utilisation of supply infrastructure. The approach also reflects the existing Supply Standard for Protected Customers under Regulation (EU) 2017/1938, ensuring that resilience assessments recognise the legal obligation to safeguard households and essential services during severe disruptions.

This proposal is timely. The Commission has completed a fitness check of the gas and electricity security framework and signalled that revisions are under consideration. Risk-preparedness plans are being updated. Infrastructure planning under the TEN-E Regulation (EU) 2022/869 already requires projects to demonstrate system value under stress scenarios. Ongoing discussions on gas storage obligations are directly relevant to preparedness and price dynamics.

In practical terms, the EPR metric could be incorporated into revised risk-assessment methodologies under the two core security regulations and used in network development planning and project prioritisation. This would give policymakers a clearer and more consistent way to identify where the system remains vulnerable to extreme energy price episodes, and which measures offer the greatest reduction in tail-price risk.

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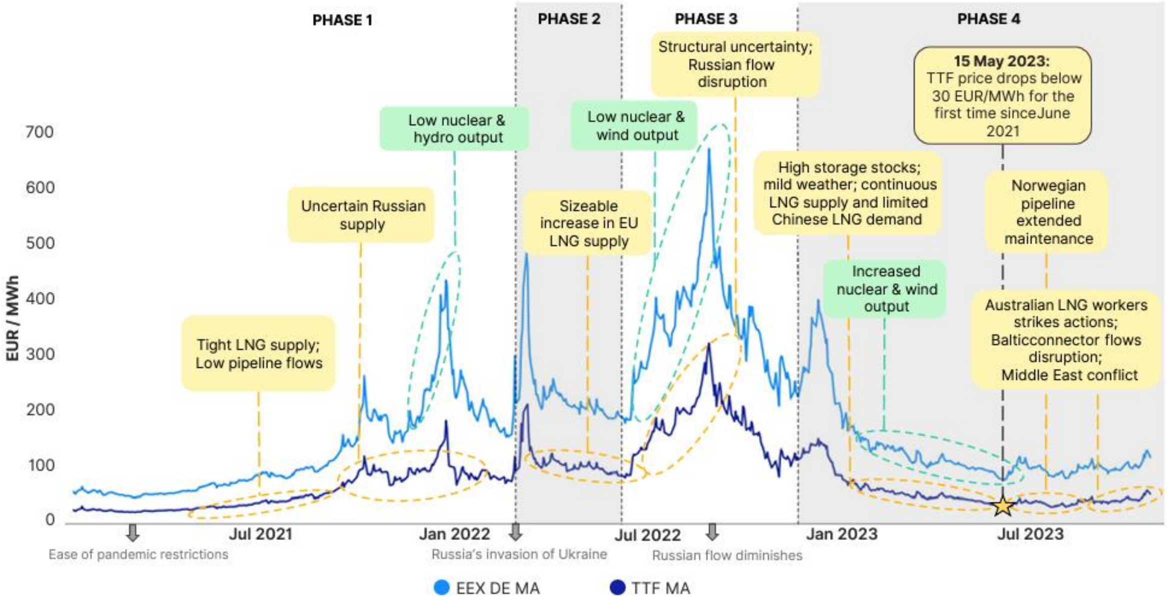
1. Introduction

The 2021-2023 European energy crisis underscored the extent to which Europe's gas and electricity markets are structurally intertwined and exposed to large, correlated external shocks. Geopolitical supply disruptions, adverse weather conditions, and reduced availability of dispatchable generation occurred simultaneously, leading to unprecedented volatility in wholesale gas and electricity prices (Figure 1). While widespread physical shortages and administrative rationing were ultimately avoided, this outcome was not automatic. It relied on the rapid deployment of exceptional policy measures, including coordinated gas storage filling and demand reduction at both the EU and Member State (MS) levels. The crisis nonetheless revealed important weaknesses in Europe's ability to cope with extreme price stress, illustrating how shocks originating in one part of the energy system can propagate across gas and electricity markets primarily through price formation, with significant and persistent economic consequences. In what follows, shocks refer to exogenous disturbances such as extreme weather or supply disruptions, while stress refers to the endogenous system conditions – including market tightness and extreme price rise – that arise when such shocks interact with structural features of coupled gas-electricity markets.

Figure 1: 2021-23 Energy crisis and energy market prices



Source: Adapted from ACER

Against this background, the European Commission launched a comprehensive fitness check of the EU energy security framework in 2024-2025, focusing on the Gas Security of Supply Regulation (EU) 2017/1938 and the Electricity Risk Preparedness Regulation (EU) 2019/941. The review covers the period 2017-2024 and examines whether the existing framework was adequate to manage the type of crisis experienced. A central conclusion is that the gas security framework, while effective at addressing short-term and localised supply disruptions, was not designed to withstand the system-wide stress induced by a prolonged supply shock. As a result, it proved insufficient on its own and had to be complemented by temporary EU- and MS-level interventions. Importantly, the Commission treats this assessment of security of supply as distinct from the emergency measures adopted under

Regulation (EU) 2022/1854 to address high electricity prices, highlighting that, while price containment and security of supply are closely related in practice, they are not analytically identical objectives.

Price amplification between gas and electricity markets during the crisis was closely linked to the role of marginal pricing in electricity markets. In Europe, gas-fired generation frequently sets the wholesale electricity price, particularly during periods of low renewable output or high demand. Sharp increases in gas prices, therefore, translated directly into extreme electricity prices, even when gas accounted for only a relatively limited share of total electricity generation. This mechanism has reignited debate over electricity market design, including proposals to reform marginal pricing or to separate renewable and fossil-based generation into different market segments. However, recent policy assessments and academic analyses (Pollitt et al., 2024) largely converge on the view that marginal pricing remains an efficient mechanism for dispatch and investment signalling. From this perspective, the extreme prices observed during the crisis reflected underlying scarcity and heightened risk, rather than a fundamental failure of market design.

This paper proceeds from that premise. It does not evaluate alternative electricity market designs, nor does it argue for abandoning marginal pricing or merit-order dispatch. Instead, it focuses on mechanisms that can enhance resilience within the existing market framework. The core question addressed is therefore not how markets should be redesigned, but how coupled gas-electricity systems can be better equipped to absorb and manage the stress generated by severe shocks, limit price amplification, and recover more rapidly, without undermining market functioning or long-term climate objectives.

Drawing on the academic literature, resilience is treated here as a multidimensional concept. At the macroeconomic level, it concerns the ability of economies to prevent large energy price increases from translating into persistent inflationary pressure and macroeconomic instability. At the market level, it relates to the extent to which price formation mechanisms amplify or dampen upstream shocks, particularly through gas-electricity coupling. At the household level, resilience is reflected in the capacity to mitigate welfare losses once prices have already risen. While existing research has made substantial progress in analysing each of these dimensions, it has largely done so in isolation, with limited integration across levels of analysis.

This paper seeks to address that gap by placing gas-electricity price coupling at the centre of the analysis. It argues that many policy responses adopted during recent crises, such as price caps, subsidies, and emergency fiscal transfers, have primarily served as ex post coping mechanisms. These measures reduced immediate harm but did little to address the structural channels through which exogenous shocks are transmitted and amplified into system-wide price stress. On the other hand, ex-ante resilience depends on underlying features of the energy system, including electricity demand-side flexibility, diversification of gas supply, storage regulation, and the design of long-term contracting structures.

The remainder of the paper is organised as follows. Section 2 synthesises the academic literature on energy price shocks and resilience. Drawing on empirical modelling evidence for Europe presented in Section 3, Section 4 evaluates a set of policy mechanisms through the lens of their contribution to price resilience within the current market design. Section 5 provides operationalisation of the proposed Energy Price Resilience (EPR) metric, while Section 6 concludes and discusses the broader implications for energy security and market governance.

2. Foundations of Energy Price Resilience

2.1 Positioning the Literature on Energy Price Resilience

The literature on energy price shocks is extensive but fragmented (see Appendix 1. Detailed Review of the Literature on Energy Price Shocks, Table A. 1). Studies span macroeconomic outcomes, market dynamics, household impacts, and uncertainty. Yet, these strands rarely speak to one another directly. As a result, resilience is discussed in different ways across the literature, with attention placed on specific transmission channels or policy tools rather than on how these elements interact within a single analytical framework.

At the macroeconomic level, a recurring finding is that economies appear more resilient to energy price shocks than in earlier periods. Inflationary and output effects are generally smaller and less persistent than those observed in past decades (Castle et al., 2023; van de Ven & Fouquet, 2017; Kilian & Zhou, 2023; Lu et al., 2024). Much of this improvement is attributed to institutional change, in particular stronger monetary policy frameworks and better-anchored inflation expectations. At the same time, the evidence is clear that this resilience is conditional. Energy price shocks can still generate substantial inflationary pressure, especially when increases pass through to retail prices or when institutional credibility is limited (Zhao et al., 2023; Abdallah & Kpodar, 2023). In most of this work, energy prices are treated as external shocks, with little discussion of how energy market structures themselves influence the scale or persistence of these effects.

Market-level studies address part of this omission by examining price formation within energy systems, especially in coupled gas-electricity markets. This literature shows that fuel price increase can be magnified under stress, as marginal pricing interacts with tight physical and operational constraints. When systems approach their limits, prices adjust sharply, with market-clearing achieved through scarcity pricing and demand response rather than widespread involuntary curtailment (Uribe et al., 2022; Ganepola et al., 2023). Regulatory design, market integration, and the allocation of risk across participants all play essential roles in shaping these outcomes. While these studies provide detailed insight into gas-electricity price coupling and amplification, they rarely connect these mechanisms to broader macroeconomic effects or distributional consequences.

A third strand focuses on responses after prices have already risen, with particular emphasis on fiscal policy and household protection. This work shows that targeted transfers, subsidies, and other social protection measures can substantially reduce welfare losses and, in some cases, moderate short-run inflation (Duparc-Portier & Figus, 2024; Burlinson et al., 2024; Glocker & Wegmüller, 2024). At the same time, these studies generally acknowledge that such measures do not reduce exposure to price volatility or alter price formation in energy markets. Ex-post interventions are therefore treated as temporary relief rather than as sources of longer-term resilience.

A relevant body of research examines uncertainty, volatility, and expectations. These studies show that even when prices stabilise, uncertainty in energy markets can delay investment, slow adjustment, and weaken economic performance (Zhao et al., 2023; Nguyen et al., 2024; Balcilar et al., 2019). This perspective draws attention to the limits of analyses that focus only on realised prices or immediate welfare impacts. However, uncertainty-focused approaches are typically developed separately from work on short-run price formation and amplification in coupled gas-electricity markets.

Thus, the literature points to several unresolved issues. First, resilience is defined differently across macroeconomic, market, and household-level analyses, with little effort to clarify how these dimensions connect. Second, although gas-electricity price coupling is well documented as an amplification channel under stress, it is rarely embedded in broader discussions of economic stability or welfare. Third, longer-term effects linked to uncertainty and volatility are analysed largely in isolation from short-run price dynamics and policy responses.

More generally, a common weakness across these strands is the limited attention paid to how energy prices are actually formed and amplified in liberalised markets, particularly during periods of stress. Where prices play a central role in allocating resources and signalling scarcity, resilience to large energy price increases cannot be assessed separately from the mechanisms that generate and transmit those prices across markets. Addressing this gap motivates the analysis in the sections that follow.

2.2 Price Formation in Liberalised and Coupled Energy Markets

In liberalised energy markets, prices are the primary mechanism for coordinating supply, demand, and investment decisions. For this reason, price formation plays a central role in determining how shocks are transmitted across the energy system. In electricity markets, wholesale prices are set through marginal pricing, in which the price in each period reflects the cost of the most expensive unit needed to meet demand. This principle is firmly grounded in standard economic theory and has long been recognised as an effective framework for short-run dispatch and long-run investment incentives in power systems (Schweppe et al., 1988; Stoft, 2002).

A key feature of marginal pricing is that outcomes are determined by conditions at the margin rather than by average system costs or overall capacity adequacy. When low-cost generation is readily available, prices remain low even in systems characterised by high fixed costs. When demand approaches system limits, or when low-cost generation becomes unavailable, prices can rise rapidly as higher-cost units are brought online. Scarcity pricing, therefore, arises by design. It reflects the economic value of energy and flexibility when the system is constrained, rather than a malfunction of the pricing mechanism itself (Pollitt et al., 2024).

In European electricity markets, natural gas frequently sits at the margin. This is particularly the case during periods of high demand, low renewable output, or reduced availability of other dispatchable technologies (Uribe et al., 2022). As a result, wholesale electricity prices tend to move closely with gas prices, even when gas represents only a modest share of total electricity generation. This creates a tight coupling between gas and electricity markets, in which shocks originating in one sector are transmitted to the other through price-setting rather than through physical shortages.

Price behaviour in such coupled systems depends heavily on system conditions. In normal circumstances, the flexibility provided by storage, interconnection, and diversified supply dampens price responses to shocks. Under stress, this flexibility can erode quickly. Multiple constraints may bind simultaneously, increasing reliance on marginal gas-fired generation to balance the system. In these situations, relatively small changes in demand or availability can trigger large price movements. Price increases during scarcity episodes tend to be sharp, while price reductions during surplus conditions are often more limited. These asymmetric and nonlinear dynamics are a familiar feature of power systems operating close to their technical and operational limits (Kirschen & Strbac, 2018).

The distributional consequences of marginal pricing during periods of stress have fuelled renewed debate over electricity market design. Proposals have included pay-as-bid pricing (Kahn et al., 2001), temporary gas price caps such as the Iberian exception (Hidalgo-Pérez et al., 2024), and dual-market arrangements separating fossil-based and renewable generation (Keay & Robinson, 2017). These proposals reflect genuine concerns about the social and political effects of extreme prices, particularly when both markets experience supply shortages. At the same time, recent European policy assessments reaffirm marginal pricing as the foundation of electricity market functioning (EC, 2025). This position is consistent with the conclusions of Pollitt et al. (2024), who review lessons from the 2021-23 crisis.

Against this background, the analysis in this paper treats marginal pricing as a maintained feature of liberalised energy markets. The focus is not on redesigning price-setting rules, but on understanding when and how price formation in coupled gas-electricity systems amplifies exogenous shocks into system-wide price stress, and under what conditions it moderates them. The paper also considers the scope for complementary mechanisms operating alongside existing market design to strengthen energy price resilience without undermining the core market design principles established in the EU to date.

2.3 From Energy Resilience to Energy Price Resilience

Energy security is commonly defined as "the uninterrupted availability of energy sources at an affordable price" (IEA, 2014). This definition captures the traditional balance between physical supply and cost. Recent crises, however, have shown that in liberalised markets, severe stress is rarely resolved through widespread physical interruptions. Instead, adjustment tends to occur through scarcity pricing and voluntary demand response. In Europe, the 2021-2023 energy crisis did not lead to generalised administrative rationing or large-scale load shedding. Aggregate system balance was largely maintained. At the same time, prices reached extreme levels and remained elevated for prolonged periods.

Adjustment occurred mainly through price signals. These included significant price-induced demand reductions in energy-intensive industry, fuel switching, and changes in household consumption behaviour (IEA, 2025). The economic and distributional effects were substantial. Inflationary pressures intensified, firms curtailed production, and governments intervened on a large scale. This experience has brought renewed attention to the concept of resilience, particularly to how it should be understood when stress is transmitted primarily through prices rather than outright system failure.

Energy resilience is typically described as the ability of an energy system to withstand disruptive events and to reduce their magnitude and duration, including the capacity to anticipate, absorb, adjust, and recover. Umunnakwe et al. (2021) formalise this idea through the "resilience trapezoid", which represents system performance over the course of a disruption and distinguishes four stages: withstanding, absorbing, restoring, and adapting. This framework has been widely applied in studies of infrastructure and energy systems (see Baldursson et al., 2023) and provides a useful way to think about how systems respond over time to high-impact, low-probability events.

Experience from recent crises suggests that in marginal-pricing markets, security of supply is often maintained through high prices and voluntary demand adjustment rather than involuntary curtailment. Prices, therefore, do more than balance the system. They also transmit scarcity into the broader economy. When price spikes are large and persistent, they can generate inflation, distributional stress, and pressure for emergency intervention. Confidence in market arrangements can weaken even when physical supply is maintained. Resilience, in this setting, cannot be assessed solely by continuity of supply. The economic and political cost of preserving that continuity through prices also matters.

For this reason, this paper focuses on energy price resilience. This is treated as a specific dimension of energy resilience that concerns how prices behave under stress. Energy price resilience does not imply stable prices in normal times, nor does it aim to eliminate scarcity pricing. The concern is instead with extreme outcomes: how large price spikes become, how long they persist, and how prices move back towards pre-shock ranges once stress eases. Drawing on the resilience trapezoid, energy price resilience is defined here as:

> *the capacity of an energy system to limit the magnitude and duration of extreme price spikes that arise when high-impact, low-probability shocks interact with structural constraints, to restore prices in an orderly manner following such shocks, and to adapt so that future shocks lead to less severe price amplification, while maintaining credible market functioning and consistency with environmental objectives.*

Three features of this definition are important. First, price resilience is inherently dynamic. It relates not only to peak prices but also to persistence, volatility, and recovery. Second, price resilience is analytically distinct from consumer protection. Measures (macro stabilisation and fiscal policies) that smooth retail prices or compensate households may be necessary for social or political reasons, but they do not in themselves reduce wholesale price stress. Third, price resilience is system-wide. In tightly coupled energy systems, outcomes in one market can propagate quickly to others.

Figure 2 provides a conceptual illustration of energy price resilience by adapting the resilience trapezoid to price-based systems. The figure distinguishes four stages of the response to price stress: withstanding, absorbing, restoring, and adapting.

Figure 2: Conceptual illustration of energy price resilience

Table 1 operationalises this framework by linking each stage to its conceptual role, its interpretation in price-based energy systems, and a set of indicative metrics.

Price resilience outcomes depend on three interacting factors: the nature of the shock, the structure of market coupling, and the state of system flexibility. In this paper, price resilience is treated as the result of a causal sequence: shock drivers → amplification through coupled markets → flexibility and infrastructure constraints → price outcomes → macroeconomic and welfare effects → policy response and longer-term adjustment. In coupled gas-electricity systems, the key amplification channel is state-dependent marginal pricing. When gas sets the marginal generation cost, tightness in gas supply is transmitted directly into electricity prices. When several constraints bind simultaneously, price responses become nonlinear, and upper-tail outcomes become more pronounced.

Policy instruments, therefore, cannot be assessed only by their immediate effect on observed prices. Some instruments primarily reduce exposure by lowering the probability of tight conditions. Others act on amplification by limiting pass-through. Some influence persistence by shaping recovery dynamics, while others affect incidence by reallocating risk across agents. Macroeconomic stabilisation and fiscal policy, although not energy-market instruments in a narrow sense, form part of the broader response to episodes of extreme price stress and are relevant within this framework (Figure 2), particularly in the restoring and adapting stages. In the restoring phase, fiscal tools can limit welfare losses and reduce the risk that temporary energy price shocks become embedded in inflation. In the adapting phase, credible fiscal frameworks can support structural adjustment and investment in flexibility, provided they avoid repeated price suppression that weakens incentives and creates lasting fiscal pressure.

The framework set out in this section structures the remainder of the paper in two ways. First, the stress-test modelling results are interpreted as evidence on exposure, amplification, and recovery under defined high-impact, low-probability events. Second, the policy discussion is organised around the stages of the resilience process, with attention to mechanisms, trade-offs, activation conditions, and interactions between energy-system measures and fiscal stabilisation tools.

Table 1: Analytical framework for energy price resilience

Resilience stage	Role in the system	Meaning in price-based markets	Indicative measures
Withstanding (preparedness)	Avoiding entry into extreme price conditions	The extent to which the system can avoid scarcity-driven price formation under adverse conditions	Frequency of scarcity episodes; exposure to marginal gas supply; deliverability under stress; adequacy margins in adverse scenarios; share of hours in which gas sets the power price during cold or low-renewable periods
Absorbing (limiting stress amplification)	Containing short-run price amplification	The ability to limit peak prices and immediate pass-through once stress materialises	Peak and upper-tail wholesale prices; gas-power price pass-through during stress hours; change in power-sector gas demand; use of flexibility such as storage discharge, demand response, or fuel switching
Restoring (orderly recovery)	Returning to lower-stress price conditions	How quickly and smoothly prices normalise after the initial shock	Speed of price reversion; storage refill patterns and associated price pressure; persistence of price differentials across hubs or regions; volatility following the shock
Adapting (structural resilience)	Lowering vulnerability to future shocks	Longer-term changes that reduce exposure and amplification in subsequent stress events	Reduced reliance on gas at the margin; greater flexibility and supply diversification; sustained demand reduction; risk allocation through contracting that limits forced demand destruction; institutional reforms that reduce uncertainty and support investment

3. Shocks Beyond 2021-2023: Evidence from European Energy-System Stress Tests Modelling

This section reviews evidence from system-level stress tests examining how Europe's coupled gas-electricity system responds to high-impact, low-probability (HILP) shocks (Table 2). The analysis draws on published modelling results reported in Chyong (2024) and its associated supplementary materials; key quantitative outputs are summarised in Appendix 2. Key Modelling ResultsWe synthesise and interpret these results through the lens of price resilience and cross-sector coupling.

Table 2: Scenario structure (2027-2031)

Scenario cluster	Description	Weather overlays
Baseline	No Russian gas from 2027; NECP 2019 renewable targets; no LNG disruption	Mild / Normal / Coldest / Coldest + Drought
US LNG Delay	40–45 bcma US LNG expansion delayed (2027–2031)	Same four weather cases
Qatar Shock 2027	One-year disruption of Qatari LNG (127 bcma) in 2027	Same four weather cases
Qatar Shock 2029	One-year disruption of Qatari LNG (127 bcma) in 2029	Same four weather cases
REPowerEU Sensitivity	Wind and solar capacity aligned with REPowerEU targets	Same four weather cases

In this paper, HILP events (shock configurations) refer to compound shock conditions that are individually plausible but whose coincidence materially amplifies system strain and price volatility. The emphasis is not on extreme outliers, but on realistic combinations of adverse weather (cold winters, low wind output, drought-induced hydro constraints) and supply-side disruptions (e.g. LNG shortfalls or delayed capacity expansion). What makes these events "high impact" is their interaction across sectors: weather simultaneously raises gas demand and reduces renewable generation, residual electricity load increases gas burn in power generation, and tighter global LNG markets reduce marginal supply elasticity. The modelling therefore focuses on these compound shock configurations rather than isolated single shocks.

The underlying model is a partial-equilibrium global energy market model linking gas and electricity markets. It represents LNG shipping, pipeline flows, storage behaviour, electricity dispatch, and demand-side response, and incorporates forty years of hourly climate data to capture inter-annual variability in temperature, wind, solar, and hydro inflows. Within each scenario, wholesale prices, storage withdrawals, cross-border flows, and fuel switching are determined endogenously, subject to infrastructure constraints, while weather conditions, supply disruptions, and policy trajectories are imposed exogenously. The time horizon covers 2027-2031, a period in which Europe operates without Russian gas imports.

The modelling evidence is structured around a Baseline and a set of shock overlays. First, the Baseline configuration is evaluated under alternative historical weather years (mild, normal, coldest, and coldest combined with drought) to isolate weather-driven shock effects. Second, supply-side disruptions are introduced under each weather year. These include delayed US LNG expansion and one-year disruptions to Qatari LNG supply (in 2027 and 2029). In addition, a policy sensitivity case aligned with REPowerEU renewable deployment is assessed. The cross-combination yields 20 model runs, allowing consistent comparison between demand-driven and supply-driven price pressures.

3.1 Weather-Driven Vulnerability

Under the Baseline and a normal weather year, EU27 natural gas demand is reported at 347 bcm in 2027 (Chyong, 2024). Power generation accounts for the largest share, at 120 bcm (35% of total demand), followed by residential buildings at 90 bcm (26%), industry at 81 bcm (23%), commercial buildings at 39 bcm (11%), and the energy industry’s own use at 17 bcm (5%). This composition highlights two features central to price resilience. The power sector is the primary channel through which gas-market tightness is transmitted into electricity prices, reflecting the role of gas-fired generation at the margin. In parallel, space-heating demand in residential and commercial buildings remains a significant source of winter stress, particularly in years with adverse weather.

Weather variations lead to significant swings in aggregate gas demand. In 2027, a shift from normal to mild weather reduces total demand by 15 bcm (around 4%), driven mainly by lower heating demand in residential buildings (-7 bcm, -8%) and commercial buildings (-3 bcm, -8%), together with a reduction in gas use for power generation (-5 bcm, -4%). Moving from normal to the coldest weather year has the opposite effect. Gas demand increases by 23 bcm (+6%) in 2027 and by 55 bcm (+18%) in 2031. Most of this increase comes from the power sector, where additional demand reaches 9 bcm in 2027 (+7%) and rises sharply to 36 bcm in 2031 (+65%). Under cold-weather shock conditions, gas demand in power generation therefore acts as the main system-wide swing component, particularly as other sources of flexibility are constrained.

On the supply side, LNG provides most of the marginal adjustment. In the coldest weather year, LNG imports increase by 20 bcm in 2027 and by 39 bcm in 2031 relative to normal weather conditions, accounting for around 90% and 70% of the marginal increase in imports, respectively. Pipeline supply offers less flexibility. The maximum incremental increase in pipeline imports is 13 bcm (in 2029), representing only 14% of the marginal import response. This asymmetry indicates that resilience during cold winters depends heavily on access to global LNG markets.

3.2 Demand-Side Response and Fuel Switching

Demand-side response (DSR) plays a limited but non-negligible role under stress conditions. In the Baseline scenario, cumulative curtailment over 2027–2031 amounts to 14 bcm (around 1% of cumulative demand) in the coldest weather year. This increases to 33 bcm (2%) in the coldest-and-drought case, reflecting tighter system conditions and higher prices under compounded stress.

The relatively modest scale of aggregate curtailment, despite large price increases in the stress scenarios, reflects the low short-run price elasticity of heating and industrial gas demand. Residential and commercial consumption is largely weather-driven and therefore only weakly responsive to price signals within a single season. Industrial adjustment, while more price-sensitive at the margin, is constrained by process rigidity, contractual obligations, and the limited availability of rapid fuel substitution options. As a result, even substantial wholesale price increases translate into limited annual demand reduction within the modelling horizon. In the stress cases, system adjustment therefore occurs primarily through increased LNG imports and power-sector fuel switching rather than through large-scale demand destruction.

DSR also declines over time. In the coldest-and-drought year, curtailment reaches 7 bcm in 2027 (around 2% of annual demand) but falls to 1 bcm (0.4%) by 2031. This decline reflects both lower average gas prices and a structural shift in the generation mix. As renewable penetration increases, the system becomes less reliant on gas at the margin, reducing the scale of price-induced curtailment required under comparable weather stress. In this sense, the modelling points to an endogenous improvement in price resilience over time as structural exposure to gas diminishes.

Fuel switching in the power sector provides a substantially larger adjustment margin than direct demand curtailment. Measured as the difference between gas use in normal and cold years, the implied swing in the power sector increases over time. In 2027, the swing reaches 8.5 bcm (7% of power-sector demand) in the coldest year and 10.5 bcm (9%) in the coldest-and-drought year. By 2031, these figures rise to 35.8 bcm (30%) and 40.3 bcm (34%), respectively. Power-sector substitution between gas and alternative generation sources therefore emerges as the central mechanism for absorbing cold-weather stress, conditional on the availability and relative cost of coal, hydropower storage, and other flexibility resources.

3.3 Wholesale Price Responses

Wholesale prices respond asymmetrically to loose and tight market conditions. Under the Baseline and normal weather, average Northwest European gas prices fall from 11.2 €/MMBtu in 2027 to 9.3 €/MMBtu in 2031. Prices remain well below crisis peaks but above pre-crisis levels. Weather effects are uneven. Mild conditions reduce gas prices by up to 10% in 2031, while cold conditions generate much larger increases. Under the coldest scenario, prices rise by 48-68%, and under the coldest and drought scenario by 53-83%. Even with expanding global LNG supply, price increases under scarcity are far larger than price reductions under loose conditions.

Electricity prices follow gas prices but with a smaller proportional response. In the Baseline, electricity prices rise by 23-32% in the coldest weather year and by 25-40% in the coldest and drought year relative to normal conditions. The more muted response reflects partial adaptation in the power sector, including gas-to-renewable switching, and a gradual weakening of gas-to-power price transmission as renewable shares increase.

3.4 LNG Supply Shock Scenarios

In the US LNG delay scenario, both gas and electricity prices remain persistently above Baseline levels. Average European gas prices are higher by 1.7-3.4 €/MMBtu (18-35%), while electricity prices increase by 11-21 €/MWh (8-14%). The price gap does not close fully by the end of the modelling period. On the quantity side, gas demand is 8 bcm lower than Baseline in 2027 (-2%) but exceeds Baseline by 2 bcm (+1%) by 2031, reflecting storage dynamics and demand destruction outside Europe. Over 2027-2031, the average difference is 2.8 bcm per year (1%).

The Qatar disruption scenarios generate sharp but relatively short-lived price effects. In the 2027 disruption, gas prices increase by 3.5 €/MMBtu (+31%) and electricity prices by 21 €/MWh (+14%), with most of the spike reversed by 2028. In the 2029 disruption, gas prices rise by 1.1 €/MMBtu (+12%) and electricity prices by 6 €/MWh (+4%), returning to Baseline by 2030. Timing matters. The earlier disruption produces larger immediate price effects, consistent with a more limited alternative LNG supply in 2027 than in 2029.

The results also point to a global feedback channel. Supply shocks induce demand destruction outside Europe, which contributes to price easing in subsequent years. Global gas demand is projected to be 14 bcm lower in the Qatar 2027 disruption scenario and 47 bcm lower in the Qatar 2029 disruption scenario over 2027-2031 under normal weather. Part of the post-shock price normalisation in Europe is therefore mediated through global demand adjustment, a pattern consistent with the experience of the 2021-2023 crisis.

3.5 Flexibility Sources and Infrastructure Constraints

Flexibility use is strongly seasonal. Hydropower storage peaks between May and October and is drawn down during winter. Underground gas storage falls to around 20 bcm between January and March, equivalent to about 6% of annual demand, before refilling to around 104 bcm (30% of annual demand) by October. LNG import terminals play a critical role under extreme weather. Monthly LNG imports reach 17-20 bcm in the coldest and coldest-plus-drought years, covering 50-60% of monthly demand, compared with 12-15 bcm (35-45%) in mild and normal years. In 2029, annual LNG imports increase from 150 bcm in the mild weather year (55% of demand) to 226 bcm in the coldest and drought year (83%), a difference of 76 bcm, or 28% of total demand, within a single year. LNG thus acts as the main backstop when compound shocks generate system-wide stress, complementing the seasonal balancing role of hydro and gas storage.

At the Member State level, exposure and bottlenecks vary widely. Eastern and Southern European countries experience higher electricity prices, reflecting limited interconnection capacity. Flexibility options also differ. Some countries rely heavily on coal-gas fuel switching, while others depend more on hydropower storage. Infrastructure utilisation patterns show that in supply-shock scenarios, certain countries reach full utilisation of electricity import capacity, while multiple pipeline interconnectors operate at 100% during peak months. On the other hand, aggregate LNG regasification utilisation remains below 35% even in the coldest and drought year. System stress is, therefore, shaped less by EU-level regasification capacity than by upstream supply availability, internal pipeline constraints, and the geographic distribution of flexibility.

3.6 Implications for Resilience Under Future HILPs

Three implications for price resilience stand out. Weather shocks are the dominant source of system-wide stress, operating through both heating demand and increased gas use in power generation. LNG provides the main marginal supply buffer in cold years, but reliance on global LNG markets exposes Europe to geopolitical risk, with the timing of disruptions strongly influencing price impacts. Resilience is also shaped by the interaction between flexibility resources, such as storage, fuel switching, and DSR, and infrastructure constraints, which remain uneven across Member States.

The evidence points to two interacting drivers of price outcomes in Europe’s coupled gas-electricity system. Weather-related demand surges increase reliance on gas-fired power and LNG imports, while external LNG supply constraints trigger episodes of scarcity that prompt demand adjustments. These dynamics motivate a policy approach that distinguishes between measures that act before a shock occurs, by reducing exposure and strengthening flexibility, and measures that operate once stress materialises, by smoothing extreme outcomes and limiting economically disruptive curtailment. Section 4 develops this distinction and evaluates policy instruments in relation to the specific stress channels and flexibility responses identified above.

4. Policy Instruments for Price Resilience in Coupled Gas-Electricity Systems

Building on the framework in Section 2 and the stress-test evidence in Section 3, this section reviews policy instruments that can strengthen price resilience in coupled gas-electricity markets. The aim is not to change marginal pricing or merit-order dispatch, but to reduce the likelihood, severity, and persistence of extreme wholesale price outcomes under HILP shock configurations.

The modelling results point to a small set of recurring drivers of price stress: correlated weather shocks that raise demand, LNG’s role as the marginal source, internal bottlenecks that concentrate scarcity, and the exhaustion of flexibility during compound events. These conditions generate asymmetric price responses: sharp spikes when the system is tight and smaller price declines when conditions are loose. For this reason, instruments are assessed against upper-tail outcomes and recovery dynamics, rather than their effects on average prices.

Policy effectiveness depends on where an instrument acts along the stress path. Some measures reduce exposure before shocks materialise. Others dampen amplification once flexibility is saturated. A further policy set shapes recovery (how quickly prices normalise and how much uncertainty remains). Finally, structural measures change the system over time by reallocating risk, diversifying supply, and reducing reliance on marginal fossil fuels. These categories overlap in practice, and each comes with trade-offs. Measures that flatten peaks can weaken scarcity signals if used repeatedly or poorly designed. Buffer-building can be costly and slow. Ex-post interventions can create fiscal risk and delay adjustment. Throughout, the benchmark is compatibility with marginal pricing and investment incentives, as well as consistency with environmental objectives.

Table 3 summarises the toolkit and the main trade-offs. Table 3 distinguishes carefully between what each instrument can realistically achieve and what it cannot. The column “*What these instruments achieve*” refers to how a measure reduces the probability or intensity of entering a stress regime – for example, by lowering correlated demand, increasing deliverability, or adding buffers that dampen peak amplification. The column “*What they do not address*” highlights the limits of each tool. Many instruments do not eliminate exposure to global LNG supplies, do not prevent cross-border contagion when interconnection binds, and do not suppress scarcity pricing once structural tightness has materialised. This distinction is important: price resilience depends on reducing exposure ex ante, not merely cushioning outcomes ex post.

Table 3: Overview of policy instruments for energy price resilience in coupled gas-electricity systems

Resilience stage	Main sources of stress	Policy aim	Main instruments	What these instruments achieve	What they do not address	Key trade-offs
Withstanding (ex-ante exposure reduction)	Weather-driven demand surges; correlated gas-power tightness; internal network bottlenecks	Lower the likelihood that joint constraints bind	Joint security and adequacy standards; network and interconnection investment; structural demand reduction	Reduce the probability of entering scarcity conditions by easing correlated demand and improving deliverability	Do not limit prices once scarcity has materialised	High upfront costs; long lead times; risk of over-investment if poorly targeted
Absorbing (buffers and flexibility)	LNG scarcity at the margin; exhaustion of short-term flexibility	Contain peak price spikes under stress	Storage obligations; strategic reserves; power-sector flexibility; demand response	Provide short-term buffers that dampen extreme price outcomes	Do not remove underlying exposure or eliminate scarcity pricing	Moral hazard risks; coordination problems; disputes over cost allocation
Restoring (recovery dynamics)	Price persistence after shocks	Support faster and more stable price normalisation	Predictable emergency frameworks; operational coordination	Reduce volatility, uncertainty, and persistence once stress begins to ease	Do not prevent initial price spikes	Dependence on governance credibility and disciplined use
Adapting (structural risk reallocation)	Recurrent reliance on marginal gas; under-investment driven by uncertainty	Reduce future exposure and amplification	Long-term contracting; supply diversification; low-carbon fuels; investment in flexibility	Shift risk away from spot markets and reduce structural dependence on fossil marginal supply	Do not eliminate short-run price volatility	Lock-in risks; distributional effects; consistency with evolving market design
Ex-post fiscal and retail measures	Welfare losses; inflation pass-through	Protect incomes and macroeconomic stability	Transfers; rebates; tax reductions; retail price smoothing	Redistribute the burden of extreme price episodes and limit second-round effects	Do not address wholesale price formation or underlying stress drivers	Fiscal sustainability; weakened price signals; risk of market fragmentation

Not all instruments offer the same leverage over price resilience, nor do they operate on the same timeline. In the near term, the highest leverage measures concern procurement structure and storage policy. Contract design, diversification of LNG sourcing, and calibration of storage refill obligations directly influence exposure to global LNG supplies and the likelihood of winter scarcity. These are the most immediate channels through which upper-tail outcomes can be moderated.

In the medium term, investments in flexibility and interconnection become more influential. Short-duration storage, demand response, and relief of internal network bottlenecks reduce the amplification of shocks once stress materialises. These measures dampen the transmission of gas shocks into electricity prices and reduce regional asymmetries.

In the longer term, structural electrification resilience – including building efficiency, flexible heat systems, low-carbon dispatchable capacity, and diversification away from marginal fossil supply – determines how often the system enters stress regimes. These measures reshape the underlying exposure to gas at the margin.

This sequencing reinforces a central conclusion: price resilience is cumulative. Near-term options buy time; medium-term flexibility reduces amplification; long-term structural change lowers systemic exposure.

4.1 Ex-ante Exposure Reduction: Reducing Joint Gas-Electricity Stress

Section 3 shows that extreme price outcomes are often triggered by correlated demand surges rather than isolated supply failures. Cold spells raise space-heating demand and power-sector gas burn at the same time. When gas becomes marginal across both vectors, even modest disturbances can produce large price moves. Exposure-reduction instruments, therefore, aim to reduce the probability that joint constraints bind.

First, this has implications for adequacy and security standards. Metrics calibrated to average conditions or applied separately to gas and electricity do not align well with the mechanisms driving tail-price outcomes. The stress tests show that in cold years, total gas demand rises sharply (over 20 bcm in a single year and more than 50 bcm by 2031), with the power sector providing a large and rising share of that swing. Standards aimed at resilience should therefore require joint gas-electricity stress tests: correlated cold weather, low renewable output, constrained cross-border flows, and an explicit focus on scarcity pricing frequency and severity, not only on load-shedding risk.

Second, network and interconnection planning needs to focus on deliverability under stress. Section 3 indicates that price stress is uneven across Member States and tends to be higher where interconnection is limited or gas deliverability is constrained. EU-wide storage and LNG capacity can look adequate in aggregate, while local bottlenecks still create regional scarcity and price spikes. Planning objectives should therefore shift from headline adequacy towards stress-time deliverability, prioritising investments that relieve binding internal constraints under adverse conditions.

Third, structural demand reduction matters because weather-driven demand swings dominate system tightness. Building efficiency, electrification paired with flexible heat systems, and industrial efficiency lower the scale of the correlated surge that must be met by marginal gas and LNG. These measures operate continuously. They reduce the probability of entering extreme price regimes, rather than relying on emergency curtailment once prices have already spiked.

4.2 Ex-ante Buffers and Flexibility: Limiting Peak Amplification

A second set of instruments does not prevent tight conditions but limits how far prices move once stress materialises. A key result in Section 3 is LNG's dominant role as the marginal supply response in extreme-weather years, alongside strongly asymmetric gas-price responses. Instruments that build buffers against LNG tightness, such as strategic reserves or coordinated procurement arrangements, can therefore reduce the likelihood of upper-tail outcomes in exceptional events. The modelling also points to a limit: when LNG constraints persist for multiple years (e.g., delayed North American LNG), price resilience weakens structurally. Repeated discretionary intervention in such settings can undermine private hedging and reduce incentives to invest in flexibility.

Gas storage targets (e.g., floor and ceiling and time range for targets) provide another buffer. Storage smooths seasonal imbalance: inventories fall sharply in winter and refill in summer. High pre-winter stocks reduce the chance that cold spells coincide with low inventories. The modelling results show that poorly calibrated storage obligations can add demand pressure in tight periods and sustain high prices. Storage targets and refill rules, therefore, need to reflect system conditions and weather benchmarks, not mechanical thresholds applied without regard to market state.

The modelling also indicates that power-sector flexibility dampens the transmission of gas price shocks into electricity prices. Gas prices rise sharply under stress, while electricity prices rise by less, consistent with partial decoupling through fuel switching, growth in renewable output, storage, and demand response. This suggests value in flexibility investments that reduce the swing in power-sector gas demand during stress: short-duration storage, demand response, and dispatchable non-gas capacity that fits decarbonisation pathways. The objective is not to remove gas from the margin in all hours but to reduce reliance on marginal gas in the hours that matter most for tail-price outcomes.

4.3 Recovery Instruments: Shortening Persistence and Reducing Uncertainty

Section 3 shows that price persistence differs sharply across shock types. Short-lived disruptions tend to produce sharp but temporary spikes, whereas multi-year tightening, such as delayed LNG supply, leads to sustained periods of elevated prices. This makes the recovery phase distinct from both ex-ante exposure reduction and buffering.

From a resilience perspective, recovery instruments do not address peak prices. Their role is to limit the duration of scarcity pricing once the underlying shock begins to ease by influencing refill behaviour, expectations, and coordination.

Emergency frameworks in the EU primarily operate through expectations rather than volumes. Existing instruments, such as the Gas Security of Supply Regulation and the Electricity Risk-Preparedness Regulation, do not aim to suppress scarcity pricing but to reduce uncertainty by clarifying roles, coordination procedures, and the conditions under which emergency measures may be activated and withdrawn. The experience of the 2021-23 crisis reinforced this channel: temporary measures, including the market correction mechanism for gas prices, were explicitly conditional and time-limited, signalling restraint as well as intervention capacity.

Operational coordination can support recovery when price persistence reflects temporary or local constraints rather than system-wide scarcity. In the electricity sector, instruments under the Electricity Risk-Preparedness Regulation and ENTSO-E coordination frameworks allow transmission system operators to manage bottlenecks, redispatch generation, and provide short-term cross-border assistance, helping to relieve local tightness that can otherwise sustain elevated prices after a shock. In the gas sector, coordination mechanisms under the Security of Gas Supply Regulation similarly address short-term deliverability constraints through flow management and solidarity arrangements.

The limits of these tools are equally clear. Where elevated prices reflect structural imbalances or sustained global LNG scarcity, operational coordination cannot restore normal conditions. In such cases, coordination may reduce volatility at the margin but does not substitute for diversification, investment in flexibility, or longer-term adaptation of the supply mix.

4.4 Structural Adaptation and Risk Allocation

The modelling results indicate that, as renewable penetration increases and power-sector gas demand declines, both demand-side response and electricity price sensitivity to gas market shocks diminish. Structural adaptation, therefore, forms the longer-run pillar of price resilience.

Risk allocation through contracting is one channel. The stress tests show that short disruptions can create large price spikes even when quantities adjust. Long-term gas contracts, PPAs, and CfDs in the electricity sector, and structured hedging in both markets, can reduce forced demand destruction and balance-sheet stress without suppressing wholesale scarcity prices.

Diversification, including renewable gases and other low-carbon gaseous fuels, is another channel. The modelling indicates that LNG remains the main backstop under extreme stress; diversification improves resilience mainly by reducing structural dependence on global LNG markets and exposure to geopolitical disruptions.

As literature suggests, institutional credibility also matters. Policy uncertainty raises risk premia and weakens investment in flexibility, storage, and low-carbon supply. Stable and credible frameworks lower uncertainty and support the investment needed for resilience over time.

4.5 Fiscal Policy and Macro-Resilience

Fiscal policy played a central role during the 2021-2023 crisis. Governments deployed transfers, tax reductions, energy rebates, and compensation schemes for firms to cushion income losses, limit inflation pass-through, and stabilise aggregate demand. The literature reviewed in Section 2 suggests that these measures reduced short-run welfare losses and helped prevent a deeper macroeconomic contraction.

Extreme energy prices constitute not only an economic burden but also a social and political stress test. Sharp and sustained increases in heating and electricity bills disproportionately affect lower-income households and energy-intensive sectors, with limited short-run substitution options. If vulnerable consumers are unable to cope, governments are forced into emergency interventions, often at short notice and, hence, likely with poor design. In this regard, equity and resilience are linked: a system that repeatedly generates price spikes that households cannot absorb and firms cannot cope with becomes politically fragile, increasing the likelihood of ad hoc market interventions that may undermine longer-term investment signals.

From the perspective of energy price resilience, however, fiscal tools operate primarily after scarcity has materialised. They redistribute the burden of price spikes rather than changing the mechanisms generating extreme wholesale prices. They do not address the main stress channels identified in Section 3: weather-driven demand surges, dependence on LNG at the margin, internal network bottlenecks, or the exhaustion of flexibility during compound events.

This distinction is important. Repeated reliance on broad fiscal shielding can weaken price signals and slow down structural adjustment. Sustained subsidies and price caps reduce incentives for demand response and efficiency improvements and can delay investment in flexibility and low-carbon supply. Fiscal capacity is also uneven across Member States. Heterogeneous national support schemes risk fragmenting the internal market and weakening cross-border solidarity during stress.

None of this makes fiscal policy optional. During severe episodes, targeted income support and temporary macro-stabilisation measures are essential to maintain social cohesion and political legitimacy. Within the resilience framework set out in Section 2, fiscal policy primarily operates in the restoring phase: limiting near-term welfare losses and preventing temporary energy price spikes from evolving into persistent inflation or political instability. Its effectiveness depends critically on being targeted, temporary, and consistent with longer-term structural incentives to improve resilience and meet environmental objectives.

5. A Framework for Measuring Energy Price Resilience

Sections 2 and 3 demonstrate that extreme price outcomes in coupled gas-electricity systems arise not from a single failure, but from compound shock configurations that generate system-wide stress: low renewable output, reduced nuclear or hydro availability, elevated demand during cold spells, and reliance on marginal LNG supply. Section 4 reviewed policy instruments that can mitigate such risks. In this section we translate these analytical insights into a structured regulatory framework, building on the EU Security of Gas Supply Regulation (2017/1938) and the EU Electricity Regulation (2019/943).

The Energy Price Resilience (EPR) metric is designed as an extension to, not a replacement for, the current security-of-supply (SoS) regulatory architecture. European gas and electricity security assessments are anchored in two distinct pillars. In gas, Regulation (EU) 2017/1938 establishes the N-1 infrastructure standard. This metric tests whether a Member State's gas system can meet demand following the loss of its largest import or transmission infrastructure during a statistically defined extreme demand day. Formally, the N-1 index compares post-contingency physical deliverability - entry capacity, storage withdrawal, indigenous production and LNG regasification capacity minus the largest infrastructure - to a benchmark "1-in-20" peak daily demand. A value of at least 100 percent constitutes formal compliance. The metric is, therefore, a technical deliverability test focused on physical continuity of supply under a defined infrastructure contingency. It does not assess wholesale price exposure, contractual structure, or marginal supply dynamics. Nor does it inherently account for internal bottlenecks unless supplemented by network modelling, or for seasonal storage depletion beyond peak-day withdrawal assumptions.

Electricity security is assessed separately under Regulation (EU) 2019/943 through the European Resource Adequacy Assessment (ERAA), coordinated by ENTSO-E and ACER. These probabilistic assessments evaluate whether generation and flexibility capacity are sufficient to meet demand under a range of scenarios. Standard outputs include Loss of Load Expectation (LOLE), Expected Energy Not Served (EENS), and related capacity margin indicators. ERAA incorporates variable renewables, demand-side response, storage, and cross-border flows, and informs national reliability standards and capacity mechanisms. Like the N-1 standard, electricity adequacy metrics are designed to assess physical sufficiency and reliability risk, not price resilience.

Thus, existing frameworks ensure continuity of supply but are not constructed to assess exposure to extreme price regimes under compound gas-electricity shock scenarios. They are conducted under different modelling structures and do not require a common set of stress narratives. Nor do they distinguish between physically contracted and price-hedged gas supply structures. The proposed EPR metric builds directly on these pillars while addressing these gaps.

First, it refines the demand benchmark against which gas infrastructure adequacy is assessed. In systems with high penetration of variable renewables and increasing electrification of heating and transport, peak gas demand is no longer driven solely by non-power consumption. Instead, it increasingly reflects residual electricity load during periods of low wind and solar output. The EPR metric, therefore, replaces the historical "1-in-20" peak-day benchmark with a compound-stress benchmark derived from a shared set of gas–electricity stress scenarios. This preserves the statutory logic of the N-1 standard while ensuring that gas adequacy is assessed against the conditions under which gas demand is most likely to surge in the power sector.

Second, the EPR metric explicitly distinguishes between physical adequacy and price resilience. Physical deliverability alone does not determine economic outcomes during stress events. When incremental supply is provided by marginal LNG cargoes clearing at spot prices, countries with high reliance on spot-indexed procurement remain exposed to extreme price volatility even if infrastructure capacity is formally sufficient. The EPR metric therefore adjusts physical adequacy to reflect three interacting features of gas procurement: the share of demand covered by fixed-price or capped contracts, the concentration of marginal LNG suppliers, and the degree of tightness in global LNG markets. When domestic spot exposure coincides with concentrated supply and a globally tight LNG market, price responses become increasingly nonlinear. The EPR metric captures this amplification through a convex price-exposure adjustment, making visible vulnerabilities that are not captured by infrastructure metrics alone.

Third, the EPR metric integrates electricity adequacy conditionally, rather than mechanically. Electricity adequacy matters for gas price resilience because residual electricity load determines gas demand in power generation during stress events. When post-contingency gas deliverability is sufficient to cover compound residual demand, electricity adequacy risk is effectively internalised within the gas benchmark and resilience is governed primarily by gas infrastructure and market exposure. When gas deliverability is insufficient, electricity scarcity becomes an independent driver of tail-price risk, as scarcity pricing in the power sector amplifies gas demand and gas hub prices. The EPR metric therefore operates as a two-dimensional metric in the former case and a three-dimensional metric in the latter, reflecting the underlying economics of coupled scarcity.

The formal definition of the EPR metric, including the compound-stress demand benchmark, the price-exposure adjustment, and the conditional integration of electricity adequacy, is summarised in Box 1. The metric combines these elements into a single, normalised index while preserving transparency about the underlying sources of vulnerability.

Box 1: Defining EPR metric

Let Ω denote a shared (for gas and electricity stress testing) scenario set incorporating extreme climate realisations, low wind and solar availability, nuclear or hydro outages, electrification trajectories, and cross-border constraints consistent with correlated weather conditions. Define compound-stress peak demand as:

$$D^* = \sum_{\omega \in \Omega} \mathrm{w}_\omega \left(D^{nonpower}(\omega) + \frac{RL^{peak}(\omega)}{\eta_{GT}} \right),$$

where $RL^{peak}(\omega)$ is peak residual electricity load under stress and η_{GT} is representative gas-to-power efficiency. Then, the refined gas continuity metric becomes:

$$N_{-1}^{+} = 100 \times \frac{S_{-L}^{phys}}{D^*},$$

where S_{-L}^{phys} is the numerator as defined in the Gas Regulation (EU) 2017/1938. This preserves the N-1 structure defined as per Regulation (EU) 2017/1938 while embedding compound gas-power stress in the demand benchmark.

Further, physical deliverability alone does not determine economic resilience. Under stress, incremental supply is frequently provided by global LNG clearing at spot indices. Contracts indexed to European gas hubs provide physical assurance but do not shield against wholesale price spikes. To capture this dimension, define a hedged coverage ratio:

$$CCR = \frac{Q^{hedged}}{D^*},$$

where Q^{hedged} includes only volumes deliverable under fixed-price or capped arrangements, or contracts indexed to alternative commodities or energy vectors (e.g., crude oil and derivative products or regulated RES and low-carbon energy CfD strike prices) with structurally weaker correlation to European gas spot prices. Contracts indexed to European gas hubs are treated as spot-exposed. Spot exposure is therefore:

$$SS = 1 - CCR$$

Further, let HHI_{LNG} denote the concentration index of global spot LNG market, defined as the difference between effective global liquefaction capacity and aggregate annual contract quantities of destination-specific (DES), point-to-point long-term LNG contracts globally.

To incorporate global market structure, define a global LNG tightness indicator:

$$GT = \frac{ACQ_{global}^{DES}}{C_{effective}^{liq}},$$

where ACQ_{global}^{DES} denotes the aggregate annual contract quantities of destination-specific (DES), point-to-point long-term LNG contracts globally – representing the least flexible segment of LNG supply – and $C_{effective}^{liq}$ denotes effective global liquefaction capacity, defined as nameplate capacity adjusted for expected availability and utilisation. Both quantities are measured on a consistent annual basis.

Higher values of GT indicate tighter global LNG markets, with a larger share of liquefaction capacity pre-committed under rigid contractual structures and therefore limited residual flexibility to respond to incremental demand shocks.

The price-exposure penalty multiplier is then defined as:

$$\phi = \frac{1}{1 + \kappa \cdot (SS \cdot HHI_{LNG} \cdot GT)^{\gamma}}, \qquad k > 0, \gamma > 1.$$

with *k>0* capturing sensitivity to concentrated spot reliance.

This formulation captures three interacting channels of price vulnerability:

1. Domestic reliance on spot-indexed procurement (SS);
2. Concentration of marginal LNG supply (HHI_{LNG});

3. Global residual supply tightness (GT).

The exponent γ>1 introduces convex amplification, reflecting the empirical observation that price responses in tight commodity markets become increasingly nonlinear as residual supply elasticity declines. Under this formulation, resilience declines more sharply when high domestic spot exposure coincides with concentrated and globally tight LNG markets.

The price-reislience-adjusted gas adequacy index is therefore:

$$N^{PR}_{-1} = N^{+}_{-1} \cdot \phi$$

This construction allows situations in which physical adequacy exceeds 100 percent yet effective resilience is materially reduced due to reliance on concentrated global spot LNG market.

Electricity adequacy enters the EPR metric through a structural link. Peak residual electricity load, $RL^{peak}(\omega)$, determines gas demand in power generation and therefore directly influences the compound-stress benchmark D*. If post-contingency gas deliverability satisfies compound residual demand, i.e., $S^{phys}_{-L} \geq D^{*}$, then electricity adequacy risk is effectively internalised within the gas continuity benchmark. In this regime, resilience is governed by gas infrastructure adequacy and price exposure, and the EPR metric reduces to a two-dimensional structure (see below).

If, instead, we have $S^{phys}_{-L} \leq D^{*}$, then electricity adequacy constraints bind. Scarcity pricing in power markets - including activation of high-cost demand response or scarcity pricing at Value of Lost Load levels - can amplify gas burn and gas hub prices. In this regime, electricity adequacy becomes an independent driver of tail-price risk. The three-dimensional EPR metric represents this general case.

Let $\widetilde{Adeq}_{elec}$denote a normalised electricity adequacy score derived from probabilistic adequacy metrics computed under the same scenario set Ω. The general-case Composite Resilience Metric is then:

$$\boldsymbol{EPR = \alpha \widetilde{N^{+}_{-1}} + \beta Adeq_{elec} + (1 - \alpha - \beta)\widetilde{N^{PR}_{-1}},}$$

where tildes denote normalised indices and α, β are weights used to aggregate the respective indices into a single EPR metric. In regimes where gas deliverability comfortably exceeds compound residual demand, the adequacy dimension adds no independent information and the EPR metric effectively collapses to the two gas-based components. In stress states where residual electricity demand exceeds gas deliverability, all three dimensions are required to capture system vulnerability.

Thus, by construction, the proposed EPR metric preserves continuity with existing EU security standards while extending them to reflect compound stress, sector coupling, and global market structure. It distinguishes clearly between infrastructure vulnerability, exposure to marginal pricing, and electricity scarcity risk, providing a structured basis for evaluating whether policy interventions (such as those discussed in Section 4) improve resilience to extreme price outcomes rather than merely satisfying existing adequacy tests.

The EPR metric framework developed above focuses primarily on compound peak-day shock scenarios and therefore aligns most closely with capacity-based adequacy indicators. In the electricity dimension, this makes metrics such as Loss of Load Expectation (LOLE) particularly appropriate, as they capture the probability of shortfall in capacity terms under extreme conditions. However, compound stress in coupled gas–electricity systems may persist for several consecutive days, particularly during prolonged low-renewable and cold-weather episodes. In such multi-day contexts, the resilience question shifts from instantaneous capacity sufficiency to cumulative energy deliverability and duration-amplified market exposure.

Appendix 3. Multi-day “Dunkelflaute” Energy Price Resilience Metric formalises this extension. First, peak-day compound demand is generalised to cumulative demand over a stress horizon of length T, weighted across a common scenario set. Second, gas deliverability is decomposed into non-storage supply operating at feasible maximum utilisation and storage constrained by inventory, thereby avoiding the implicit assumption that infrastructure can operate indefinitely at nameplate capacity. Third, the price-exposure mechanism is duration-adjusted, reflecting the empirical regularity that sustained reliance on marginal LNG procurement in tight global markets produces convex price amplification. Fourth, the framework explicitly incorporates the statutory Supply Standard for Protected Customers under Regulation (EU) 2017/1938 as a binding lower bound: resilience must, at a minimum, ensure cumulative supply to protected demand during prolonged stress, with non-protected demand bearing adjustment through prices or curtailment when physical volumes are insufficient.

In the electricity dimension, energy-based indicators such as Expected Energy Not Served (EENS) become more appropriate than purely capacity-based metrics, as they capture cumulative deficits over sustained periods rather than instantaneous margins. The peak-day and multi-day extensions therefore address complementary aspects of resilience: the former captures the risk of entry into scarcity regimes, while the latter captures the persistence and economic amplification of stress once such regimes materialise.

6. Discussion and Conclusions

6.1. Key Findings and Contributions

The 2021-2023 European energy crisis demonstrated that security of supply in liberalised markets can be preserved without widespread physical interruption, yet still generate severe economic disruption through prices. Gas and electricity markets continued to clear. Administrative rationing was largely avoided. Nevertheless, wholesale prices reached extreme levels and remained elevated long enough to produce significant macroeconomic, distributional, and political consequences. This experience underscores a central point: in marginal-pricing systems, scarcity pricing is not a failure mode but the mechanism through which physical balance is maintained. The resilience question therefore shifts from preventing interruption to limiting the magnitude and persistence of price stress generated when exogenous shocks interact with binding constraints – network and flexibility options.

This paper makes three contributions.

First, it develops a conceptual framework that distinguishes energy price resilience from broader notions of energy security. Energy price resilience is defined as the capacity of a coupled energy system to limit the magnitude, duration, and amplification of extreme wholesale price spikes arising when high-impact, low-probability shock configurations generate system-wide stress. Adapting the resilience trapezoid to price-based markets clarifies the sequence: shock drivers → amplification through sector coupling → flexibility constraints → price stress → macroeconomic and distributional effects. This distinction separates scarcity pricing, which reflects binding physical and market conditions, from policy design choices that determine exposure and amplification.

Second, the stress-test modelling evidence shows that future price stress in Europe's coupled gas-electricity system is most likely to arise from compound shock configurations rather than isolated disturbances. Cold-weather shocks simultaneously raise heating demand and residual electricity load, increasing gas burn in the power sector. LNG acts as the principal marginal supply buffer under such conditions, shifting resilience toward dependence on global LNG market structure. Price responses are asymmetric: tight conditions produce large upward movements, while loose conditions generate smaller downward adjustments. Flexibility resources – storage, fuel switching, demand response – mitigate stress but are unevenly distributed across Member States, so aggregate adequacy does not automatically translate into local price resilience when internal network bottlenecks bind.

Third, the paper shows that resilience is a portfolio problem. No single instrument prevents extreme price stress. Exposure reduction, buffering, recovery design, and structural adaptation operate at different points along the shock-to-stress transmission path. Some instruments are complements – storage and interconnection, for example – while others are partial substitutes, such as structural demand reduction and additional LNG import capacity. Recognising these interactions is essential for avoiding over-investment in one domain and under-investment in another.

6.2. Policy Recommendations

The policy implications follow directly from the structure of price formation in coupled gas-electricity markets. Extreme outcomes do not arise from a single failure, but from the interaction of correlated demand surges, LNG supply tightness, internal network constraints, and limits to flexibility. Resilience policy should therefore aim to reduce exposure ex ante and dampen amplification when stress materialises, while limiting attempts to suppress prices once scarcity is already binding.

(1) Introduce a Compound-Stress Benchmark through the EPR Metric

Current EU security of supply frameworks are anchored in physical adequacy. The gas N-1 standard evaluates infrastructure deliverability against a historical peak-day benchmark. Electricity adequacy assessments evaluate probabilistic capacity sufficiency. Neither is designed to assess exposure to extreme price regimes under compound gas-electricity stress.

The proposed Energy Price Resilience (EPR) metric extends these pillars. We propose to replace the historical peak-day benchmark with a compound-stress demand benchmark derived from shared gas-electricity shock scenarios. It distinguishes physical deliverability from price exposure by incorporating procurement structure, reliance on spot-indexed gas purchases, supplier concentration, and global gas market tightness. It integrates electricity adequacy conditionally, reflecting the economics of coupled scarcity when residual electricity load amplifies gas demand.

Operationally, this implies that EU security assessments should adopt a harmonised scenario set and explicitly evaluate exposure to global LNG markets rather than infrastructure capacity alone. The objective is not to eliminate scarcity pricing, but to make transparent the structural conditions under which scarcity becomes nonlinear.

(2) Procurement Structure and Gas Storage Governance

Where the EPR metric reveals elevated spot purchase exposure or concentrated LNG supply reliance, procurement design and gas storage governance provide levers for reducing upper-tail price risk.

Diversified LNG sourcing and a balanced mix of contract structures reduce vulnerability to global spot market tightness. Physical access is not equivalent to economic protection if incremental volumes clear at volatile gas hub-linked indices.

Seasonal gas storage smooths winter-summer imbalances and reduces the probability that cold spells coincide with depleted inventories. However, storage refill obligations must be state-contingent and flexible rather than rigid and mechanical. Rigid or poorly calibrated filling targets can create predictable injection pressure in tight markets, amplifying summer price dynamics and distorting forward price signals. Storage governance should therefore reflect system conditions and coordinated risk management, not purely administrative capacity thresholds targets.

(3) Invest in Electricity-Sector Flexibility and Deliverability

Resilience depends on the ability of the electricity system to avoid amplification once stress materialises. Short-duration electricity storage, demand response, dispatchable low-carbon capacity, and relief of internal network bottlenecks reduce the probability that gas-fired generation sets the marginal price in peak hours. These instruments dampen the transmission of gas shocks into electricity prices.

Storage and interconnection are complementary. Storage increases the energy available under stress, but its value depends on deliverability across constrained zones. Interconnection without buffers can transmit scarcity; buffers without interconnection can remain locally trapped. Coordinated planning is therefore essential.

(4) Embed Flexibility in Structural Electrification

Over the longer term, resilience depends on structural exposure to marginal fossil gas. Electrification with renewables supports decarbonisation but does not automatically improve price resilience.

Electrified heat, hydrogen production, and data-centre demand can amplify stress if operated inflexibly, particularly in cold, low-renewable conditions when gas-fired generation is most likely to set the marginal price. Inflexible new loads increase residual electricity demand precisely when constraints bind.

Flexibility must therefore be embedded in new demand vectors. Thermal storage, hybrid heat systems, electrolyser load-shedding capability, and demand-responsive industrial and digital loads reduce the probability that electrification deepens tail-price risk. Electrification improves resilience only when it lowers correlated demand during stress periods.

(5) Fiscal Stabilisation and the Limits of Price-Suppression Interventions

Fiscal measures are essential for social and political stability during episodes of price stress, but they operate mainly after scarcity has materialised. Transfers, rebates, and tax reductions cushion welfare losses and limit macroeconomic spillovers, yet they do not address the root cause of wholesale market stress. Broad fiscal shielding can weaken scarcity signals, slow structural adjustment, and create asymmetric protection across Member States. Fiscal tools are, therefore, complementary to, not substitutes for, exposure reduction and flexibility measures.

From a resilience perspective, it is important to distinguish between measures that reduce structural exposure to stress and those that suppress price signals once scarcity has emerged. Economic theory suggests that several forms of price suppression or cost reallocation, while potentially justified as temporary crisis tools, should not be treated as structural resilience instruments.

Temporary caps on the gas price used for power generation, such as the Iberian mechanism, illustrate the trade-off. By lowering the marginal cost of gas-fired generation, such measures reduce wholesale electricity prices domestically but also increase gas burn and alter cross-border flows when neighbouring markets clear at higher prices. In integrated markets, subsidising a marginal input predictably affects quantities and trade patterns; it shifts the incidence of scarcity rather than eliminating it. More generally, interventions that distort marginal costs in coupled markets can generate spillovers across jurisdictions and weaken allocative efficiency.

Similarly, proposals to remove or reimburse ETS carbon costs for gas-fired generation distort marginal dispatch incentives by lowering the effective cost of gas-fired generation relative to low-carbon alternatives. This can increase gas demand in the short term and alter cross-border trade patterns without reducing EU-wide emissions. More importantly, reimbursing carbon costs weakens the investment signal that emissions trading is designed to provide. Auction revenues under the EU ETS are intended to support the energy transition, including renewables and innovation. Redirecting those revenues to shield fossil generation shifts resources away from structural decarbonisation and may slow investment in low-carbon resources. The effect is not to improve resilience, but to postpone the adjustment required to reduce reliance on marginal gas sources.

Further, rigid gas storage-filling mandates implemented without compatible forward hedging mechanisms raise a related concern. If injection targets are time-bound and effectively price-inelastic, public or quasi-public buyers become predictable participants in gas spot markets. Basic commodity-market analysis implies that such inelastic demand can amplify forward prices and encourage anticipatory strategic behaviour by traders. The issue is not storage per se but the design of obligations in a way that avoids systematic distortions.

Proposals to replace uniform marginal pricing with pay-as-bid auctions are unlikely to reduce wholesale electricity costs in a systematic way because bidders will most likely adjust their offers to reflect expected clearing prices (which at time of scarcity will be gas fired generators), so pay-as-bid primarily changes bidding strategies rather than underlying costs at the margin when markets are under stress.

Finally, dual or “split market” arrangements separating fossil and renewable generation may reduce visible gas price pass-through, but they do not eliminate scarcity. They reallocate rents and risk across segments of the market and introduce new coordination challenges in balancing and adequacy. Recent reforms in the EU have therefore focused on strengthening long-term contracting (PPAs and CfDs) alongside marginal pricing, rather than structurally separating markets.

6.3. Concluding Remarks, Limitations, and Future Research

The analysis suggests that Europe’s future energy security challenges are more likely to manifest as episodes of acute price stress than as widespread physical interruption. Marginal pricing remains an efficient allocation mechanism under normal conditions. Extreme outcomes arise when exogenous shocks interact with constrained flexibility and sector coupling. Resilience policy must therefore focus on reducing exposure and amplification rather than suppressing scarcity pricing after the fact.

Several limitations warrant caution.

First, the modelling framework is partial equilibrium and focuses on wholesale market dynamics. It does not incorporate full macroeconomic feedback, strategic behaviour by market participants, or financial market channels and speculative trading. Second, the calibration of the price-exposure adjustment in the EPR metric depends on empirical assumptions regarding LNG market tightness and spot concentration that require further validation. Third, the stress scenarios considered, while being grounded on some realism, cannot exhaust the space of possible correlated shocks, particularly as climate patterns and global energy trade and geopolitics evolve.

Future research should extend the framework in three directions. One avenue is empirical estimation of nonlinear price amplification under global LNG tightness to refine the convexity parameter embedded in the EPR metric. A second is integration with macro-financial models to assess how wholesale price stress propagates into inflation expectations and fiscal sustainability. A third concerns the resilience implications of deeper sector coupling, including hydrogen market design and large-scale electrification of heat and industry.

Energy price resilience does not imply the elimination of volatility. It implies reducing the frequency and severity of scarcity events while preserving credible market functioning. As Europe’s energy system decarbonises and becomes more tightly coupled across vectors, this distinction becomes increasingly central to maintaining both economic stability and political legitimacy.

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Appendix 1. Detailed Review of the Literature on Energy Price Shocks

Table A. 1: Literature on Resilience to Energy Price Shocks

Paper	Level of analysis	Energy market focus	Core transmission mechanism	Ex-ante resilience	Ex-post resilience	Primary notion of resilience
Castle et al. (2023)	Macro (UK)	Aggregate energy	Cost-push inflation, productivity	Institutions, energy intensity	n.a.	Inflation stability
van de Ven & Fouquet (2017)	Macro (cross-time)	Aggregate energy	Cost-push, policy response	Monetary credibility	n.a.	Reduced macro sensitivity
Zhao et al. (2023)	Macro (global)	Fossil energy (incl. gas)	Price volatility, geopolitics	Structural integration	n.a.	Economic stability
Uribe et al. (2022)	Market (EU)	Gas-electricity coupling	Merit-order pass-through, nonlinearity	Market integration	n.a.	Price transmission stability
Nguyen et al. (2024)	Macro / sectoral	Energy as input	Supply-chain amplification	Industrial structure	n.a.	Output resilience
Balcilar et al. (2019)	Macro / transition	Aggregate energy	Uncertainty, expectations	Policy credibility	n.a.	Investment continuity
Duparc-Portier & Figus (2024)	Policy / welfare	Retail gas & electricity	Income smoothing	n.a.	Fiscal transfers	Welfare protection
Ganepola et al. (2023)	Market (UK)	Gas-electricity coupling	Risk allocation, regulation	n.a.	Emergency intervention	System robustness
Burlinson et al. (2024)	Household	Retail gas & electricity	Affordability, income effects	n.a.	Targeted support	Household coping capacity

Paper	Level of analysis	Energy market focus	Core transmission mechanism	Ex-ante resilience	Ex-post resilience	Primary notion of resilience
Kilian & Zhou (2023)	Macro	Aggregate energy	Inflation pass-through	Monetary regimes	n.a.	Inflation containment
Guo et al. (2016)	Macro (China)	Coal-power linkage	Upstream fuel dominance	Pricing institutions	n.a.	Inflation resilience
Glocker & Wegmüller (2024)	Macro / policy	Aggregate energy	Fiscal offset of inflation		Fiscal stabilisation	Inflation smoothing
Abdallah & Kpodar (2023)	Macro	Retail energy prices	CPI and second-round effects	Anchored expectations	n.a.	Inflation persistence control
Lu et al. (2024)	Macro (UK)	Aggregate energy	Energy-triggered inflation episodes	Institutional reform	n.a.	Episode containment

Appendix 2. Key Modelling Results

Table A. 2: Baseline Demand Levels and Weather-Driven Variation

Theme	Metric / indicator	Key result(s)	Scenario / scope
Baseline demand level	EU27 total gas demand (bcm)	347 bcm	2027, Normal weather, Baseline
	Sectoral breakdown (bcm)	PWR 120; RES 90; IND 81; COM 39; own_use 17	2027, Normal weather, Baseline
Weather-driven swings	Δ total gas demand (Normal → Mild)	−15 bcm	2027, Baseline
	Drivers of Normal → Mild	RES −7; COM −3; PWR −4	2027, Baseline
	Δ total gas demand (Normal → Coldest)	+23 bcm (2027); +55 bcm (2031)	Baseline
	Power-sector contribution	PWR +9 (2027); +36 (2031)	Baseline

Source: Chyong (2024)

Table A. 3: Demand-Side Response and Fuel Switching

Theme	Metric / indicator	Key result(s)	Scenario / scope
Cumulative DSR	Curtailment (bcm)	Coldest: 14 bcm (2027–2031); Coldest+drought: 33 bcm	Baseline
DSR over time	Annual curtailment trend	7 bcm (2027) → 1 bcm (2031) in Coldest+drought	Baseline
Fuel switching (power sector)	Gas swing (Normal vs Coldest)	8.5 bcm (2027); 35.8 bcm (2031)	Baseline
	Gas swing (Normal vs Coldest+drought)	10.5 bcm (2027); 40.3 bcm (2031)	Baseline
	Sectoral DSR detail	See Table 4 in main text	2027–2031

Source: Chyong (2024)

Table A. 4: Baseline Price Levels and Weather Asymmetry

Theme	Metric / indicator	Key result(s)	Scenario / scope
Baseline prices	NWE gas price (€/MMBtu)	11.2 (2027) → 9.3 (2031)	Normal weather
	Electricity price (€/MWh)	145 (2027) → 130 (2031)	Normal weather
Gas price uplift vs Normal	Coldest	+48% to +68%	2027–2031
	Coldest+drought	+53% to +83%	2027–2031
Electricity price uplift vs Normal	Coldest	+23% to +32%	2027–2031
	Coldest+drought	+25% to +40%	2027–2031

Source: Chyong (2024)

Table A. 5: LNG Shock Scenarios (Normal Weather)

(a) Demand Impacts

Scenario	Annual demand path (bcm, 2027–2031)	Cumulative
Baseline	347 / 333 / 321 / 318 / 309	1629
US Delay	339 / 331 / 318 / 316 / 311	1615
QA27	329 / 337 / 322 / 315 / 308	1611
QA29	347 / 336 / 312 / 318 / 311	1624

(b) Price Impacts

Scenario	Gas price impact	Electricity price impact
US Delay	+1.7 to +3.4 €/MMBtu (18–35%)	+11 to +21 €/MWh (8–14%)
QA27	+3.5 €/MMBtu (+31%) in 2027; reversion by 2028	+21 €/MWh (+14%)
QA29	+1.1 €/MMBtu (+12%) in 2029; reversion by 2030	+6 €/MWh (+4%)

Source: Chyong (2024)

Table A. 6: Flexibility and Infrastructure Under Stress

Theme	Metric	Key result(s)	Scenario
Gas storage	Seasonal range	~20 bcm (winter low) → 104 bcm (summer peak)	Baseline
	Annual average levels	53–56 bcm (2027); 57–61 bcm (2031)	Across weather
LNG imports	Monthly imports	12–15 bcm (mild/normal) vs 17–20 bcm (coldest)	Baseline
	Annual swing (2029)	150 bcm (mild) vs 226 bcm (coldest+drought); +76 bcm	Baseline
	Terminal utilisation	<35% EU-wide peak month	Infrastructure analysis
	Germany utilisation	38% max (2031 coldest+drought)	Infrastructure analysis

Source: Chyong (2024)

Table A. 7: Structural Mitigation: REPowerEU Sensitivity

Theme	Metric	Key result(s)	Scope
Gas demand	Baseline vs REPowerEU	347 → 309 bcm (Baseline) vs 292 → 240 bcm (REPowerEU)	Normal weather
Power-sector gas	Cumulative displacement	51 bcm switching; PWR 68 → 17 bcm (REPowerEU) vs 120 → 83 (Baseline)	Model period
Price impacts	Gas price reduction	−1.6 €/MMBtu (20%) in 2027 mild; up to −8.2 €/MMBtu (50%) in 2031 coldest+drought	Sensitivity

Source: Chyong (2024)

Appendix 3. Multi-day “Dunkelflaute” Energy Price Resilience Metric

The baseline EPR metric in Section 5 is constructed around compound peak-day stress and therefore aligns naturally with capacity-based adequacy concepts such as the gas N-1 infrastructure standard and electricity LOLE-type metrics.

However, prolonged periods of persistently low wind and solar output, reduced hydro availability, nuclear outages, and coincident cold-weather demand, can generate sustained high residual load over multiple consecutive days. Such Dunkelflaute-type events shift the relevant resilience question from instantaneous capacity sufficiency to cumulative energy deliverability under sustained stress.

The extension developed here preserves the economic logic of the EPR metric while allowing resilience to be assessed over a multi-day stress horizon of duration T.

Multi-Day Compound Demand

Let Ω denote the shared gas-electricity stress scenario set defined in Section 5. Let $\tau = 1, \dots, T$ index consecutive days within a prolonged stress episode. Define cumulative compound gas demand under scenario ω as:

$$D^{multi}(\omega) = \sum_{\tau=1}^{T} \left(D_{\tau}^{nonpower}(\omega) + \frac{RL_{\tau}(\omega)}{\eta_{GT}} \right),$$

where:

- $RL_{\tau}(\omega)$ is daily residual electricity load under stress ω,
- η_{GT} is representative gas-to-power efficiency.

This benchmark captures cumulative gas demand arising from sustained low renewable output combined with elevated heating demand.

Multi-Day Gas Deliverability

Unlike peak-day N-1, a naïve extension of deliverability as “capacity × T” is not appropriate unless the utilisation assumption is made explicit. To maintain economic consistency, non-storage supply (pipeline imports, LNG regasification, indigenous production) is assumed to operate at a feasible maximum utilisation rate under sustained high-price conditions.

Let:

$$\bar{E}(\omega) = u^{max} \cdot C^{entry}(\omega),$$

where:

- $C^{entry}(\omega)$ denotes available entry capacity under scenario ω,

- $u^{max} \in (0,1]$is a maximum feasible utilisation rate, informed by historical winter utilisation or engineering availability benchmarks.

Non-storage deliverability over *T* days is then:

$$S_T^{nonstor}(\omega) = T \cdot \bar{E}(\omega)$$

Storage remains inventory-constrained. Let $I_0^{stor}(\omega)$denote initial storage inventory, and $\bar{W}_\tau^{stor}(\omega)$ denote maximum daily withdrawal capacity.

Then storage deliverability over T days is:

$$S_T^{stor}(\omega) = \min \left\{ I_0^{stor}(\omega), \sum_{\tau=1}^{T} \bar{W}_\tau^{stor}(\omega) \right\}$$

Total physical deliverability over T days becomes:

$$S_T^{phys}(\omega) = S_T^{nonstor}(\omega) + S_T^{stor}(\omega)$$

Define scenario-specific multi-day gas adequacy:

$$N^{multi}(\omega) = 100 \times \frac{S_T^{phys}(\omega)}{D^{multi}(\omega)}$$

The aggregated gas adequacy metric is:

$$\widetilde{N^{multi}} = \sum_{\omega \in \Omega} w_\omega \; \widetilde{N^{multi}}(\omega)$$

Protected Customer Supply Standard

Regulation (EU) 2017/1938 requires Member States to ensure uninterrupted gas supply to protected customers during severe disruptions. Let cumulative protected-customer demand under scenario ω over the stress horizon be:

$$D^{prot}(\omega) = \sum_{\tau=1}^{T} D_\tau^{prot}(\omega)$$

Under EU law, resilience must satisfy:

$$S_T^{phys}(\omega) \geq D^{prot}(\omega)$$

If this condition fails, the statutory supply standard is violated and emergency or solidarity mechanisms are triggered. Thus, two distinct regimes therefore arise:

1. **Protected-demand violation:** If $S_T^{phys}(\omega) < D^{prot}(\omega)$, then physical supply continuity fails at the level of legally protected customers.
2. **Non-protected adjustment regime:** If $D^{prot}(\omega) \leq S_T^{phys}(\omega) < D^{multi}(\omega)$, then protected demand is met, but non-protected customers bear adjustment through price-induced demand reduction or curtailment.

The protected-customer standard therefore acts as a legally binding lower bound within the multi-day gas adequacy assessment.

Duration-Adjusted Price Exposure

Even where physical volumes remain available, sustained stress amplifies economic exposure. The duration-adjusted price-exposure multiplier becomes:

$$\phi(T,\omega) = \frac{1}{1 + \kappa(SS \cdot HHI_{LNG} \cdot GT \cdot g(T))^{\gamma}}$$

with:

$$g(T) = T^{\delta}, \delta > 1$$

where:

- SS denotes domestic spot exposure,
- HHI_{LNG} captures concentration of the global spot LNG market,
- GT reflects global LNG tightness,
- $\kappa > 0, \gamma > 1, \delta > 1.$

Convex duration effects reflect declining residual supply elasticity and nonlinear price amplification under tight market conditions. Then, define price-adjusted adequacy:

$$N^{multi,PR}(\omega) = N^{multi}(\omega) \cdot \phi(T,\omega)$$

and its weighted aggregation:

$$N^{\widetilde{multi,PR}} = \sum_{\omega\in\Omega} w_{\omega}\ N^{\widetilde{multi,PR}}(\omega)$$

Electricity Energy Adequacy

For prolonged stress, energy-based electricity metrics are more appropriate than instantaneous capacity measures. Define:

$$Adeq_{elec}^{energy}(\omega) = 1 - \frac{EENS(\omega)}{EENS^{ref}}$$

with weighted aggregation:

$$\widetilde{Adeq_{elec}^{energy}} = \sum_{\omega\in\Omega} w_{\omega}\ Adeq_{elec}^{\widetilde{energy}}(\omega)$$

Multi-Day Energy Price Resilience Metric

The extended EPR metric under prolonged Dunkelflaute stress is:

$$EPR^{multi} = \alpha N^{\widetilde{multi}} + \beta \widetilde{Adeq_{elec}^{energy}} + (1 - \alpha - \beta) N^{\widetilde{multi,PR}}$$

The peak-day EPR metric evaluates entry into scarcity regimes. The multi-day extension evaluates persistence of scarcity. The protected-customer constraint clarifies the distributional consequences of prolonged stress:

- Physical failure below D^{prot} represents statutory breach.
- Stress between D^{prot} and D^{multi} represents price-driven adjustment borne by non-protected consumers.

The multi-day EPR metric therefore integrates infrastructure adequacy, duration-amplified market exposure, electricity energy adequacy, and statutory supply-priority obligations within a unified resilience framework consistent with Regulation (EU) 2017/1938 and Regulation (EU) 2019/943.

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