Assessing the Resilience of the European Electricity System in the Age of Variable Renewables: Indicators, Data and Limitations

Master thesis

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Abbreviations

ACER: European Union Agency for the Cooperation of Energy Regulators

EENS: Expected Energy Not Served

ENTSO-E: European Network of Transmission System Operators for Electricity

ERAA: European Resource Adequacy Assessment

EU: European Union

HHI: Herfindahl-Hirschman Index

IEA: International Energy Agency

LOLE: Loss of Load Expectation

NTC: Net Transfer Capacity

RE: Renewable Energy

RoCoF: Rate of change of frequency

RTE: Réseau de Transport d'Électricité

SAIDI: System Average Interruption Duration Index

TSO: Transmission system operators

TYNDP: Ten-Year Network Development Plan

VOLL: Value of Lost Load

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1 Introduction

In recent years, the European energy system has faced a series of major shocks. From the COVID-19 pandemic to Russia's invasion of Ukraine in 2022, and the current tensions in the Middle East, these geopolitical crises have profoundly challenged the security and stability of Europe's energy supply (Guarascio et al., 2024; United Nations, 2023). These events have highlighted the vulnerability of Member States' energy systems by underscoring both their heavy reliance on fossil fuel imports and their exposure to international crises (European Commission – Press Release, 2026; United Nations, 2023). They have thus reinforced the need to develop energy infrastructure that is both more robust and more resilient (European Commission – Press Release, 2026).

Initially, under Ursula von der Leyen's first term in office (2019–2024), energy resilience was intrinsically linked to the climate objectives of the Green Deal and, later, the "Fit for 55" package (Monie et al., 2025; Von Der Leyen, 2019). However, the deterioration of the global context, marked by the resurgence of power struggles and rivalry between major powers, necessitated a rebalancing of European policy (Von Der Leyen, 2024). Indeed, the European Union (EU) is now paying greater attention to economic competitiveness, the development of new international partnerships, and the strengthening of its defence capabilities and strategic sovereignty (Von Der Leyen, 2024).

Paradoxically, the proliferation of geopolitical and economic crises has reinforced the view that the energy transition is a key lever for reducing Europe's vulnerabilities (Guarascio et al., 2024; Toute l'Europe, 2026b). By reducing its dependence on imported fossil fuels, the EU can simultaneously improve its security of supply, limit its exposure to geopolitical shocks and strengthen its strategic autonomy (Toute l'Europe, 2026b). It is precisely with this in mind that the REPowerEU plan has been devised, aiming to accelerate the diversification of energy sources, the development of renewable energy (RE) and the reduction of energy consumption, in order to build an energy system that is more sustainable, more resilient and more sovereign (Ah-Voun et al., 2024; Guarascio et al., 2024; Monie et al., 2025; Toute l'Europe, 2026a).

Furthermore, energy systems are currently undergoing profound structural changes: electricity demand continues to rise, sectoral integration between electricity, transport, industry and heating is intensifying, and the share of RE in the electricity mix is growing rapidly (IEA, 2023a). In Europe, this transformation is driven in particular by the rapid development of wind and solar photovoltaic energy, which play a central role in strategies to decarbonise the energy system (Chyong & Schmidt, 2026; IEA, 2020). In 2023, RE accounted for 44.7% of total electricity generation in the EU, of which 38.5% was generated by wind power and 20.5% by solar photovoltaics, representing particularly rapid growth compared to previous years (Eurostat, 2024b, 2025). This trend reflects the acceleration of decarbonisation policies but is also profoundly transforming the functioning of the European electricity system. This study will focus on these two variable sources, wind and solar, due to their intermittent nature and their growing share in the European electricity system (Asiaban et al., 2021).

However, the increasing integration of these RE sources poses new challenges for the operation of electricity systems. Unlike conventional power stations, variable RE sources depend on weather conditions and therefore have intermittent and difficult-to-predict output (Asiaban et al., 2021). This variability profoundly alters the traditional balance between electricity generation and consumption and requires the electricity system to adapt in order to maintain its stability and security of supply (Asiaban et al., 2021). Several studies have thus shown that the large-scale integration of variable RE raises technical, institutional and organisational challenges for European electricity systems (Monie et al., 2025; Verzijlbergh et al., 2017).

In this context, the notion of resilience emerges as a key concept for analysing the ability of electricity systems to cope with these transformations. A resilient energy system is generally defined as a system capable of anticipating, withstanding and adapting to disruptions whilst continuing to perform its essential functions, in particular the reliable supply of energy (United Nations, 2023). However, the practical assessment of this resilience remains complex and relies on the use of specific indicators and the availability of reliable data to measure them. The quality, granularity and consistency of this data play a decisive role in this analysis (Monie et al., 2025).

This study is part of that broader context. Its aim is to explore **how to assess the resilience of a European electricity system incorporating a high proportion of variable RE sources, particularly wind and solar power**. More specifically, this study aims to clarify the concept of resilience as applied to electricity systems, to identify the indicators used to assess it, to determine the data required to measure these indicators and to examine the extent to which existing European and national data actually enable such an assessment.

This work thus seeks to answer the following question:

To what extent do the available indicators and existing data allow for the assessment of the resilience of a European electricity system with high RE penetration and what are the limitations of such an assessment?

The study is organised as follows. The first section presents the conceptual framework: it defines resilience as it applies to electricity systems, distinguishes it from related concepts, and outlines the specific characteristics of variable RE sources that make assessing resilience complex. The second section identifies the indicators used to assess this resilience across four dimensions (technical, security of supply, economic and institutional) and specifies the data required to measure them. The third part applies this framework to a concrete case: a comparison between Germany and France based on four key indicators, which serves to illustrate the limitations of the available data. Finally, the last part discusses the implications of these results and suggests avenues for future research.

2 Literature Review

2.1 Resilience

Resilience is a cross-cutting concept whose origins lie in engineering and ecology, before being gradually extended to socio-technical systems (Jesse et al., 2019). Whilst engineering approaches measure resilience by the speed of return to a state of equilibrium following a shock, ecological perspectives focus on the ability to absorb a disturbance without shifting to a different state of operation (Jesse et al., 2019). These two approaches were subsequently extended to socio-technical systems, recognising that a system's ability to cope with disturbances depends not only on its physical characteristics, but also on its organisational and institutional dimensions (Jesse et al., 2019). This development is particularly relevant to contemporary energy systems: modern energy systems are indeed increasingly exposed to disturbances, whether linked to climate change or to the variability of electricity supply from renewable sources (Monie et al., 2025).

There is no consensus in the literature on a single definition of energy resilience. Resilience is often viewed as a reactive process that occurs after a disruptive event, focusing on the ability to recover from adversity (Monie et al., 2025). However, it can also be understood as a broader concept encompassing preventive and resistant dimensions, including anticipation, preparation, resistance and absorption before and during a shock (Monie et al., 2025). The International Energy Agency (IEA) defines energy system resilience as "*the capacity of the energy system and its components to cope with a hazardous event or trend, to respond in ways that maintain its essential functions, identity and structure as well as its capacity for adaptation, learning and transformation. It encompasses the following concepts: robustness, resourcefulness, recovery*" (Jasiūnas et al., 2021). The United Nations Economic Commission for Europe, for its part, emphasises that resilience is not limited to the technical robustness of infrastructure, but also includes economic (energy security and price stability), social (equitable access to energy) and environmental (transition to net-zero emissions) dimensions (United Nations, 2023).

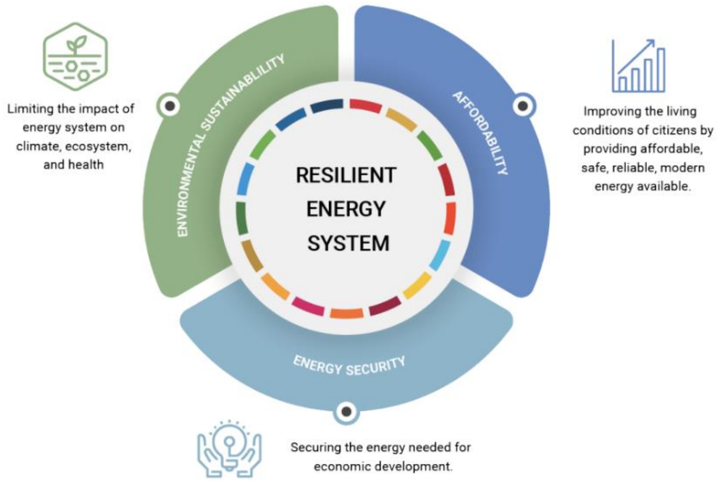

Figure 1: The three pillars of a resilient energy system (United Nations, 2023)

Finally, resilience is closely linked to the concept of energy vulnerability, which refers to a system's exposure to structural risks: dependence on imports, price volatility and climate-related hazards (Guarascio et al., 2024). Reducing vulnerability and strengthening resilience are two complementary objectives: one addresses exposure to risks, the other the capacity to cope with and recover from them (Guarascio et al., 2024). It is this capacity to withstand extreme shocks while accounting for institutional dimensions that sets resilience apart from related concepts such as security of supply, reliability, stability and flexibility, as discussed in the following section.

2.2 Related concepts

Before treating resilience as an analytical framework, it is important to distinguish it from four related concepts that are frequently used in European energy literature and policy. These concepts are closely linked to resilience, but differ from it in terms of their scope and the type of disruptions they seek to characterise.

Security of supply is the dominant concept in European energy policies. The IEA defines energy security as "*uninterrupted availability of energy sources at an affordable price*" (Schmitz et al., 2025). This definition, whilst useful, remains focused on normal operating conditions and on the physical and economic availability of energy. It does not capture a system's ability to cope with extreme shocks, to adapt to them structurally, and to recover from them which is precisely what resilience is all about (Schmitz et al., 2025). The distinction between energy security, resilience, security of supply and related terms remains, in fact, often unclear in the literature and official documents (Schmitz et al., 2025).

Reliability is the long-standing technical benchmark. It is based on two conditions: adequacy, i.e. the availability of sufficient resources in generation and transmission to meet demand with a reasonable margin, and operational security, i.e. the system's ability to withstand contingent disruptions without a widespread interruption to supply (IEEE/CIGRE, 2004; Schmitz et al., 2025). The fundamental distinction from resilience lies in the nature of the events addressed. Unlike resilience, which deals with high-impact low-probability events, reliability addresses high-probability and low-impact events (Schmitz et al., 2025).

Flexibility is the concept whose growing importance is most directly linked to the integration of variable RE sources. The European Network of Transmission System Operators for Electricity (ENTSO-E) defines it as "*the ability of the power system to cope with variability and uncertainty in demand, generation and grid availability*" (ENTSO-E, 2022b). Flexibility therefore operates within the context of the system's day-to-day operation. It is a necessary but not sufficient condition for resilience: a flexible system will be better equipped to absorb daily fluctuations from renewable sources, but this does not guarantee its ability to withstand major disruptions and recover from them in the long term (Monie et al., 2025).

Stability refers to the ability of an electrical system to maintain a state of operational equilibrium following a physical disturbance, whilst preserving the integrity of the network (IEEE/CIGRE, 2004). It is a necessary but insufficient condition: to be truly robust and resilient, the electricity grid must go beyond stability and be capable of coping with major equipment failures, human attacks and natural disasters (Arghandeh et al., 2016). Unlike resilience, which incorporates phases of anticipation, adaptation and long-term recovery, stability focuses on the instantaneous physical behaviour of the grid, a time horizon that is too narrow to characterise a system's ability to survive extreme shocks and recover sustainably (Monie et al., 2025).

These four concepts are necessary but not sufficient conditions for resilience (Schmitz et al., 2025). In the literature, the term "resilience" is often used arbitrarily, sometimes as a synonym for stability or security, which illustrates the conceptual confusion that this section seeks to clarify (Monie et al., 2025). Only resilience simultaneously encompasses the capacity to cope with extreme shocks, to adapt structurally and to incorporate institutional and social dimensions (United Nations, 2023).

2.3 European electricity system

The European electricity system is a prime example of a complex socio-technical system, in which resilience depends on the interaction between physical infrastructure, market mechanisms and institutional frameworks (Verzijlbergh et al., 2017). The ENTSO-E brings together 40 transmission system operators (TSO) from 36 countries, responsible for the secure and coordinated operation of the European electricity system, the world's largest interconnected electricity network (ENTSO-E, 2026b). These TSO ensure the transmission of electricity on high- and extra-high-voltage grids and maintain a constant balance between generation and consumption (ENTSO-E, 2026b).

The system operates on the basis of a series of markets organised across different time scales. The day-ahead market determines the preliminary economic allocation of electricity for the following day, followed by an intraday market that allows for adjustments to generation and consumption based on more accurate forecasts (European Commission, 2026). The balancing mechanism then intervenes in real time to ensure that generation equals demand at all times and this is one of the key roles of TSO (ENTSO-E, 2021).

This system is currently undergoing a profound transformation. The share of renewables in the European electricity mix is growing rapidly, reaching 44.7% of total generation in 2023 (Eurostat, 2024b), driving accelerated electrification of the transport, heating and industrial sectors (IEA, 2023b). This makes coordination at European level increasingly critical for the stability and resilience of the system (Verzijlbergh et al., 2017).

The integration of large quantities of variable RE sources does indeed pose fundamental challenges for the operation and governance of the energy system. The institutional fragmentation of the European electricity sector will become increasingly restrictive as the development of variable RES requires ever closer coordination between countries, between the different levels of the electricity system and between markets operating on different time scales (Verzijlbergh et al., 2017). Current market rules, designed for systems with controllable generation, are gradually being challenged by the inherent variability of RE, an institutional issue that neither reliability nor flexibility alone can resolve, and which specifically calls for an analytical framework in terms of resilience (Monie et al., 2025; Verzijlbergh et al., 2017).

It is against this backdrop that the specific characteristics of wind and solar power (intermittency, seasonal and intra-daily variability and lack of inertia) now constitute the main challenge to the resilience of the European electricity system, as discussed in the following section.

2.4 Characteristics of renewable energy

Wind and solar photovoltaic power differ fundamentally from conventional power stations in that they are intermittent and cannot be controlled (Impram et al., 2020). Unlike thermal or nuclear power stations, where output can be adjusted to meet demand, the output of variable RE sources depends entirely on weather conditions and cannot be controlled by grid operators (Asiaban et al., 2021). The main challenge associated with the transition to RE sources lies precisely in their intermittent and unpredictable nature, as well as their uncontrollable nature, which creates a structural imbalance between electricity generation and consumption (Asiaban et al., 2021).

This variability is evident across several time scales. On an intra-daily scale, solar generation follows the day/night cycle, peaking at midday before dropping to zero at night, whilst wind generation tends to be higher in the early morning and evening (Asare-Addo, 2026). On a seasonal scale, wind power generation is higher in winter and spring, whilst solar power generation peaks in summer (Asare-Addo, 2026). However, these complementary cycles are not sufficient to ensure a permanent balance between generation and demand, and imply growing needs for flexibility and storage (Impram et al., 2020).

Beyond operational variability, the large-scale integration of variable RE sources is fundamentally altering the physical characteristics of the electricity grid. Conventional synchronous power stations provide natural mechanical inertia, stored in the rotating mass of their generators, which dampens sudden fluctuations in frequency when there is an imbalance between generation and consumption

(Fernández-Guillamón et al., 2019). However, wind and solar power are connected to the grid via electronic converters that physically decouple them from the grid, thereby reducing the effective inertia available (Fernández-Guillamón et al., 2019). This reduction in system inertia translates in practice into a faster rate of change of frequency (RoCoF) and larger frequency deviations during disturbances, threatening grid stability (Fernández-Guillamón et al., 2019).

The third dimension of vulnerability concerns prolonged periods of simultaneously low wind and solar generation, referred to in the literature by the German term "*Dunkelflaute*", literally "dark and windless period". These episodes, which occur mainly in winter in Europe during persistent anticyclonic conditions, pose a growing challenge to modern electricity systems in which conventional flexible generation capacity is in rapid decline (Beck-Bang et al., 2026; Kittel & Schill, 2024). During these events, electricity demand is generally high whilst renewable generation is virtually zero, putting pressure on available storage and balancing capacity (Beck-Bang et al., 2026). These periods constitute high-impact, low-probability events that go beyond traditional analytical frameworks based solely on reliability or flexibility, and for which resilience approaches offer a relevant complementary perspective (Kittel & Schill, 2024).

These combined characteristics (intermittency, multi-scale variability, reduced inertia and the risk of "*Dunkelflaute*") make assessing the resilience of the European electricity system particularly complex. They imply that traditional reliability indicators, designed for systems with controllable generation, are no longer sufficient to capture the new forms of vulnerability caused by high penetration of variable RE (Monie et al., 2025).

2.5 Summary

The four preceding sections provide a coherent conceptual framework for this work. Resilience, defined as a system's ability to anticipate, withstand, absorb, adapt to and recover from disruptions, differs from related concepts (security of supply, reliability, flexibility, stability) in that it is the only concept to simultaneously cover low-probability extreme shocks and institutional, economic and social dimensions (Monie et al., 2025; Schmitz et al., 2025). This distinction is fundamental: in a European electricity system with high penetration of variable RE sources, the challenges are not limited to technical issues of real-time balancing, but raise profound questions of governance, coordination between national and European stakeholders, and the suitability of regulatory frameworks for a rapidly changing energy landscape (Verzijlbergh et al., 2017).

However, the specific characteristics of wind and solar power (intermittency, multi-scale variability, reduced inertia and the risk of "*Dunkelflaute*") make assessing this resilience particularly complex (Monie et al., 2025; Parag et al., 2026). They require indicators that go beyond traditional reliability metrics and capture the technical, economic, institutional and security-of-supply dimensions of the system. The central question of this work is therefore as follows: to what extent do the available indicators and existing data enable the assessment of the resilience of a European electricity system with high RE penetration, and what are the limitations of such an assessment? The following section addresses this question.

3 Resilience indicators

3.1 Introduction

The assessment of an electricity system's resilience cannot be based on a single indicator. As Schmitz et al. (2025) show, relying on a single aggregate indicator of energy resilience does not provide a complete picture: the researchers instead advocate a multi-indicator framework to capture the complexity of assessing resilience (Schmitz et al., 2025). This complexity stems from the multidimensional nature of resilience as defined in this study: a resilient electricity system must be technically robust, economically stable, secure in terms of supply and institutionally coordinated (Monie et al., 2025; United Nations, 2023).

However, the measurement of the resilience of electricity systems is a field still under development and it has significant shortcomings. A recent review identifies seven major shortcomings in current resilience indicators: "*conceptual overlap with reliability, lack of standardization, inadequate treatment of major events, limited integration of supply chain risks, context-specific and non-scalable indicators, insufficient attention to societal and equity dimensions, and poor adaptation to emerging threats such as cyberattacks and compound climate events*" (Parag et al., 2026). These observations show that current approaches remain fragmented, inconsistent and poorly aligned with the evolving structure of electricity systems. These shortcomings are particularly problematic in a context of high penetration of variable RE sources. Intermittency, reduced inertia and the risk of "*Dunkelflaute*" are precisely the type of emerging threats and extreme events that traditional reliability indicators fail to capture (Parag et al., 2026).

These shortcomings are not merely technical: they have direct policy implications. In decarbonised energy systems, traditional indicators based on energy availability and prices are no longer sufficient. They fail to capture the system's dynamic ability to adapt to shocks (Schmitz et al., 2025). Yet it is precisely these adaptive capacities that lie at the heart of resilience (Monie et al., 2025). European policymakers are therefore currently making investment decisions based on indicators designed for an energy system that no longer exists (Parag et al., 2026; Schmitz et al., 2025). The European Parliament's Committee on Industry, Research and Energy also emphasises that data sharing and interoperability are essential for network planning and optimisation, and encourages Member States and regulators to accelerate the development of indicators measuring the performance of smart grids (Stürgkh, 2025).

This is why this section does not merely list existing indicators, but seeks to construct a genuine analytical framework structured around four complementary dimensions: technical, security of supply, economic and institutional. For each dimension, the indicators are analysed from three angles: their specific relevance to resilience beyond mere reliability, their limitations and the trade-offs they entail, and the need for new data that they reveal. This approach directly addresses the central question of this work: to what extent do the data currently available actually enable us to assess the resilience of a European electricity system with high penetration of variable RE sources?

3.2 Technical dimension

The technical dimension is the most extensively documented in the literature on the resilience of electricity systems (Schmitz et al., 2025). It comprises four complementary types of indicators: adequacy, frequency stability, flexibility and interconnections.

System adequacy

The first group of indicators relates to system adequacy, i.e. its ability to meet electricity demand at all times using available generation resources (Schmitz et al., 2025). The main indicator used at European level is the Loss of Load Expectation (LOLE). It is defined as an estimate of the number of hours per year during which supply cannot meet demand (ENTSO-E, 2026a). It is supplemented by the Expected Energy Not Served (EENS), which quantifies the volume of energy that will not be supplied due to outages (Schmitz et al., 2025). These two indicators are calculated by ENTSO-E as part of the European Resource Adequacy Assessment (ERAA), published annually, making them accessible and standardised data sources at European level. The data required to calculate them include the installed generation mix, available capacity by country, and long-term meteorological time series to model the variability of renewable generation (ENTSO-E, 2026a).

LOLE and EENS are directly linked to resilience as they assess the system's ability to meet demand during prolonged weather stress scenarios. It is precisely this type of extreme event that the transition to variable RE sources makes more critical (Schmitz et al., 2025).

Each EU Member State sets its own acceptable LOLE threshold. This threshold varies significantly from one country to another: from 1 hour per year in Sweden to 15 hours in the Czech Republic (ACER, 2022). In practical terms, this means that a level of risk deemed acceptable in the Czech Republic would be considered unacceptable in Sweden. This heterogeneity makes any comparison of resilience between European countries difficult. Without a common standard, it is impossible to assess whether the European electricity system as a whole is resilient (Parag et al., 2026).

Earlier ERAA editions relied exclusively on historical climate time series, which limited their ability to capture the frequency and intensity of future extreme events. ENTSO-E has begun addressing this shortcoming: since the 2024 edition, prospective climate projections have been integrated via the Pan-European Climate Database (PECD v4), developed by the Copernicus Climate Change Service (Copernicus, 2025b). This represents a significant methodological improvement, though questions remain as to whether current projections fully capture the most extreme climate scenarios relevant to resilience assessment (Parag et al., 2026).

Frequency stability

With the rise of variable RE sources, frequency stability has become a key technical challenge. Wind and solar RE sources are connected to the grid via electronic converters which, in principle, do not provide any additional inertia to the system. This can increase the rate of frequency variation to the point of threatening the security of the system (ENTSO-E, 2020). The indicator used to measure this stability is the RoCoF, which quantifies the rate at which the grid frequency changes during an imbalance (ENTSO-E, 2020).

This indicator captures a new physical vulnerability. As grid inertia decreases due to the replacement of synchronous power stations with RE sources, the risk of a frequency collapse during a sudden shock increases (Fernández-Guillamón et al., 2019).

These measurements require high-resolution real-time data. Such data is available from national TSO but is poorly harmonised at European level. There is no common standard defining acceptable RoCoF thresholds at EU level. This is a documented regulatory gap (Abele & Gonzalez, 2023).

Harmonisation of RoCoF measurements among European TSO is necessary. This involves data that the ENTSO-E Transparency platform does not yet publish (ACER, 2025).

Flexibility and curtailment

The RE curtailment rate measures the proportion of available renewable generation that the system cannot absorb. When RE sources create transmission constraints, the system operator is forced to reduce their feed-in; this is known as curtailment (Impram et al., 2020). A high rate indicates a lack of structural flexibility (Impram et al., 2020).

Curtailment does not pose an immediate threat to reliability. However, it signals a structural lack of flexibility and a system that cannot absorb available renewable generation is, by definition, less capable of adapting to sudden demand shifts or supply shocks (Impram et al., 2020; Monie et al., 2025).

Curtailment data is available via the ENTSO-E Transparency platform. However, some Member States do not publish it systematically. The European Parliament emphasises that data sharing and interoperability are essential for grid planning and optimisation (Stürgkh, 2025). Without comparable data, it is impossible to assess whether RE integration targets are actually being met (Parag et al., 2026; Stürgkh, 2025).

Granular and harmonised data on curtailment by country and by technology are required. Such data do not yet exist in a standardised form at European level (ACER, 2025).

Interconnections

Finally, the capacity for electricity exchange between countries is a key indicator of the technical resilience of the European electricity system. Net Transfer Capacity (NTC) refers to the commercial transfer capacity between two countries, i.e. the maximum capacity for electricity exchange after deducting the transmission reliability margin (Abadie & Chamorro, 2021; ENTSO-E, 2000). A high level of interconnection enables available resources to be shared between countries during a disruption, thereby contributing directly to the system's resilience (Verzijlbergh et al., 2017). NTC data are published by ENTSO-E and constitute one of the best-documented sources at European level.

Interconnections are a mechanism for collective resilience. During a national "*Dunkelflaute*", they enable energy to be imported from neighbouring countries that are not affected. They transform a national risk into a shared risk at European level (Beck-Bang et al., 2026).

The NTC measures theoretical capacity. It does not capture the actual availability of capacity during a crisis affecting several countries simultaneously. During a European "*Dunkelflaute*", several countries may experience a deficit at the same time, rendering interconnections less useful than the NTC suggests (Beck-Bang et al., 2026). This is a major policy blind spot in current crisis preparedness plans (Parag et al., 2026).

Data on the actual availability of interconnections during past extreme events is required (Parag et al., 2026). This would enable an assessment of the actual resilience of the interconnected grid, beyond its nominal capacity.

3.3 Security of supply dimension

Security of supply is the second key aspect of the resilience of the European electricity system. Against a backdrop of accelerated energy transition and a reduction in conventional dispatchable generation capacity, it encompasses three types of indicators: import dependency, diversification of supply sources, and exposure to prolonged periods of low renewable generation.

Import dependency ratio

The energy import dependency ratio is defined as the ratio of net energy imports to gross available energy, expressed as a percentage (Eurostat, 2024a). This indicator is published annually by Eurostat for all EU Member States. It directly reflects a system's exposure to geopolitical risks. International sanctions, trade disputes or diplomatic conflicts can indeed restrict energy imports and expose dependent countries to supply shortages and price rises (Wang et al., 2026).

This indicator captures a structural vulnerability that reliability metrics do not measure. A system may be reliable under normal conditions but collapse in the event of a sudden geopolitical shock that cuts off supplies. This is precisely the type of extreme event that resilience seeks to anticipate (Guarascio et al., 2024).

This indicator measures overall dependence on imports, but does not distinguish between types of imported energy. A country may have a high dependence on gas imports but abundant renewable electricity generation. The indicator should therefore be interpreted in conjunction with the national electricity mix (Schmitz et al., 2025).

Data are available via the Eurostat database (code SDG_07_50), with long time series that are comparable across Member States (Eurostat, 2024a). However, this indicator does not capture the political risk associated with supplier countries. Augmented versions of the dependency ratio that integrate country-level political risk scores exist in the literature but are not yet standardised at European level (Guarascio et al., 2024).

Diversification of sources – HHI index

Reliance on imports must be complemented by an indicator of the diversification of supply sources. The Herfindahl-Hirschman Index (HHI) is widely used to describe the concentration or diversification of an energy resource portfolio across different suppliers. It is calculated as the sum of the squares of each supplier's market share. High concentration leads to a high HHI; low values indicate a diversified portfolio (De Rosa et al., 2022).

A high HHI signals excessive dependence on a small number of suppliers or technologies. De Rosa et al. (2022) have shown that the EU's energy security is reduced by approximately 30% due to the high proportion of imports from a limited number of countries. This concentration increases the system's vulnerability to a disruption targeting one of these suppliers (De Rosa et al., 2022).

The traditional HHI does not take into account the political risks associated with supplier countries. A portfolio that appears to be diversified may still be vulnerable if several suppliers are subject to the same geopolitical risks (Wang et al., 2026).

The necessary data (market shares of energy suppliers by country) is available from Eurostat and ACER, but the level of detail varies across Member States.

Exposure to "*Dunkelflaute*" – system adequacy during extreme periods

The third group of indicators focuses on the system's exposure to prolonged periods of simultaneously low wind and solar power generation, referred to as "*Dunkelflaute*". These events are rare but their impact can be severe. Assessing them makes an important contribution to analysing the resilience of future energy systems with high RE penetration (Beck-Bang et al., 2026; Kittel & Schill, 2024). Several indicators can be used to characterise them. The annual frequency and duration of "*Dunkelflaute*" events by country or region indicate the system's structural exposure. The expected level of Energy Not Served (ENS) during these episodes quantifies the impact on supply. Available reserve capacity (the ratio of mobilisable flexible capacity to residual peak demand) measures the system's margin for manoeuvre in the face of these shocks (ENTSO-E, 2026a; Kittel & Schill, 2024).

These indicators capture high-impact, low-probability events that conventional reliability metrics do not measure (Kittel & Schill, 2024). They are directly linked to resilience rather than day-to-day reliability.

There is as yet no standardised definition of "*Dunkelflaute*" at the European level. Detection and measurement methods vary across studies, making cross-country comparisons difficult (Kittel & Schill, 2024). This is a methodological shortcoming with direct policy implications: without a harmonised indicator, national crisis preparedness plans lack a comparable basis (Parag et al., 2026).

The necessary data include long-term meteorological time series with high spatial resolution. The ERA5 reanalyses from the Copernicus programme are the main available source (Copernicus, 2025a). These data are publicly accessible. However, processing them requires advanced technical capabilities (Parag et al., 2026). Their availability at national level with sufficient granularity remains uneven across countries.

3.4 Economic dimension

The economic dimension of resilience aims to measure the financial impact of disruptions on the electricity system and on consumers. It comprises two types of indicators: price volatility indicators and outage cost indicators.

Price volatility and the frequency of negative prices

The rise of variable RE sources has introduced a new economic signal into electricity markets: negative prices. This is an abnormal situation in which generators have to pay to feed electricity into the grid. These events have evolved from isolated incidents into a significant market signal (Sun et al., 2026). Their occurrence is directly linked to the inflexibility of the system. The presence of variable RE sources increases the need for system flexibility. The emergence of negative prices in Central and Western European markets confirms this issue, referred to in the literature as "*the incompressibility of electricity systems*" (Brijs et al., 2015). In 2023, 27 of the 50 European price zones recorded the highest number of negative prices since 2017 (ACER, 2024).

The frequency of negative prices is an indicator of economic resilience that can be interpreted in two ways. It signals an excess of production that cannot be absorbed, which points to a lack of structural flexibility. It also signals increased volatility, which undermines the economic viability of investments in new capacity (Sun et al., 2026).

This indicator measures a symptom but not the cause. A country may have few negative prices not because it is resilient, but because it still has a lot of controllable capacity that absorbs surpluses. Comparing this indicator across countries without taking the generation mix into account leads to erroneous conclusions.

Hourly price data is available via the ENTSO-E Transparency platform for all European price zones (ENTSO-E, 2026a). It constitutes one of the most harmonised sources at European level.

Cost of Outages – VOLL

The Value of Lost Load (VOLL) is defined as the economic value that consumers place on the energy not supplied in the event of a power outage. It is widely used by the industry and regulators to assess the operational conditions of an energy system (Longo et al., 2018). It estimates the economic impact of supply interruptions by reflecting society's willingness to pay to avoid outages. Its calculation is influenced by the timing and duration of the outage, as well as by regional economic conditions (Schmitz et al., 2025).

The VOLL translates the impact of disruptions into economic terms. It thus enables the cost of a prolonged "*Dunkelflaute*", a type of extreme event not captured by conventional reliability metrics, to be assessed. It provides decision-makers with a basis for justifying investments in resilience (Ovaere et al., 2019).

The VOLL varies significantly between countries and sectors. Substantial discrepancies have been identified in the calculation practices of 13 EU Member States. These reveal fundamental challenges for comparability and standardisation, and highlight the need for clearer guidance and more consistent application (Kapeller et al., 2026). Without harmonisation, comparing economic resilience across European countries remains very difficult.

Regulation (EU) 2019/943 requires each Member State to produce a national estimate of the VOLL in accordance with the ACER methodology (Regulation UE/2019/941, 2019). The data combine national economic data and operational data on actual outages, available from national TSO and Eurostat. However, their comparability remains limited by methodological differences between countries (Kapeller et al., 2026).

These two indicators capture the two sides of the economic vulnerability of a system with high RE penetration. The frequency of negative prices signals excess production that cannot be absorbed. The VOLL quantifies the cost of supply failures. Their complementary nature illustrates why the assessment of economic resilience cannot rely on a single indicator (Schmitz et al., 2025).

3.5 Institutional dimension

The institutional dimension is the most difficult to quantify, but it is an integral part of a comprehensive assessment of resilience. The public institutions that govern the energy system play a key role in determining the resilience of the system as a whole by setting the rules for the development and operation of its technical and economic components (Jasiūnas et al., 2021). A technically robust system may therefore prove vulnerable if governance frameworks do not allow for effective coordination in the event of a crisis. Inadequate coordination and collaboration can indeed lead to individual response measures that unintentionally create counterproductive impacts on interconnected systems (Schmitz et al., 2025). Furthermore, Policymakers and system operators must consider technical, economic and political dimensions together to ensure electricity security, as the transition to clean energy, cyber threats and climate change increasingly intersect (IEA, 2020).

Coordination between system operators – the TYNDP as an indicator

The first institutional indicator concerns the degree of coordination between TSO at European level. The Ten-Year Network Development Plan (TYNDP) is the reference tool. It assesses the extent to which infrastructure projects contribute to climate targets, market integration and security of supply (ENTSO-E, 2022a).

The ratio between the capacity planned in the TYNDP and the capacity actually delivered serves as an operational indicator of the gap between planned and actual coordination. This gap is documented: in the 2020 TYNDP, only half of the 50 GW of demand identified for 2030 could be linked to existing projects. In some cases, these gaps reflect the financing and authorisation constraints faced by TSO (ENTSO-E, 2023).

This indicator captures the system's collective capacity to prepare structurally for future shocks. A persistent gap between planned requirements and actual achievements signals institutional vulnerability, regardless of the network's current technical performance (Verzijlbergh et al., 2017).

The TYNDP data are published by ENTSO-E. Interpreting them remains complex. On their own, they do not allow for an assessment of the quality of policy coordination between Member States, only the progress of infrastructure projects.

National crisis preparedness plans

The second institutional indicator concerns the existence and quality of national electricity crisis management plans. Regulation (EU) 2019/941 requires each Member State to draw up a risk preparedness plan comprising national, regional and bilateral measures to prevent, prepare for and manage electricity crises (Regulation UE/2019/941, 2019). These plans are submitted to the European Commission for its opinion and updated at least every four years.

These plans serve as an indicator of the system's capacity for anticipation and response, two central phases of resilience. A country whose plan is incomplete or out of date is less prepared to cope with an extreme shock, even if its technical indicators are good.

The plans are published on the European Commission's website. Their comparability across Member States remains very limited. Differences in methodology and level of detail make any comparative assessment difficult. There is no standardised indicator for rating or ranking the quality of these plans at European level (Parag et al., 2026).

Limitations of this dimension

The institutional dimension differs from the other three in that there are no standardised quantitative indicators at European level. The available indicators are mainly qualitative: the existence of a crisis plan, the degree of regional coordination and the progress of TYNDP projects. Comparing these across Member States is made difficult by the fragmentation of governance structures (Verzijlbergh et al., 2017). This limitation illustrates why relying on a single aggregated resilience indicator cannot provide a complete picture: each dimension requires its own data and the institutional dimension is the one for which data gaps are the most significant (Schmitz et al., 2025).

3.6 Analytical summary and summary table

It should first be noted that the indicators presented in the previous sections do not constitute an exhaustive list. Other indicators exist in the literature, such as the SAIDI (System Average Interruption Duration Index), which measures the average duration of outages per consumer, or cybersecurity indicators for critical infrastructure. The latter could complement this framework depending on the chosen analytical context (Parag et al., 2026; Schmitz et al., 2025).

The four dimensions presented—technical, security of supply, economic and institutional—are not independent. They interact in complex and sometimes contradictory ways.

The technical dimension and the security of supply dimension are closely linked. A system with a low LOLE (good adequacy) may nevertheless be vulnerable during a "*Dunkelflaute*" if its reserve capacity is insufficient. Conversely, a high level of curtailment (a sign of technical inflexibility) may coincide with good security of supply if interconnections offset local surpluses (Beck-Bang et al., 2026).

The economic dimension acts as a warning signal for the first two. The frequency of negative prices highlights the tensions between variable renewable generation and system flexibility. The VOLL makes it possible to quantify the cost of the failures identified by the technical indicators, thereby bridging the gap between engineering and public policy (Ovaere et al., 2019).

The institutional dimension determines the quality of all the others. Without coordination between TSO, interconnections (NTC) are not fully utilised. Without harmonised contingency plans, security of supply indicators cannot be compared across countries. This is the dimension where data gaps are most significant and, paradoxically, the one that determines the collective resilience of the European system (Jasiūnas et al., 2021; Verzijlbergh et al., 2017).

Finally, several trade-offs are worth highlighting. Improving technical flexibility (reducing curtailment) may require investments that increase costs for consumers, something that the VOLL does not fully capture. Harmonising LOLE standards across countries improves comparability, but may constrain Member States' sovereignty in defining their acceptable risk level. These tensions illustrate why assessing resilience cannot be a purely technical exercise: it involves fundamental policy choices (IEA, 2020; Parag et al., 2026).

Table 1: Summary of resilience indicators

Dimension	Indicator	Required data	Main source	Avail.
Technical	LOLE	Generation mix, capacity by country, long-term meteorological time series	ENTSO-E ERAA	✓
	EENS	Volume of energy not supplied during outages	ENTSO-E ERAA	✓
	RoCoF	High-resolution real-time measurements, system inertia data	National TSO	~
	Curtailment rate	Available vs. actually injected RE generation	ENTSO-E Transparency	~
	NTC	Cross-border electricity exchange capacity	ENTSO-E Transparency	✓
Security of supply	Imports dependency ratio	Net energy imports / gross available energy	Eurostat (SDG_07_50)	✓
	HHI Index	Market shares of energy suppliers by country	Eurostat/ACER	✓
	« Dunkelflaute » (frequency / duration)	Long-term high-resolution meteorological time series (ERA5)	Copernicus/ERA5	~
	Reserve capacity ratio	Mobilisable flexible capacity / residual peak demand	ENTSO-E ERAA	✓
Economic	Negative prices (frequency)	Hourly day-ahead and intraday prices by price zone	EPEX/Nord Pool/ENTSO-E	✓
	VOLL	Willingness to pay, data on actual outages	ACER (Decision No 23/2020) / National TSO	~
Institutional	TYNDP planned/delivered gap	Planned vs. actually built interconnection capacity	ENTSO-E TYNDP	~
	Crisis preparedness plans	Existence and quality of plans (Regulation EU/2019/941)	European Commission	✗

✓ Data available and harmonised at EU level, ~ Available but with varying levels of detail across Member States, ✗ Not standardised, making comparison difficult

Diagram of interactions between dimensions

The diagram below illustrates how the four dimensions interact. The arrows indicate the causal relationships between indicators.

The institutional dimension influences all three other dimensions. Technical indicators inform the assessment of security of supply, which translates into economic impacts via the VOLL and negative prices.

4 Case study and discussion

4.1 Reasons for the comparative choice

Germany and France provide two particularly instructive case studies for illustrating the limitations of the indicators identified in Section 3. These two countries are closely interconnected; they both belong to the Central Europe coordination region defined by ENTSO-E (Risk-preparedness plan Germany, 2022). Yet their energy trajectories diverge radically.

The table below clearly illustrates this. In 2023, Germany generated almost 60% of its electricity from renewable sources, with wind (32%) and solar (12%) being the top two sources (Fraunhofer ISE, 2024). Nuclear power accounted for just 1.5% of the mix, following the shutdown of the last three reactors in April 2023. Fossil fuels (coal and gas) still accounted for around 36% of production. France presents a radically different picture: nuclear power accounts for 64.8% of electricity generation there, followed by hydro (11.9%), wind (10.3%) and solar (4.4%) (RTE, 2024). Variable renewables therefore account for only around 15% of the French mix, compared with 44% in Germany.

These two contrasting models enable the practical application of four of the key indicators identified in this study : supply adequacy (LOLE), flexibility (negative prices), import dependency and institutional governance (crisis preparedness plans) and highlight their limitations.

Table 2: Comparison of electricity mixes: Germany and France (2023)

Source	Germany (%)	France (%)
Nuclear	1.5 %	64.8 %
Wind	32 %	10.3 %
Solar PV	12 %	4.4 %
Hydro	4.5 %	11.9 %
Biomass	9.7 %	2.1 %
Coal (brown and hard)	26 %	< 0.2 %
Natural gas	10.5 %	6.1 %
Others	3.8 %	< 0.5 %
TOTAL	100 %	100 %

This table compares the electricity generation mix of the two countries for the year 2023, based on official data published by Fraunhofer ISE for Germany and by Réseau de Transport d'Électricité (RTE) for France (Fraunhofer ISE, 2024; RTE, 2024).

4.2 Application of indicators

Adequacy – LOLE: two systems vulnerable for opposite reasons

LOLE is the benchmark adequacy indicator at European level. Applying it to the two countries immediately highlights a fundamental limitation: the two countries use different LOLE standards. France sets its LOLE standard at 3 hours per year, as enshrined in its Energy Code (IEA, 2022). Germany, meanwhile, applies a standard of 4 hours per year (Astier & Ovaere, 2022).This difference, although seemingly modest, illustrates differing levels of acceptable risk between two countries that are nevertheless closely interconnected.

In Germany, the phase-out of nuclear power has led to increased reliance on imports during periods of low RE production. Modelling shows that, on average, Germany has net imports of around 28 TWh per year following the nuclear phase-out, and that in several adverse weather scenarios, additional back-up capacity would be required to meet demand (Wiebrow, 2026). In France, the winter of 2022–2023 was marked by an unprecedented crisis in the nuclear fleet. Nuclear generation fell to a historic low of 279 TWh in 2022, compared with a usual average of over 380 TWh (RTE, 2025). ENTSO-E had identified major uncertainties regarding the availability of French nuclear power, highlighting a risk of simultaneous shortages in several countries (ENTSO-E, 2022c). In 2022, for the first time since 1980, France also became a net importer of electricity with a balance of 16.5 TWh (RTE, 2023). The LOLE simultaneously reached high levels in several neighbouring countries, with concurrent shortages documented by ENTSO-E (ENTSO-E, 2022c). The crisis has since been overcome: nuclear generation recovered to 320 TWh in 2023 and then 361.7 TWh in 2024 (RTE, 2025). This episode nevertheless illustrates a structural limitation of the LOLE indicator: it does not capture the nature of the vulnerability of a system that is highly dependent on a single technology (ENTSO-E, 2022c). Furthermore, the ERAA 2022 projections show that Germany risks exceeding its own LOLE standard over several years. The cause is the simultaneous closure of nuclear and coal-fired power stations, without replacement capacity fully compensating during periods of low renewable generation (ENTSO-E, 2026a).

This case highlights a direct limitation of the LOLE indicator: it measures the probability of future failure, but does not capture the structural nature of the vulnerability. France's vulnerability stems from excessive reliance on a single controllable technology, namely nuclear power. Germany's vulnerability stems from the intermittency of RE sources. Two radically different causes, the same indicator, but necessarily distinct resilience policies.

Import dependency ratio – two distinct structural vulnerabilities

The import dependency ratio is a third key indicator. In 2024, Germany had an energy dependency ratio of 67%, compared with 42% for France (Eurostat, 2026). This difference is mainly due to the structure of electricity generation in the two countries. France meets more than half of its energy needs through nuclear power generation (RTE, 2024). Germany, by contrast, has gradually replaced its controllable capacity with variable RE sources, which has reduced its dependence on electricity but maintained a high dependence on gas and oil imports for its industrial and heating needs (Eurostat, 2026).

This discrepancy directly illustrates the limitation of the indicator identified in section 3.3. Traditional energy security metrics have historically focused on the availability and affordability of fossil fuels. They struggle to capture the dynamic nature of an energy system in transition and its ability to adapt to shocks (Schmitz et al., 2025). In other words, an aggregate dependency rate of 67% for Germany and 42% for France says little about the true nature of their respective vulnerabilities.

For Germany, as for other major European economies, dependence on gas and oil imports exposes the country to the volatility of international markets, with direct repercussions on industrial costs and economic stability (Peng et al., 2025). France, despite a lower rate, remains exposed to a different vulnerability: nuclear power is subject to institutional risks and risks relating to the supply of imported uranium that are not captured by the aggregate indicator, as illustrated by the crisis in the availability of the nuclear fleet in 2022. Nuclear power is indeed subject to unexpected natural, institutional and geopolitical risks, the probability of which may seem low but whose impact, when they materialise, is significant (Jasiūnas et al., 2021).

Two structurally different dependency profiles, a single metric — the same analytical limit as for the LOLE.

Flexibility – negative prices: the same indicator, conflicting signals

The frequency of negative prices presents a striking contrast between the two countries. In Germany, the number of hours with negative day-ahead prices reached 301 hours in 2023, a significant increase compared with previous years (Sun et al., 2026). In France, negative prices remain much rarer: the nuclear fleet's modulation capacity absorbs surpluses (Sun et al., 2026).

This contrast illustrates precisely the limitation highlighted in section 3.4: the same indicator gives opposing signals depending on the national context. In Germany, the high frequency of negative prices signals a structural lack of flexibility linked to the massive integration of variable RE sources. In France, the low frequency of negative prices does not mean that the system is more resilient. It simply reflects the modulating capacity of nuclear power, which can itself constitute a vulnerability during availability crises. Comparing these two indicators without taking the electricity mix into account therefore leads to misleading conclusions (Brijs et al., 2015).

Institutional governance – crisis preparedness plans: a common framework, divergent architectures

Both countries submitted their electricity risk preparedness plans to the European Commission in January 2022, in accordance with Regulation (EU) 2019/941 (Regulation UE/2019/941, 2019). The German plan identifies nine priority national scenarios: cyber-attacks, heatwaves, droughts, gas or coal shortages, pandemics and forest fires, amongst others. These are drawn up by the Bundesnetzagentur (BNetzA) under the supervision of the Federal Ministry for Economic Affairs. The competent authority is clearly designated, the roles between TSO and public authorities are explicitly allocated and regular crisis response simulations are planned (Risk-preparedness plan Germany, 2022).

The French plan adopts a different structure: more centralised, it relies on the RTE as the sole TSO and designates load shedding as a key crisis management measure (Risk-preparedness plan France, 2022). This structural difference reflects two profoundly distinct traditions of energy governance. French energy governance is characterised by large-scale centralised infrastructure and has historically been controlled by a technocratic network (Bocquillon & Evrard, 2022). In Germany, by contrast, energy strategy is based on a decentralised structure in which the Länder experiment and innovate, creating multi-level governance (Renn & Marshall, 2016).

However, although both plans formally meet the requirements of the European regulation, they are not comparable. They do not share the same performance metrics, the same thresholds for triggering crisis measures, nor the same indicators for assessing their effectiveness ex post. This is precisely the institutional limitation identified in section 3.5: a common European regulatory framework is not sufficient to produce comparable data. Without harmonisation of governance indicators, it is difficult to assess whether one of the two countries is institutionally more resilient than the other and therefore difficult to answer the central question of this study regarding the institutional dimension (Parag et al., 2026; Verzijlbergh et al., 2017).

4.3 Discussion

Is resilience truly measurable?

The case of Germany and France shows that a partial assessment is possible. The technical and economic dimensions can be measured using existing data. However, the comparison reveals a significant limitation. The same indicators yield opposite results depending on the national context. The French 3-hour LOLE and the German 4-hour LOLE measure the same thing but with different thresholds. Negative prices indicate opposite structural vulnerabilities in the two countries. Resilience is therefore partially measurable but not comparable between countries without prior harmonisation of standards (Parag et al., 2026; Schmitz et al., 2025). Moreover, resilience to extreme events can only be measured by considering all phases of the disturbance, rather than at a single point in time within the system (Jasiūnas et al., 2021).

Which aspects remain unseen?

Several key aspects are not captured by the indicators identified. The actual level of policy coordination between German and French TSO is not reflected in any metric. The actual quality of contingency plans cannot be assessed or ranked (Parag et al., 2026)

The social dimension is completely absent. Energy disruptions disproportionately affect vulnerable groups and the social costs are high when these are not taken into account (Jaeger-Erben et al., 2025; Kökény et al., 2025). In 2022, more than 41 million Europeans were unable to heat their homes adequately (European Parliament, 2022). The poorest households are significantly more exposed to energy poverty (Kökény et al., 2025). No identified indicator measures who is most affected by the crisis. This is a shortcoming confirmed by recent work on the blind spots in resilience metrics (Parag et al., 2026).

Is the European data sufficient?

No. This single example involving two countries is enough to illustrate the point. LOLE standards are not harmonised across Member States. Curtailment data is not published systematically. The RoCoF is not available on the ENTSO-E Transparency platform. National crisis plans are not comparable despite a common regulatory framework. Most existing indices are based on energy availability and prices. They do not capture the dynamic nature of the system or its ability to adapt (Schmitz et al., 2025). There is currently no European resilience observatory with standardised indicators and harmonised data. This is precisely what the European Parliament recommends in its report on electricity networks (Stürgkh, 2025).

Is resilience becoming too technocratic?

This is the most important question from a political and institutional perspective. The available indicators favour measurable technical and economic aspects. In doing so, they lend an appearance of neutrality to decisions that are fundamentally political. Achieving a just transition involves balancing economic, social and environmental priorities. It also requires the participation of diverse stakeholders to ensure the democratic legitimacy of energy choices (Radtke, 2025). However, no indicator measures who decides on the acceptable level of risk. None captures the basis of legitimacy on which trade-offs between safety, cost and equity are resolved. Resilience thus risks becoming a tool for technocratic legitimisation. Parag et al. (2026) explicitly document this drift among the blind spots of current metrics. Making resilience operational therefore involves not only filling data gaps but also repoliticising the choices that lie behind the indicators.

5 Conclusion

This study set out to answer the following question: To what extent do the available indicators and existing data allow for the assessment of the resilience of a European electricity system with high RE penetration, and what are the limitations of such an assessment?

What this study shows

Resilience cannot be reduced to a single figure. It requires combining technical, economic, security-of-supply and institutional indicators. Some of these exist and are accessible: LOLE, NTC, import dependency ratio, negative prices. Others remain fragmented or non-comparable across countries: RoCoF, curtailment data, VOLL, crisis preparedness plans. The comparison between Germany and France illustrates this clearly. The same indicators produce opposite signals depending on the national context. A common regulatory framework is not sufficient to generate comparable data. Resilience is therefore partially measurable but not yet comparable at European level.

This finding directly answers the research question: existing data and indicators allow for a partial assessment of resilience. The technical and economic dimensions are relatively well covered. The security-of-supply and institutional dimensions suffer from significant data gaps. And several essential dimensions such as social equity, democratic legitimacy of risk choices, cybersecurity, remain entirely invisible in the available data.

Limitations of this study

This work has several limitations. The case study is deliberately narrow: two countries, four indicators. It does not claim to cover all dimensions of resilience. The social aspects of resilience who bears the cost of disruptions and according to what criteria, remain largely invisible in the available data. This is an important limitation and not merely a technical one. Furthermore, the pace of the energy transition means that some of the figures and sources used here may evolve rapidly.

Avenues for future research

Three directions deserve further attention. First, the harmonisation of resilience indicators at European level is a priority. Without it, cross-country comparison remains impossible and the resilience of the European system as a whole cannot be assessed. Second, integrating social dimensions into assessment frameworks is essential: who suffers most from disruptions, according to what criteria and with what consequences for vulnerable households (Kökény et al., 2025; Parag et al., 2026). Third, the question of the democratic legitimacy of resilience choices: who decides on the acceptable level of risk, and through what procedure, remains open. These issues go beyond technical considerations and lie at the heart of European energy governance.

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7 Appendices

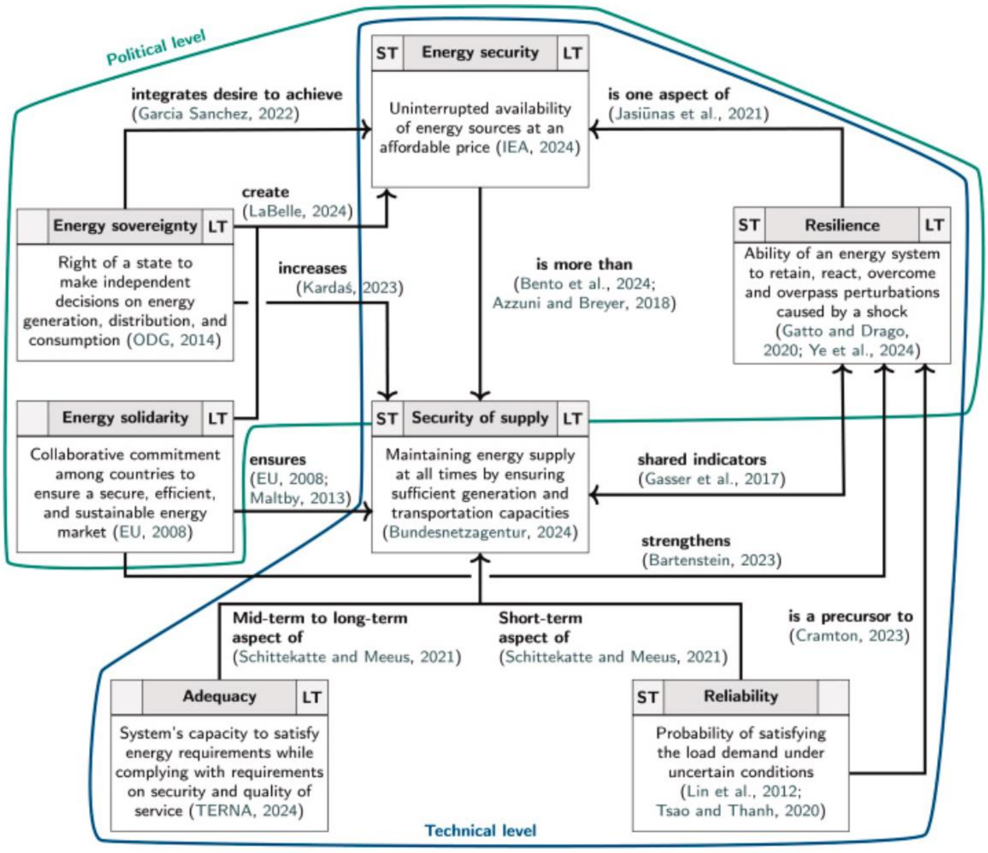

Figure 2: Relationships between key concepts of energy security and resilience in energy systems (Schmitz et al., 2025).

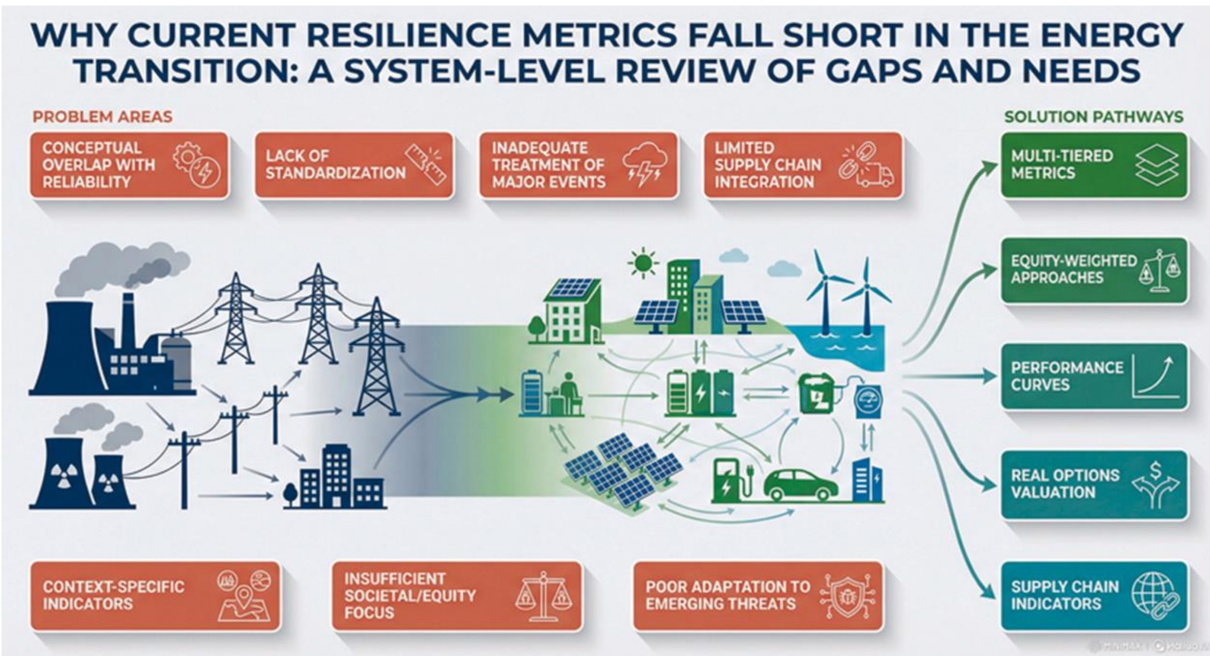

Figure 3 : The seven major shortcomings in current resilience indicators (Parag et al., 2026).

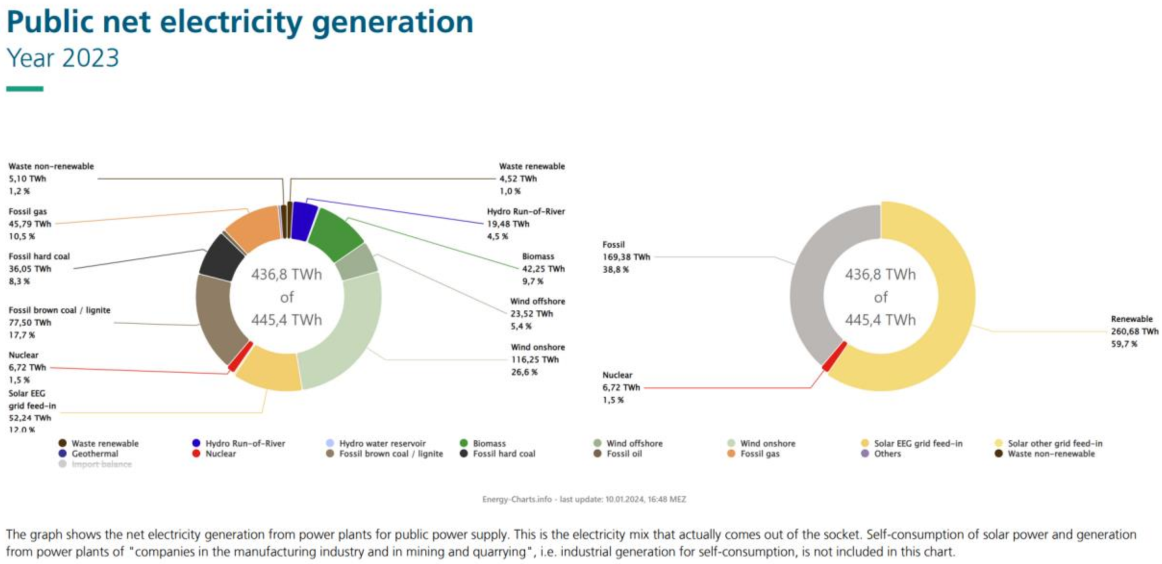

Figure 4: Public net electricity generation in Germany (Fraunhofer ISE, 2024)

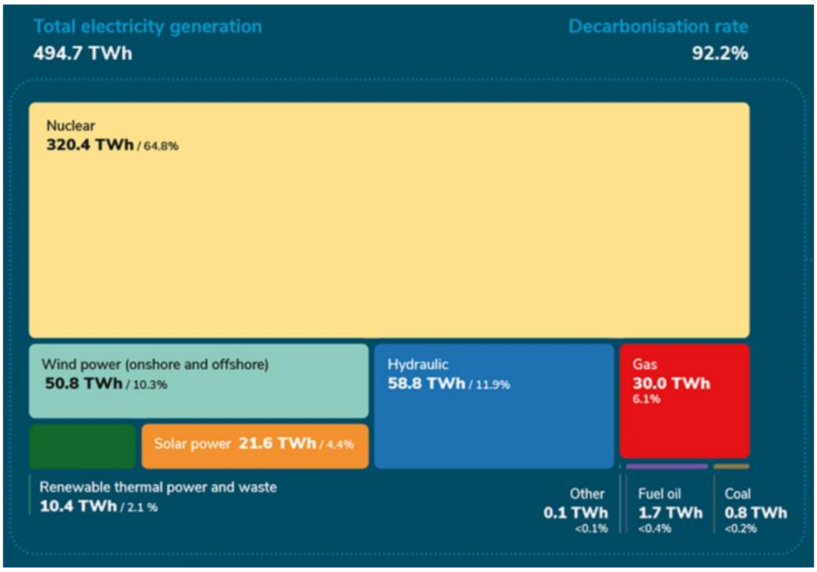

Figure 5: Different sources of electricity generation in France (RTE, 2023).

Table 3: Comparison of electricity mixes: Germany and France (2023) (Fraunhofer ISE, 2024; RTE, 2023)

Sources	Germany (TWh)	Germany (%)	France (TWh)	France (%)
Nuclear	6.7	1.5 %	320.4	64.8 %
Wind	139.8	32 %	50.8	10.3 %
Solar PV	52.2	12 %	21.6	4.4 %
Hydro	19.5	4.5 %	58.8	11.9 %
Biomass	42.3	9.7 %	10.4	2.1 %
Coal (brown and hard)	113.6	26 %	0.8	< 0.2 %
Natural gas	45.8	10.5 %	30	6.1 %
Others	17	3.8 %	1,8	< 0.5 %
TOTAL	~ 437	100 %	~ 495	100

Table 4: Comprehensive synthesis of resilience indicators

Dimension	Indicator	Required data	Main Source	Avail.	Main gap
Technical	LOLE	Generation mix, capacity by country, long-term meteorological time series	ENTSO-E ERAA	✓	National standards not harmonised (1 to 15h depending on country)
	EENS	Volume of energy not supplied during outages	ENTSO-E ERAA	✓	Complements LOLE; same comparability limitation
	RoCoF	High-resolution real-time measurements, system inertia data	National TSO	~	No common EU standard; not published on ENTSO-E Transparency Platform
	Curtailment rate	Available vs. actually injected RES generation	ENTSO-E Transparency	~	Not published systematically across all Member States
	NTC	Cross-border electricity exchange capacity	ENTSO-E Transparency	✓	Theoretical capacity ≠ actual availability during simultaneous crises
Security of supply	Import dependency ratio	Net energy imports / gross available energy	Eurostat (SDG_07_50)	✓	Does not distinguish between types of imported energy
	HHI index	Market shares of energy suppliers by country	Eurostat/ACER	✓	Does not integrate political risks of supplier countries
	« Dunkelflaute » (frequency / duration)	Long-term high-resolution meteorological time series (ERA5)	Copernicus/ERA5	~	No standardised definition at EU level
	Reserve capacity ratio	Mobilisable flexible capacity / residual peak demand	ENTSO-E ERAA	✓	Varying granularity across countries
Economic	Negative prices (frequency)	Hourly day-ahead and intraday prices by price zone	EPEX/Nord Pool/ENTSO-E	✓	Symptom of inflexibility, not its direct cause
	VOLL	Willingness to pay, data on actual outages	ACER (Decision No 23/2020) / National TSO	~	Large methodological variations across EU Member States
Institutional	TYNDP planned / delivered gap	Planned vs. actually built interconnection capacity	ENTSO-E TYNDP	~	Reflects project progress, not actual political coordination
	Crisis preparedness plans	Existence and quality of plans (Regulation EU/2019/941)	European Commission	✗	Not standardised, very difficult to compare across countries

✓ Data available and harmonised at EU level, ~ Available but with varying levels of detail across Member States, ✗ Not standardised, making comparison difficult