ENTSO-E Report

System Flexibility Needs for the Energy Transition

December 2024

ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the **association for the cooperation of the European transmission system operators (TSOs)**. The 40 member TSOs, representing 36 countries, are responsible for the **secure and coordinated operation** of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E **brings together the unique expertise of TSOs for the benefit of European citizens** by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

Our mission

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the **security of the interconnected power system in all time frames at pan-European level** and the **optimal functioning and development of the European interconnected electricity markets**, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

Our vision

ENTSO-E plays a central role in enabling Europe to become the first **climate-neutral continent by 2050** by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires **sector integration** and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources.

ENTSO-E acts to ensure that this energy system **keeps consumers at its centre** and is operated and developed with **climate objectives** and **social welfare** in mind.

ENTSO-E is committed to use its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive roadmap of how a climate-neutral Europe looks.

Our values

ENTSO-E acts in **solidarity** as a community of TSOs united by a shared **responsibility.**

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by **optimising social welfare** in its dimensions of safety, economy, environment, and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and **innovative responses to prepare for the future** and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with **transparency** and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

Our contributions

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its legally mandated tasks, ENTSO-E's key responsibilities include the following:

- Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;
- Assessment of the adequacy of the system in different timeframes;
- Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);
- Coordination of research, development and innovation activities of TSOs;
- Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the **implementation and monitoring** of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

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Summary

The European Commission's renewable energy and climate targets envision a future in which over 45 % of Europe's energy will come from renewable sources by 2030, aiming for carbon neutrality by 2050. This transition will primarily be driven by significant growth in wind and solar energy development and the progressive electrification of energy demand.

Flexible resources are needed to effectively manage the resulting variability of generation and consumption to achieve these targets, while addressing the energy system's increasing complexity. This approach is also emphasised by ENTSO-E's *Vision for a Carbon Neutral Energy System*, published in October 2022. In the *Vision*, flexibility needs have been identified and qualitatively characterised in both a short and long-duration timeframe, aligning with future system needs and the gradual phase-out of fossil fuel generation.

This report is the result of work mandated by ENTSO-E's members as a follow-up to the ENTSO-E Vision and Strategic Roadmap, both of which identified flexibility as a crucial factor for both the present and the future power system and underscored the need for quantitative analysis of flexibility requirements to initiate discussion and build further expertise on the topic.

The European Commission has recognised the importance of flexibility and the need for quantitative assessments through its Electricity Market Design Reform (EMDR). The new regulation that entered into force in July 2024 mandates regular national flexibility needs assessments and tasks ENTSO-E and EU DSO Entity with developing a common methodology for the analysis of flexibility needs by transmission system operators (TSOs) and distribution system operators (DSOs) of each member state.

ENTSO-E is dedicated to making meaningful contributions to this critical task and more generally in the discussion on flexibility, leveraging its members' extensive experience in operating the electricity system and their knowledge of adequacy and network planning studies to support all relevant stakeholders, including decision-making bodies at the national and pan-EU level.

The analysis has been essential in enhancing the understanding of this complex topic and deriving key conclusions on the most relevant system flexibility needs. The findings are already supporting the association in effectively fulfilling the ongoing EMDR mandate.

The study investigates and provides insights into the evolution of some system flexibility needs over various timeframes leading up to 2030 and beyond, using as input the datasets from the National Trends Scenario,[1] along with climate data from the ENTSO-E Pan-European Climatic Database, complementing previous ENTSO-E studies. The work exclusively concentrates on the requirements of the power system and remains technologically neutral. It does not recommend which specific resources or technologies might be required to fulfil these needs, however, the contribution of existing and planned interconnections toward mitigating these needs is assessed.

In this report, we propose several flexibility needs indicators, covering system flexibility needs from the seasonal up to the hourly timeframe:

1. **Needs due to multi-day periods of variable renewable (vRES) shortage:** characterised by periods of prolonged mismatch in vRES generation and system demand, during which flexibility resources such as storage and demand-side response are depleted.

2. **Needs arising from residual load variability up to the day-ahead:** flexibility needs associated with vRES and demand variability in annual, weekly, and daily timeframes as well as those arising from residual load ramping.

3. **Flexibility needs due to forecast errors in the intraday timeframe:** flexibility needs to cover uncertainty following the day-ahead due to forecast errors in generation and demand.

This study does not address other relevant flexibility needs such as those related to network constraints.

ENTSO-E's analysis characterises and provides key insights into the evolution of these flexibility needs, indicating the following:

- **Increasing flexibility requirements:** The need for system flexibility is expected to significantly increase in the short to medium term, driven by the integration of vRES, the phase-out of fossil thermal generation, and the electrification of demand. Energy flexibility needs linked to generation and demand variability are projected to double between 2025 and 2033 across all examined timeframes.
- **Short-duration and ramping flexibility:** Due to the same drivers, the need for short-duration flexibility and ramping capabilities—particularly concerning forecast errors and system operation—is expected to roughly double by 2030, varying based on country size and generation mix.
- **Extended system stress events:** Countries with a significant reliance on vRES generation are likely to face increased system stress due to prolonged vRES shortage periods. Such events might occur 2 – 4 times annually, lasting on average up to 6 – 10 days and resulting in a vRES generation gap ranging between just a few MWh up to several TWh in the worst scenarios for the largest countries.
- **Regional implications of vRES shortages:** Prolonged shortages in vRES generation are anticipated to affect multiple countries within the same region, heightening the risk of system stress and reducing the mitigation effect of interconnections.
- **Role of interconnectors:** Interconnectors will play a crucial role in mitigating flexibility needs across various timeframes except at the time of prolonged shortages in vRES generation that affect multiple countries

The findings highlight the importance for ENTSO-E and TSOs to explore flexibility needs and their incorporation into comprehensive assessments by all stakeholders. This is fundamental to quantify flexibility needs and facilitate the effective and timely deployment of resources to cover them. Moving forward, ENTSO-E and TSOs should continue to refine metrics and methods to proactively identify and address emerging system challenges.

1 Dataset used for the European Resource Adequacy Assessment 2023.

1 Introduction

The ENTSO-E Ten-Year Network Development Plan and the European Commission's renewable energy targets project that over 45 % of Europe's energy will come from renewable sources by 2030, predominantly driven by wind and solar energy (vRES). As the EU electricity system's installed capacity increasingly relies on these non-dispatchable resources, and as a significant portion of fossil-based dispatchable capacity is phased out, maintaining a balance between supply and demand while meeting renewables integration targets will become increasingly challenging.

In this future scenario, the flexibility brought by dispatchable generation, demand-side response, storage interconnectors, and all other flexibility technologies will be essential for ensuring that the power system can cope with variability and uncertainty in demand, generation, and grid availability. Their combined capacity will need to address the heightened weather dependency, variability, and inherent uncertainty in the system.

Objectives of the Flexibility Study

This study aims to provide a first quantification of flexibility needs arising from the system's variability (assuming perfect foresight) and uncertainty (due to forecast errors). Additional objectives include characterising events of extended vRES shortages that might lead to system stress and assessing the contribution of interconnections in mitigating these needs.

The flexibility study was initiated as a result of ENTSO-E's Vision for a Carbon Neutral Energy System work to enhance understanding within the ENTSO-E community and communicate externally and raise awareness of the critical importance of flexibility in managing the future electricity system. Following the publication of the Electricity Market Design Reform (EMDR) in March 2023, the European Commission confirmed the importance of flexibility and proposed introducing national flexibility needs assessment to support member states in identifying flexibility targets. The resulting revised regulation that entered into force in July 2024 tasks ENTSO-E with designing the methodology for national assessments under this mandate, together with EU DSO Entity. This study has been fundamental in building insights and knowledge on this complex topic and has led the way to defining such a methodology, which is currently under development and expected to be finalised by April 2025.

This study focuses on characterising the future system's needs based on ENTSO-E's "National Trends" 2030 scenario and – when relevant – quantifying the contributions of existing and planned flexibility solutions under the same scenario assumptions.

The assessment computes a set of indicators to derive insights into flexibility needs to achieve these objectives. However, it does not aim to determine an optimal mix of flexibility solutions to fulfil these needs.

This report seeks to provide ENTSO-E members with a comprehensive understanding of flexibility and its integration into the electricity system, addressing supply and demand challenges as we move towards a more renewable-dominated energy landscape.

2 What are power system flexibility needs?

Power system flexibility is defined as the ability of a power system to effectively manage the variability and uncertainty of electricity demand, supply, and grid availability across a range of timeframes, from seconds to years.

To understand flexibility, it is important to distinguish it from the concept of adequacy. Adequacy refers to the power system's capacity to meet peak demand at all times, ensuring sufficient generation resources to maintain reliable supply under both expected and unexpected conditions.

By contrast, flexibility is the system's ability to adjust dynamically to variability in supply and demand. This includes the capability to respond to rapid changes in consumption and generation, manage renewable energy variability, and maintain grid stability. Flexibility relies on various services and technologies that can quickly ramp up or down, shift loads, or store energy to balance the grid in real time across multiple timeframes.

Factors driving flexibility needs

Several factors are expected to amplify flexibility needs in European countries:

- **Increasing electricity demand:** Variations in temperature, behavioural shifts, daylight changes, and unusual events affect the timing and volume of electricity demand. The ongoing electrification of sectors such as buildings, industry, and transport will increases overall electricity consumption, changing demand patterns and potentially raising peak loads.
- **Rising penetration of variable renewable energy sources (vRES):** The inherently limited accuracy of forecasts pertaining to solar and wind energy calls for flexibility solutions such as dispatchable generation, storage, and demand-side management to keep supply and demand in equilibrium. As vRES adoption increases in line with EU decarbonisation targets, the demand for flexibility will rise significantly increase.
- **Potential energy system disruptions:** Climate change is causing more frequent extreme weather events, such as droughts and storms, which can further increase the variability and uncertainty of generation and demand, as well as affecting grid infrastructure availability.

Flexibility Indicators

Transitioning to a fully carbon-neutral electricity system – predicated on electrified consumption and primarily renewable electricity generation – will create a highly weather-dependent landscape. This transition will increase the complexity and volatility of both generation and demand, necessitating considerable flexibility to maintain acceptable levels of system stability and resilience.

As we move toward carbon neutrality, the nature and volume of flexibility needs will evolve, along with the portfolio of flexibility resources. The power system will gradually phase out its reliance on fossil fuel dispatchable generation, which currently significantly contributes to flexibility and ancillary services. Instead, a timely deployment of various carbon-neutral flexibility resources will be required. These resources will be provided by existing and new flexible generation, active demand response, storage, sector integration, and optimised grid usage.

From a system perspective, flexibility needs can be categorised into several types, each requiring different resources. For the purposes of this report, we will consider the following flexibility indicators:

Long-duration indicator: Needs due to multi-day periods of variable renewable (vRES) shortage

This indicator focuses on identifying and characterising periods of prolonged renewable energy sources shortage, often referred to using the German term "Dunkelflaute". These periods of prolonged vRES shortage often coincide with high electricity demand, leading to the depletion of storage and demand side response capacities, which typically require regular patterns of charge/discharge or usage. By examining these situations, this indicator aims to quantify the associated system needs and provide insights into the level of system stress experienced. It also assesses the effectiveness of interconnections in alleviating such stress.

Long-duration indicator: Needs arising from residual load variability up to the day-ahead

This indicator is concerned with the flexibility requirements arising from the variability of vRES and demand over annual, weekly, and daily timeframes. It helps in understanding how fluctuations in electricity production and consumption influence the system's needs over different periods.

Additionally, it begins to explore the flexibility demands related to residual load ramps, reflecting sharp changes in the difference between demand and vRES supply. This indicator's goal is to quantify these needs and enable a deeper analysis of the drivers and contributions of interconnections in meeting these challenges.

Short-duration indicator: Needs due to forecast errors in the intraday timeframe

This indicator addresses short-duration flexibility needs arising from forecast uncertainties in vRES availability and demand after the day-ahead planning stage. By examining real-time deviations from planned electricity schedules, this indicator provides a detailed understanding of the operational flexibility required to respond to unexpected variations. It aims to offer insights into the necessary short-duration measures to maintain system stability in fluctuating conditions.

The need for both short- and long-duration flexibility resources is explained in Figure 1 below. While efficient and capable of delivering substantial power, short-duration flexibility resources lack the energy storage capacity to sustain supply over several days. Thus, they must be complemented by high energy-density resources to cover long-duration needs resulting from variations over several days, weeks, or seasons.

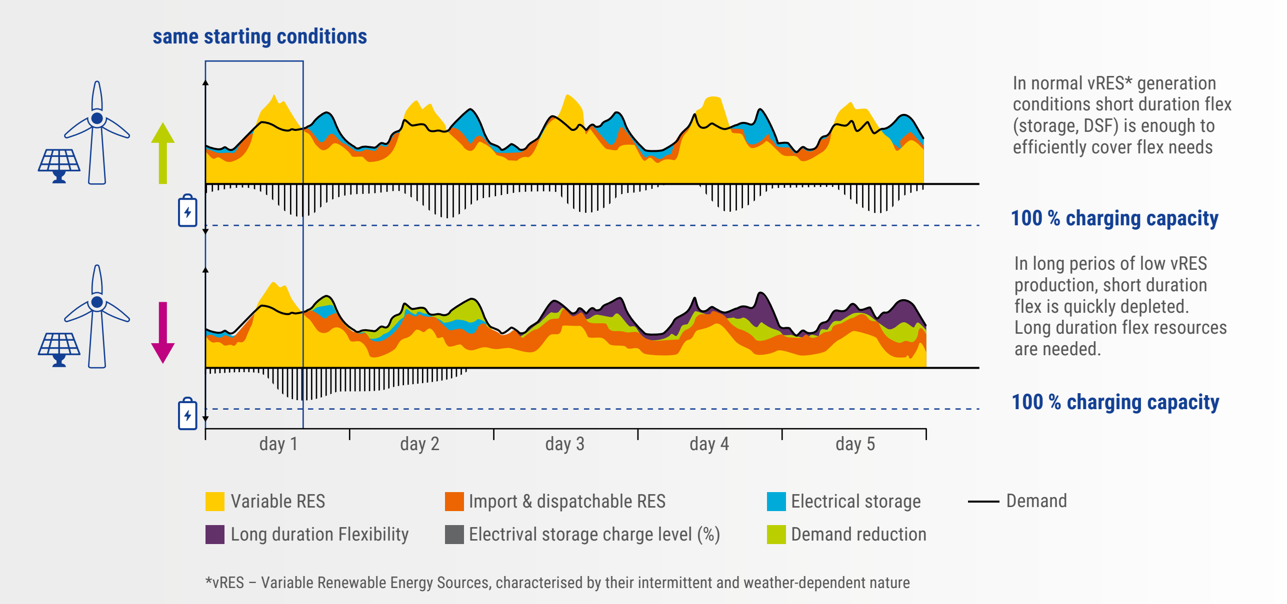


Figure 1: Use of short- and long-duration flexibility resources in different grid conditions

The flexibility needs considered in this study are not exhaustive, given that needs related – for example – to network constraints as well as intra-hourly needs are not considered.

3 How frequent are extended periods of variable renewable energy production scarcity?

When the generation of electricity from vRES is inadequate, system demand is typically met by dispatchable generation units, storage resources, and interconnections with neighbouring countries. However, with fewer dispatchable thermal generation units available as the decarbonisation of the system progresses, prolonged shortages in vRES or high demand can deplete storage resources, resulting in considerable strain on the system, particularly if these conditions affect multiple adjacent zones. Therefore, it is essential to quantify the magnitude and frequency of these vRES shortages as indicators of system stress and flexibility needs. This section asseses those flexibility needs during extended periods of weather-dependent vRES shortages. While adequacy assessments take such shortages into account, this analysis seeks to provide deeper insights into the expected duration and severity of vRES shortages, regional correlations, and the impact of interconnections.

The methodology applied in this chapter involves a purely statistical analysis utilising the European Resource Adequacy Assessment (ERAA) 2023 input dataset alongside the National Trends Scenario from the ERAA 2023 framework to model the 2030 target for modelled zones within the EU. In line with the ERAA methodology, a zone represents the largest geographic area that does not exceed the size of a bidding zone or country.

The conclusions presented in the following were derived from 35 historical climate years sourced from the ENTSO-E Pan-European Climatic Database. It is assumed that vRES shortages—or generation gaps—are present when one or more of the following conditions persists over four or more consecutive days:

- the total vRES generation falls within the lowest 10 % of values in the dataset;
- the ratio of vRES generation to system demand falls within the lowest 10 % of values in the dataset;
- the ratio of residual load to system demand exceeds the highest 10 % of values in the dataset.

The conditions are applied individually for each modelled zone. The vRES gap is defined as the energy required for a zone to revert to normal operating conditions.

Figure 2 illustrates the annual vRES gaps for each zone experienced over the 35 climate years in the database. The vRES gap has been normalised against the electricity demand during respective periods of vRES shortage to facilitate comparisons among zones. Many ENTSO-E member states exhibit considerable variability in vRES gaps, with the mean annual vRES gap reaching 15 – 20 % of demand during stress periods and peaking at 35 % in the most severe years simulated.

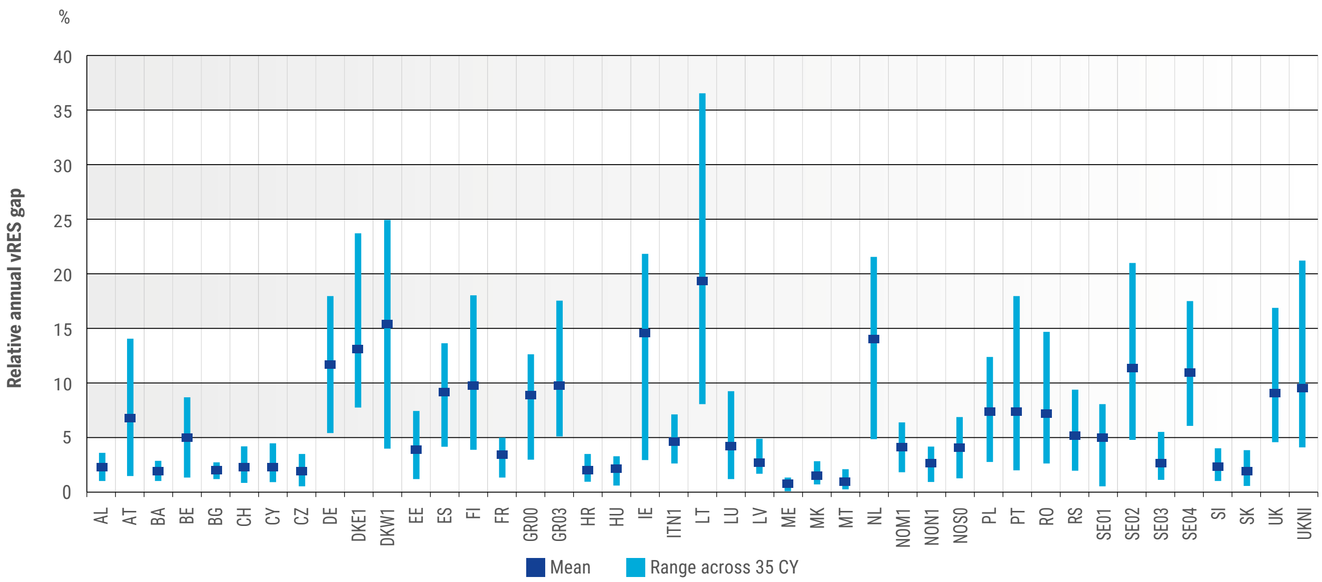


Figure 2: Annual vRES gap relative to electricity demand in modelled zones over 35 climate years

Given that analysing individual zones in isolation fails to accurately capture the dynamics of an interconnected European power system, it is essential to extend the analysis to account for cross-border interconnections. Each zone's contribution to its neighbours is defined by the minimum value of the hourly net transfer capacity and the available vRES generation that can be exported without causing a local shortage.

Table 1 provides detailed results from this analysis. Across Europe, events of extended vRES shortages result in a total vRES gap of 22 TWh per year, representing around 9 % of the electricity demand during the shortage periods. The largest individual vRES shortage event involved a gap of 1 TWh. When these individual national vRES gaps are aggregated and energy sharing between neighbouring countries is considered, this relative gap shrinks to 4 % of energy demand in these shortage periods, and the largest individual vRES shortage is reduced in size by almost 20 %.

As shown in Figure 3, incorporating potential contributions from neighbouring countries reduces the annual vRES gap across all bidding zones. One of the most significant impacts can be seen in occurs in France, where cross-border contributions reduce the annual vRES gap by over 90 %.

The results suggest that the vRES gap can be mitigated across all examined zones within an interconnected system. Variations in reduction levels can be attributed to simultaneous energy constraints in neighbouring countries, which might limit their export capacity. For instance, due to Portugal's geographic position on the edge of the Iberian Peninsula, it is probable that Spain might also face concurrent shortages, reducing its ability to contribute. Conversely, due to having multiple neighbouring countries, France is less likely to experience simultaneous shortages across all borders, allowing for greater external contributions and a notable reduction in its vRES gap.

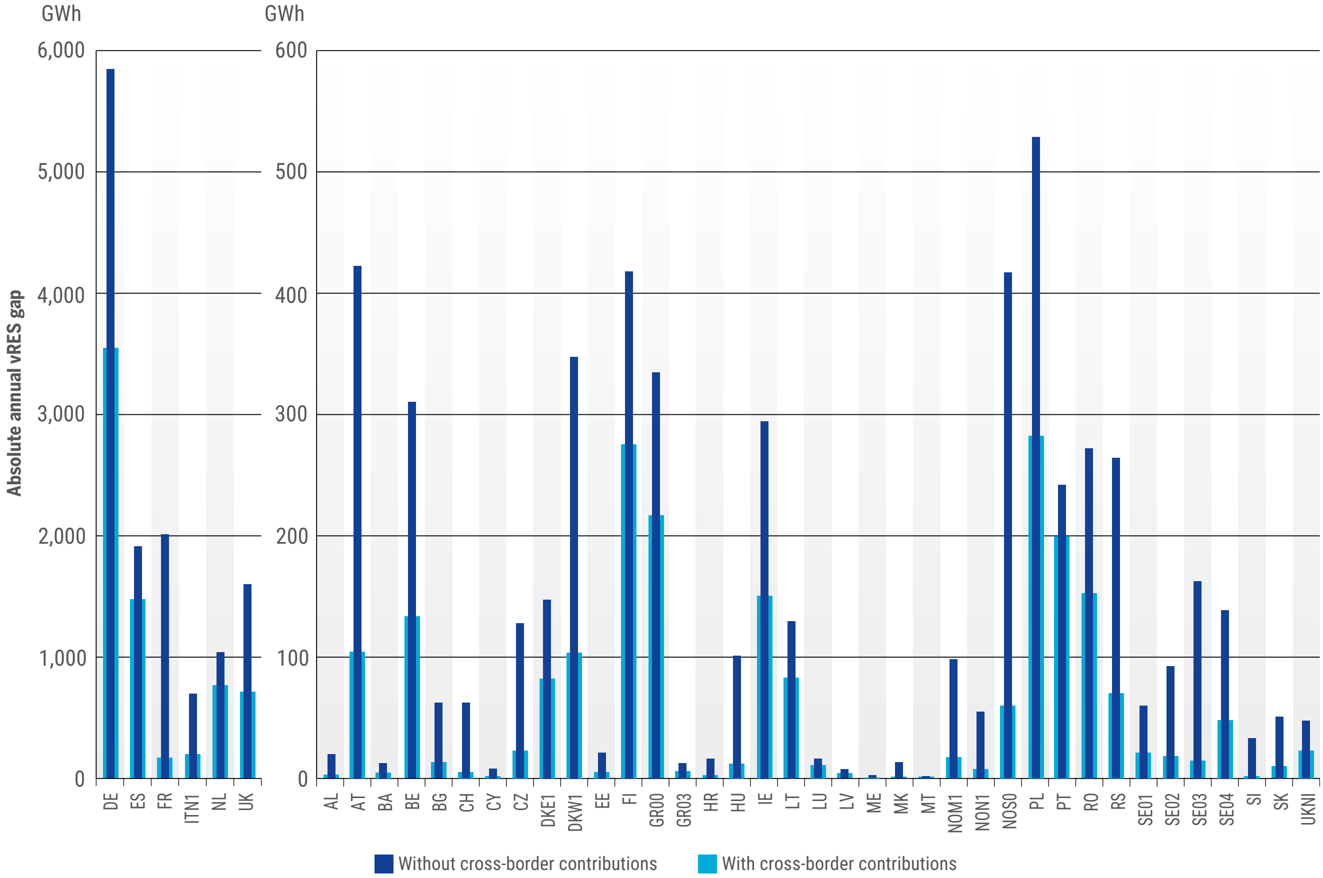


Figure 3: Absolute annual vRES gap before and after the contributions from neighbouring study zones over 35 calendar years

	Without cross-border contributions	With cross-border contributions
Relative annual vRES gap	9.30 %	4.38 %
Absolute annual vRES gap	22,451 GWh	9,878 GWh
Daily max vRES gap	1,044 GWh	827 GWh

Table 1: Pan-European annual vRES gap before and after the contributions from neighbouring zones

A coincidence analysis was performed across the modelled zones to further evaluate the impact of concurrent events. Figure 4 presents the outcomes for (a) the Nordic and southwestern regions, and (b) the Greece-Italy regions of Europe, reflecting the average coincidences across 35 climate years. In this matrix, each indicator shows the percentage of coincident shortage energy between two bidding zones relative to the total shortage in the row zone.

In Figure 5 (a), the strongest correlation in the Nordics is observed between SE03 and the neighbouring SE04, with a correlation of 55 %. This indicates that 55 % of SE04's total vRES shortage incidents coincide with shortages in SE03, while 43 % of SE03's shortages are associated with SE04. In the southwestern region, the strongest correlation is observed between Spain and Portugal, at 55 %. Similar trends are evident in the Greece–Italy region, shown in Figure 4 (b), where ITS1 and ITCA experience simultaneous vRES shortages on 87 % of days and ITCN and ITCS on 73 % of days.

This coincidence analysis suggests that stress events often affect multiple zones within the same region, particularly in neighbouring countries, thereby amplifying system stress at the regional level across interconnected grids.

Nordics and southwestern Europe

		Nordic								SW Europe		
		NOS0	NOM1	NON1	SE03	SE01	SE02	SE04	FI	PT	ES	FR
Nordic	NOS0		34	23	27	5	5	21	7	8	15	21
	NOM1	40		30	31	8	14	12	10	6	7	21
	NON1	23	31		8	14	6	5	12	5	8	6
	SE03	35	41	13		5	10	43	12	10	13	32
	SE01	9	20	30	10		41	10	45	1	3	7
	SE02	8	35	15	17	46		13	42	0	4	13
	SE04	38	26	12	55	7	9		7	11	11	19
	FI	16	18	31	20	38	30	7		5	3	9
SW Europe	PT	9	7	7	8	0	0	6	1		55	34
	ES	15	7	6	9	1	1	4	1	47		51
	FR	21	14	4	17	2	3	7	2	21	45	

Greece/Italy region

		Greece / Italy										
		CH	ITN1	ITCN	ITCS	ITSA	ITS1	ITCA	ITSI	MT	GR00	GR03
Greece / Italy	CH		35	23	21	14	17	14	15	14	9	6
	ITN1	15		52	40	21	25	22	21	11	30	9
	ITCN	13	59		73	31	42	34	38	19	28	8
	ITCS	9	43	67		40	54	43	44	26	23	7
	ITSA	8	27	37	43		50	50	65	20	21	6
	ITS1	8	29	40	51	49		87	63	27	29	13
	ITCA	7	31	36	41	49	82		62	25	28	11
	ITSI	7	21	34	41	63	54	54		22	18	6
	MT	7	19	30	33	27	47	41	35		10	3
	GR00	6	42	28	31	21	32	32	24	6		34
	GR03	6	26	13	13	13	22	20	12	5	53	

Number of days with vRES shortages

0 10 20 30 40 50 60 70 80 90 100

Figure 4: Coincidence of days with vRES shortages between zones (a) in the Nordics and southwestern Europe (b) in the Greece/Italy region

4 How does the variability of the residual load affect flexibility needs?

Energy production from variable renewable energy sources (vRES) and electricity demand are influenced by various factors, including seasonal, weekly, and daily trends. Understanding these fluctuations is essential to maintaining a reliable and resilient energy system.

This chapter examines the variability of the residual load, defined as the remaining electricity demand after accounting for variable generation from vRES. Analysing residual load variations across daily, weekly, and annual timeframes provides a basis for assessing the system's flexibility requirements.

Flexibility needs across different timeframes

Daily variations encompass fluctuations in residual load, capturing how demand and renewable generation change throughout the day. Weekly variations comprise fluctuations between days of the same week, revealing patterns that might arise from habitual consumption behaviours or periodic events. Annual variations consider long-duration seasonal changes, reflecting the significant impact of shifting weather conditions and daylight hours on renewable energy generation and overall demand.

Figure 5 (a) and (b) show how different renewable energy sources and the electricity demand affect national flexibility needs in each timeframe. Whereas Italy's largest driver of daily needs is photovoltaic (PV) generation, Norway's daily needs are mainly influenced by demand patterns.

Figure 5 (c) depicts the share of flexibility needs associated with the various flexibility timeframes in different member states, indicating that the allocation of flexibility needs varies between regions. In general, daily needs are mostly driven by PV variability, while weekly needs are driven by wind hydro and seasonal demand variability. Nonetheless, as the expected evolutions of generation mixes and demand patterns vary among member states, individual solutions will be required to address the resulting flexibility needs.

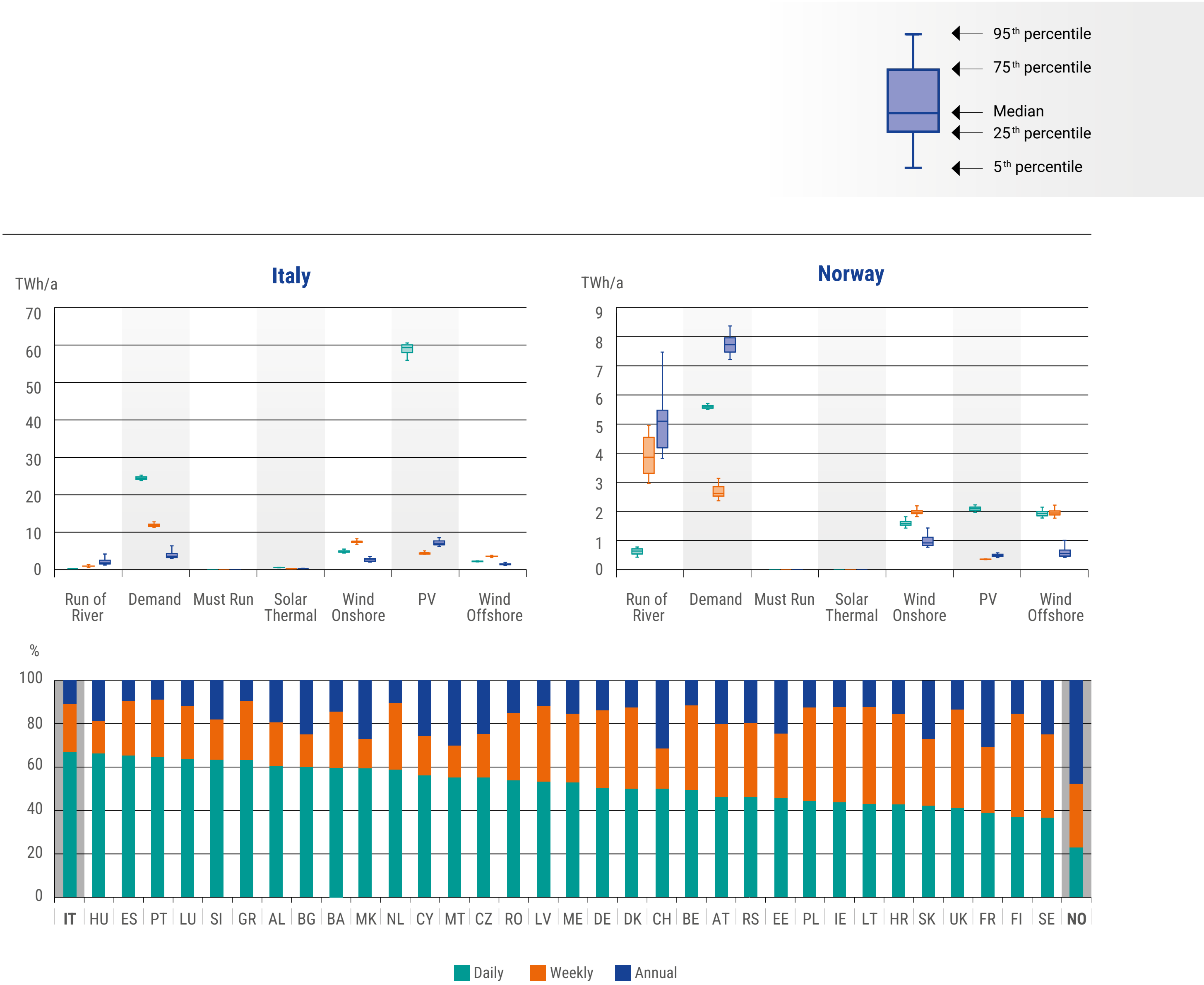


Figure 5: Flexibility needs in (a) Italy and (b) Norway due to generation and demand variability by source in 2030, as well as (c) the share of flexibility needs by timeframe across several ENTSO-E member states in 2030

This chapter applies two primary methods to estimate the energy and capacity components of the residual load variability in the annual, weekly, and daily timeframes to be used for comparative analysis across target years and conditions. The first method applies a frequency decomposition[2] approach to analyse the spectrum of the residual load curve, providing insights into periodic load patterns. These techniques are first applied to each individual country, whose needs are then aggregated to determine pan-European needs. The results of these calculations are shown in Figures 6 – 8.

As illustrated in Figure 6, the variability of the residual load is expected to significantly increase over the next decade. The system flexibility needs resulting from this change are expected to at least double across all timeframes by 2033. This trend emphasises the growing challenges faced by energy systems in balancing supply and demand as reliance on variable renewable sources escalates.

Further insights can be drawn from Figures 7 and 8, which depict the anticipated flexibility energy needs across the timeframes analysed. Across all timeframes, energy per timeframe is expected to approximately double until 2033. This analysis is indicative of the growing uncertainty in long-term energy system planning, particularly in the daily and weekly timeframes, where the needs predictions lie anywhere between 0.7 TWh and 2.6 TWh per day or 2.5 TWh and 17 TWh per week in 2033, depending on the weather year simulated.

The variability observed underscores the importance of developing robust flexibility solutions that can respond to the unpredictable nature of renewable energy production and consumption patterns, ensuring a reliable and resilient energy system in the face of evolving challenges.

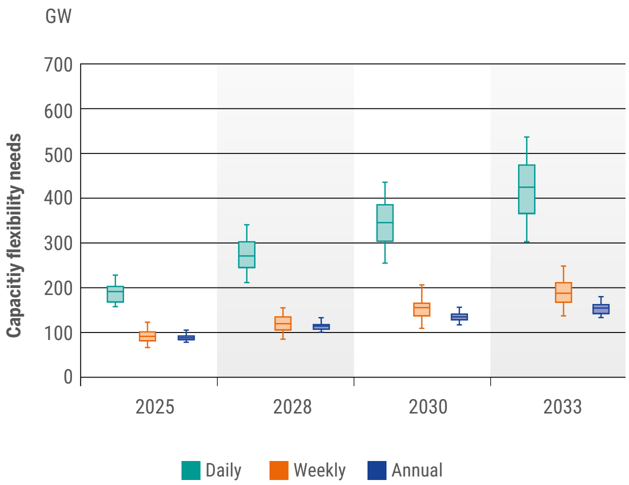


Figure 6: Evolution of European flexibility capacity needs from 2025 to 2033

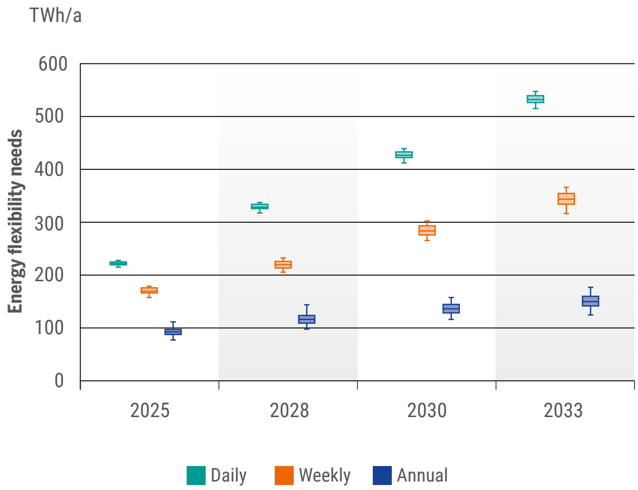


Figure 7: Evolution of annual European flexibility energy needs from 2025 to 2033

2 This method applies the fast Fourier transform.

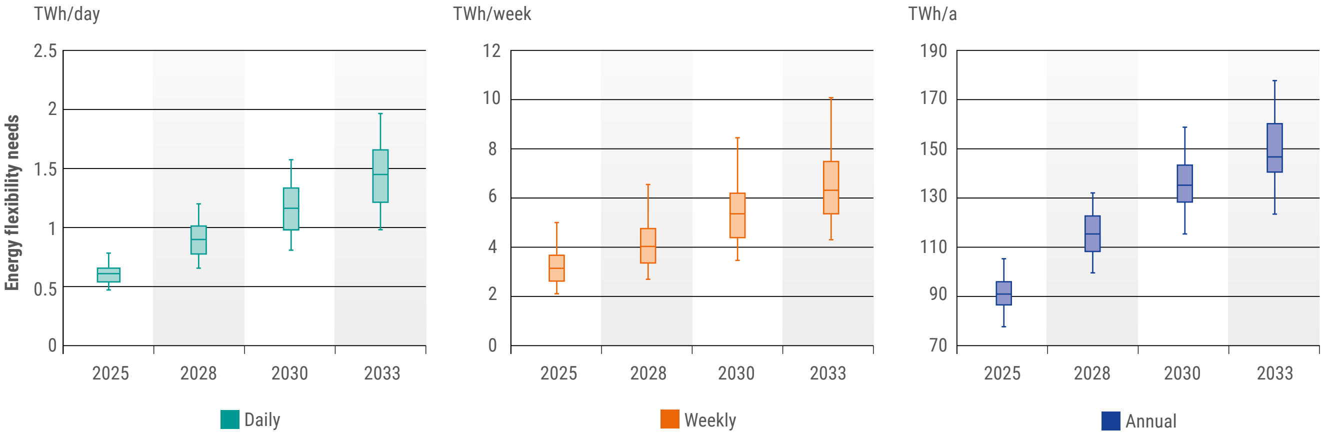


Figure 8: Evolution of European flexibility energy needs in the (a) daily, (b) weekly, and (c) annual timeframes from 2025 to 2033

In the analysis presented in this chapter, we explore not only the aggregated flexibility needs of individual countries but also the potential for reducing these needs through cross-border electricity exchanges. For this purpose, net transfer capacities of all cross-border transmission lines are included in the simulation model of flexibility requirements across 35 modelled climate years. A time decomposition approach[3] determines residual load variability by examining deviations from daily, weekly and monthly averages. The findings – illustrated in Figure 9 – reveal key insights regarding the contribution of interconnections towards mitigating overall flexibility energy needs. As the time decomposition approach employed differs from the previously used fast Fourier transform (FFT) approach, the flexibility needs calculated are not identical, although the two methods exhibit similar evolution trends across target years.

European energy-related flexibility requirements within the daily timeframe are projected to reach nearly 450 TWh per year by 2030. However, accounting for available net transfer capacities (NTCs) between modelling zone could reduce this need by approximately 15 % when optimising based on deviations from the annual average. When optimised around daily averages, this requirement could be further reduced to roughly 350 TWh, reflecting a 22 % reduction compared to a system without interconnections. Similar reductions apply across weekly and annual timeframes. For the weekly timeframe, annual flexibility needs would be around 340 TWh without interconnections but drop to approximately 260 TWh in a system that leverages NTCs. On an annual scale, flexibility requirements decrease by roughly 35 % when including NTC contributions.

In conclusion, the analysis highlights the significant impact of cross-border interconnectors in reducing flexibility needs across European energy systems. By allowing electricity to flow between regions, interconnectors help to balance residual load variability and reduce the reliance on national resources alone to meet flexibility needs. Optimising the use of NTCs notably reduces flexibility needs compared to a non-interconnected system. This reduction is observed across various timeframes, with interconnectors lowering overall flexibility needs and enhancing the European energy grid's resilience and efficiency, supporting a more balanced and stable transition towards renewable energy.

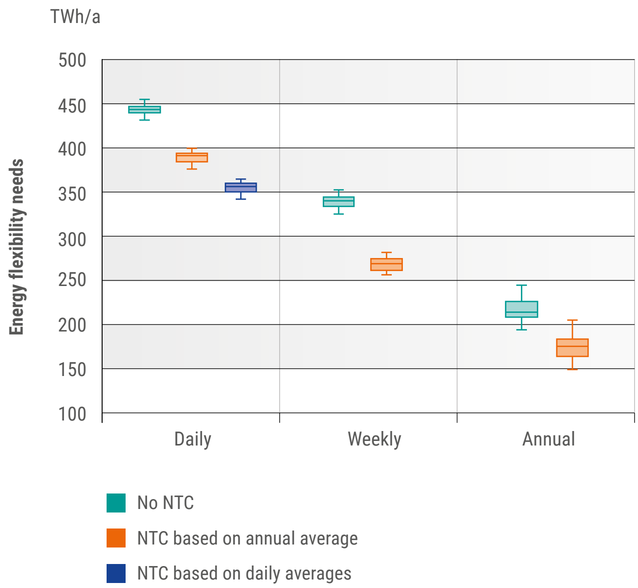


Figure 9: Impact of optimal use of cross-border net transfer capacities on annual European flexibility energy needs in the daily, weekly, and annual timeframes in 2030

3 A time decomposition approach based on the Artelys methodology employed in the METIS project (2018).

Flexibility needs caused by residual load ramp rates

In previous sections, it was established that electricity demand and variable renewable energy sources (vRES) are major contributors to variability in the electricity system. Assuming perfect forecasting, this variability is represented by hourly residual load ramp rates. This analysis examines the evolution of inter-hourly ramping rates, calculated from the residual load time series using ERAA 2023 input data for each nation considered through 2030.

The results – shown in Figure 10 – compare the maximum upward ramping requirements observed in 2023 with the projected maximum upward ramping needs for 2030. The bars represent the maximum upward ramping requirements range across 35 climatic years. The data indicate that ramping requirements are expected to rise across Europe, with moderate increases experienced in some countries and a threefold increase over the same period in others. A similar trend is observed for downward ramping needs.

The overall increase in maximum ramping rates is primarily driven by the expected growth in vRES capacity and heightened demand variability. While these trends suggest the potential for significant system stress, further assessments are necessary to evaluate the ability of each country to manage these ramping demands with its available flexible assets.

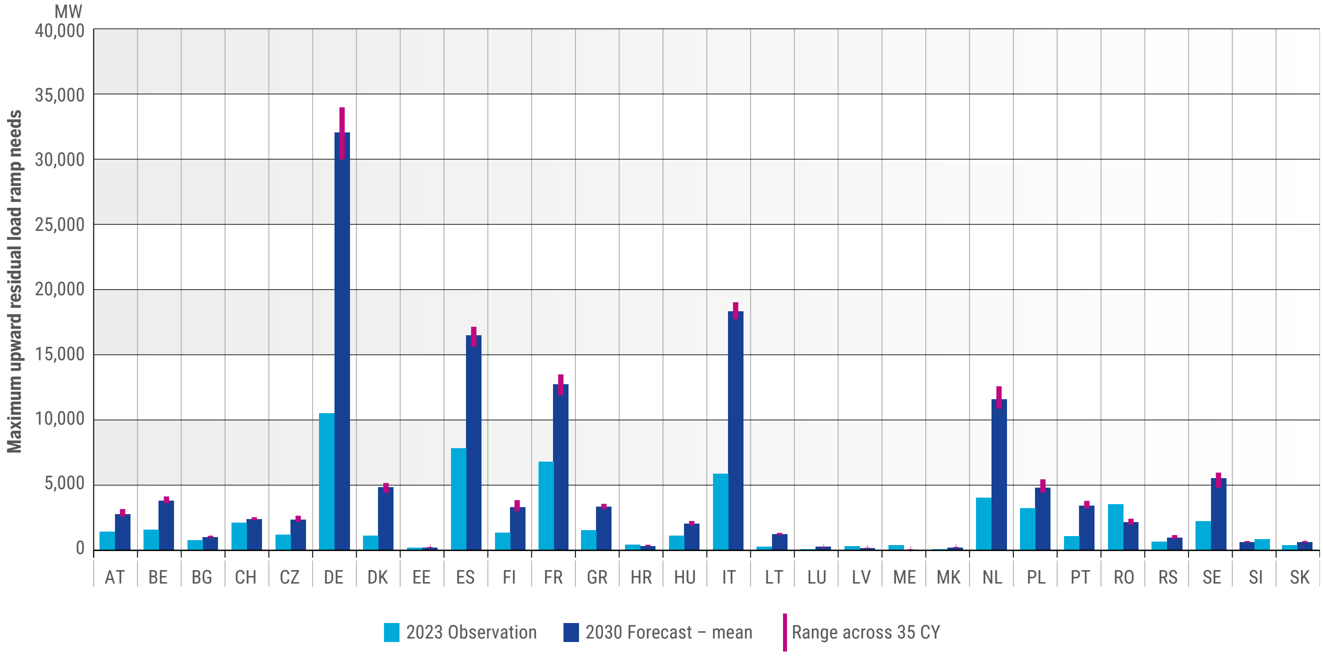


Figure 10: Maximum upward residual load ramp needs in 2023 compared to the required needs in 2030

5 How do errors in the short-term forecasting of variable renewable energy generation and electricity load affect flexibility needs?

In previous sections, we evaluated flexibility needs up to day-ahead under the assumption of ideal foresight. The assessment of short-duration flexibility needs complements these prior assessments by considering flexibility needs associated with unanticipated hourly fluctuations following the day-ahead forecasts. These short-duration flexibility needs are caused by forecasting errors in load and generation, as well as the unplanned forced outages of generation and transmission assets.

This chapter focuses on the flexibility needs arising from these factors, while considering the market players' capacity to balance their positions and the TSO's reserve capacity. Limiting the analysis to reserve capacity alone would underestimate the actual flexibility needed, as markets play a significant role in post-day-ahead balancing.[4]

4 This is the case for countries operating in self-dispatch mode.

Quantifying Forecasting Errors

Forecast errors of wind, PV and load experienced in several ENTSO-E member states in 2021 serve as the baseline for this assessment and were extrapolated to future target years (2025, 2028, 2030, and 2033). This was achieved by using projections of installed renewable capacity and peak demand averaged from three climatic years (1995, 2008, 2009) with weighting factors assuming that forecast accuracy is improving by 1 % per year. These projections align with scenarios from ERAA and TYNDP.

Figure 11 (a) demonstrates that the statistical distribution of over- and under-estimations in the forecast are approximately evenly distributed across the countries considered.

Overall, wind power forecasts tend to have larger errors than PV power forecasts, regardless of geographical location. Additionally, load forecast errors vary across regions and exceed the forecast errors observed for renewable sources in some areas. Figure 11 (b) shows forecast errors for vRES increase over time, corresponding with the anticipated growth in installed wind and solar capacity in Spain in this period. Although the distribution of forecasting errors remains largely symmetric, more extreme outliers are observed in under-forecasts. By contrast, load forecast errors are expected to remain relatively stable due to limited load growth and gradual improvements in forecasting accuracy.

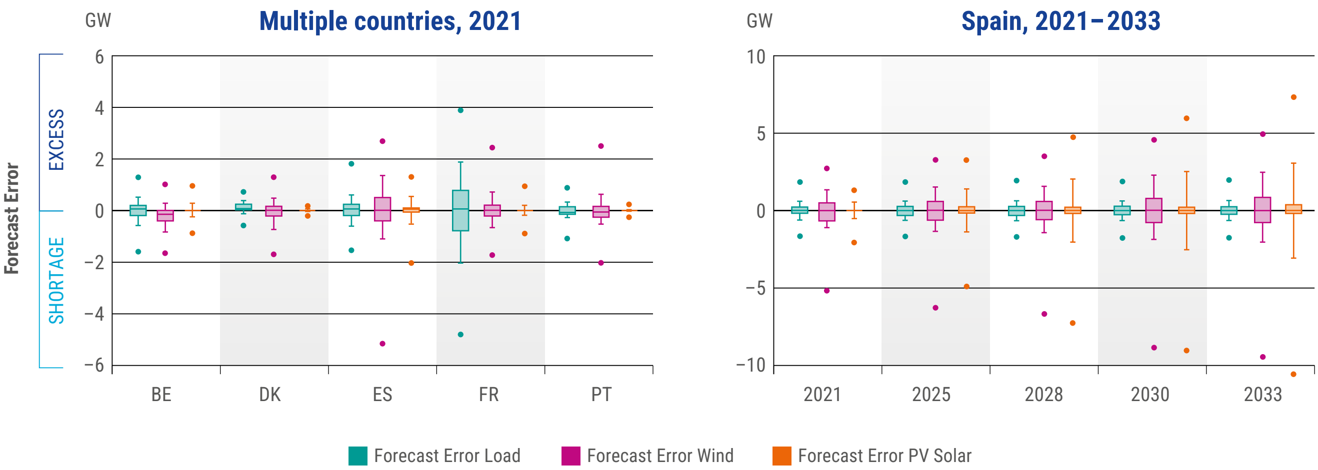
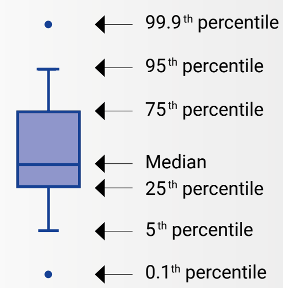


Figure 11: Distribution of intraday forecast errors (a) 2021 across multiple countries and (b) over the next ten years in Spain [5]



5 DK corresponds to DKW1, on- and offshore wind are aggregated.

Intraday Flexibility Needs in Isolated Member States

Each country's short-duration flexibility needs are determined by aggregating its forecast errors, assuming no interconnection with other countries. This reflects the total forecast uncertainty that must be managed within the country's own system. Additionally, the required capacity for intra-hourly adjustments is assessed, referred to as the country's ramping flexibility needs.

Figure 12 (a) shows that the resulting short-duration flexibility needs align with observed forecast errors. While forecast errors often offset each other across most countries, they can also accumulate, leading to extreme outliers and higher peak requirements. Figure 12 (b) further illustrates that both short-duration and ramping needs are projected to increase in absolute terms through 2030.

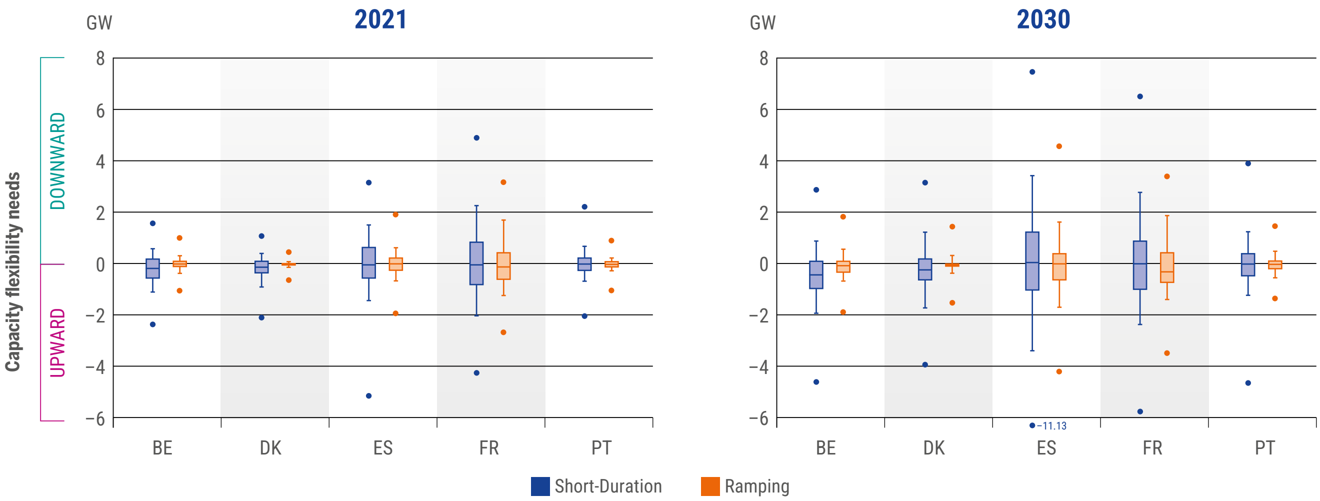


Figure 12: Short-duration flexibility needs across multiple countries in (a) 2021 and (b) 2030[5]

Absolute values alone do not account for installed vRES capacity and therefore neglect key dimensions of the analysis. By normalising short-duration and ramping needs relative to each country's installed vRES capacity, we obtain a metric that enables comparison across countries of varying sizes.[6]

Figure 13 (b) shows that relative short-duration downwards flexibility needs range from 8 to 27 percent of installed vRES capacity, with larger countries generally exhibiting lower needs per unit of renewable capacity installed. Downward ramping flexibility needs range between 5 % and 17 %.

Notably, France's downward flexibility need per unit of installed vRES is twice that of Spain's.

This observed trend of lower relative needs in larger countries can be attributed to their broader geographical distribution and more diverse asset mix, which allows for greater netting of forecast errors. The disparity between France and Spain can be explained by France's lower installed vRES capacity in 2021 (see Figure 13 (a)) and its significant influence of larger load forecast errors, as observed in Figures 11 and 12.

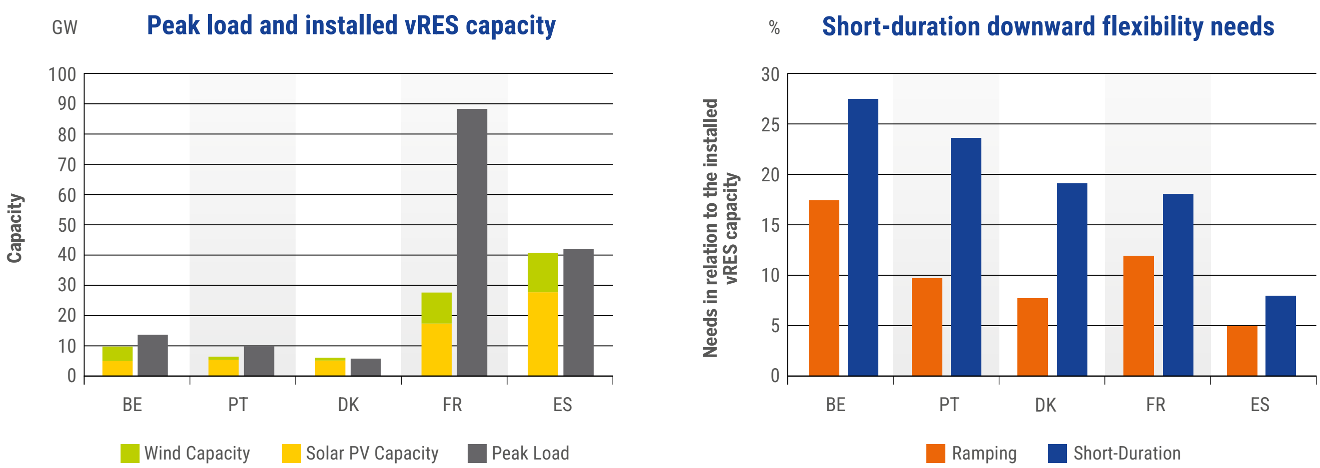


Figure 13: (a) Peak load and installed vRES capacity and
(b) short-duration downward flexibility needs expressed as a share of the total installed RES capacity in 2021[5]

6 Note that the short-duration and ramping needs used to calculate this metric are based on 0.1st and 99.9th percentile of the corresponding needs.

Intraday Flexibility Needs in an Interconnected System

Thus far, we have assessed the flexibility needs of individual countries in isolation. In the final step, we aggregate the flexibility needs of neighbouring countries to evaluate total system requirements. Without regional intraday or balancing markets, each country must independently meet its own flexibility needs. In the following section, we conduct an analysis of aggregated short-duration flexibility needs.

Figure 14 (a) illustrates that netting reduces absolute short-duration flexibility needs by approximately 50 %. In isolated systems, the downward short-duration need is projected to rise from 12 GW to 28 GW by 2030, while this need could be limited to 7 GW or 12 GW, respectively, in a theoretical interconnected system with unlimited transfer capacity. Similarly, net ramping flexibility requirements are halved, resulting in a projected downward ramping need of 6 GW by 2030.

Considering these projections in light of the anticipated growth in vRES capacity – as shown in Figure 14 (b) – the netted short-duration needs normalized by the installed vRES decreases from 8 % to 5 % by 2030, despite a significant rise in absolute short-duration needs. A similar trend is observed in netted downward ramping flexibility needs, which decline from 4 % to 2 % of total installed vRES capacity.

The absolute values reflect the growing strain on the electricity system from rising short-duration and ramping flexibility needs. However, the findings emphasise the crucial role of regional collaboration in reducing these flexibility requirements and strengthening system resilience.

Furthermore, when viewed in relation to the concurrent growth in total vRES capacity, short-duration and ramping flexibility needs decrease proportionally. This trend is likely driven by expanded installed capacity, a more diversified asset mix, and improvements in forecast accuracy, all of which collectively increase the potential for netting forecast errors.

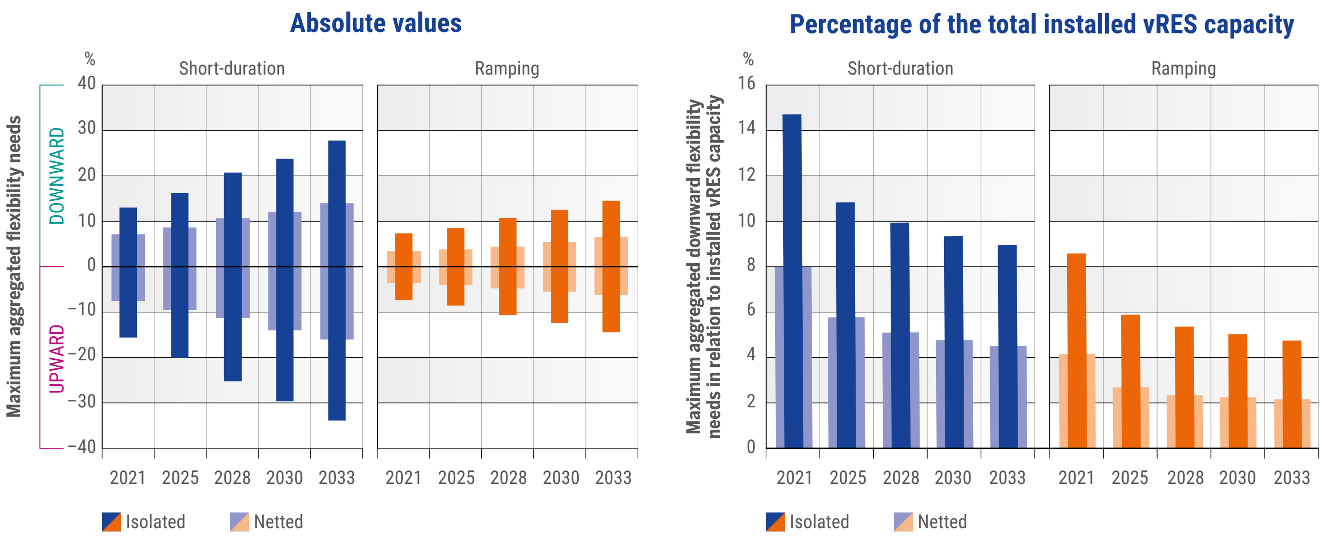


Figure 14: Aggregated European short-duration and ramping needs in (a) absolute values and (b) as a percentage of the total installed vRES capacity

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Review and Drafting team

Mario Sisinni .... Terna/Convenor TF Flexibility
Riccardo Mario .... Terna
Christoph Mistlbauer .... APG
Kristof De Vos .... Elia
Monika Topel .... Svenska kraftnät
Emily Little .... RTE
Nuno Fidalgo Martins .... REN
Jan Mervart .... ČEPS
Franck Dia Wagoum .... ENTSO-E
Ioannis Theologitis .... ENTSO-E
Samy Geronymos .... ENTSO-E
Shilpa Bindu .... ENTSO-E

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8 Rue de Spa | 1000 Brussels | Belgium
www.entsoe.eu | info@entsoe.eu

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