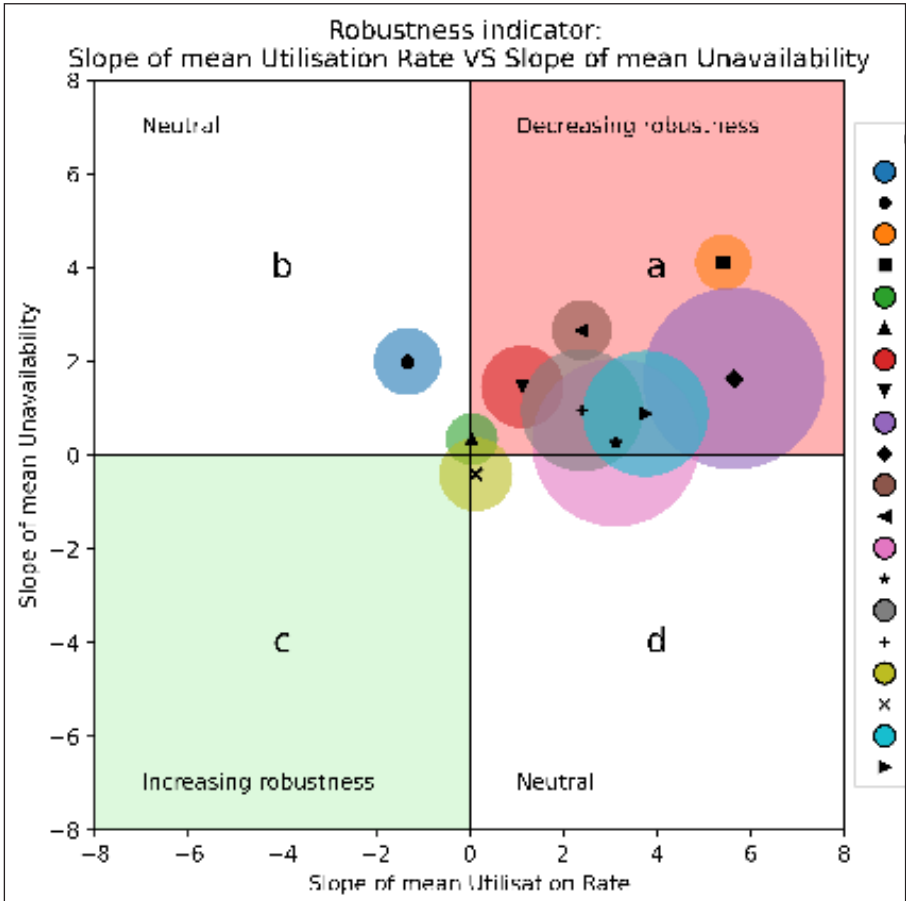
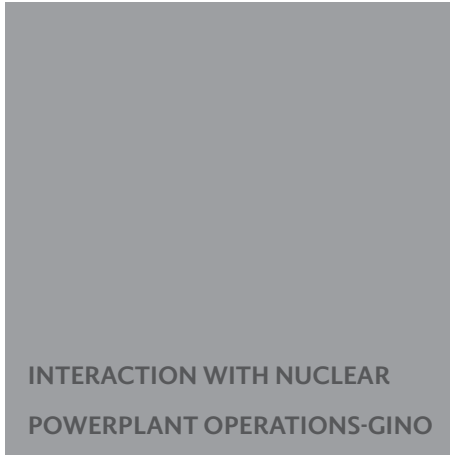
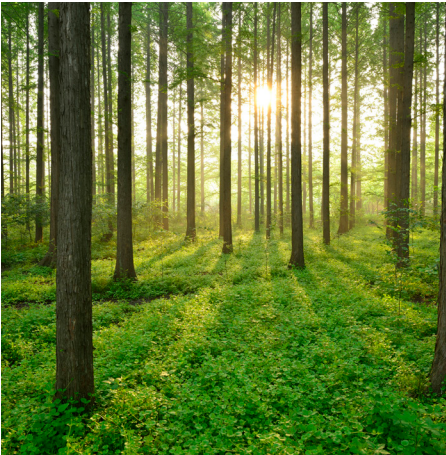


ROBUSTNESS INDICATORS FOR POWER SYSTEMS

REPORT 2024:1062



Robustness indicators for power systems

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Foreword

This report forms the results of a project performed within the Energiforsk Grid Interaction with Nuclear power plant Operations Program. The Energiforsk Grid Interaction with Nuclear power plant Operations (GINO) Program aims to increase the knowledge of aspects of the interactions between the external grid and the Nordic nuclear power plants.

The Nordic power system is undergoing significant transformations driven by the global energy transition toward renewable energy sources. This also brings changes in what can be called the system robustness - the system's ability to withstand an unexpected event without degradation in performance.

The purpose of this study was to investigate the possibility to develop relevant robustness indicators based on public data, with the aim to provide an improved view of the evolution of grid performance over time.

The results showed that by focusing on three impact factors; frequency, inertia, and transfer corridors, a limited yet useful set of robustness indicators could be developed and analyzed. The trends identified suggest the need for proactive measures to mitigate emerging risks, but also open up to further work on the indicators themselves.

The study was carried out by Emil Hillberg, Tommie Lindquist, Gustaf Bengtsson and Erik Weihs from RISE Research Institutes of Sweden. The study was performed within the Energiforsk GINO Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, Strålsäkerhetsmyndigheten and Svenska Kraftnät.

These are the results and conclusions of a project, which is part of a research Program run by Energiforsk. The author/authors are responsible for the content.

Summary

The Nordic power system is undergoing significant transformations driven by the global energy transition toward renewable energy sources and market integration in Europe. This report presents a comprehensive analysis of the power system's robustness by focusing on three impact factors: frequency, inertia, and transfer corridors. The methodology used in this report is based on assessment of public data, using measurements and statistics to address the trends in robustness.

In the evolving landscape of the Nordic grid, the system's ability to maintain frequency stability is a vital indicator of robustness. Low-inertia (kinetic energy) scenarios make the system more vulnerable to disturbances that imply rapid frequency fluctuations, which can challenge operators in maintaining a safe operational balance. As the system's inertia profile continues to evolve, particularly with the reduction in conventional generation, there is a clear need for enhanced real-time monitoring and the deployment of additional reserves to manage frequency extremes effectively. Through predictive modelling, this report highlights how frequency extremes can be anticipated using a linear regression model that links power imbalances and kinetic energy.

The report also delves into the critical role that inertia plays in stabilizing the power system, particularly during significant disruptions. By addressing robustness in the form of correlation between inertia and various operational factors—such as power generation by source, actual load, and cross-border flows—the findings reveal that certain renewable energy sources, such as wind power, have a notable reduction on the system inertia. This introduces fast fluctuations in the system that can strain the grid's stability. On the other hand, nuclear power, while still contributing to increased system inertia, has seen a diminishing role in recent years. The study also uncovers a growing correlation between day-ahead spot prices and inertia, emphasizing the importance of ensuring that price signals reflect operational realities, especially during periods when inertia is low.

Another critical aspect of grid robustness relates to the ability to efficiently transfer power between regions, particularly during periods of high demand. The report introduces new highly interesting indicator in the form of transfer corridor unavailability vs transfer corridor utilization rate. This robustness indicator provides insights into how well the grid can handle power transfers under different conditions. A concerning trend has emerged where the utilization of major transfer corridors has increased, but so has also their unavailability due to operational constraints or maintenance. This dual trend is problematic, as it reduces the grid's capacity to respond to demand during peak periods, thereby decreasing the system's overall robustness.

The findings of this report point to the increasing pressure the Nordic power system faces as it adapts to higher levels of renewable energy integration and rising electricity demand.

Keywords

Robustness, Frequency, Inertia, Transfer Corridors, Availability, Utilisation

Robusthet, Frekvens, Tröghet, Snitt, Tillgänglighet, Utnyttjande

Sammanfattning

Det nordiska kraftsystemet genomgår betydande förändring vilken drivs av en global energiomställning och en marknadsintegration i Europa. Denna rapport syftar till att ge en omfattande analys av kraftsystemets robusthet genom att fokusera på tre påverkansfaktorer: frekvens, tröghet och överföringskorridorer. Metodiken som använts i detta arbete baseras på studier av offentliga data, där mätdata och statistisk information nyttjats för att utvärdera trender i robusthet.

Elsystemets förmåga att upprätthålla frekvensstabilitet är en viktig indikator på robusthet. Scenarier med låg tröghet (kinetisk energi) gör systemet mer sårbart för störningar som innebär snabba frekvensfluktuationer, vilket kan påverka operatörers möjlighet att upprätthålla en säker drift. Eftersom systemets tröghet påverkas av utvecklingen, särskilt av minskad synkront kopplad produktion, finns ett tydligt behov av förbättrad realtidsövervakning och av ytterligare reserver för att effektivt hantera extrema frekvenser. Genom prediktiv modellering belyser denna rapport hur frekvensextremer kan förutses med hjälp av en linjär regressionsmodell som kopplar samman obalans i effekt med kinetisk energi.

Rapporten beskriver även en fördjupad studie av robusthet i form av korrelation mellan tröghet och olika driftsfaktorer, såsom elproduktion per produktionsslag, elektrisk last, och flöden mellan prisområden. Resultaten påvisar att förnybara energikällor har en märkbar minskning på systemets tröghet. Å andra sidan påvisas att kärnkraften, samtidigt som den fortfarande bidrar till ökad tröghet, haft en minskad korrelation de senaste åren. Studien avslöjar också en växande korrelation mellan dagen före-marknaden och tröghet, vilket betonar vikten av att prissignaler återspeglar operativa verkligheter, särskilt under perioder när trögheten är låg.

En annan kritisk aspekt av nätens robusthet är förmågan att effektivt överföra el mellan områden, särskilt under perioder med hög efterfrågan. Rapporten introducerar en ny, och mycket intressant, indikator i form av otillgänglighet i överföringskorridorer kontra utnyttjandegrad av överföringskorridorer. Denna robusthetsindikator ger insikt i hur väl nätet kan hantera el överföring under olika förhållanden. En oroande trend har uppstått där utnyttjandet av större överföringskorridorer har ökat, men så även deras otillgänglighet på grund av operativa begränsningar eller underhåll. Denna dubbla trend är problematisk, eftersom den minskar nätets kapacitet att svara på efterfrågan under höglast, och därmed minskar systemets totala robusthet.

Resultaten av denna rapport pekar på det ökande trycket som det nordiska kraftsystemet står inför när det anpassar sig till högre nivåer av förnybar energi samt en ökad efterfrågan av el.

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1 Introduction

The aim of this project has been to identify relevant robustness indicators, with the main goal to provide an improved view of the evolution of grid properties over time.

As a response to the climate change, the energy transition is taking us toward a future net-zero emission energy system foreseen to have considerable levels of variable renewable energy sources, enabling the replacement of fossil fuels in sectors such as heating, industrial processes, and transport. The intermittency of such energy resources places significant systemic requirements on the energy sector in general, and the electric power system in particular.

The escalated strain on the power system with more unpredictable and volatile power flows introduces a big challenge on the operation and planning of the grid. This situation makes an overall assessment of the power system functionality in the form of grid properties, and how these develop over time, very valuable.

Often vulnerability is utilised for indicators, where vulnerability can be seen as the opposite of robustness. Several vulnerability indicators have been developed, related e.g., to structural vulnerabilities. However, it is a challenge to find a common indicator which can quantify the robustness, or vulnerability, of all grid properties in general.

A nuclear power plant needs a stable power supply during both normal and abnormal conditions, in order to maintain an acceptable nuclear safety and to support the transmission system to maintain its ability to reliably deliver power to customers. By having a way to quantify changes in grid properties it may be possible to better optimise design choices when nuclear power plant modifications are carried out to maintain or improve safety levels with regards to power quality.

Furthermore, improved indicators to estimate grid properties are of value for the grid operators as well as for nuclear power plant owners, in order to provide decision support for example regarding planning of maintenance to ensure the robustness and reliability of the power system.

The aim of this project has been to propose and present robustness indicators of grid properties over time. Preferably quantifiable indicators, or if not possible the methodology to obtain such indicators. The main goal was to provide a better and clearer view of the evolution of grid properties.

The work presented in this report addresses the ability of creating robustness indicators based on publicly available open data and has focused on three impact factors: 1) frequency; 2) inertia; and 3) transfer corridors. These impact factors have been selected based on their importance from a system and a regional perspective of the power system. Several other aspects, e.g., bus voltages, power quality, short-circuit levels, and available resources for different type of services, are as well important from a robustness perspective, but have not been addressed in detail within this work.

This report is structured in the following way:

- Chapter 2 provides a general overview of the robustness concepts placed in relation to risk, reliability, stability and resilience;
- Chapter 3 presents a discussion of different type of indicators;
- Chapters 4-6 include the main results from the robustness assessment studies of the three main impact factors:
 - power system robustness evaluation through frequency extremes,
 - power system robustness evaluation through correlation assessment of the system inertia,
 - and power system robustness evaluation through transfer corridor unavailability and utilisation;
- finally, in Chapter 7, the authors present conclusions and discussion related to possible future steps.

2 Reliability, Resilience, and Robustness

Reliability, resilience, and robustness are some of the concepts which can describe the functional performance of the power system. Unique definitions are however lacking for several of these, and it is therefore important to clarify the intended meaning when using them in communication and for quantification. In this chapter we provide short descriptions of these concept, including discussion also on *risk, adequacy, security, stability, and vulnerability*.

2.1 RISK

Risk is typically considered as a combination of the impact and the probability of an event, [1]. Risks in the power system may relate to technical and non-technical aspects, e.g.: safety, environmental, financial, and reputational. Part of the total risk space include reliability, which in turn partly relate to the risks related to large disturbances / extraordinary events, as illustrated by Figure 1.

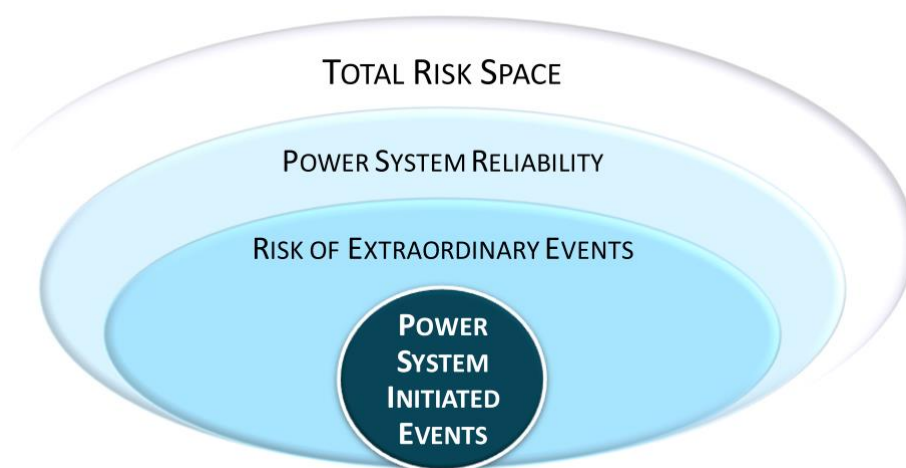


Figure 1 Risk space, covering a broad range of various type of risks, from [2].

2.2 RELIABILITY

Power system reliability relates to the overall objective of the system to perform its function, [2]. Reliability quantifies the ability of an electric power system to supply adequate electric service on a nearly continuous basis with few interruptions over an extended period of time, [1]. Common among many reliability definitions is the subdivision into adequacy and security, as illustrated in Figure 2. As such, adequacy and security can be described as:

Adequacy is the ability of the power system to satisfy the consumer load demand, [2]. Adequacy considerations include component ratings and voltage limits under steady-state conditions, connected to planned and unplanned component outages.

Security is the ability of the power system to maintain interconnected operation, [2]. Security considerations include component ratings, voltage and frequency limits, loss of load, and instability, connected to disturbances and system failures, such as short circuits and the loss of system components.

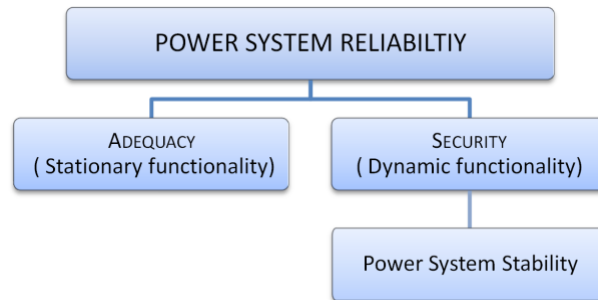


Figure 2 Classification of power system reliability, from [2].

2.3 STABILITY

Power system stability is the ability of an electric power system to regain a state of operating equilibrium after being subjected to a disturbance, [3]. Stability may be classified into several separate phenomena, including the classical: rotor angle stability, frequency stability, and voltage stability, and the more recent areas of: resonance stability and converter driven stability, as illustrated in Figure 3.

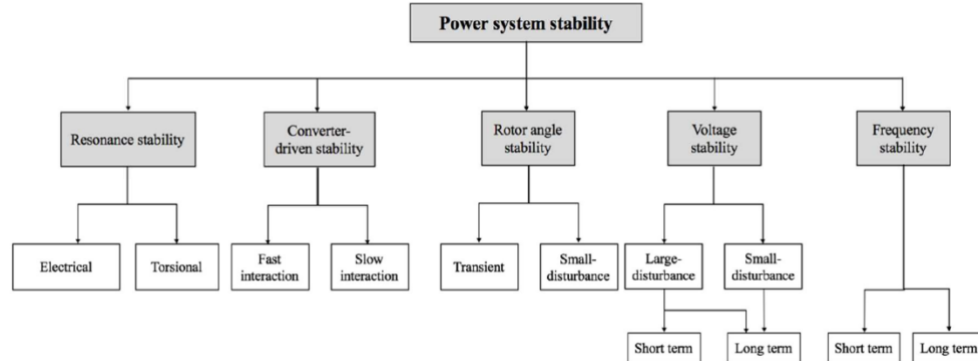


Figure 3 Classification of power system stability, from [3].

2.4 RESILIENCE

Resilience of the power system reflect its ability to limit the extent, severity, and duration of an extraordinary event, [4]. Assessment of resilience include the ability to withstand an event, the rapid recovery from a disturbance, as well as its adaptability to prepare against future threats, [5]. The resilience concept may be considered to include robustness, as illustrated in Figure 4.

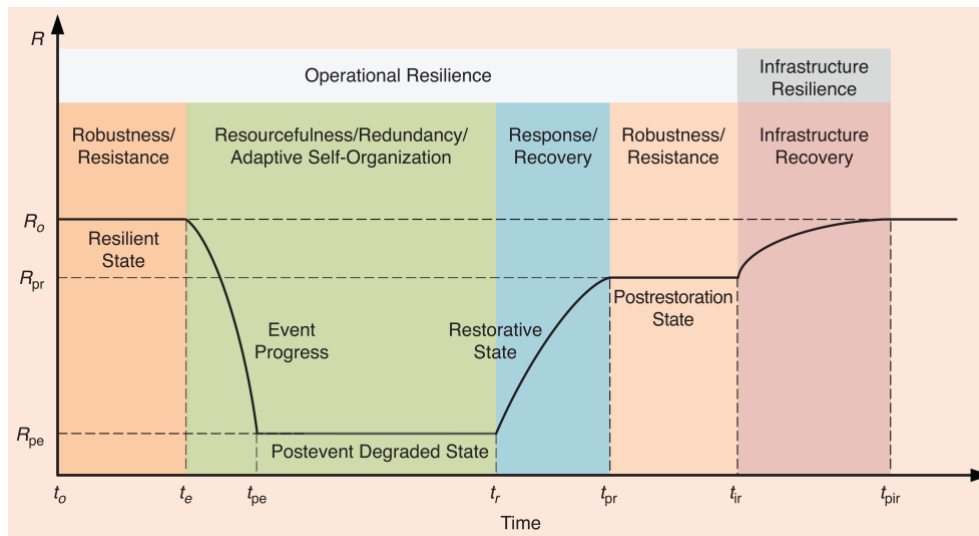


Figure 4 Conceptual resilience curve, from [6].

2.5 ROBUSTNESS

Power system robustness is the degree to which a network is able to withstand an unexpected event without degradation in performance, [7]. Robustness quantifies the impact as a consequence of an unexpected perturbation. Robustness and resilience are related concepts, however reflecting distinct properties of a system. One could say that robustness relates to the performance degradation, while resilience relates to the ability to recovery, of an unexpected event, [8]. Svenska kraftnät consider robustness a necessary property of the power system to maintain secure operation, describing robustness to include e.g. sufficient margins in order to cope with disturbances, [9].

Vulnerability is seen as the opposite concept of robustness, [7]. Vulnerability is a more established concept when it comes to indicators. Several vulnerability indicators have been developed to quantify specific parts of the risk space regarding certain vulnerabilities, including structural vulnerabilities [10], performance metrics based vulnerabilities [11], or stability related vulnerabilities [12]. Various types of vulnerability assessment methods can be found in [13]. The breadth of vulnerability indicators, and how they are expressed, constitutes a challenge to identify indicators which are valuable to address the general robustness of the power system.

In this project we intend to address indicators suitable to reflect how the technical performance of the grid develop over time. The indicators will provide information on the impact on the grid when affected by a disturbance, and as such the proposed indicators will be able to reveal part of the robustness of the power system.

It should be noted that in control theory, the concept of robustness and robust controls are well established. Whereas power system robustness is a much wider concept that is still lacking in general quantifiable indicators.

3 Indicator types

It is possible to create robustness indicators based on different categories of data. In this section the following aspects are discussed: data availability, time frame, foresight, locality, and superposition.

3.1 DATA AVAILABILITY

The project has focused on working with openly available information, to limit the dependency of proprietary information. The two main reasons for this were: firstly, indicators can be provided publicly without any data sensitivity requirements, secondly, there is an inherent difficulty in sharing of proprietary data which constitutes a challenge in the development and the use of such indicator outside the organizations owning the data.

However, this approach has the limitation that proprietary information, such as local and/or high-resolution measurement data, as well as detailed information from the grid, production units, and demand, cannot be used in the robustness assessment.

3.2 TIME FRAME

The time frames used in the evaluation of robustness influence the functionality of a robustness indicator.

Long term trends, on annual or decade level, could also include evaluation of very fast phenomena identified through high-resolution measurements. Such data could be part of a robustness indicator that is updated with regular intervals.

In this project, only open data has been available. However, with the availability of additional proprietary high-resolution data, robustness estimations could include trends in power system damping, power quality, or resonance levels.

3.3 FORESIGHT

Two categories of robustness indicators can be developed regarding foresight: lag indicators or lead indicators.

3.3.1 Lag indicators

These are the most common type of indicators, provide information from a historical and present perspective. The value of lag indicators are connected to the assessment of how the power system robustness has developed over time and places the actual state in relation to historical levels.

3.3.2 Lead indicators

These indicators provide information of how the robustness of the system will develop in the future. Lead indicators depend on forecasted information of future

developments, which could be based on mathematical progressions of lag indicators as well as forecasted environmental, regulatory, and/or societal developments.

3.4 LOCALITY

Three main categories of indicators may be defined: global, regional and local.

3.4.1 Global indicators

Indicators of a global nature could be able to provide an index for the whole Nordic power system as such, providing a value from a holistic system perspective. Global aspects include e.g. frequency, inertia, and adequacy of frequency supportive reserves. An example of a global indicator is the inertia of the Nordic power system as provided by Fingrid, [14], see Figure 5.



Figure 5 Example view of the inertia of the Nordic power system, presenting the inertia [GWs] for a selected period of time, from [14].

3.4.2 Regional indicators

Indicators of a regional nature could be suitable to give insights into regional limitations of the power system, influencing societal development. Regional aspects include e.g. transfer capacities and utilization, energy prices, and adequacy of voltage supportive reserves. An example of a regional indicator is the energy price and actual power transfers as provided by Svenska kraftnät, [15], see Figure 6.

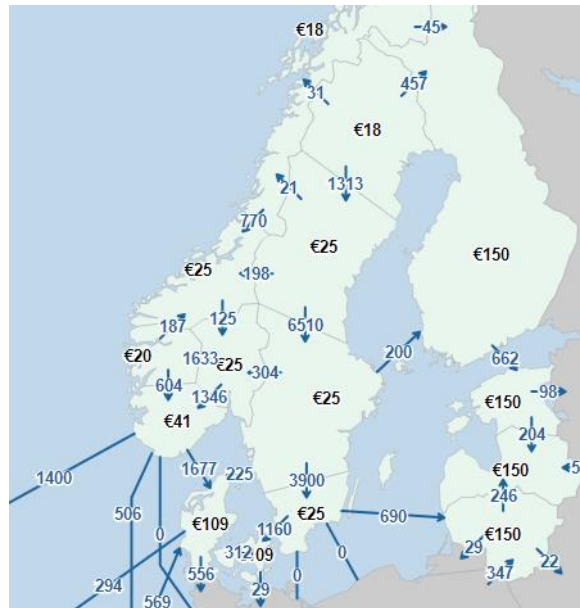


Figure 6 Example view of energy price and actual power transfers, presenting power flow [MW] between areas and energy price [€/MWh] in areas of the Nordic power system for a selected time instant, from [15].

3.4.3 Local indicators

Indicators of a local nature could provide additional value for a specific location. Local aspects include e.g. bus voltages, power quality, and short-circuit levels, and may have a direct impact on the ability of a power plant to function. Several local indicators could be used simultaneously to illustrate the quality or robustness in different parts of the grid at the same instant in time. Local indicators do however depend more directly on local measurement and other proprietary data. An example of an open indicator of local nature is the “Short-circuit levels of the Danish power grid”, provided by Energinet [16], see Figure 7.

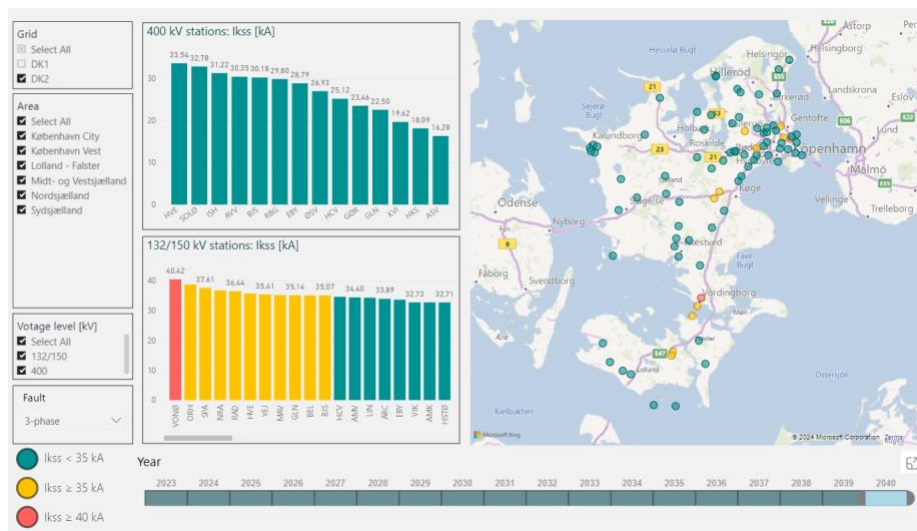


Figure 7 Example view from short-circuit levels of the Danish power grid, presenting an overview of estimated short-circuit level [kA] for different power stations for a selected year, from [16].

3.5 SUPERPOSITION

In superposition of data, each part can be utilized and form an integral part of a collective indicator built on different type of information. In this way additional dimensions of the data can be revealed, which could confirm or contradict a specific trend or conclusion.

In this report, three different type of superposition is utilized:

1. estimation of *frequency* extremes utilizing *frequency* measurements and *inertia* calculation, which is further described in chapter 4,
2. correlation evaluation in *inertia* fluctuations with *spot prices* (and several other factors), as presented in chapter 5,
3. relation between *transfer capacity unavailability* and *utilization*, which is analyzed in chapter 6.

4 Robustness indicator: frequency extremes

This chapter presents a robustness indicator addressing frequency extreme estimation. The indicator is calculated based on inertia measurements and is utilizing a previously developed calculation method. Recent events have been used to validate the method and to discuss future frequency extreme scenarios.

4.1 INTRODUCTION

The scope of the project is to present robustness indicators of grid properties over time. As the frequency of the power system is a key indicator of the power systems stability and balance, the starting point for this work focus on addressing frequency extremes as a measure of the power system robustness. To estimate frequency extremes, open-source data of the inertia of the Nordic power system have been utilised, together with information regarding the largest available asset which if tripped would result in the largest frequency excursion.

When there is a temporary mismatch between power generation and consumption, the frequency starts to deviate from its nominal level. Inertia is a property that resists changes in frequency and has traditionally mainly been provided by the rotating mass of synchronous machine - turbine systems used for electricity generation. However, as renewable energy sources (RES) become increasingly penetrated in the power systems and thus replace conventional generation, the energy transition is resulting in a lower overall system inertia since RES are interfaced to the power system with inverters and do not contribute to the inertia.

If a disturbance occurs, such as a sudden loss of load or production, the system's response in frequency depends on the size of the disturbance, the available inertia, and the available reserves. Maintaining frequency within specific limits is crucial to avoid unintended disconnections of power production or consumption. A significant concern is the rapid frequency deviation that can happen after a sudden power imbalance, which is particularly challenging in systems with low inertia.

In the Nordic synchronous area frequency must remain within the instantaneous limits range of 49.0 - 51.0 Hz. If it goes beyond these limits system protective measures like under-frequency load shedding or over-frequency generator tripping, will automatically be activated. To address frequency instability, operators can deploy faster reserves, increase system inertia, or reduce the scale of disturbances. Monitoring the robustness related to the risk of frequency instability involves estimating the maximum possible frequency deviation after a disturbance. Although this can be simulated if the system model is accurate, real-world uncertainties and incomplete information often make precise predictions challenging.

4.2 ROBUSTNESS INDICATOR – NORDIC TSO PERSPECTIVE

In the evolving energy landscape, maintaining frequency stability poses a critical challenge for transmission system operators (TSOs). The ability of the grid to respond effectively to frequency deviations—particularly in low-inertia scenarios—is essential for avoiding blackouts and ensuring grid reliability. To address this issue, the Nordic TSOs published the "Future System Inertia 2" report [17], which, although a few years old, offers valuable insights into the relationship between system inertia and robustness during frequency disturbances. Key takeaways from the "Future System Inertia 2" report are summarized below.

- **Insights from other synchronous regions:** Through surveys and interviews with other synchronous regions, the "Future System Inertia 2" report highlights that low inertia is a common challenge across various power systems. Regions with low inertia are employing different strategies to mitigate this issue, including synthetic inertia, flexible thermal units, and battery storage. These solutions provide valuable lessons for the Nordic TSOs as they confront similar challenges.
- **Future Kinetic Energy Estimation:** The "Future System Inertia 2" report presents future kinetic energy scenarios for the Nordic system, with projections for 2020 and 2025. These scenarios estimate the likely range of kinetic energy available in the system, which is resisting the change in frequency. While the "Future System Inertia 2" report anticipates that the minimum kinetic energy levels will improve by 2025, low-inertia situations will still arise, although less frequently. Table 1 below shows the probability of kinetic energy levels falling below critical thresholds. It can be noted that in 2021, the actual level of kinetic energy in the Nordic power system was at a record low of 110 GWs [18].

Table 1 Probability of low kinetic energy situations.

Year	Kinetic energy in GWs below a percentile of forecasted distribution [17]		
	90%	95%	99%
2020	150	136	120
2025	159	147	134

- **Mitigation and Operational tools:** The "Future System Inertia 2" report evaluates a range of mitigation strategies designed to address low-inertia situations. Key measures include the deployment of Fast-Frequency Reserves (FFR), emergency power control (EPC), and load disconnection. Using a multi-criteria assessment, the "Future System Inertia 2" report identifies active power injections and redesigned EPC settings as the most effective short-term solutions to manage frequency deviations. To further support grid stability, the Nordic TSOs are improving real-time inertia estimation and forecasting tools, which are now integrated into SCADA systems. These tools use linear regression models to predict extreme

frequency deviations in real-time, allowing operators to make informed decisions during critical events.

- **Robustness indicator:** Although not explicitly called robustness indicator, the "Future System Inertia 2" report introduces an indicator specifically designed to estimate frequency extremes, based on inertia measurements and a developed calculation method. This indicator provides insight into how the system responds to major disturbances, such as the sudden loss of power generation, and is explored further in the next section.

4.3 FREQUENCY EXTREMES AS ROBUSTNESS INDICATOR

The "Future System Inertia 2" report and article [19] introduce a method to predict the maximum instantaneous frequency deviations for dimensioning incidents. It should be noted that when the "Future System Inertia 2" report was published, FFR was not yet utilized in the Nordic grid. Since then, several measures have been deployed which influence the validity of this method. However, in this study we have been addressing how this method can be utilized as a robustness indicator. In this sense, FFR and other solutions are measures which provide increased robustness. The method presented in the "Future System Inertia 2" report, is based on the swing equation, and provides insight into how power imbalances impact the system's frequency response. The swing equation, which models the motion of a rotating mass, links the rotor dynamics to the balance between mechanical and electrical power. When multiple generators swing coherently, the system can be approximated by a one-machine equivalent model. This model is used in the Laplace domain to analyse how sudden power imbalances cause frequency deviations.

4.3.1 Method to predict frequency extremes

The study utilizes linear regression to model the relationship between power imbalance and frequency deviation. This approach separates the analysis into over-frequency and under-frequency disturbances to estimate the maximum deviation from the nominal frequency. Figure 8 is used for explanation of the method, including an example of a frequency deviation and an illustration of the linear regression of frequency deviation.

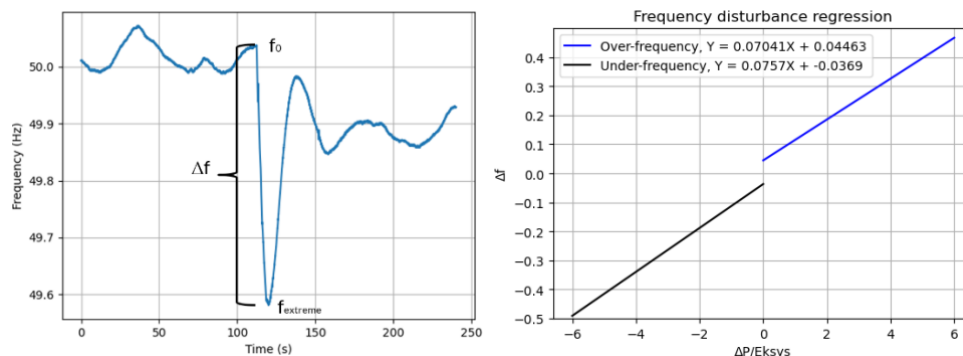


Figure 8. Left: System frequency following a generator trip. Right: Linear regression of frequency deviation relative to power imbalance and kinetic energy, from [19].

In Figure 8, f_0 is the frequency at the time of the incident and $f_{extreme}$ is the maximum frequency deviation. The difference in frequency is $\Delta f = f_0 - f_{extrem}$. Δf are split between over-/ underfrequency, and can be estimated by means of linear regression, through the following expressions:

$$\begin{aligned}\Delta f_{over} &\approx \alpha_{over} \frac{\Delta P}{E_k} + \beta_{over} \\ \Delta f_{under} &\approx \alpha_{under} \frac{\Delta P}{E_k} + \beta_{under}\end{aligned}\tag{1}$$

Here, $\Delta P/E_k$ is the ratio between the power deviation and kinetic energy, and α and β are the linear regression parameters of the equation $y = \alpha x + \beta$. The linear regression parameters are estimated from known actual events, forming the piecewise linear curve presented on the right-hand side of Figure 8. The values of α and β for the linear regression models are shown in the figure legend, as presented in [19]. This method assumes that no measures are in place which mitigative large frequency deviations. In practice, the FFR is such measure. Furthermore, the frequency deviation is also influenced by the operational conditions and amount of available frequency reserves, which complicate the precise prediction of frequency extremes.

4.3.2 Dimensioning units and Kinetic Energy

In power system operation, dimensioning units refer to the largest individual production or transmission elements whose failure would result in the most significant disturbances. These units are central to the system's ability to handle N-1 faults, and is a fundamental reliability criterion requiring that the grid withstand the loss of its largest unit—be it a generator, transmission line, or HVDC link (or in the future large individual loads)—without causing widespread disruptions.

In the Nordic power system, dimensioning units include both the largest production plants, such as nuclear power plant, and major HVDC interconnectors linking different regions or countries. System operators must continuously monitor these elements to ensure reliable operation against potential failures. If unmitigated, such failures can cause significant under- or over-frequency deviations, depending on the type of incident.

The two key variables in equation (1) are:

- ΔP : the power imbalance caused by an event, such as the loss of a large generator, HVDC link or load center.
- E_k : the system's kinetic energy, which depends on the inertia provided mainly by synchronous machines in the grid.

By inputting the appropriate values for ΔP (based on the dimensioning units) and E_k (from system inertia measurements), the maximum expected frequency deviation can be predicted during both over-frequency and under-frequency events.

The largest dimensioning units in the Nordic power system are summarized in the tables below. These units set the scale of potential frequency excursions, with the most significant under-frequency event being a result of the loss of Oskarshamn 3 (1450 MW) and the largest over-frequency event from the loss of NordLink 1-2 (1400 MW). These dimensioning units provide the basis for understanding the system's vulnerability during high-impact disturbances.

Table 2 Largest production units in the Nordic power system, [20], [21].

Production unit	Net capacity [MW]
Oskarshamn 3	1450
Olkiluoto 3	1300 ¹
Forsmark 3	1230
Ringhals 4	1130
Forsmark 2	1128
Forsmark 1	1018
Ringhals 3	1064

Table 3 HVDC cables in the Nordic power system, [22].

HVDC-Link	Rated power, parallel monopolar or bipolar capacity [MW]
Baltic Cable	600
Estlink 1,2	1000
Kontek	600
Konti-Skan 1,2	715
NordBalt	700
NordLink 1,2	1400
NorNed	700
North Sea Link 1,2	1400
Skagerrak 1,2,3	1000
Skagerrak 4	682
Storebaelt	600
SwePol	600

Kinetic energy (E_k) in the Nordic system represents the grid's ability to resist rapid frequency changes. This is directly tied to the inertia provided by conventional synchronous generators. The kinetic energy E_k of the Nordic power system is described below as a time series from 2015-2023 in GWs, as collected from Fingrid's Open Data [23].

¹ Actual maximum production is 1600 MW, but a system protection scheme is used to limit the impact to maximum 1300 MW [21].

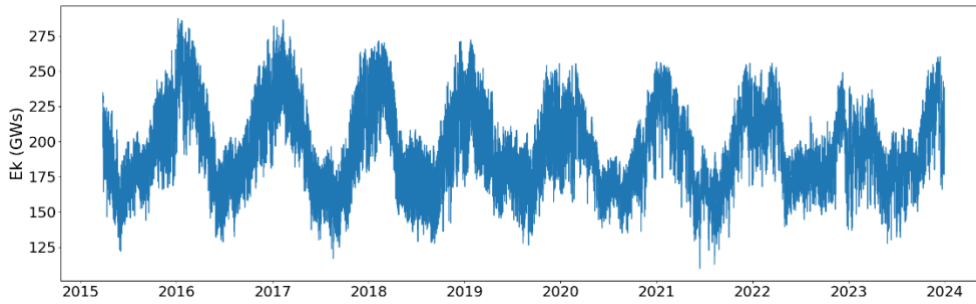


Figure 9. Kinetic inertia in the Nordic power system from year 2015 to 2023.

4.3.3 Validating the method

To ensure the continued accuracy of the linear regression models for predicting frequency extremes, it is essential to validate them with recent data. This section reviews the performance of the models by comparing predictions against actual frequency deviations observed in recent events, particularly from 2022 to 2024. The validation process starts by reviewing the frequency extremes predicted by the models in 2017, as detailed in the TSO report from that year [17], presented in Table 4.

Table 4 Estimated and actual frequency extremes from 2017, [17].

Time (CET)	Cause	$E_{k,sys}$ (GWs)	ΔP (MW)	$f_{extreme}$ actual (Hz)	$f_{extreme}$ estimated (Hz)	f_{error} (Hz)
06-06-2017 05:36	NorNed HVDC	152	-493	49.72	49.74	-0.02
06-13-2017 03:55	NorNed HVDC	145	729	50.36	50.36	0.00
06-27-2017 21:33	NorNed HVDC	172	729	50.35	50.32	0.03
07-14-2017 08:56	Nuclear unit	179	-449	49.72	49.71	0.01
07-23-2017 20:28	NordBalt HVDC	165	733	50.30	50.33	-0.03
09-02-2017 17:53	NorNed HVDC	168	617	50.25	50.24	0.01

The results from the 2017 model validation showed a minimal error range between -0.03 - 0.03 Hz. This historical data provides a baseline for comparison with more recent events.

By evaluating the consistency between past predictions and actual outcomes, it can be determined whether the models have maintained their accuracy over time. To confirm the reliability of the parametrization for 2024, recent frequency disturbances have been analyzed for the following incidents:

- **OL3 Incidents:** Two disturbances associated with OL3 occurred on November 9, 2022, and June 3, 2024. Both cases provided additional data points for validating the model's accuracy. Frequency recordings are presented in Figure 10

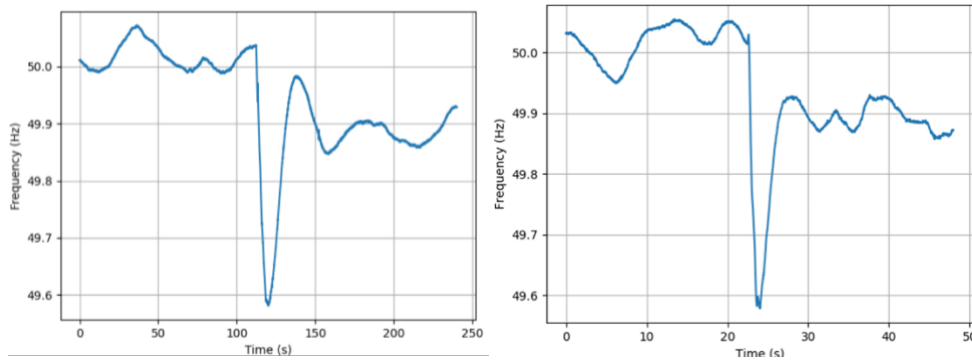


Figure 10. OL3 trips frequency recordings: 2022-11-09 11:43 (left) 2024-06-03 10:41 (right).

The comparison between the predicted frequency deviations and the actual measurements, presented in Table 5, are supporting the accuracy of the models. The deviations between predicted and actual values have errors ranging from 0.00 - 0.01 Hz. These results validate that the models remain reliable and effective for estimating frequency extremes in the current operational context.

Table 5 Estimated and actual frequency extremes from events in 2022-2024.

Time (CET)	Cause	Ek (GWs)	ΔP (MW)	f_0 (Hz)	fex act (Hz)	fext est (Hz)	fext err (Hz)
2022-11-09 11:43	OL3	211	-1300	50.02	49.59	49.59	0.0
2024-06-03 10:41	OL3	199	-1300	50.02	49.57	49.56	0.01

4.3.4 Evaluation of frequency extremes

This section builds on the presented and validated method, to estimate the potential frequency extremes (in case no mitigative actions would have been in place) in the Nordic system between 2015 and 2023. Here, we highlight the potential maximum and minimum frequency deviations and compare these with established control thresholds. Finally, an examination of the impact of future system inertia levels is presented.

Figure 11 presents the results of the extreme frequency estimations for the period 2015 - 2023, utilizing the inertia time series shown in Figure 9. It should be noted that these results include the assumptions that no mitigative actions (such as FFR) would have been in place to limit the frequency extremes, as well as the assumption that the largest critical units were always present with maximum power. The results show the potential frequency extremes during this period, with the assumption that f_0 is 50 Hz. As the normal operating band for the frequency is between 49.9 and 50.1 Hz, the expected deviation range for f_0 is ± 0.1 Hz.

In the most extreme cases presented in Figure 11, the estimated system frequency could drop to 49.04 Hz or rise to 51.94 Hz. In reality, FFR as a mitigative actions is present to prevent such excursions. Furthermore, it should be noted that the largest generating units are typically not in full production during the seasons of low inertia. Considering the possibility that the originating frequency f_0 could be

deviating an additional ± 0.1 Hz, these conditions could also result in the triggering of critical system protective measures such as load shedding or generation disconnection. While such frequency deviations are generally unlikely, FFR and other mitigative actions are normally preventing extreme frequencies.

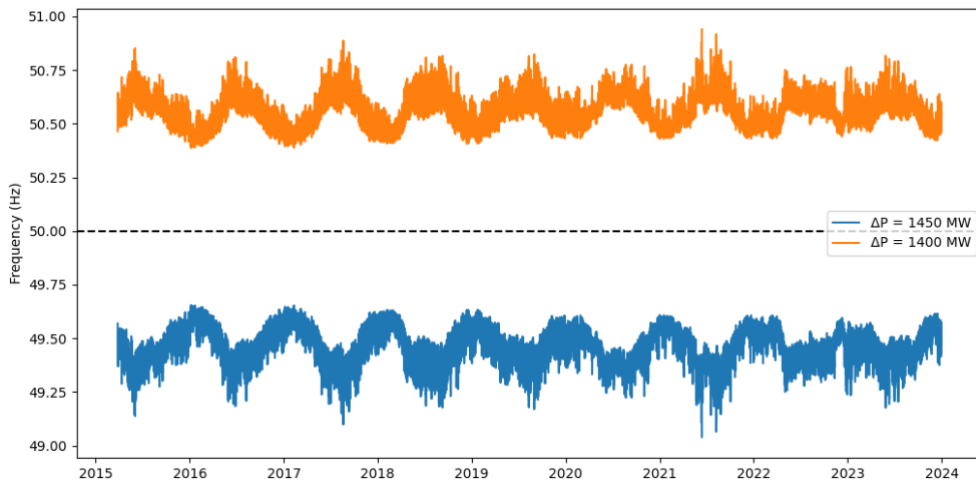


Figure 11. Estimated potential frequency extremes for 2015-2023.

A year-by-year analysis of the potential frequency extremes shows that 2021 experienced the highest variations, while 2016 had the lowest, as illustrated in Figure 12. This visualization of frequency extremes over 8760 hours in a year provides insight into the robustness during different periods.

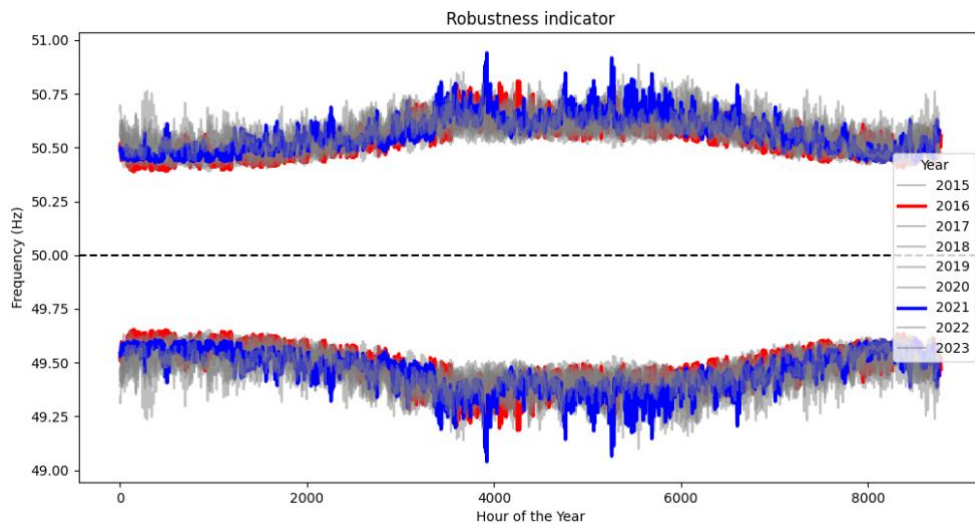


Figure 12. Estimated potential frequency extremes for 2015-2023, visualized over one year. Lowest variations 2016 (red) highest variations 2021 (blue).

To further explore the effect of system inertia on frequency stability, a sensitivity analysis was performed where kinetic energy was increased and decreased by 20%. This presents two possible future scenarios, where a higher share of converter-based generation results in a decrease (-20% inertia) while an increased

amount of synchronous machines results in an increase (+20% inertia). Figure 13 presents the results of such possible future scenarios, where the worst case for each hour presented in Figure 12 has been utilized to evaluate the possible future extreme situations.

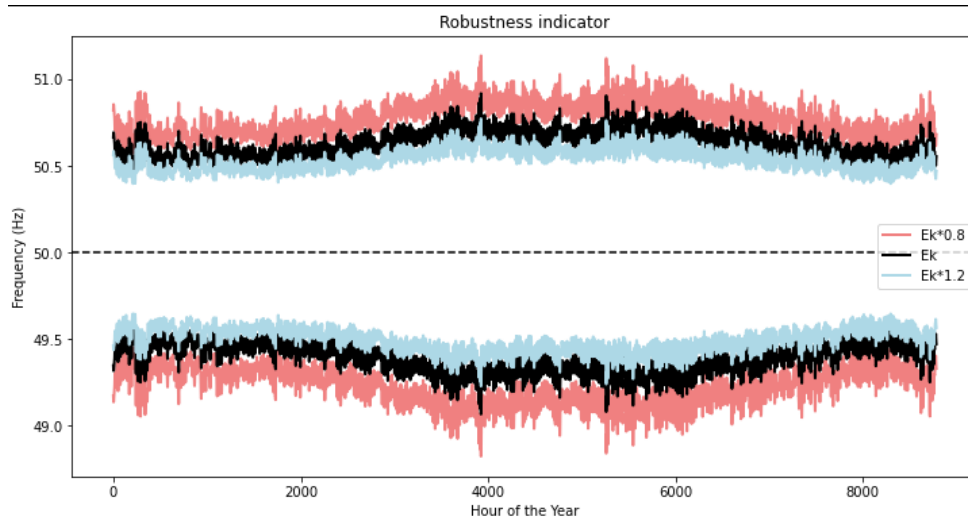


Figure 13. Estimated potential frequency extremes with varying system inertia. Ek-20% (red), Ek current (black), and Ek+20% (blue).

As can be seen in Figure 13, the lowered inertia increases the risk of breaching critical thresholds, potentially triggering load shedding or generation disconnection. These findings underline the value of the proposed robustness indicator, and its usefulness as a leading indicator in the evaluation of future scenarios. The illustrated sensitivity of the system to reductions in inertia confirm the frequency extremes' close ties to kinetic energy. A deeper understanding of these dynamics allows system operators to better anticipate and manage extreme frequency events, ensuring the continued stability and reliability of the Nordic power system under varying operational conditions.

4.4 DISCUSSION

By modeling the relationship between kinetic energy and frequency deviations over time, the presented robustness indicator provides insights that can be of value for planning and operational planning. The robustness indicator derived from the method allow for a better understanding of potential risks and necessary interventions under different present and forecasted scenarios.

The analysis of frequency extremes illustrates one side of the robustness of the Nordic power system. Frequency is a key measure of system stability, with extreme deviations indicating how critical disturbances could threaten the integrity of the grid. The correlation between frequency stability and system inertia is particularly important, as the latter acts as a buffer against sudden frequency shifts. However, the ongoing energy transition, with the increased integration of inverter-based RES, is leading to a reduction in system inertia. The mitigation strategies, such as the introduction of Fast-Frequency Reserves (FFR), emergency

power controls, and enhanced inertia estimation techniques, are tools for managing these risks.

The method is validated against recent extreme frequency events, and demonstrates a high level of accuracy in predicting system behavior during disturbances. However, while the method performs well under current system conditions, the long-term implications of low-inertia scenarios remain uncertain.

Looking forward, a robustness indicator based on frequency extremes will need to evolve alongside the power system. The ability to predict and manage extreme frequency deviations will depend on the continued development of real-time monitoring and forecasting tools. Furthermore, the method need to be able to consider availability (and unavailability) of existing and future mitigating measures, including implementation of new technologies like synthetic inertia and other fast acting control solutions. Operators may have to reassess the thresholds for system integrity protection schemes, such as load shedding and HVDC emergency support, to ensure that the power system can maintain stability under a broader range of operating conditions. There is also the possibility to limit the size of the dimensioning incident, as discussed in [24]. In addition, frequency controllers might be different in the future, and the way TSOs are reserving power can become more adaptive to the inertia fluctuations, thus altering the linear relationship between Δf and $\Delta P/Ek$.

As the method used to calculate this robustness indicator is directly depending on the inertia, assessment of factors influencing the inertia is a logical step to take which is described in detail in the chapter 5.

5 Robustness indicator: Inertia correlation

This chapter presents several robustness indicators, based on correlation analysis between kinetic inertia in the Nordic power system and various influencing variables, based on data from 2015 to 2023. The variables of the correlation analysis include: power generation, load, cross-border flow, production and transmission unavailability, and electricity spot prices. The kinetic inertia data is decomposed into annual, weekly, and daily trends, plus residuals, to understand the impact on different variables at various time resolutions.

5.1 INTRODUCTION

As indicated by the presentation of robustness indicator *Frequency extremes*, in chapter 4, the influence of the changes in kinetic inertia has a direct impact on the evaluation. Therefore, a thorough evaluation between inertia fluctuations and various system parameters is a logical next step. This study comprises a correlation analysis between the recorded kinetic inertia of the Nordic power system (Finland, Sweden, Norway, and eastern Denmark) and various variables believed to impact inertia. The study includes analyses of correlation variations over time and investigations of periods of extremes.

Correlation analysis can be used to better understand the impact of variables in a larger dataset, where multiple variables can be compared to one of interest to initially determine if there is any covariance or co-dependency. Any correlation between variables can only indicate some covariance; further studies are needed to determine how they are connected.

The correlation study is based on the linear correlation of timeseries, with a 1-hour resolution, made up of recorded values of kinetic inertia and each of the variables listed in Table 6. The resulting Person Correlation Coefficient (CC), given as a value on $[-1, 1]$, implies a variability between inertia and the investigated variable – also providing an understanding of whether a variable has a positive or a negative impact.

5.1.1 Heatmap explanation

In this report, the resulting correlation coefficients are presented as heatmaps, where results correspond to a colour gradient, as illustrated by Figure 14. Any positive correlations can be identified as fields in the colours light green to yellow while negative correlations are coloured from turquoise to dark blue. From this figure, one can, for example, identify the strongest positive correlation between the annual inertia trend and the nuclear production in SE3 (index level 0.743), coloured in a green-yellow hue. Similarly, the strongest negative correlation of the inertia residual and the coefficient for wind production in SE4 (index level -0.487), coloured in a blue hue.



Figure 14. Example heatmap with results from inertia correlation with electricity production (divided by type and location).

5.2 INPUT DATA

A raw timeseries of kinetic inertia, based on modelled data and real-time telemetry of individual generators were collected from Fingrid's Open Data [23]. To fit the resolution of the correlation variables, the timeseries were resampled from 1min to a 1h resolution using an average value.

5.2.1 Correlation variables

The raw timeseries of variables listed in Table 6, except power generation in Sweden from the year 2015 to 2022, was collected from ENTSO-E Transparency Platform [25]. Power generation data from the mentioned period was collected from Mimer [26].

Table 6 Studied correlation variables and sections where the robustness indicator is described.

Section	Variable		Bidding zone / Cross section	Resolution	Period
5.3	Production per generation type	Wind	SE1, SE2, SE3, SE4, FI	1h	2015-2023
		Nuclear		1h	2015-2023
		Hydro		1h	2015-2023
		Solar		1h	2015-2023
5.4	Actual load		SE1, SE2, SE3, SE4	1h	2015-2023
5.5	Cross-border flow		SE1-SE2 SE2-SE3 SE3-SE4 SE1-NO4 SE1-FI SE2-NO3 SE3-NO1 SE3-FI SE3-DK1 SE4-LT SE4-DK2 SE4-DE SE4-PL ² ----- 2nd iteration ----- DK2-DE NO2-GB* NO2-NL	1h	2015-2023

² Excluded from the study due to the lack of data earlier than 2022.

		NO2-DE NO2-DK1 FI-EE		
5.6	Transmission unavailability	SE1-SE2 SE2-SE3 SE3-SE4 SE1-NO4 SE1-FI SE2-NO3 SE3-NO1 SE3-FI	1h	2015-2023
5.7	Generation unavailability	SE1, SE2, SE3, SE4	1h	2015-2023
5.8	Day ahead electricity spot price	SE1, SE2, SE3, SE4	1h	2015-2023

Cross-border flows through HVDC cables were included in a second iteration to investigate impacts from periods with unavailable capacity due to limitations and outages.

The study is limited to electricity generated from wind, nuclear, solar, and hydro. Thermal generation was excluded from this study.

All data is set to the CET/CEST time zone.

5.2.2 Inertia

The kinetic inertia in the Nordic power system has historically been a fairly smooth periodical waveform, somewhat resembling a sine wave, with lower levels down to approximately 150 GWs in the summer and higher levels up to around 250 GWs during winter, as can be seen in Figure 15 below.

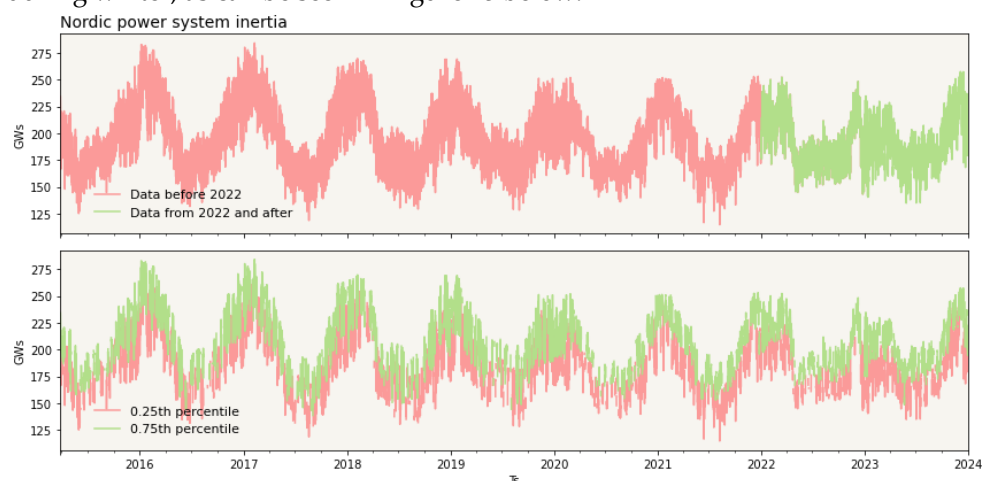


Figure 15. Kinetic inertia in the Nordic power system from year 2015 to end of 2023. Separated into data before 2022 and data from 2022 and after. Lower graph shows extremes, with data filtered for values under the lower quantile and data above the upper quantile.

The inertia level, and its fluctuation, can be set in relation to the total inertia of all Nordic nuclear power generation in operation in 2024 – which is estimated to be

roughly 80 to 90 GWs, based on the assumption that the inertia constant H is 5.9 s [27].

Changes in the sinusoidal fluctuations of the inertia can be observed from 2022, where the magnitude dropped during winter months and the pattern started to fluctuate more intensively, visualized in the top graph of Figure 15. This period is isolated and used as a comparative scenario to understand which CC changes the most – creating an idea of what impacted the altered pattern.

Values below the lower quantile and values above the upper quantile were sorted out and used a scenario of extremes in this study, see results in bottom graph of Figure 15.

The time series of the Nordic power system kinetic inertia, Ek , was decomposed into multi seasonal trends with annual, weekly and daily horizons, including residual behaviour on top by using an additive method as presented in the equation below.

$$Ek = Ek_{annual\ trend} + Ek_{weekly\ trend} + Ek_{daily\ trend} + Ek_{residuals}$$

The open python library *statsmodel* [28] was used to decompose the raw kinetic inertia time series.

The decomposition was used to differentiate the impact of investigated variable for trends occurring at different time resolutions. The decomposition part related to as residuals, is a reflection of noise and fast changes of the kinetic inertia. A sample of resulting decomposition with annual, weekly and daily trends from 2021 can be seen in Figure 16 below. Note that the x-axis varies for the graphs. These trends vary throughout the studied time period, and this figure is only presenting a snapshot of how the trends look like in a relevant time window.

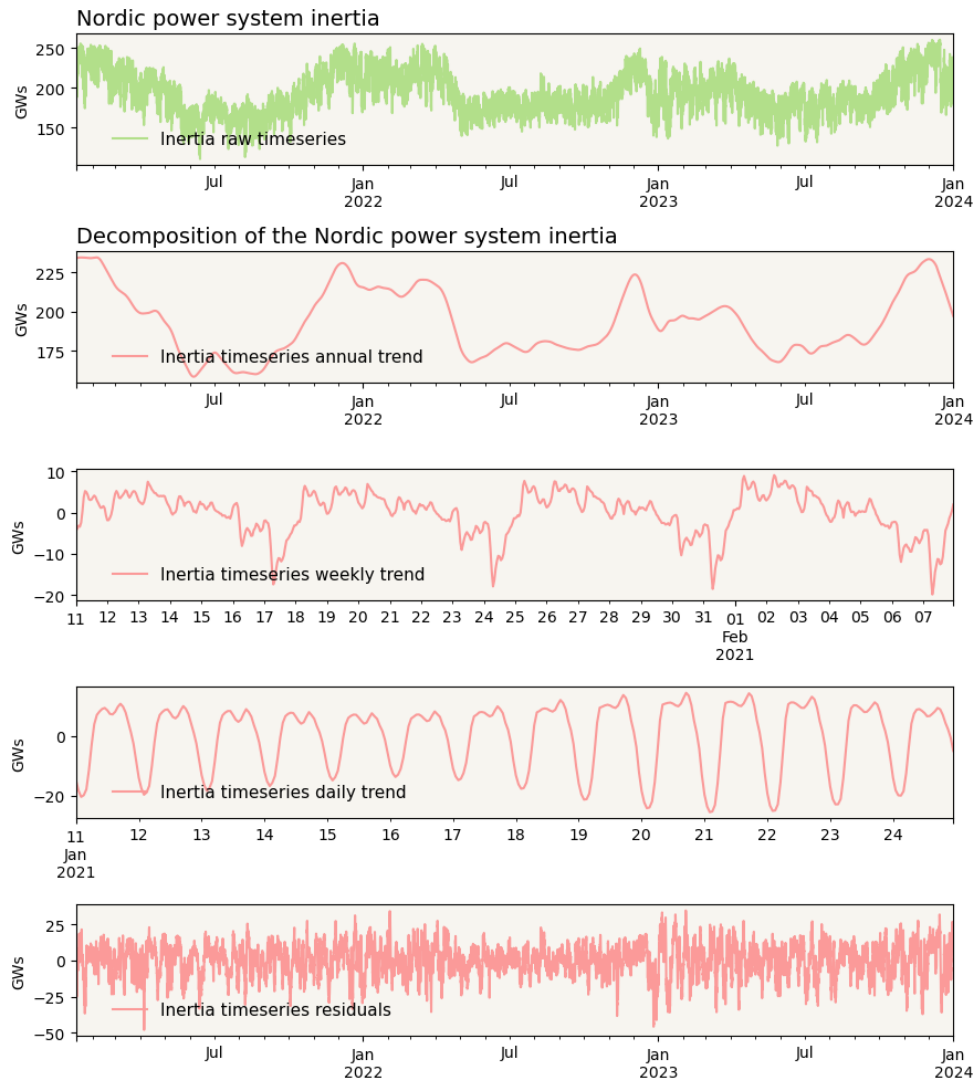


Figure 16. Sample inertia data, consisting of a raw timeseries (green) decomposed into four trends (red).

5.3 INERTIA CORRELATION: PRODUCTION PER GENERATION TYPE

In this section, we have been utilising time series with produced electricity by generation type, where values are analysed as positive (i.e., using a grid perspective, the production is seen as power fed to the transmission grid).

The resulting correlation is displayed in the two following heatmaps, with a color scheme corresponding to the magnitude each combination of variables produced. Inertia is set as one dimension, and production per type and bidding zone is set as the other. The heatmap also includes a numeric presentation of the magnitude for each element in the matrix.

As an example, the original timeseries data of kinetic inertia before the year 2022 is presented as one dimension on the y-axis. The found correlation between it and hydro power in Finland, found on the x-axis, is 0.377, and the cell is colored in a green hue corresponding to the gradient on the figure's right-hand side. The

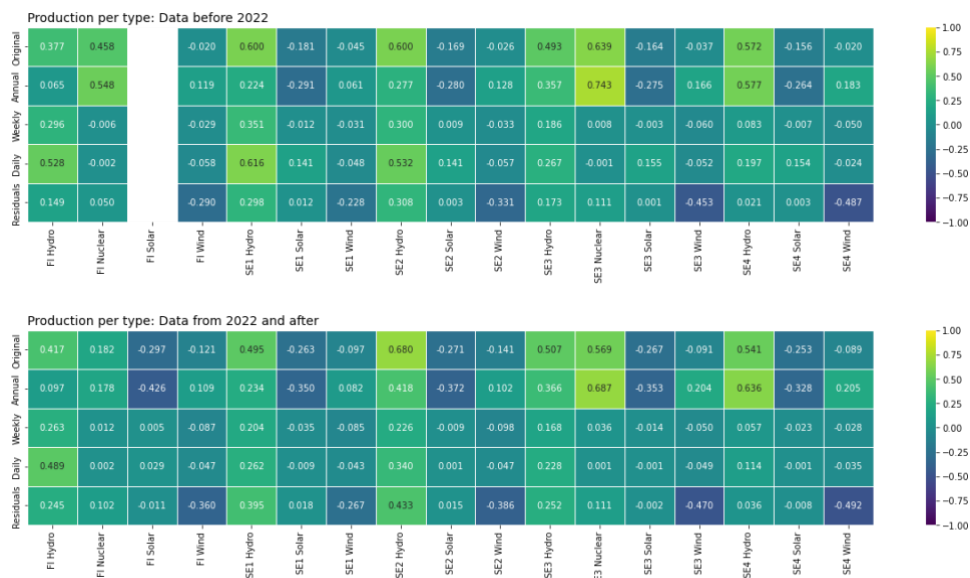
remaining elements are the results of the combination of dimensions on the y and x axes in the figure.

Any positive value implies a linear relationship where the two timeseries show similar behavior, while negative values imply an opposite behavior. The magnitude reflects the strength of a linear relationship, where a magnitude of 1 represents a perfect correlation. Thus, there's a noticeable positive correlation between the kinetic inertia and the hydro power in Finland.

The bottom heatmap is included to highlight any larger relative changes in magnitude between the two scenarios: data before 2022 and data from 2022 and after. A filter ignoring coefficients within the interval -0.15 to 0.15 is applied to reduce noise. The magnitude equals the percentage change, and the color scheme corresponds to the relative change. As an example, the correlation between inertia and production from solar in SE2 has increased by 60% when the two scenarios are compared.

Results indicate that electricity produced from wind in the south of Sweden has a major negative impact on the residual trend of kinetic inertia (blue fields with values below -0.45 in the upper two heatmaps in Figure 17). This means that wind can introduce fast changes, reducing inertia while power is produced. The same occurs with power produced from wind in the north of Sweden and in Finland, but with less magnitude. The last two years' trend indicates an increased impact from wind in FI, SE1, and SE2, while almost no difference can be seen for SE3 and SE4.

Electricity produced from nuclear has provided fewer positive impacts on the system's inertia in the last two years compared to the period before 2022. This correlation is significant when it comes to nuclear in Finland. A large change can be seen between the CC for years prior to 2022 and years after 2022 for both annual trends and the raw data.



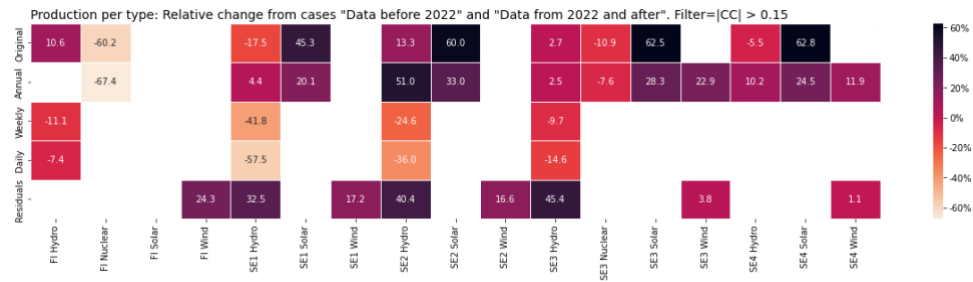


Figure 17. Inertia correlation with electricity production (divided by type and location). Top: Assessment period 2015 - 2021. Middle: Assessment period 2022 and after. Bottom: Relative change between both assessment periods, for inertia correlation above a set threshold.

The increased solar penetration has resulted in negative impacts on the annual trend in recent years, indicating that inertia decreases during periods when solar is available in the summer months. The drop in inertia during these months can also be related to the planned maintenance of nuclear plants, resulting in less power produced from nuclear. A change can be noted in how hydro is impacting inertia, as it seems to have increased its role in both fast and slow correlation. This change is reflected especially for hydro in SE2, in the nearly 50% change in CC from data prior to 2022 compared to data after 2022.

5.4 INERTIA CORRELATION: ACTUAL LOAD

The variable "Actual load" represents the aggregated electrical demand (from all sectors) for each bidding zone in Sweden. Values are analysed as negative from a grid perspective, meaning the load is seen as power withdrawn from the transmission grid.

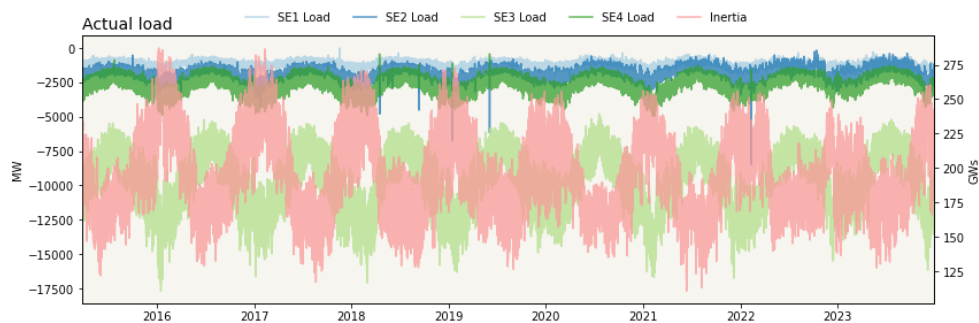


Figure 18. Actual load [MW] (primary y-axis) in Swedish bidding zones. Inertia [GWs] (secondary y-axis).

The resulting correlation coefficients indicate a small change when comparing recent years to data from before 2022. The trend shows a reduced negative correlation between inertia and load in all of Sweden's bidding zones. The load curve in Figure 18 maintains its form throughout the entire studied period, while the inertia curve's periodic waveform transforms in the last two years, causing a reduced correlation between the two.

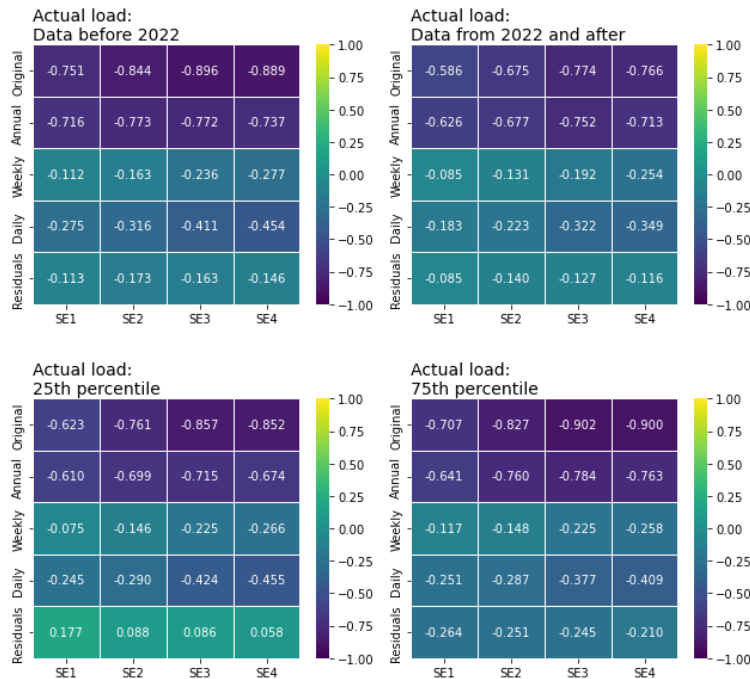


Figure 19 Inertia correlation with electricity load in the Swedish bidding zones. Top left: Assessment period 2015 - 2021. Top right: Assessment period 2022 and after. Bottom: Filtered upper and lower inertia extremes.

There are fewer signs of correlation between the lower extreme (lower quantile) of inertia and load, while the upper extreme more closely resembles the results of “data before 2022” (upper left heatmap in Figure 19). This is likely more related to the type of power generation rather than the amount of load.

5.5 INERTIA CORRELATION: CROSS-BORDER FLOW

Time series with the measured cross-border flow of active power between neighbouring bidding zones in the Nordic power system. Cross-border flows within Norway and Denmark are excluded in this study due to limited time. Values are presented as positive if power is flowing from north to south or if flows are directed outwards towards neighbouring nation, with Sweden set as the centre. The first bidding zone in each cross-section indicates the source of the flow, e.g., SE1 is the origin for the cross-section SE1-SE2.

5.5.1 First iteration

The resulting CC for cross-border flows within Sweden and for a set of neighbouring bidding zones, according to Table 6, is presented in Figure 20 below.

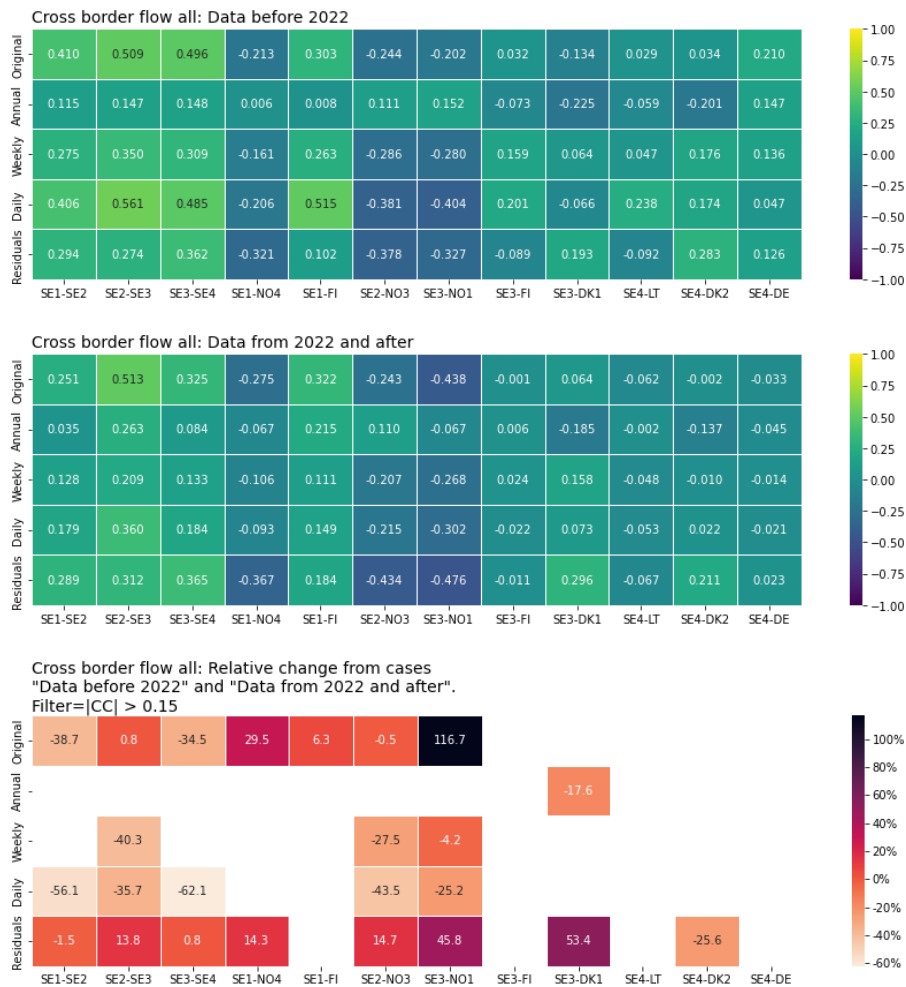


Figure 20. Inertia correlation with cross-border flow within and from Sweden (divided by location). Top: Assessment period 2015 - 2021. Middle: Assessment period 2022 and after. Bottom: Relative change between both assessment periods, for inertia correlation above a set threshold.

Three cross-border flows between SE2-SE3, SE3-SE4, and SE1-FI have historically shown fairly high positive correlation tendencies. The correlation has reduced over the last two years, which could be the result of changed flows. These changes can be seen in 6.4, "Actual Flow," where graphs of normal distributions indicate a redirection of cross-border flows over time.

Flows from Sweden to Norway all have negative resulting CC, with decreased values for the last two years, specifically in the residual trends. This indicates that power has flowed from Norway during periods with high inertia and vice versa. This could be the result of exported electricity produced from renewables in the other Nordic countries.

5.5.2 Second iteration

A second iteration of studying impacts on inertia by cross-border flows through HVDC links.

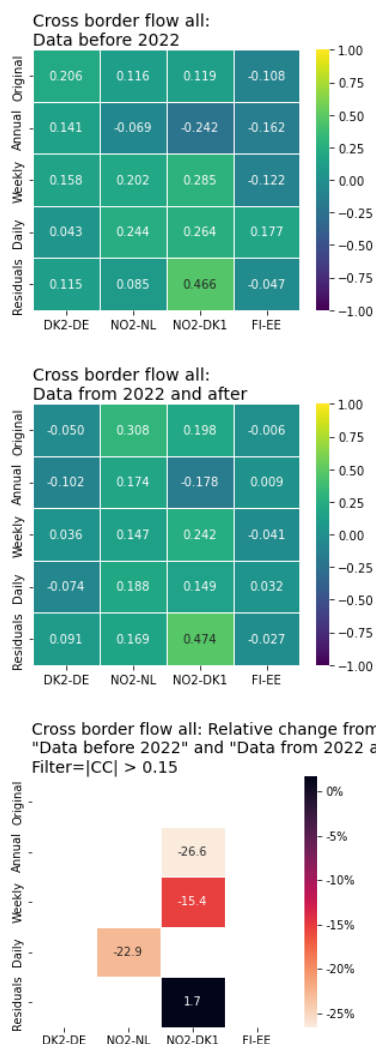


Figure 21. Inertia correlation with cross-border flow of Nordic HVDC links excluding Sweden (divided by location). Top: Assessment period 2015 - 2021. Middle: Assessment period 2022 and after. Bottom: Relative change between both assessment periods, for inertia correlation above a set threshold.

5.6 INERTIA CORRELATION: TRANSMISSION UNAVAILABILITY

The time series consists of the aggregated transmission unavailability in MW over a period when transmission across bidding zone borders was unavailable, specifically registered unavailable assets in interconnections and in the transmission grid that reduce cross-zonal capacities between bidding zones by 100 MW or more. Values are given in MW over the period the transmission source or sources were unavailable. Data is missing for flows between SE3-DK1, SE4-DK2, SE4-DE, and SE4-LT.

A fairly strong positive correlation between cross-border flows through NO2-DK1 and residual can be seen in both cases. It can also be noted that the annual and residual correlations are of opposite signs.

No large changes can be observed between data before 2022 and data from 2022 and after.

Any positive correlation between inertia and flows from Denmark towards Germany has mostly changed to small negative correlations during the year 2022 and after.

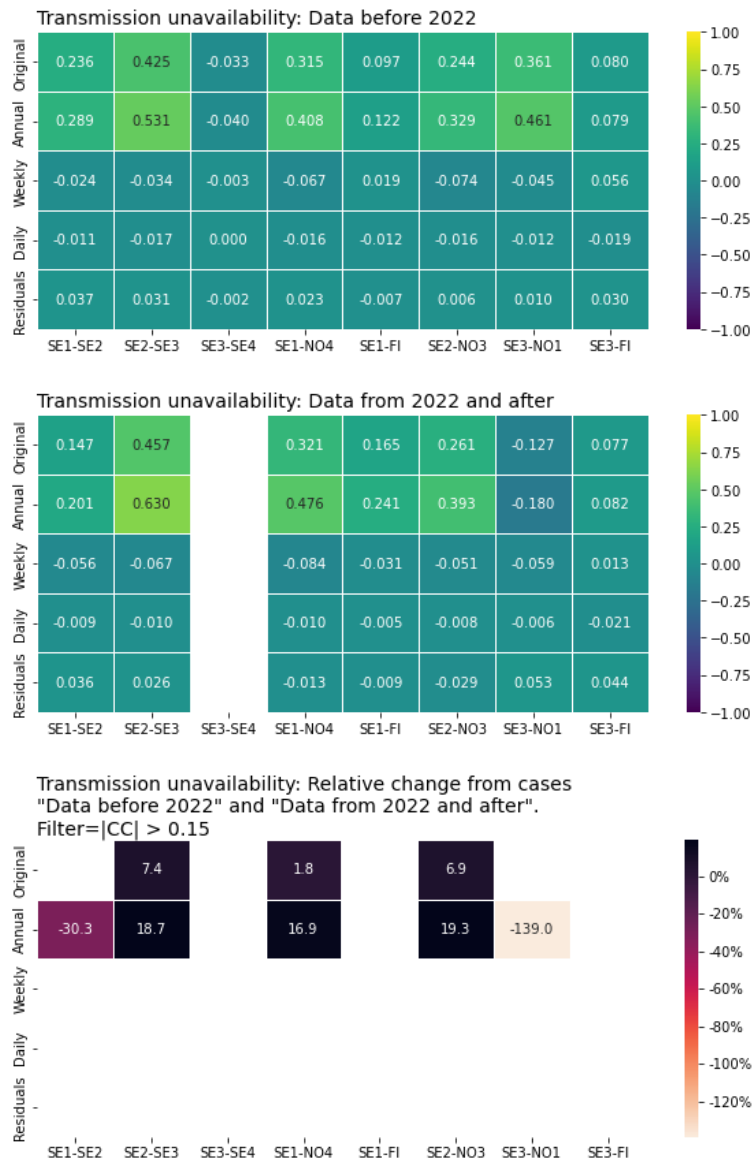


Figure 22. Inertia correlation with transmission unavailability within and from Sweden (divided by location). Top: Assessment period 2015 - 2021. Middle: Assessment period 2022 and after. Bottom: Relative change between both assessment periods, for inertia correlation above a set threshold. No registered events occurred in SE3-SE4 after 2022.

Unavailable transmissions have little or no impact on trends with shorter horizons, e.g., daily trends or residuals. Unavailable transmissions between SE2-SE3 seem to strongly correlate with inertia, while any disruptions of flows originating in SE3 only showed some correlation before 2022 in the case of transmissions unavailable between SE3-NO1.

5.7 INERTIA CORRELATION: GENERATION UNAVAILABILITY

The time series consists of aggregated unavailability in MW over a period when generation sources within a bidding zone were operating with reduced availability. Nuclear generation is located in bidding zones SE3 and FI.

5.7.1 Forced unavailability

There are few indications that any reported forced outages, resulting in periods of reduced production and generation, impact the system inertia.

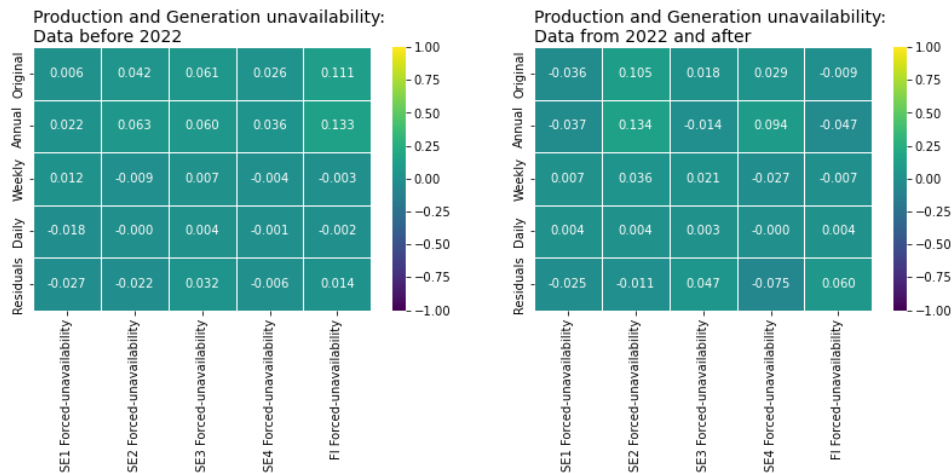


Figure 23. Inertia correlation with forced generation unavailability in Sweden and Finland (separated by location). Left: Assessment period 2015 - 2021. Right: Assessment period 2022 and after.

A change can be noticed in SE2 in recent years, but the CC remains small, making it difficult to imply any covariance between unavailability and inertia in this kind of study. This is due to long periods with no registered events of unavailability, as can be seen in Figure 24, resulting in inertia being compared to values of 0 for most of the time.



Figure 24. Plots of timeseries with inertia and forced unavailability in SE3 and FI.

5.7.2 Planned unavailability

Results indicate a moderate correlation between decreased generation availability due to planned maintenance and changes in inertia, especially in bidding zones SE3 and FI. The annual trend's CC increases for years after 2022 in SE3, which can be a result of greater dependency on nuclear power and the impact of periods of unavailable nuclear power on system inertia.

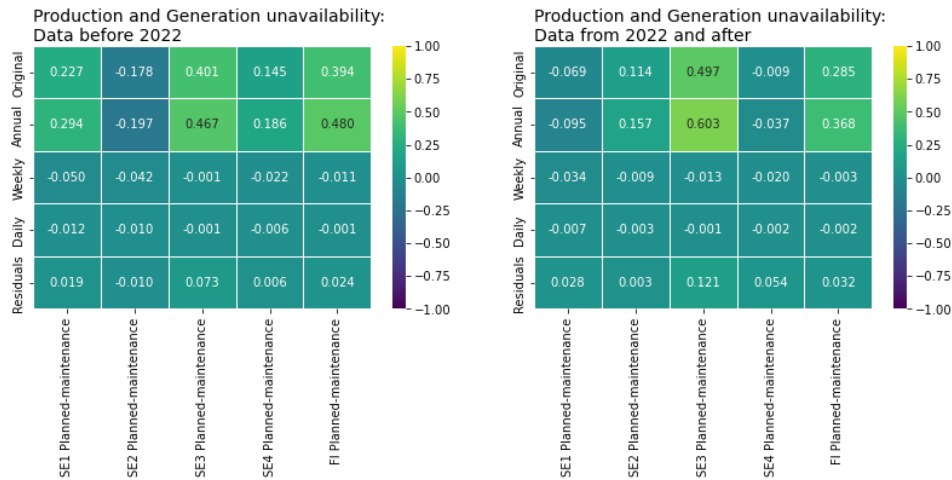


Figure 25. Inertia correlation with planned generation unavailability in Sweden and Finland (separated by location). Left: Assessment period 2015 - 2021. Right: Assessment period 2022 and after.

A negative correlation in SE2 for the years prior to 2022 changed to positive correlations in the years after 2022. The covariance of power generated in SE1 had a negligible impact during the year 2022 and afterward.

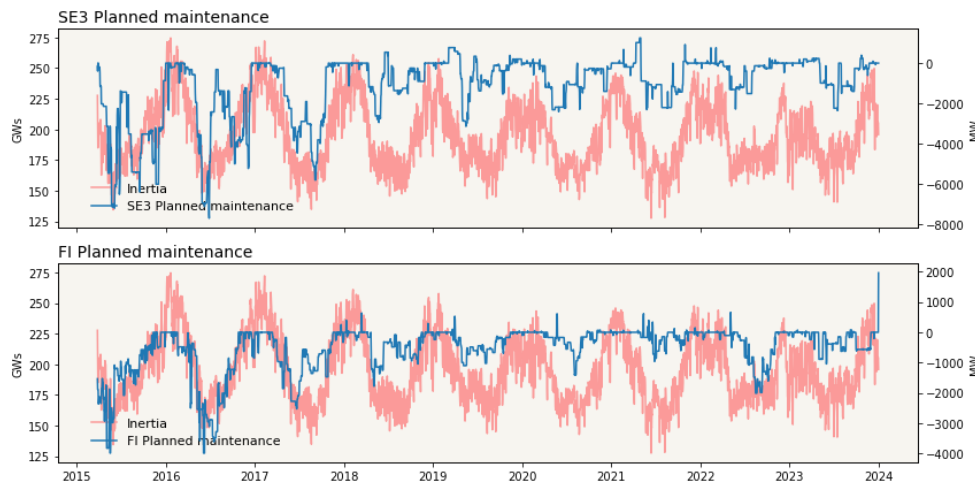


Figure 26. Plots of timeseries with Inertia and planned unavailability in SE3 and FI.

Events of planned unavailability have been registered more frequently, enabling the study of the correlation between planned unavailability and inertia. Planned unavailability appears to have a greater impact compared to forced unavailability. Additionally, any period with significant drops in available production seems to correspond to local fluctuations in the plotted inertia, as shown in Figure 26.

5.8 INERTIA CORRELATION: DAY AHEAD SPOT PRICE

Values consist of registered day ahead electricity spot prices from the Swedish bidding zones.

The correlation between price and inertia has increased over the last two years compared to the results for data before 2022, as seen in Figure 27, and an increased positive correlation between the original inertia time series and price data. Prices in

bidding zones SE3 and SE4 are more impacted by inertia trends with shorter horizons, such as weekly and daily trends, and residuals. In contrast, the prices in SE1 and SE2 seem to be affected only by the annual trend and the residuals.

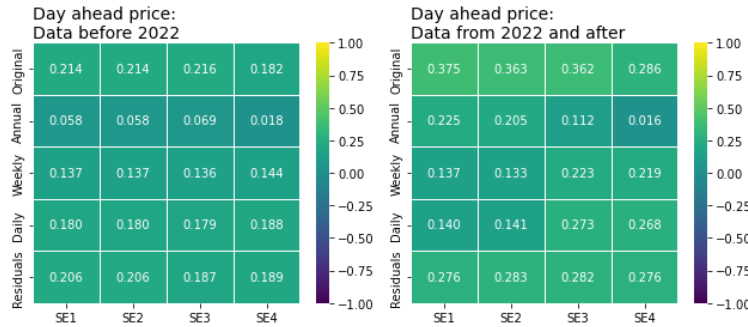


Figure 27. Inertia correlation with day ahead electricity spot prices in the Swedish bidding zones. Left: Assessment period 2015 - 2021. Right: Assessment period 2022 and after.

Correlation coefficients indicate that fluctuations in price follows the fluctuations in inertia. This can be the result of lower prices when renewables are producing power, which can result in energy available at low cost, contributing to less inertia.

5.9 DISCUSSION

Robustness indicators based on inertia correlation pose an interesting contribution to the completeness of the robustness assessment.

This study reveals several important insights about the impact of different types of power generation and other factors on the kinetic inertia of the Nordic power system. Wind power in southern Sweden seem to have a significant negative impact on the residual trend of kinetic inertia, introducing fast changes and reducing inertia during power production. This effect is also observed in northern Sweden and Finland, though to a lesser extent.

The positive impact of nuclear power on system inertia has decreased in recent years, particularly in Finland. There is a notable change in correlation coefficients between periods before and after 2022, despite the fact that Olkiluoto 3 was placed in full operation during 2023. Increased solar penetration has negatively affected the annual trend of inertia, especially during the summer months. This is also related to the planned maintenance of nuclear plants during these periods.

Hydro power's role in both fast and slow correlation has increased, as reflected in a nearly 50% change in correlation coefficients from data before 2022 compared to data after 2022. The aggregated electrical demand for each Swedish bidding zone shows a reduced negative correlation with inertia in recent years. While the load curve remains consistent, the inertia curve's periodic waveform has transformed, reducing the correlation between the two, which could indicate a tendency towards higher over-frequency when losing load.

Historically, high positive correlations for cross-border flows within Sweden and neighboring zones have diminished over the last two years, possibly due to changed flows. Flows from Sweden to Norway show negative correlations, indicating power flow from Norway during high inertia periods. Transmission

unavailability shows little impact on short-term trends but strongly correlates with inertia between SE2-SE3. Disruptions originating in SE3 showed some correlation before 2022.

Based on these results, a deeper assessment of the robustness in relation to power transfer corridors poses an interesting path forward, which is presented in detail in chapter 6.

There might be some limits identifying any fast changes in kinetic inertia, due to long periods of time investigated with the possibility of results canceling each other. A follow-up study with shorter periods of time could be a solution to identify any impact of rapid fluctuations and fast changes.

6 Robustness indicators: transfer corridor unavailability and utilisation rate

This chapter presents results from analyses of open-source data to study whether the Nordic Power System has become less robust during the time period 2015 – 2023. The study introduces three robustness indicators: Transfer Corridor Unavailability, Transfer Corridor Utilisation Rate and Cancelled Planned Outages. Furthermore, a special study of the development of the actual power flows in transfer corridors SE1-SE2 and SE2-SE3 is presented in the chapter.

Regarding the usefulness of the indicators, it is concluded that the data published in the public domain concerning Cancelled Planned Outages is not sufficient in order to draw any solid conclusions about power system robustness. However, the possibility of a maintenance back-log being formed cannot be rejected and would need further investigation.

When it comes to the overall power system robustness a combination of the Unavailability and Utilisation Rate indicators provides evidence of a trend towards a decrease in power system robustness during the time period of 2015 to 2023. Therefore, the initial hypothesis that the Nordic Power System has become less robust cannot be rejected.

6.1 INTRODUCTION

From the analysis of robustness indicators on *Inertia correlation*, presented in chapter 5, power transfer corridors have been selected for further analysis. Therefore, in this section we investigate to what extent the development of the power system robustness may be evaluated using data from transfer corridors that are publicly available from the ENTSO-E transparency platform [25]. The aim is to develop indicators of system robustness by using only publicly available market data. Using these indicators the hypothesis that the power system has become less robust is evaluated. The work is focused on the Nordic power system and as such, only the transfer corridors between Sweden, Norway, and Finland are included in the analysis.

Looking at the graph in Figure 28 showing the unavailability and utilisation rate for transmission corridor SE2-SE3 over the years 2015-2023, it seems as though the unavailability is increasing, at the same time as the utilisation of the corridor is also increasing. This may indicate that the system is being operated closer to its limits and that operating margins are being reduced. To investigate these matters in more detail the following sections focus on the robustness indicators: Transfer Corridor Unavailability, Utilisation Rate, and Cancelled Planned Outages.

This work has involved a lot of data analysis using open-source market data from ENTSO-E [25], and sometimes there has been an insufficient amount of data, making some analysis impossible, e.g. for certain corridors. In such cases the

results for this corridor have been intentionally excluded and will not be in the analysis or shown in the plots.

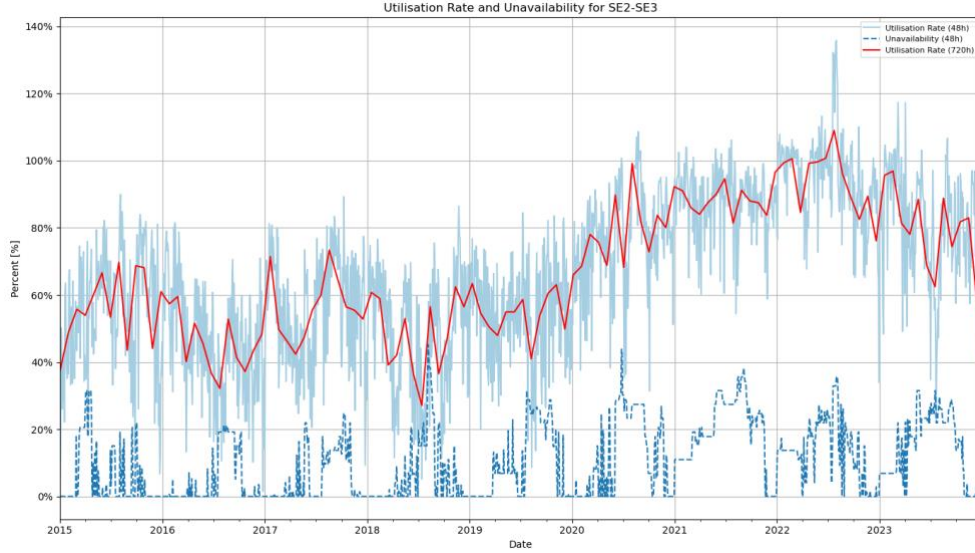


Figure 28. Utilisation Rate as an 48h average (light blue curve) with an overlaid 720h average (red curve) and Unavailability (dashed curve) for SE2-SE3 during 2015 to 2023.

6.2 TRANSFER CORRIDOR UNAVAILABILITY

The unavailability indicator is a measure of the proportion of the maximum rated Net Transfer Capability (NTC_{max}) which is available to the market on average, calculated for each year.

The Transfer Corridor Unavailability for corridor i and year j is defined as:

$$U_{ij} = \frac{\sum 1 - \left(\frac{NTC_i}{NTC_{max_i}} \right)}{35040}$$

where NTC_i is the Net Transfer Capability presented one day-ahead and NTC_{max_i} is the maximum rated NTC for every transfer corridor, which is published in [29]. The constant 35040 is simply 8760 h per year $\times$ 4 since the time resolution for the calculations is set to 15 minutes. The unavailability may also be expressed in terms of percent, where 0% means that no power could be transferred during that time period, and 100% means that the maximum rated transfer capacity could be utilised during the entire time period.

An example of the unavailability indicator for transfer corridor SE2-SE3, is shown in Figure 29, calculated for every 15 minutes and presented as a 72h average. In Figure 30, a straight line is fitted to the mean unavailability for corridor SE2-SE3 for each year during the studied time period. A significant increase in the mean unavailability can be seen in the figure, which means that the average available capacity of the transfer corridor has been decreasing during that time period.

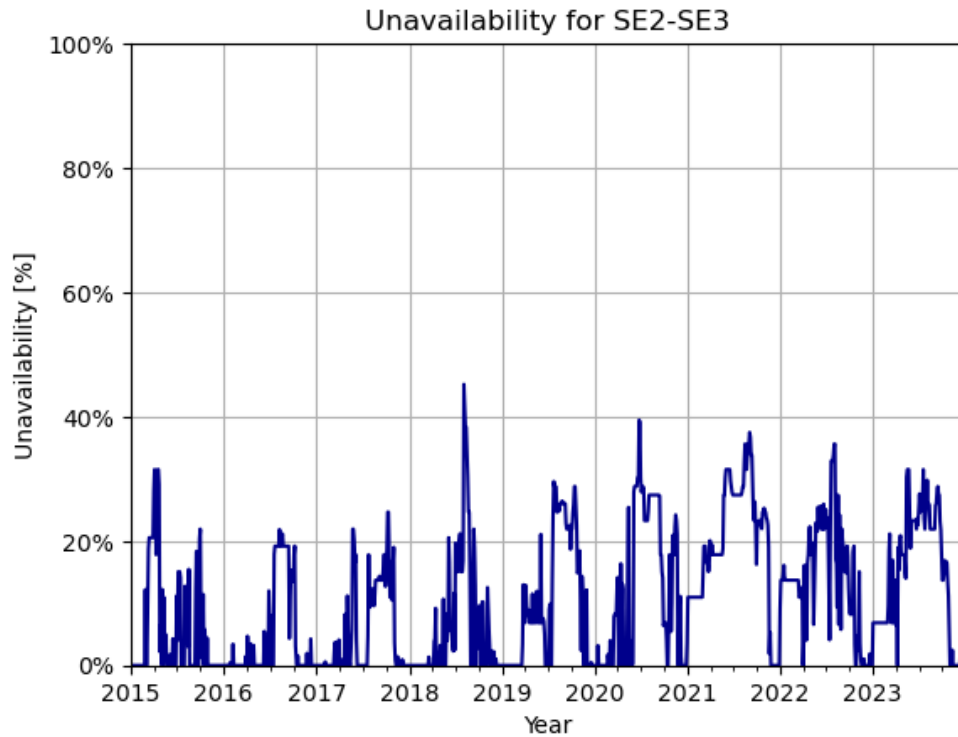


Figure 29. The Unavailability for transfer corridor SE2-SE3, as a 72h average for the years 2015-2023.

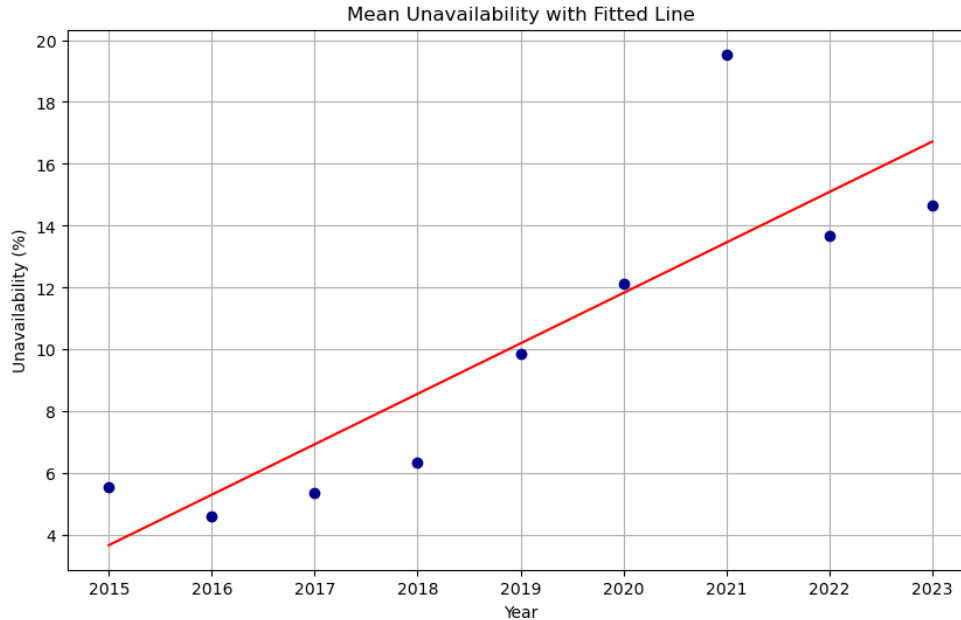


Figure 30. The mean unavailability for transfer corridor SE2-SE3, during 2015 to 2023.

In Figure 31 straight lines are fitted to the mean values of the unavailability of all studied transfer corridors in the Nordic Power System. From the figure, it can be seen that all but two studied transfer corridors have had an increased unavailability from 2015 to 2023. To study this in some more detail, the unavailability has been divided into three groups: internal Swedish corridors,

internal Norwegian corridors and corridors between the respective countries, as shown in Figure 32. The figure shows that the decrease in unavailability is present in two internal corridors in Norway. These corridors are quite limited in their transfer capabilities, with an NTC_{max} of 400 MW (NO3->NO4) and 500 MW (NO1->NO3), respectively [29]. Furthermore, the power only flows in that particular direction 3.6% of the time with an average power of 96 MW and 38.4% of the time with an average power of 155 MW, respectively. Consequently, these corridors do not significantly affect the overall situation of the Nordic Power System. The trend for the Nordic Power System is thus quite clear when it comes to a total increase in transfer corridor unavailability during the years 2015 to 2023.

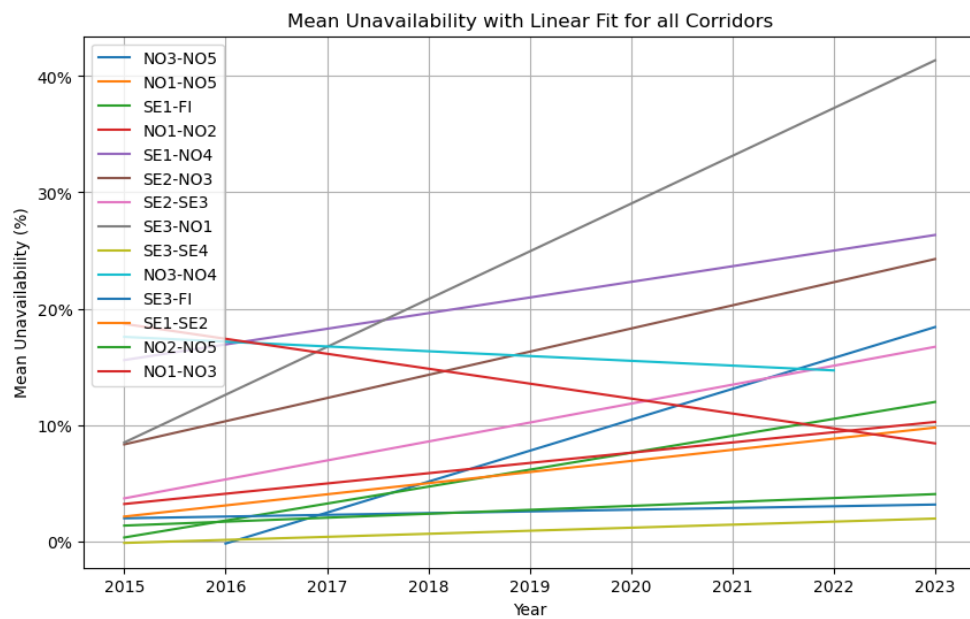


Figure 31. The mean Unavailability for all studied transfer corridors in the Nordic Power system.

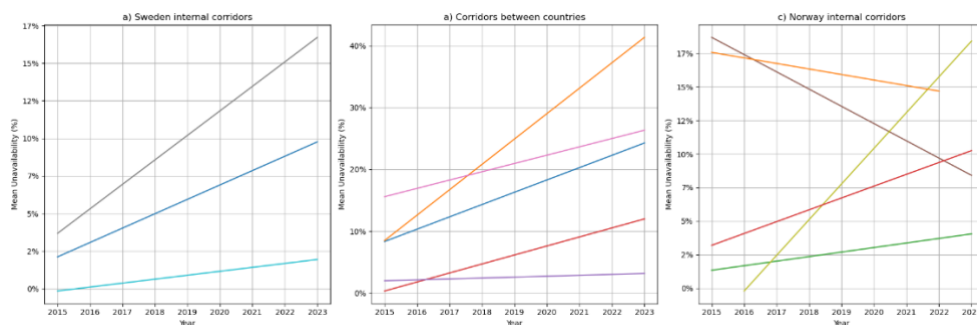


Figure 32. The mean Unavailability for all studied transfer corridors in the Nordic Power system divided by a) Sweden internal corridors b) corridors between the countries c) Norway internal corridors.

However, an increase in the Unavailability of the transfer corridors over time cannot, by itself, be seen as a sign of a reduction in power system robustness. It is only worrying if the Unavailability is high at the same time as the demand for the corridor's full capacity is needed. Consequently, the focus of the investigation in the next section is the Transfer Corridor Utilisation Rate.

6.3 TRANSFER CORRIDOR UTILISATION RATE

The Utilisation Rate is a measure of how close on average, the actual power flow is to the limit set by the Net Transfer Capability (NTC). The Transfer Corridor Utilisation Rate for corridor i and year j is defined as:

$$UR_{ij} = \frac{\sum \frac{F_i}{NTC_i}}{35040}$$

which is the average Utilisation Rate per transmission corridor i , where NTC_i is the Net Transfer Capability as presented one day-ahead, and F_i is the actual power flow. The Utilisation Rate may also be expressed in terms of percent, where 0% means that no power transfer is needed and 100% means that all of the available NTC is needed.

In Figure 33 a graph showing a straight line fitted to the mean Utilisation Rate of transfer corridor SE2-SE3 for the time period from 2015 to 2023, clearly demonstrates an increasing trend. In Figure 34, the same results are shown for all transfer corridors. From the figure, there seems to be an increasing trend for the utilisation as well on average, for all corridors.

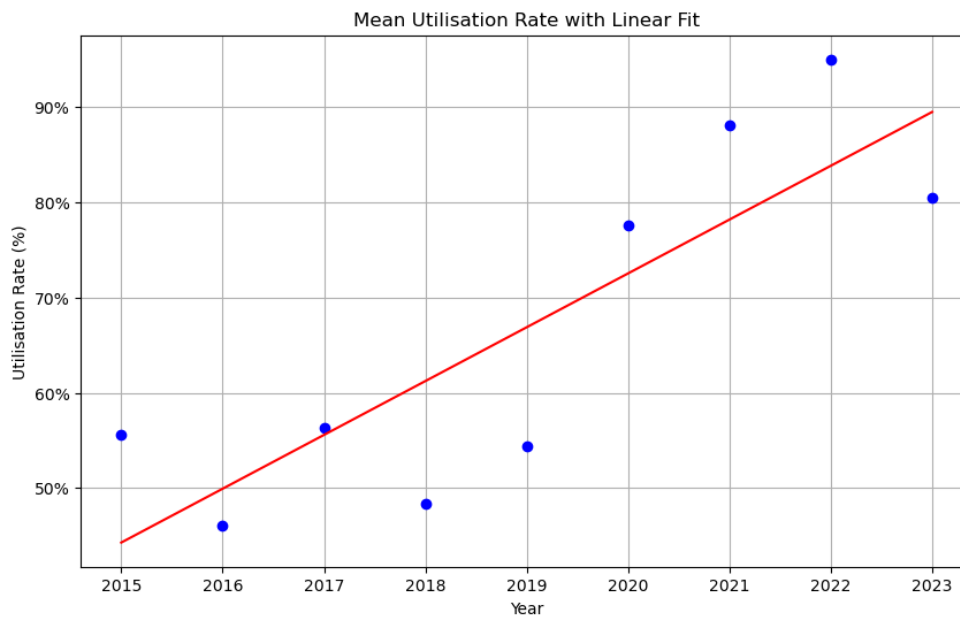


Figure 33. Mean Utilisation Rate of transfer corridor SE2-SE3, during 2015 to 2023.

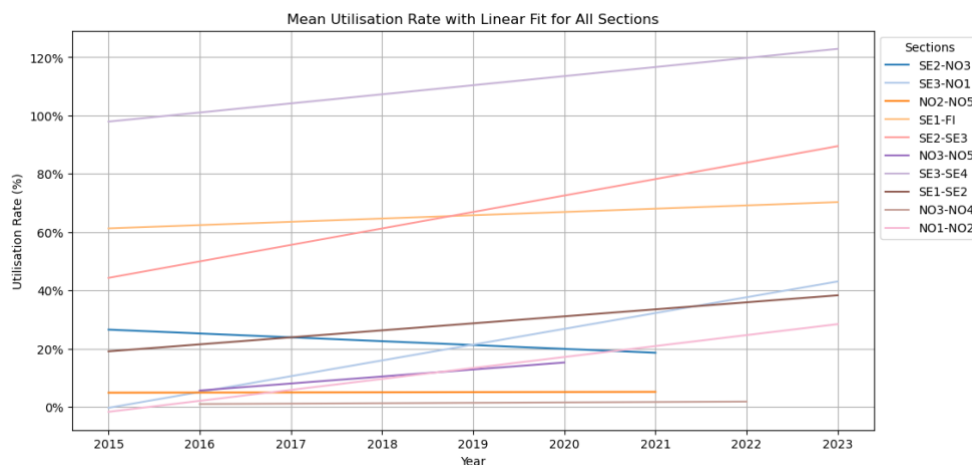


Figure 34. Mean Utilisation Rate for all transfers corridors (with enough data) in the Nordic Power System during 2015 to 2023

The reason for the increase in Utilisation Rate may be due to an increase in power flow as well as a decrease in *NTC*. Regardless of the reason, the effect is that the margins are decreasing and the indicator may thus be considered a measure of robustness.

6.4 ACTUAL FLOW

Input from the reference group led us to study the pattern of the actual flows across the transfer corridors SE1-SE2 and SE2-SE3, looking specifically at the direction of the flow.

Looking first at the transfer corridor SE1-SE2, Figure 35 shows that the flow has been mostly going from SE1 to SE2 during 2015 to 2020 but with a significant proportion of the flow also going in the opposite direction. Flow from SE1 to SE2 has a positive direction in the figure and is thus the power above the red line, and the opposite goes for flow in the direction from SE2 to SE1.

Figure 36 shows normal distributions fitted to the historical power flows for each year from 2015 to 2023. Positive flow, where the power is above 0 MW in the figure, indicates that power is flowing from SE1 to SE2. Figure 37 shows the trend of the expected values from Figure 36 with a fitted linear trend line. From the figure it can be seen that during 2021 to 2023 the average flow from SE1 to SE2 has almost doubled. During the same period the flow in the opposite direction has been heavily reduced, as can be seen in Figure 38, where the blue bars indicate the proportion of power flow from SE2 to SE1 and vice versa for the red bars.

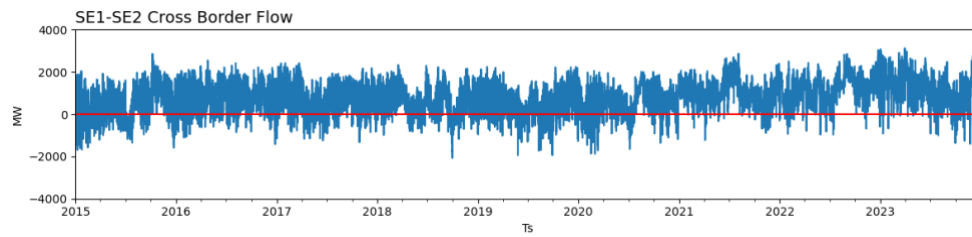


Figure 35. Actual flow across SE1-SE2 from 2015 to 2023, positive MW means flow in the direction SE1->SE2 and negative means SE2->SE1

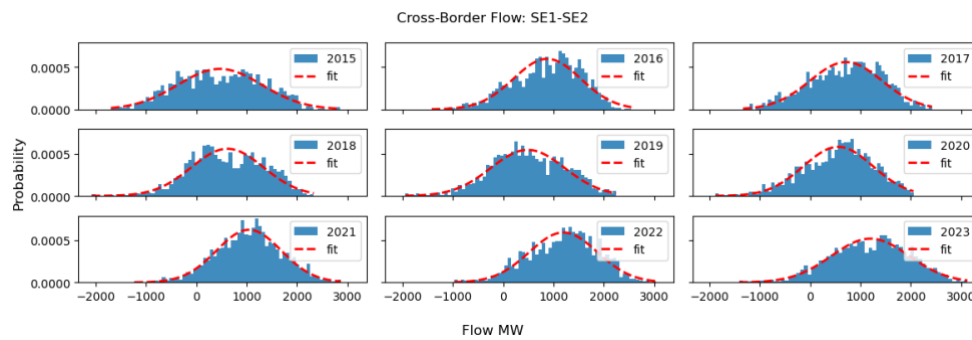


Figure 36. Actual flow for SE1-SE2 fitted to a normal distribution for each year from 2015 to 2023, positive MW means flow in the direction SE1->SE2 and negative means SE2->SE1

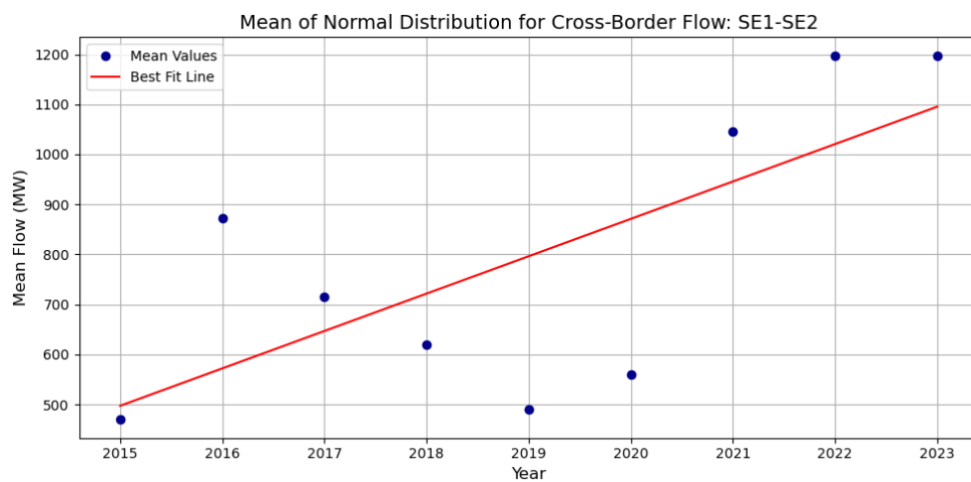


Figure 37 Mean of fitted normal distribution of actual flow of SE1-SE2 during 2015 to 2023

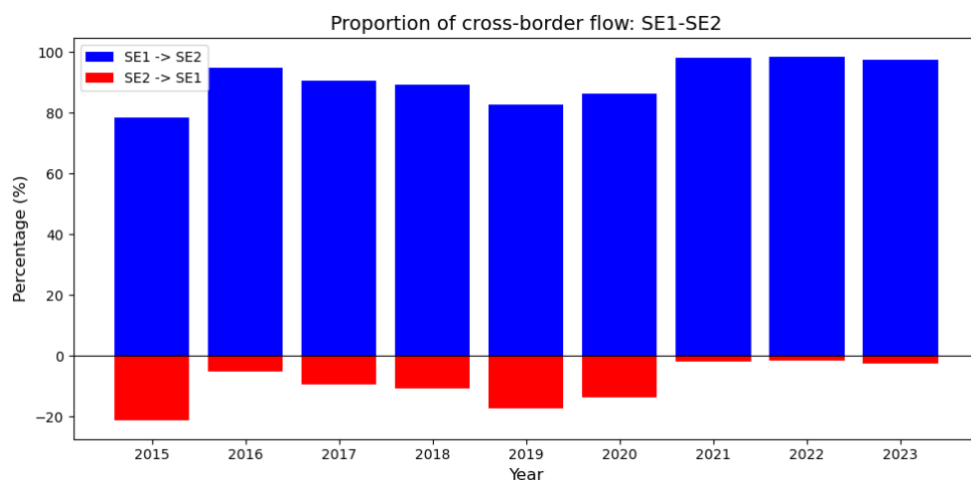


Figure 38. Proportion of the power flow across SE1-SE2, positive numbers means SE1->SE2 and negative numbers means SE2->SE1

For transfer corridor SE2-SE3 the trend is somewhat similar to that of SE1-SE2, with the exception that the flow has, more or less always, been going in the direction SE2->SE3, as can be seen in Figure 39 and Figure 42. When looking at the normal distributions fitted to the actual flow in Figure 40 it can be seen that starting in 2020 the variance is decreasing due to the absence of hours with smaller power flows. The power transfer is higher for longer periods of time starting from 2020. This is also supported by studying Figure 41, where the trend is quite clear that the mean power transfer is increasing every year. Since there is almost no flow from SE3->SE2, as can be seen in Figure 42, this increase is caused by the increase in power transfer.

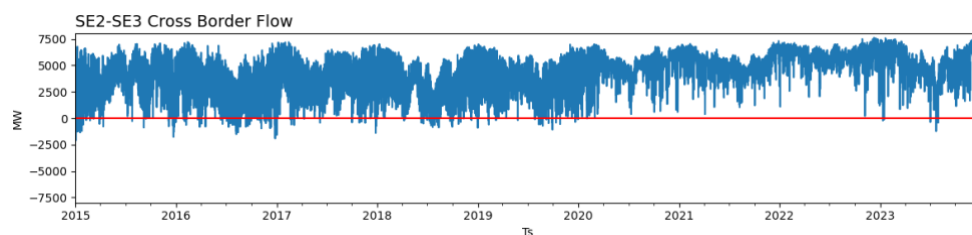


Figure 39 Actual flow across SE2-SE3 from 2015 to 2023, positive MW means flow in the direction SE2->SE3 and negative means SE3->SE2

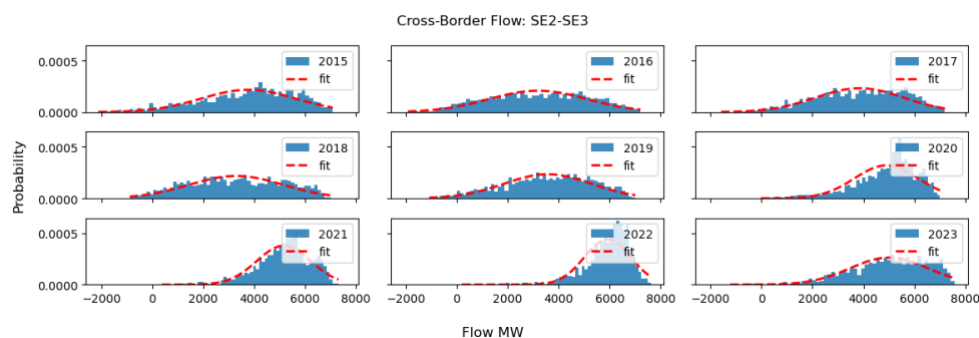


Figure 40. Actual flow for SE2-SE3 fitted to a normal distribution for each year from 2015 to 2023

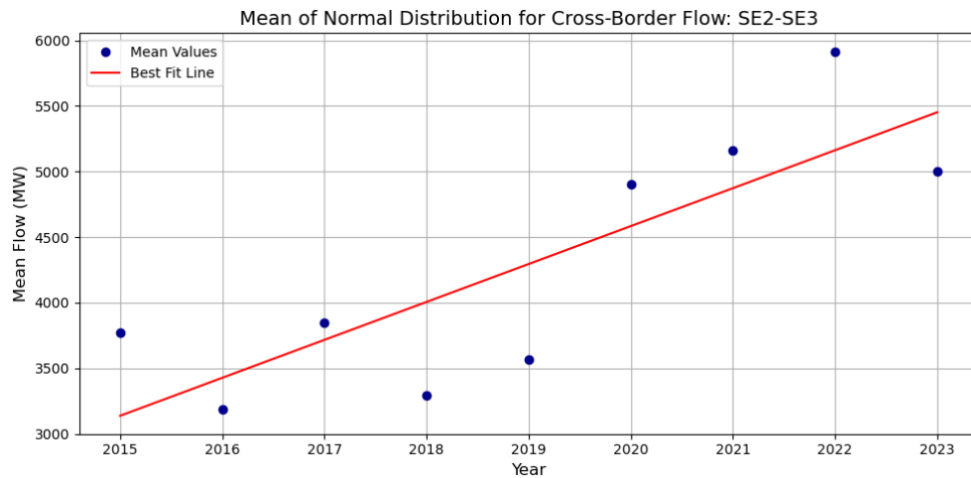


Figure 41. Mean of fitted normal distribution of actual flow of SE2-SE3 during 2015 to 2023

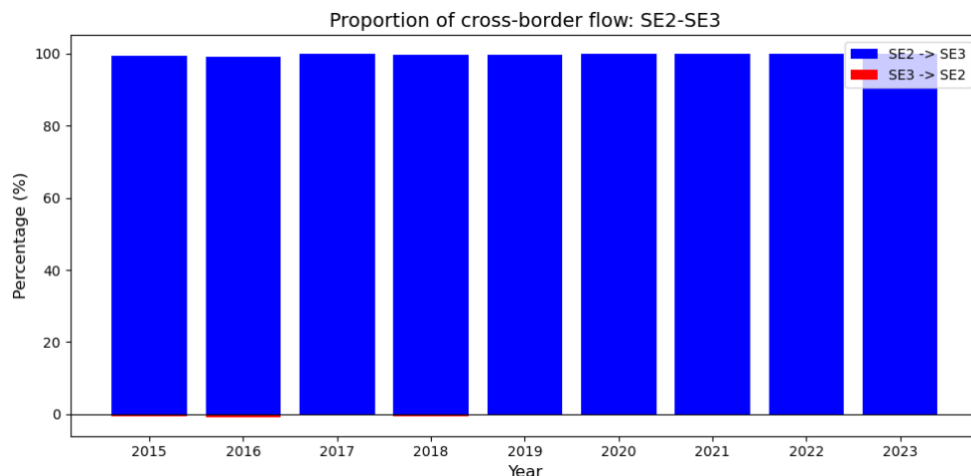


Figure 42. Proportion of the power flow across SE2-SE3, positive proportion means SE2->SE3 and negative numbers means SE3->SE2

6.5 CANCELLED PLANNED OUTAGES

Another cause for concern regarding the future robustness of the Nordic Power System is the number of planned outages that, for some reason, have been cancelled. The assumption is that a majority of these outages are planned to carry out necessary maintenance to overhead lines and to substation equipment and that a cancelled outage means deferring that maintenance to a later time. If such a pattern is repeated over the years this may cause a maintenance backlog that could affect both the system reliability (increased failure rates) as well as its availability (more and longer outages for maintenance needed in the future).

Furthermore, it may be argued that an increase in the proportion of planned outages that are being cancelled is a sign of reduced robustness in itself, as it means that some expected level of security has not been fulfilled at the time of the outage. However, since it is not possible for us to deduce why the planned outages were cancelled, it is uncertain to which degree this argument holds. For instance, a

planned maintenance action may have been carried out as live-work, rather than taking an outage.

An indicator for evaluating the number of cancelled planned outages is formulated as:

$$CM_{ij} = \frac{\sum \text{Cancelled}}{\sum \text{Planned} - \sum \text{Cancelled}}$$

which is the proportion of planned outages that has been cancelled for transmission corridor i and year j . The CM indicator may also be expressed in terms of percent, where 0% means that no planned outages were cancelled and 100% means that all planned outages for maintenance have been cancelled for that corridor and time period.

Figure 43 shows straight lines fitted to the yearly average of CM for all corridors for the period 2015-2023. The figure illustrates that all corridors except one have had a significant increase in the proportion of planned maintenance outages that have been cancelled. The trends shown in Figure 43 could be an indication that a significant backlog of maintenance is accumulating.

However, from the publicly available data used in this study, it is not possible to deduce whether a maintenance backlog is actually forming or if all cancelled maintenance actions from one year are being carried out in the following years without adding new cancelled outages.

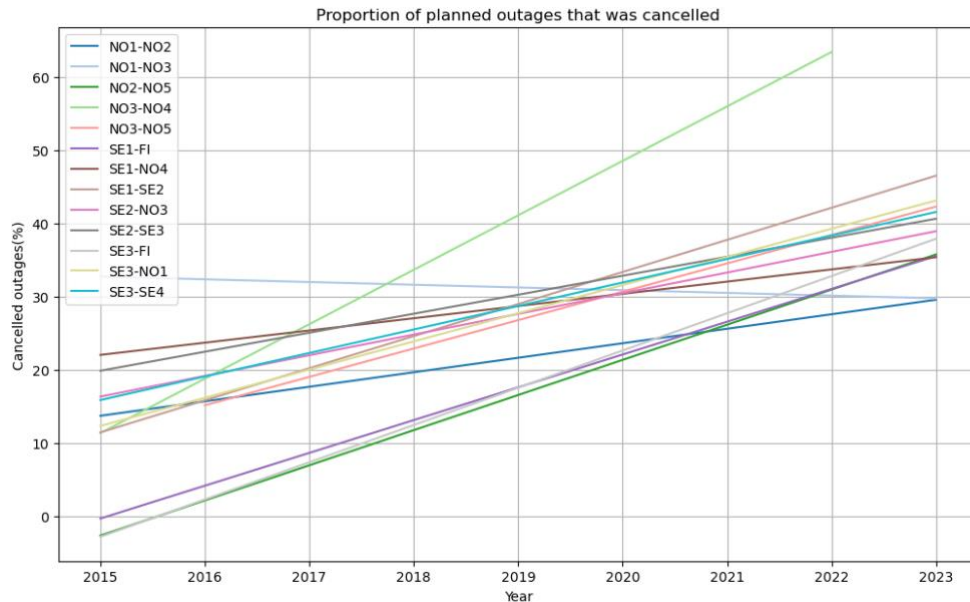


Figure 43. Straight lines fitted to the yearly average of planned outages for maintenance that were cancelled for all corridors for the period 2015-2023

Additionally, the trend may not be as clear as Figure 43 indicates. By taking the yearly averages of CM for all transfer corridors and fitting a normal distribution, a somewhat different pattern may be seen in Figure 44, where the error bars indicate a confidence interval of one standard deviation. It appears as the proportion of cancelled outages is fairly stable along the span of 10-30%/year on average, with the exception of 2021 and 2022, which stand out as years with a very large

proportion of planned outages being cancelled. The question is whether or not this planned maintenance has been carried out in the later years or if a maintenance backlog is being formed. The publicly available data used in this study is not detailed enough to let us answer this question confidently and therefore the presence of cancelled planned outages may not, by itself, be used as a robustness indicator.

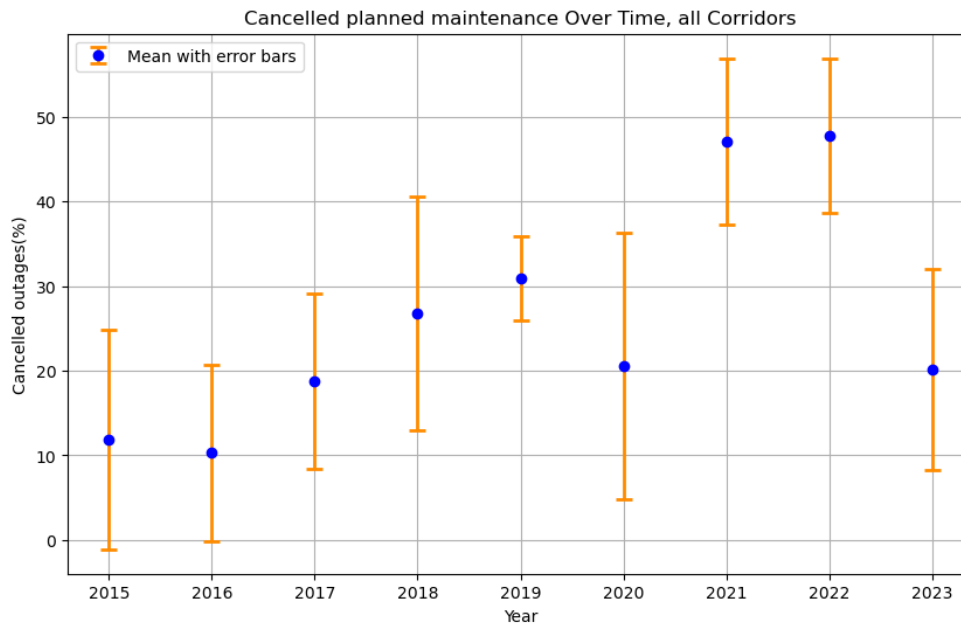


Figure 44. Normal distributions of the proportion of planned outages that have been cancelled in the Nordic Power system, with error bars for one standard deviation.

6.6 DISCUSSION

As these analyses heavily rely on data regarding Net Transfer Capabilities for different transfer corridors, this type of analysis may not be possible as the Nordic Power System operators switch to the Nordic Flow-based Capacity Calculation Methodology (Nordic CCM) at the end of October 2024 [30], making any future tracking of these indicators difficult.

6.6.1 Data issues

The values of NTC have been collected from the ENTSO-E transparency platform and these values are set on the day-ahead. However, there may be more capacity available than the $NTC_{\max}$ and this is due to the fact that the TSO does not know in advance which generators will actually be running during a certain hour or weather conditions may sometimes change in a favourable way increasing the capacity. This means that there may be more capacity available than $NTC_{\max}$ if the “right” generators are running, and “only” $NTC_{\max}$ if some other generators (located elsewhere in the price area) are running. Since it is not certain on the day ahead if the favourable generators will actually be running (generators may break down etc.) this higher than $NTC_{\max}$ capacity cannot be made available until the actual hour. The result is that there will be a, sometimes significant, difference

between the day-ahead *NTC*, which has been used in the calculations in this report, and the actual *NTC* given on the hour. This behaviour is clear from Figure 45, where the pattern of actual flows is being larger than the *NTC*, and even NTC_{max} , for that transfer corridor.

There are no clear signs of this effect being a system-wide trend and is in fact only present for the corridors SE3-NO1, SE1-FI1 and SE2-SE3.

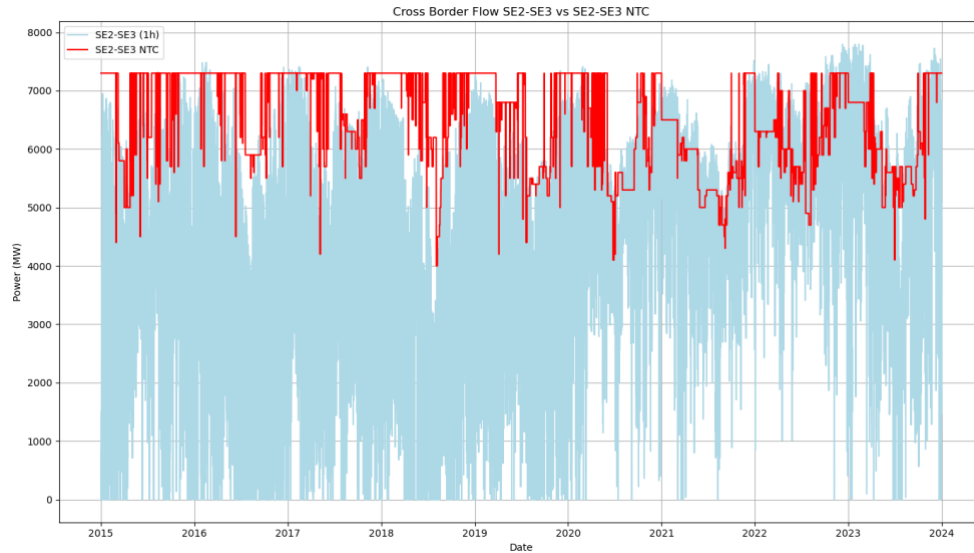


Figure 45. Actual flows (blue curve) and the *NTC* (red curve) given on the day-ahead for SE2-SE3 during 2015 to 2023.

In Figure 46 instances where the actual flows across SE2-SE3 are (sometimes significantly) higher than one day-ahead values are stored at ENTSO-E. One explanation for this may be that sometimes one (or more) by-passed series capacitors have been taken into service earlier than previously planned.

These phenomena also means that the values for the Utilisation Rate will be higher than 100% for the corridors SE3-NO1, SE1-FI1 and SE2-SE3, during these specific hours, see example in Figure 28. This, however, will not affect the overall conclusions of this study, since the increase is reflected in the linear trends, as demonstrated in Figure 33.

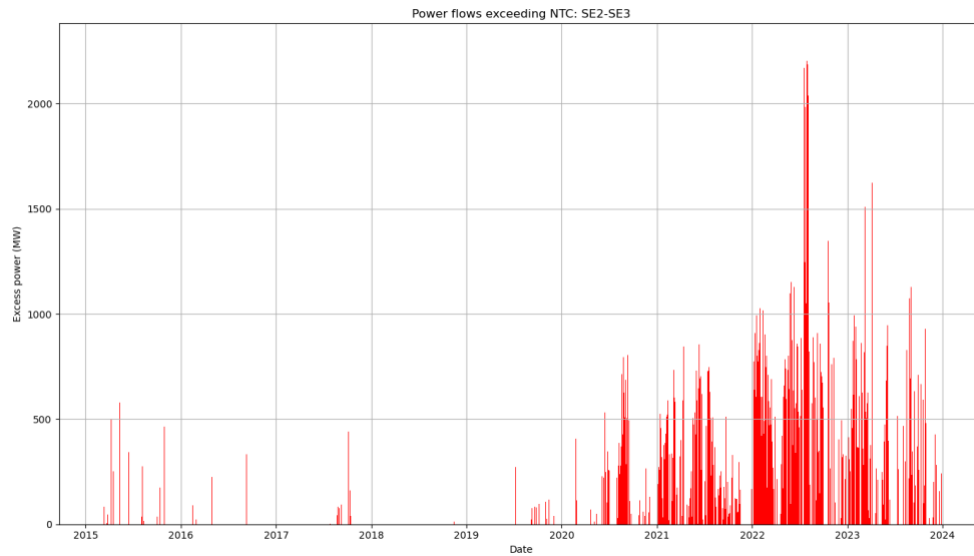


Figure 46. Actual flows across SE2-SE3 that exceeds the day-ahead NTC.

Since this study relies only on publicly available data which sometimes contain errors or missing data, there will be instances where different datasets do not match. This will typically manifest as certain corridors missing from some analysis, as in Figure 34 where only results from 10 of the 14 studies corridors are present.

6.6.2 Has the power system become less robust?

Figure 47 illustrates a proposed Robustness Indicator combining the slopes of the mean Utilisation Rate and mean Unavailability from Figure 31 and Figure 34, where the size of the circles is proportional to their NTC_{max} , respectively.

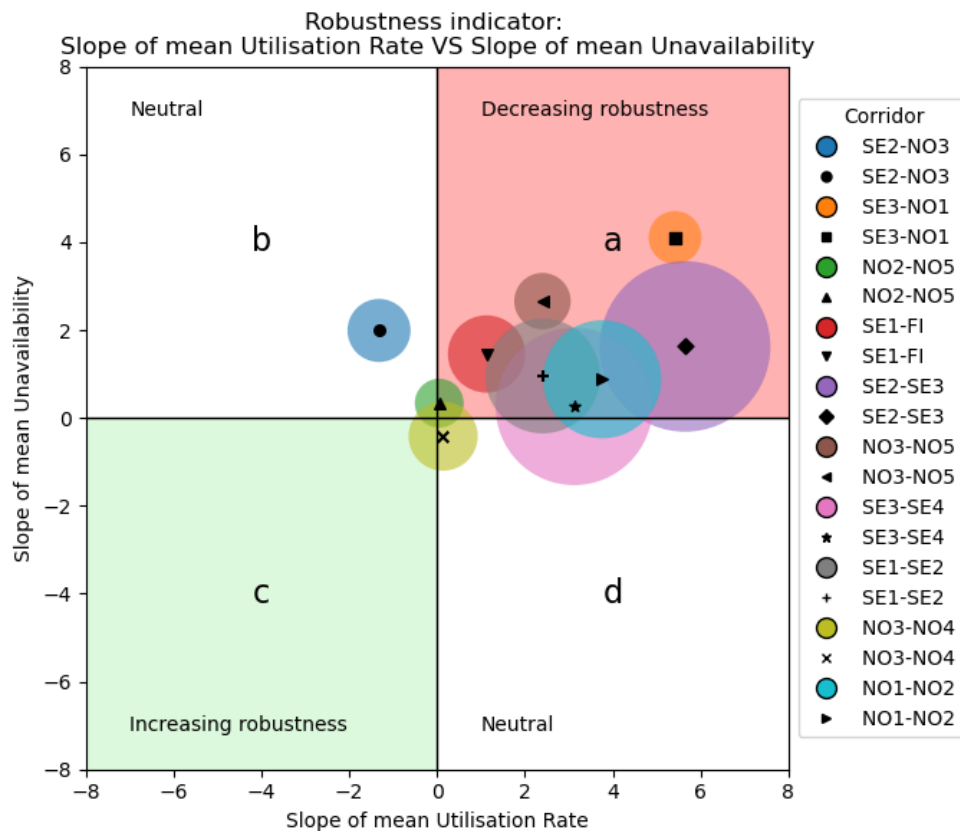


Figure 47. Robustness KPI combining the slopes of the mean Utilisation Rate and mean Unavailability together with the size of the NTC_{max} determining the size of the circles

The significance of each quadrant in the figure is:

- a) **Decreasing robustness.** In this situation both the Unavailability and the Utilisation Rate are increasing. This is problematic since available transfer capacity is decreasing while the demand is increasing. This leads to decreasing margins and is a sign of a reduction in robustness.
- b) **No clear indication.** The unavailability is increasing but this is not an immediate issue as the rate of utilisation is decreasing at the same time, and so is the demand for the transfer capacity. No clear conclusions regarding robustness can be drawn.
- c) **Increasing robustness.** Here the Unavailability is decreasing at the same time as the Utilisation Rate is decreasing. This means that the system is becoming more available at the same time as the demand for transfer capacity is decreasing leading to larger margins. The system robustness is increasing in this situation.
- d) **No clear indication.** In this quadrant, the Utilisation Rate is increasing and is being met by an increase in availability (decrease in Unavailability). No clear conclusions regarding robustness can be drawn.

The results illustrated in Figure 47 show that 91,6% of the system's transfer corridors (weighted by their respective $NTC_{\max}$) is located in quadrant a) with decreasing robustness, and 3,8% and 4,6% respectively in the neutral quadrants b) and c). No transfer corridor has seen an improved robustness, according to the proposed indicator.

In summary, based on the open data provided by the ENTSO-E transparency platform, the proposed Robustness Indicator clearly indicates that the Nordic Power System has, on average, become less robust during the studied time period of 2015 – 2023.

7 Conclusions

In this report, we present an assessment of robustness indicators aimed at providing insights into the evolving characteristics of the Nordic grid.

The work has addressed global and regional robustness indicators using open data, with a focus on three impact factors: 1) frequency; 2) inertia; and 3) transfer corridors.

Robustness is a broad expression, and in this report the following definition has been used: “Robustness reflects the power system’s ability to withstand an unexpected event without degradation in performance”.

Key findings include:

- **Frequency extremes:** Analysing the relationship between kinetic energy and frequency deviations offers insights into potential risks, aiding in operation and planning under various current and forecasted scenarios. Frequency robustness emerges as a relevant indicator for anticipating system responses to disturbances, especially in low-inertia situations.
- **Inertia correlation:** The study of inertia correlations with variables such as power generation, load, cross-border flow, production and transmission unavailability, and electricity spot prices, highlights how system inertia fluctuates over time. This correlation-based approach enriches the robustness assessment, providing a nuanced view of the factors affecting stability and resilience.
- **Transfer corridor unavailability and utilisation rate:** By analysing the combined impact of unavailability and utilization rates, the study identified a trend toward decreased robustness within the Nordic power system from 2015 to 2023. The observed rise in corridor utilization, alongside increasing operational constraints, highlight the need for effective management strategies to preserve grid stability.
- **Maintenance and cancelled outages:** The rising trend of cancelled planned outages may signal a maintenance backlog, potentially affecting long-term system reliability. While public data limitations prevent definitive conclusions on this issue, a more comprehensive review of maintenance practices and outage records would help assess the potential impact of delayed maintenance on system robustness. Should this trend continue, system operators may need to prioritize proactive maintenance schedules to avoid compounding operational vulnerabilities.

The project demonstrates the feasibility of developing both global and regional robustness indicators solely based on public data. Although this study provides a broad view of robustness, several limitations exist, including proprietary data access and the evolving implementation of remedial solutions. These limitations are influencing the extension of the conclusions which can be drawn from the results.

Solutions which are implemented to provide increased robustness need to be further addressed and their impact on specific robustness indicators should not be neglected. Specific measures, such as Fast-Frequency Reserves (FFR), system protection schemes, and other remedial actions, enables an increased grid utilisation without decreased robustness. New methodologies like flow-based capacity calculation, impact grid utilisation which can further decrease the required margins in the grid while not necessarily decreasing the robustness.

In addition, other aspects that are worth mentioning in the discussion on robustness include what level of robustness to aim for from a socio-economic perspective. Such considerations have not been part of this work.

This project highlight the importance of diverse robustness factors and their collective value in assessing power system robustness. The proposed composite robustness indicator, which combines the slopes of the mean utilisation rate and mean unavailability, is identified as a promising tool. Further evaluation of this indicator would provide greater insight its reliability and its implications of the evolution of the robustness of the Nordic power system.

8 Future work

Given the substantial data available for detailed studies, several recommendations can be made to enhance robustness indicators.

Ideas for future work include:

- **Enhanced Correlation Analysis:** By conducting time-segmented analyses of time-series data, future research could provide a more detailed view of individual parameter correlations. This would allow for the identification of extreme values in correlation factors, which could reveal rapid fluctuations and periods of unavailability.
- **Broader Scope of Analysis:** Future work could expand the analysis to include hydro power generation impact in Norway and assess how mitigation strategies and control unit limitations affect frequency extremes. These insights would deepen the understanding of robustness in a more geographically inclusive context.
- **Assessment of Maintenance Backlog:** Investigating the possibility of a rising maintenance backlog by developing methods to determine long-term probabilistic “envelopes” for future planned outages for maintenance. One concern is that these maintenance envelopes may be reduced as more planned outages are required for other planned work, such as investment projects. It would also be important to study any possible effects of the introduction of the flow-based methodology for capacity calculations on the strategic long-term outage planning.
- **Refinement of Composite Robustness Indicators:** Tracing the evolution of robustness indicators over time would provide valuable insights into trends in grid robustness. Additionally, investigating the uncertainty within these indicators would enhance the reliability of conclusions drawn from robustness assessments..

This project did not conduct any extensive assessment of local robustness indicators due to the absence of proprietary data. Studies of local robustness indicators could be of interest to address the robustness on the point of connection of an existing power plant as well as in the planning phase for a new power plant. A future project aiming to address local robustness indicators, could benefit from proceeding in three steps:

1. **Data Sharing Arrangement:** Establish a framework for sharing a predefined set of proprietary data, including high-resolution measurements from power quality meters and basic grid connection information for the targeted site.
2. **Data Collection and Analysis:** Gather measurement data and additional open data over a representative period that includes varied system states. If relevant historical data is available, this could serve as a basis for the analysis.

3. **Local Indicator Assessment:** Use the collected data to evaluate local robustness indicators, correlating site-specific statistics with global and local measurements from the study period to verify consistency.

9 References

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ROBUSTNESS INDICATORS FOR POWER SYSTEMS

Robustness reflects the power system's ability to withstand an unexpected event without degradation in performance.

The Nordic power system is undergoing significant transformations driven by the global energy transition toward renewable energy sources. This report aims to provide a comprehensive analysis of the power system's robustness by focusing on three impact factors: frequency, inertia, and transfer corridors.

The findings of this report point to the increasing pressure the Nordic power system faces as it adapts to higher levels of renewable energy integration and rising electricity demand. While the system has traditionally been resilient, the trends identified here suggest the need for proactive measures to mitigate emerging risks.

A new step in energy research

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