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Zonal Flexibility Assessment of High-Renewable Power Systems: A KPI-Based Study of the SE3 Bidding Zone in Sweden

Chenyu Su[1], Yixing Du[1], Anders Avelin[1], Maher Azaza[1], Hailong Li[1*]

[1] School of Business, Society and Technology, Mälardalens University, 72123 Västerås, Sweden

[*]E-mail: hailong.li@mdu.se

Abstract. High renewable energy penetration increases system flexibility requirements, making zone-level assessment essential for long-term system planning. Many previous studies relied on single-metric approaches, capturing only specific aspects of flexibility. More recent work introduced multiple indicators but still assumed fixed reserve margins that fail to reflect the actual flexibility requirements. This study assesses flexibility using four key performance indicators (KPIs): (1) Net Load Ramp Requirement (NLRR), the maximum generation adjustment rate needed to balance net load changes; (2) Insufficient Ramping Resource Expectation (IRRE), the probability that ramping demand exceeds available capacity; (3) Flexibility Reserve Margin (FRM), excess flexible capacity beyond worst-case renewable variability; and (4) Interconnection Flexibility Index (IFI), the extent to which renewable fluctuations can be balanced through interconnection-based cross-border exchanges. The assessment is applied to evaluate the flexibility status for one of the bidding zones of Sweden, SE3, using hourly data of 2024. Results indicated high flexibility adequacy, with limited ramping shortages and strong interconnection support. For example, the maximum NLRR reached 340 MW/h in winter, indicating significant upward flexibility demand. IRRE was 0.03% or 3 hours/year, implying ramp-scarcity occurs infrequently. The minimum FRM was 287%, showing that SE3 had strong flexibility support, mainly from interconnections (78%) and hydropower, and IFI reached 501% for upward ramping (import increases) and 424% for downward ramping (import decreases), indicating strong inter-zonal buffering. These KPIs-based results suggest that SE3 maintained high operational flexibility in 2024, mainly supported by cross-border interconnections, providing a basis for future flexibility risk assessment under extreme conditions.

1. Introduction

The rapid growth of variable renewable energy (VRE) sources, such as wind and solar, is transforming modern electricity systems worldwide. While VRE plays a key role in decarbonization, its variability and uncertainty pose challenges for real-time balancing of supply and demand. To address these challenges, the concept of system flexibility, defined as the ability of a power system to respond to changes in demand and supply, has become increasingly important (Salman et al., 2021).

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Several early studies on system flexibility focused on single indicators designed to capture specific aspects of flexibility. Initial flexibility metrics focused on capacity-based measures, such as the Net Load Ramp Requirement (NLRR). Lannoye et al. (Lannoye et al., 2012) advanced the field by introducing the Insufficient Ramping Resource Expectation (IRRE), a probabilistic measure of ramping shortages. In order to consider different factors of system flexibility, such as adequacy and ramping, various indicators should be used (Heggarty et al., 2020). However, most studies relied on assumed reserve levels or predefined scenarios rather than actual operational data, which may not reflect real system operations. For example, Li et al. (Li et al., 2024) used probabilistic indicators but their approach remains scenario-based without considering market-procured reserves.

This study addresses this gap by assessing the flexibility status for one of the bidding zones of Sweden, SE3, using data from 2024. It applies four indicators: NLRR, IRRE, Flexibility Reserve Margin (FRM), and Interconnection Flexibility Index (IFI), and incorporates actual reserve capacities from Sweden's balancing markets and provides an operational baseline to inform planning.

2. Methodology

2.1 Data Sources and Processing

This study focuses on the SE3 bidding zone and uses hourly data for 2024 obtained from ENTSO-E Transparency Platform. The dataset includes hourly electricity demand, wind, solar, and hydro generation as well as cross-border power flows with adjacent zones (SE2, SE4, DK1, NO1, and FI) (OPERATORS, 2019), and actual reserve procurement data from Svenska kraftnät, including hourly volumes of Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR). This market-based approach reflects real operational decisions rather than assumed reserve settings, thereby enabling a more realistic assessment of system flexibility.

2.2 Flexibility Metrics

This study applies four complementary KPIs, each reflecting a key aspect of system flexibility: ramping needs, adequacy risk, operational margin, and interconnection support.

(1) Net Load Ramp Requirement (NLRR)

NLRR reflects ramping stress from net load variability. It quantifies the maximum hour-to-hour ramping stress induced by VRE variability. The functions are formulated as shown in Eq. (1)-(3):

$$NetLoad(t) = Demand(t) - VRE(t) \quad (1)$$

$$NLRR_{up} = \mathrm{M}ax_t\{NetLoad(t) - NetLoad(t-1)\} \quad (2)$$

$$NLRR_{down} = Max_t\{NetLoad(t-1) - NetLoad(t)\} \quad (3)$$

where $NetLoad(t)$ and $NetLoad(t-1)$ represent the net load at time t and the previous hour, respectively; $Demand(t)$ is the total electricity demand at time t; $VRE(t)$ is the combined wind and solar generation at time t; and $NLRR_{up}$ and $NLRR_{down}$ represent the required upward and downward ramping capability.

(2) Insufficient Ramping Resource Expectation (IRRE)

IRRE quantifies reliability risks from limited ramping capacity. It assesses the frequency of ramping inadequacy, defined as the proportion of time when ramping needs exceed available capacity:

$$IRRE = \frac{\mathrm{N}(\Delta NetLoad(t) > R_{available})}{N_{total}} \times 100\% \quad (4)$$

where $N(\Delta NetLoad(t) > R_{available})$ is the number of intervals where the net load change exceeds the available ramp capacity, N_{total} is the total number of time intervals, and $R_{available}$ is the total available ramping capacity comprising procured reserves (FCR and aFRR), hydropower ramping capability, and interconnection capacity.

(3) Flexibility Reserve Margin (FRM)

FRM measures operational headroom in the system. It quantifies the relative buffer between available and required flexibility:

$$FRM = \frac{F_{avail} - F_{req}}{F_{req}} \times 100\% \quad (5)$$

where F_{avail} is the total available flexible capacity comprising reserves, hydropower ramping capability, and interconnection capacity at each hour, and F_{req} represents the maximum absolute hourly VRE variability observed.

(4) Interconnection Flexibility Index (IFI)

IFI highlights inter-regional support and the role of cross-border exchanges. It measures the contribution of cross-border interconnectors to system flexibility by comparing import/export changes against VRE fluctuations:

$$IFI_{up} = \frac{Max_{t\epsilon T}[Import(t) - Import(t-1)]}{Max_{t\epsilon T}|\Delta VRE(t)|} \times 100\% \quad (6)$$

$$IFI_{down} = \frac{|Min_{t\epsilon T}[Import(t) - Import(t-1)]|}{Max_{t\epsilon T}|\Delta VRE(t)|} \times 100\% \quad (7)$$

where $Import(t)$ is the net import at time t, $\Delta VRE(t)$ is the change in VRE generation at time t, and T is the set of evaluated time intervals.

3. Results

3.1 Net Load Ramp Requirement (NLRR)

The SE3 net load ramps range from -1,500 to +1,500 MW/h, with an approximately normal distribution but a slight rightward skew (Figure 1a). Although downward ramps occur more often, upward ramps show higher average values (278 vs 229 MW/h) and larger peak levels (1,489 vs 1,420 MW/h). This means SE3 needs more upward flexibility to manage these ramping events.

Monthly analysis (Figure 1b) reveals pronounced seasonal patterns. Winter exhibits the highest ramping needs: 343 MW/h upward in February and 265 MW/h downward in January, while summer values drop to 208 MW/h upward and 173 MW/h downward in July. Winter shows higher ramping needs than summer in both upward and downward directions. These differences are primarily due to increased heating demand with reduced solar generation from shorter daylight hours. These seasonal differences highlight the importance of planning for winter peak flexibility requirements. Overall, SE3 faces flexibility problems during upward ramping, especially in winter.

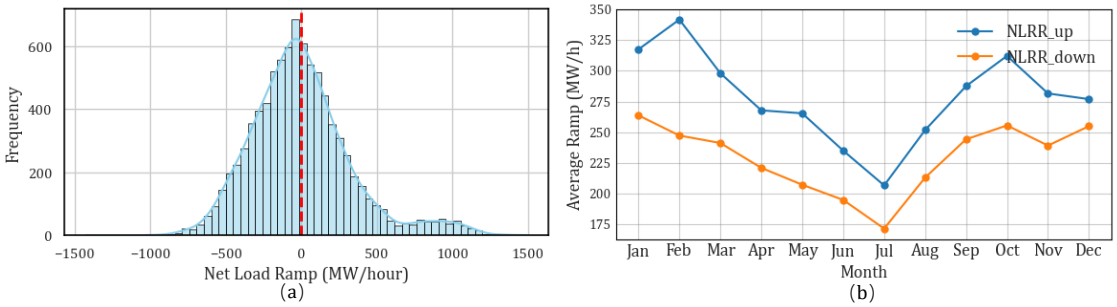

Figure 1. Net Load Ramp Requirement Distribution (a) and Seasonal Patterns in SE3 (b).

3.2 *Insufficient Ramping Resource Expectation (IRRE)*

The available ramping capacity in SE3 during 2024 ranged from -1500 MW to +2000 MW, while most ramping needs stayed within ±500 MW. This ramping capacity came from hydropower and cross-border imports. In the 2023 adequacy assessment for Sweden, the model assumed no ramping shortages (i.e., IRRE = 0) and projected a Loss of Load Expectation (LOLE) was 1.16 hours per year (Energimarknadsinspektionen, 2025), which already exceeded the national reliability target of 1 hour per year set by the government in 2022 (kraftnät, 2023). Our analysis based on 2024 operational data found that IRRE was 0.03%. This means there were 3 hours out of 8,784 during which available ramping capacity was insufficient to meet net load changes. These shortages happened during one upward ramping event in July and two downward events in May and August (Figure 2).

These results show that ramping shortages did occur, even though they were not captured in the earlier model. Ignoring ramping problems can lead to underestimating the real LOLE. This is important in systems like SE3, where local flexibility is limited and renewable penetration is high. Therefore, short-term ramping constraints should be considered in future adequacy studies to better reflect the real reliability of the system.

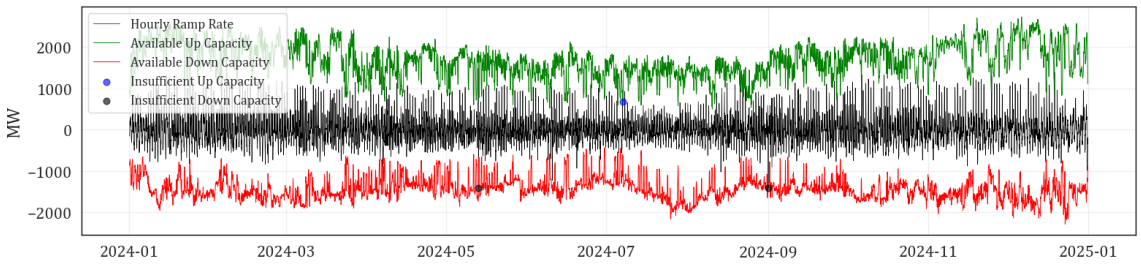

Figure 2. Available Capacity and Ramping Requirements Analysis

3.3 Flexibility Reserve Margin (FRM)

FRM ranged from 287% to 3847%, with seasonal averages of 2341% in winter and 1756% in summer. The minimum value (287%) indicates that even during the most constrained hour, available flexibility capacity exceeded worst-case VRE variability by 2.87 times. The flexible capacity comprised interconnections (78%), hydropower (16%), automatic frequency restoration reserves (4%), and frequency containment reserves (2%). Interconnection dependency increased seasonally, from 72% in summer to 84% in winter, compensating for higher winter ramping demand and reduced hydropower availability. Despite higher winter demand, FRM remained robust due to increased cross-border support.

3.4 Interconnection Flexibility Index (IFI)

IFI results show that interconnection ramping capability reached 501% upward and 424% downward, exceeding maximum VRE variability by four to five times. SE3 utilized all five neighbouring connections, with SE2 (35%) and NO1 (28%) dominating cross-border flexibility, while DK1, SE4, and FI contributed 16%, 12%, and 9% respectively. The dominance of SE2 and NO1 reflects their larger transmission capacities and strategic geographic positions connecting SE3 to both Swedish and Norwegian hydropower systems. The upward-downward asymmetry reflects SE3's net import position, with greater capacity to increase imports than to reduce them. These results confirm that interconnection capacity currently exceeds operational needs.

3.5 System Performance Integration

The four-indicator analysis confirms that SE3 achieves high flexibility adequacy through regional integration rather than local capacity. With only 10% of flexibility from local sources, the system maintains 99.97% adequacy by systematically relying on cross-border resources, which scale from 72% in summer to 84% in winter to meet seasonal demand variations. However, these results present two risks. First, flexibility is concentrated in two connections, SE2 (35%) and NO1 (28%), making the system vulnerable to simultaneous disruptions. Second, local capacity remains at marginal levels, raising concerns about resilience if neighbouring systems face concurrent stress. While current margins are substantial (FRM averaging 2034%), they assume continued cross-border availability, highlighting the importance of enhancing local flexibility in future system planning.

4 Conclusion

This study applies four indicators to assess power system flexibility under high renewable penetration. Applied to one of the bidding zones of Sweden, SE3, using 2024 operational data, the analysis demonstrates that SE3 maintained high flexibility adequacy through effective cross-border coordination and market-based reserve procurement. However, the observed adequacy primarily reflects cross-border flexibility rather than local flexibility resources, particularly SE2 and NO1. While this interconnection-based approach achieves high adequacy under normal conditions, it raises concerns about resilience when neighbouring systems face concurrent stress. The seasonal variation in interconnection dependency further indicates that flexibility planning must adapt dynamically rather than rely on static capacity targets. This study is limited to one year of operational data, which does not capture extreme weather events. Future research should investigate how climate variations affect the flexibility requirements of SE3 and how emerging technologies such as battery storage and demand response can enhance system resilience.

Acknowledgements

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