APPENDIX 1: METHODOLOGY

Overview

This flexibility needs estimation evaluates power system flexibility needs, at the global and regional levels, resulting from the variability of VRE generation and electricity demand. The assessment does not consider the flexibility that can be provided by conventional flexibility suppliers (existing or planned) such as dispatchable generators, pumped-hydro storage, interconnectors and others. Therefore, the estimates of flexibility needs from this analysis must be taken to represent a technical upper limit to the amount of flexibility required. The amount of additional flexibility required (which can be viewed as a potential flexibility gap) may be less than estimated from these assessments, as conventional flexibility suppliers can already cover some of the identified flexibility needs.

Methodology

The methodology used builds on the framework presented in (Koolen, De Felice and Busch, 2023), adapting it to data availability constraints while skipping economic dispatch analysis, intended to include flexibility from conventional suppliers in the calculations.

(Koolen, De Felice and Busch, 2023) define ‘FR^T’ as the yearly flexibility requirements with a granularity of time ‘T’ as:

$$FR^T = \sum_T \frac{1}{2} \sum_t \left| RL_t - \overline{RL_t} \right|$$

Where ‘RL_t’ represents the residual/net load at time step‘t’, and ‘$\overline{RL_t}$’ the average residual/net load over all time steps ‘t’ within ‘T’.

The assessment is made for three timescales: daily, weekly and monthly. Each flexibility type has a distinct solution or a set of solutions. For example, batteries are typically best suited to provide flexibility on a daily, hourly or sub-hourly timescale, whereas hydro storage is more effective at providing flexibility over a monthly timescale. Without identifying optimal combinations of flexibility solutions, which are highly system-dependent, the methodology aims to determine the flexibility requirements in these three different timescales following a technology-neutral approach.

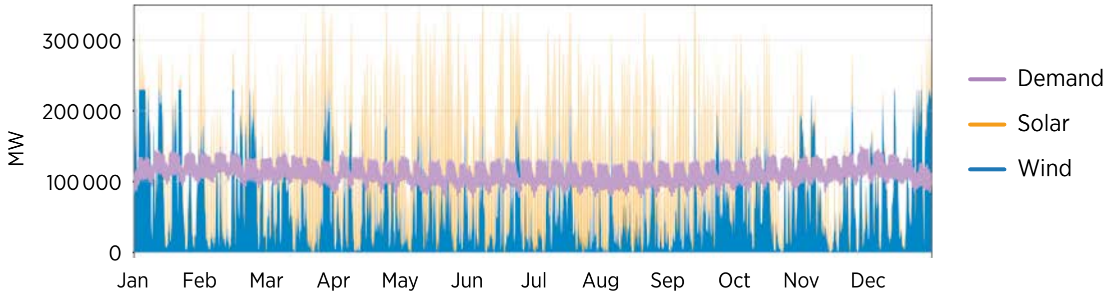
The methodology estimates the flexibility needs in the power system considering the variability of generation and demand. The methodology considers generation only from the variable renewable energy (VRE) sources of wind and solar, in accordance with their projected installed capacities in IRENA global and regional analyses. After evaluation of baseline flexibility needs, clean flexibility solutions such as battery storage, interconnections, LDES and DSM are considered individually, to estimate their potential to reduce flexibility needs. Future IRENA work will explore the potential and role of each of the flexibility solutions in more detail. This constitutes the primary analysis where baseline flexibility needs and reduced flexibility needs including solutions are estimated, measured in TWh. Secondary analysis providing additional insights on capacity flexibility measured in GW, and a further two types of system flexibility needs (ramping and short-term), are presented in Appendix 2.

An illustrative example of calculations

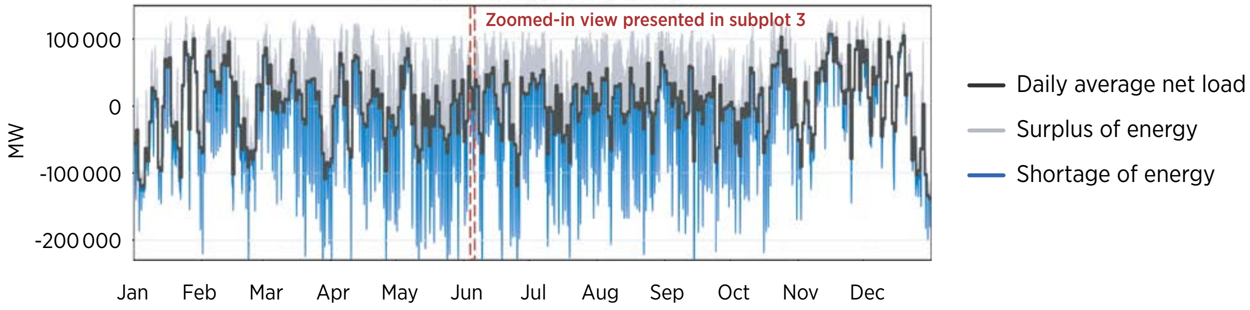
Primary inputs to the calculations are hourly time series data for electricity demand and solar PV and wind generation, as shown in Figure A1, for a sample country in a specific scenario and study year. The net load is computed as the difference between demand and the combined output from solar and wind generation. Daily average net load values are then compared with hourly net load values, allowing the quantification of surplus and shortages in energy. Subplot 2 illustrates the hourly net load alongside its daily average, with surplus periods shaded in grey (above the average) and shortages in blue (below the average). Subplot 3 provides a zoomed-in two-day segment. It is important to note that the daily average is different for each day, and energy shortage and surplus are calculated around them to estimate flexibility needs.

Figure A1 Illustration of flexibility needs methodology

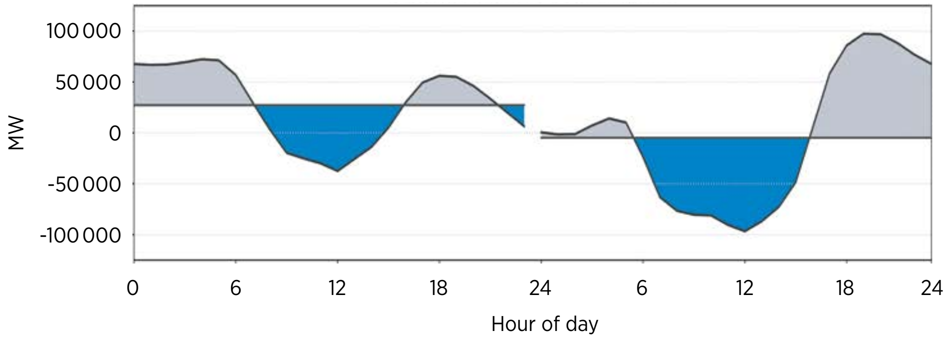
1. HOURLY PROFILES



2. NET LOAD – HOURLY AND DAILY AVERAGE



3. ZOOMED-IN VIEW FROM SUBPLOT 2



Total daily flexibility need is half of the sum of blue and grey areas

Note: This is a sample plot to illustrate the calculation of daily flexibility needs; the same methodology, aligned with respective timescales, is applied to calculate weekly and monthly flexibility.

Scenarios

Flexibility needs are assessed for the following two scenarios:

- **IRENA 1.5°C Scenario:** The 1.5°C Scenario describes an energy transition pathway aligned with the 1.5°C climate goal to limit global average temperature increase by the end of the present century to 1.5°C, relative to pre-industrial levels. It priorities readily available technology solutions, which can be scaled up to meet the 1.5°C goal (IRENA, 2024a).
- **IRENA Planned Energy Scenario:** The Planned Energy Scenario is the primary reference case for IRENA's *World energy transition outlook*. It provides a perspective on energy system developments based on governments' energy plans and other planned targets and policies in place at the time of analysis, with a focus on G20 countries' goals (IRENA, 2024a).

Demand

Hourly electricity demand profiles are obtained from datasets used in IRENA's regional and global analyses. These profiles are generated using IRENA's methodology that reflects projected increases in electrification and the integration of new, complex load patterns expected in the future. It is important to note that the profiles do not consider demand-side flexibility for baseline flexibility needs estimation.

Supply

Hourly capacity factor profiles for solar and wind, as well as their respective projected installed capacity, were obtained from IRENA's regional and global analyses. The profiles were scaled to their projected installed capacity for each future study year to generate total VRE generation profiles. The profiles do not account for potential future changes in weather patterns due to climate change.

Flexibility needs calculation

Demand and supply data were then compared at an hourly level to assess periods of VRE generation surplus and shortage relative to demand. Based on this comparison, flexibility is calculated as half of the sum of the cumulative difference between the net load time series and the average net load over a specified period of a day, week or month. The timescale of the flexibility assessment determines the resolution of the net load time series and the net load average used in the calculation. Daily flexibility is calculated by comparing hourly net load values to the daily average; weekly flexibility uses daily values compared to the weekly average; and monthly flexibility compares weekly net load data to the monthly average.

Sensitivity analysis

Sensitivity analysis was conducted to determine the indicative potential of each flexibility solution to reduce flexibility requirements. One key limitation in this analysis is that each clean flexibility solution, such as interconnectors, demand-side management (DSM), battery storage and long-duration energy storage (LDES), is assessed individually rather than in combination. This approach does not capture the potential interplay among these solutions, which is essential to identify an optimal mix to reduce flexibility needs in a power system. Hence the actual contribution of each solution, which is also highly dependent on system characteristics, may differ significantly from the estimates presented in this report. Further details are presented as follows:

A. Interconnectors

Based on spatial and grid connectivity, a region is divided into a number of subregions. Power transfer capacities between subregions, specific to each scenario and studied year, are sourced from IRENA regional and global analyses. These capacities enable the transfer of surplus generation from one region to another facing a deficit. By applying these transfer constraints, regional net loads are rebalanced, based on which modified (or reduced) flexibility needs are calculated. The difference between baseline flexibility needs and modified flexibility needs with interconnectors provides the indicative potential of interconnectors to reduce system flexibility needs.

To analyse different levels of interconnections, four hypothetical cases of varying levels of regional interconnectivity are considered:

a. non-interconnected: no interconnections between countries;
b. fully interconnected: copper plate configuration with all countries fully interconnected with each other;
c. subregions interconnected separately: a number of subregions modelled as copper plates but non-interconnected with each other; and
d. subregions interconnected separately plus intra subregional flows: option c. plus interconnectors between subregions.

Table A1 Projected net transfer capacities in Africa in MW

REGION 1	REGION 2	YEAR 2020s	2030	2040	2050
East	**Central**	335	2 023	9 317	12 825
West	**North**	-	516	516	1 392
Central	**South**	230	1 435	6 121	8 224
Central	**West**	-	-	790	8 215
East	**North**	913	2 200	7 010	29 133
East	**South**	300	1 049	1 226	12 345

Source: Forthcoming IRENA regional analysis for Africa .
Note: MW = megawatt.

B. DSM

This is modelled by shifting a fixed percentage (10%) of electricity demand from evening peak hours to midday hours, aligning with solar generation. The difference between baseline flexibility needs and modified flexibility needs with DSM provides the indicative potential of DSM to reduce system flexibility needs.

C. Battery storage

Battery MW capacity is approximated on a fixed percentage (15%) of each country's peak load and then, using a predefined assumption on storage hours (four hours), battery storage capacity is determined.

Using computationally intensive capacity optimisation models to determine more accurate battery storage capacity is beyond the scope of this analysis. Based on determined battery size, battery dispatch optimisation is performed independently for each country using hourly net load profiles. The optimisation minimises net load variability by controlling battery charging and discharging, while respecting key operational constraints such as charge/discharge limits, state-of-charge boundaries and round-trip efficiency. The resulting smoothed net load profiles, reflecting the effect of battery integration, are then used to recalculate modified (or reduced) flexibility needs. The difference between baseline flexibility needs and modified flexibility needs with battery provides the indicative potential of battery storage to reduce system flexibility needs.

D. LDES

LDES energy capacity is approximated on a fixed percentage of each country's annual energy demand (1.5%) and then LDES MW capacity is determined using predefined assumption on storage hours (36 hours). LDES dispatch optimisation is performed independently for each country using hourly net load profiles. The optimisation prioritises the reduction of prolonged energy deficits over minimising net load variability, targeting multi-hour or multi-day shortages, better representing seasonal or week-scale storage systems. Operational technology features such as lower round-trip efficiency are also included. The modified net load profiles, reflecting the effect of LDES integration, are then used to recalculate flexibility needs. The difference between baseline flexibility needs and modified flexibility needs with LDES provides the indicative potential of LDES to reduce system flexibility needs.

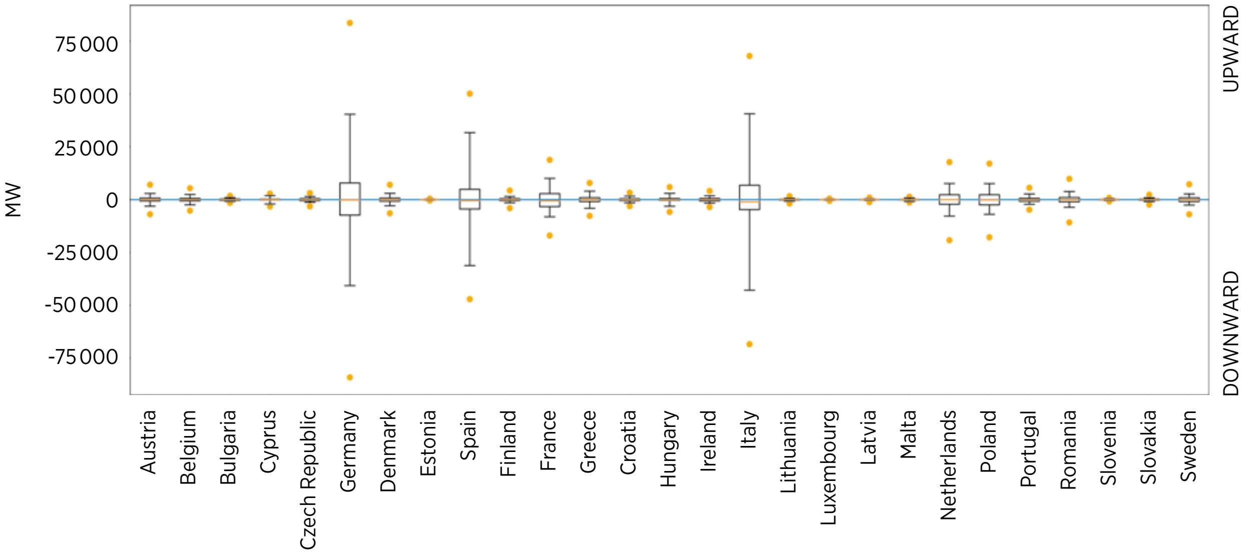
APPENDIX 2: ADDITIONAL INSIGHTS

RAMPING NEEDS, SHORT-TERM FLEXIBILITY (FORECAST ERRORS) NEEDS AND CAPACITY FLEXIBILITY NEEDS

Ramping needs

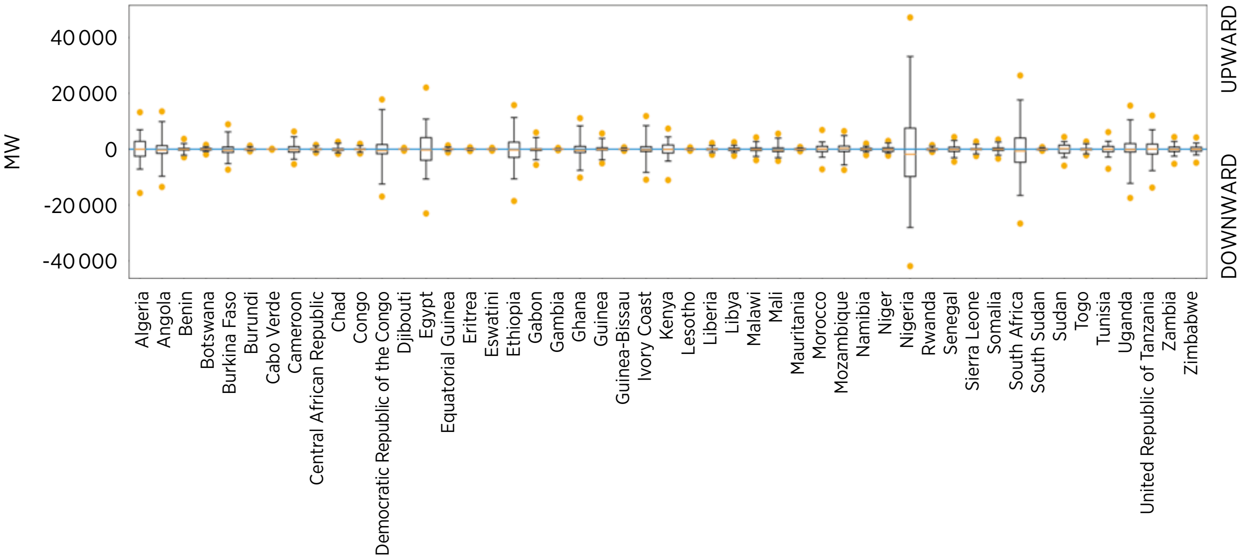
Upward and downward ramping needs are computed based on net load profiles in consecutive time steps. Ramping flexibility needs for the EU-27 and Africa are shown in Figure A2 and Figure A3.

Figure A2 Estimated ramping flexibility needs in 2050 for IRENA 1.5°C Scenario for the EU-27



Notes: Boxes indicate the interquartile range (P25–P75), capturing the central 50% of ramp magnitudes. Whiskers extend to the 5th and 95th percentiles (P5–P95), showing the main spread of upward and downward ramping events. Orange dots mark the 0.1st and 99.9th percentiles (P0.1 and P99.9), highlighting extreme ramping events that occur infrequently, but are critical for ramping flexibility requirements.

Figure A3 Estimated ramping flexibility needs in 2050 for sample decarbonisation case in Africa

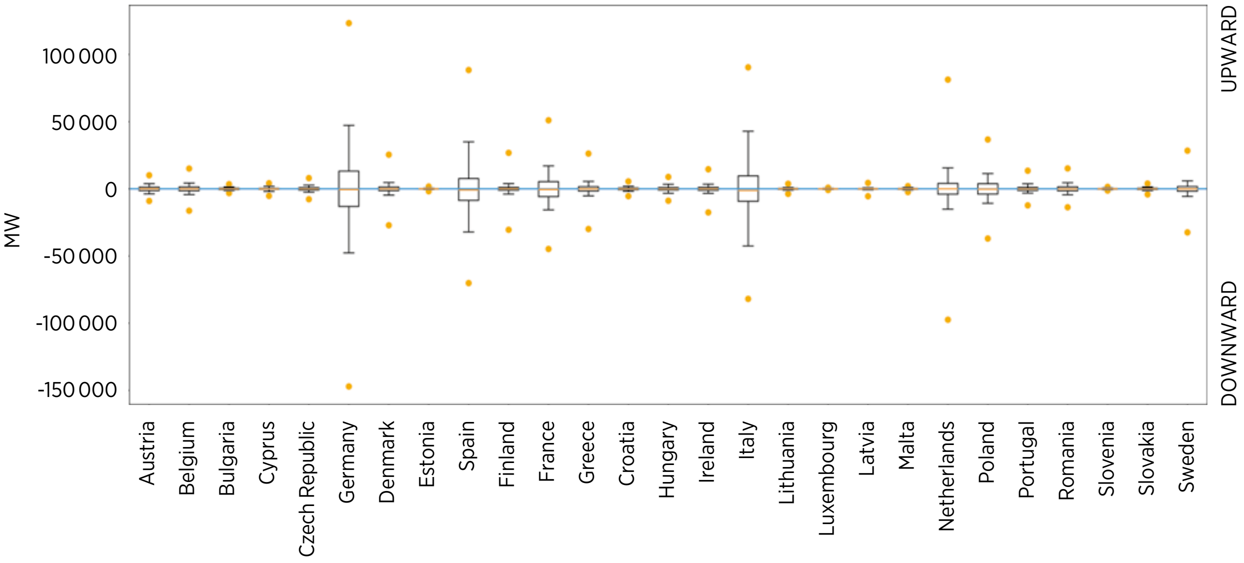


Notes: Boxes indicate the interquartile range (P25–P75), capturing the central 50% of ramp magnitudes. Whiskers extend to the 5th and 95th percentiles (P5–P95), showing the main spread of upward and downward ramping events. Orange dots mark the 0.1st and 99.9th percentiles (P0.1 and P99.9), highlighting extreme ramping events that occur infrequently, but are critical for ramping flexibility requirements.

Short-term flexibility (forecast errors) needs

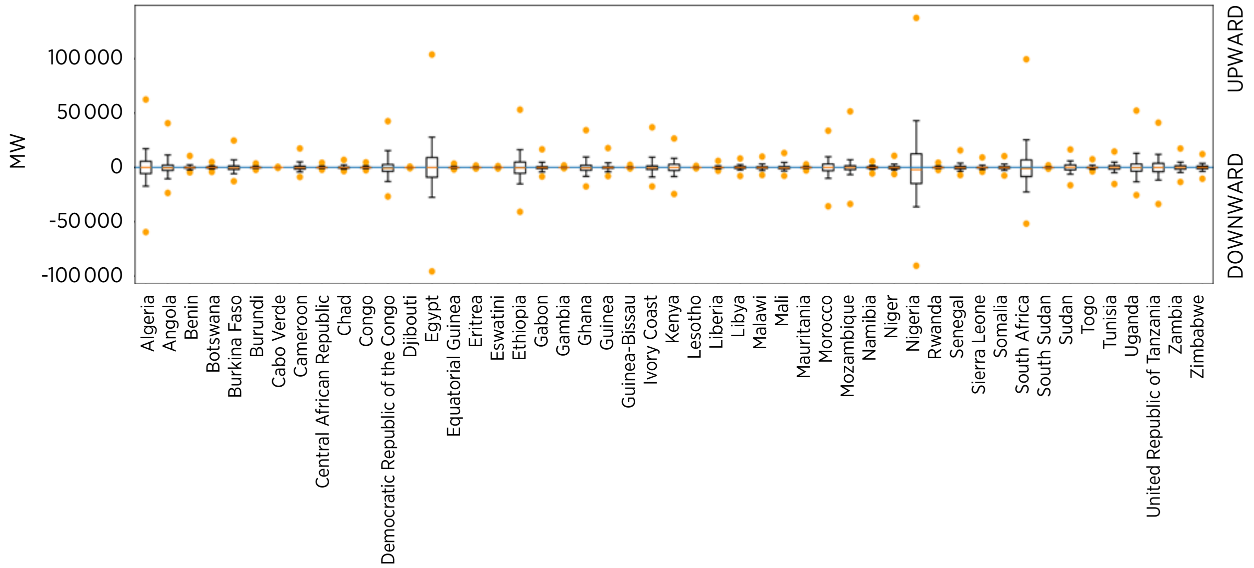
A sample historical time-series of system-level forecast errors was obtained for the Germany 50 Hertz system and was utilised to introduce forecast errors in hourly profiles of solar, wind and demand (50hertz.com). Each of the forecast errors for solar, wind and load have distinct patterns. Modified net load profiles generated utilising these forecast errors are used to determine short-term flexibility needs. Short-term flexibility needs for the EU-27 and Africa are shown in Figures A4 and A5.

Figure A4 Estimated short-term flexibility needs in 2050 for IRENA 1.5°C Scenario for EU-27



Notes: Boxes indicate the interquartile range (P25–P75), capturing the central 50% of ramp magnitudes. Whiskers extend to the 5th and 95th percentiles (P5–P95), showing the main spread of upward and downward ramping events. Orange dots mark the 0.1st and 99.9th percentiles (P0.1 and P99.9), highlighting extreme ramping events that occur infrequently, but are critical for short-term flexibility requirements.

Figure A5 Estimated ramping flexibility needs in 2050 for sample decarbonisation case in Africa

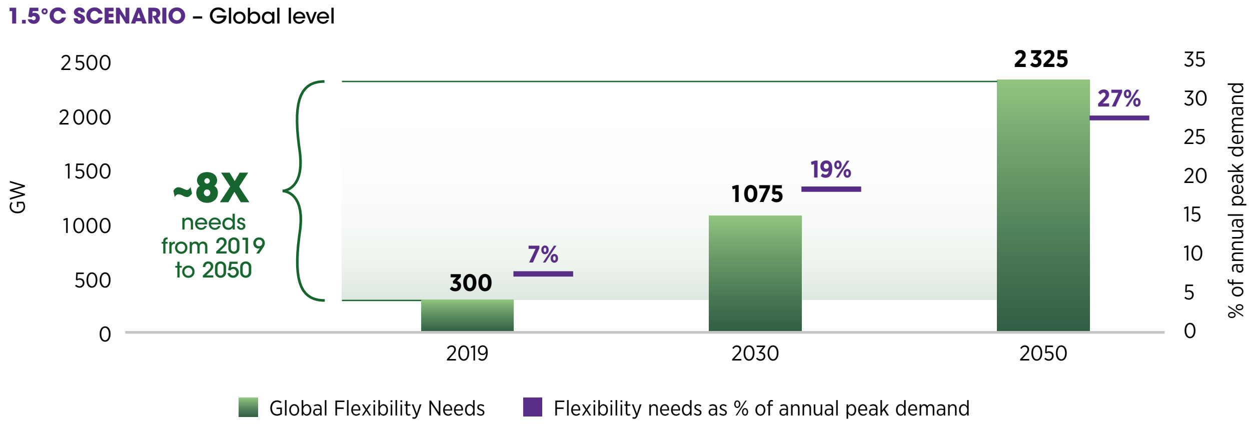


Notes: Boxes indicate the interquartile range (P25–P75), capturing the central 50% of ramp magnitudes. Whiskers extend to the 5th and 95th percentiles (P5–P95), showing the main spread of upward and downward ramping events. Orange dots mark the 0.1st and 99.9th percentiles (P0.1 and P99.9), highlighting extreme ramping events that occur infrequently, but are critical for short-term flexibility requirements.

Capacity flexibility needs

The same methodology as explained in Appendix 1 was used to determine system flexibility needs in terms of capacity measured in GW. Instead of calculating area under hourly net load curves (as was the case for calculating energy flexibility), capacity flexibility is the maximum value of difference between hourly net load and its average. Capacity flexibility needs at a global level for the 1.5° C scenario are shown in Figure A6.

Figure A6 Estimated capacity flexibility needs in 2050 for IRENA 1.5°C Scenario at global level



Notes: The height of the bars indicates flexibility requirements in GW, scaled according to primary y axis (left); Purple horizontal markers show flexibility needs as a percentage of annual peak demand, scaled according to secondary y axis (right).