TYNDP 2022

System Needs Study

System dynamic and operational challenges

Final Version · May 2023

entsoe

ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the **association for the cooperation of the European transmission system operators (TSOs)**. The 39 member TSOs, representing 35 countries, are responsible for the **secure and coordinated operation** of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

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

Our mission

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

Our vision

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

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

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

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

Our values

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

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

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

Our contributions

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

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

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

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

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

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Ten-Year Network Development Plan 2022

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Hyperlinks are high-lighted in bold text and underlined throughout the report. You can click on them to access further information.

ENTSO-E System needs visualisation platform
https://needs.entsoe.eu

Questions?

Contact us as at **tyndp@entsoe.eu**

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Executive Summary

System-wide energy efficiency, direct electrification and increasing the share of renewable generation are the primary tools for decarbonising Europe. The scale of the energy transition and its impacts on the system is beyond compare. The installed capacity of renewable energy sources (RES) must be increased drastically to provide the energy necessary to cover both the increase in the electricity demand and the phase out of fossil fuels.

As a result, power will be generated increasingly by weather-dependent and electronically interfaced devices, and the share of synchronous generators providing inertia will be reduced. Since the current transmission system relies heavily on such synchronous generators, its behaviour will change significantly in response to this evolution. This poses a major challenge for the system's stability and, therefore, for the security of supply

The Ten-Year Network Development Plan (TYNDP) illustrate possible trends for the evolution of the energy system. Given this framework, this report illustrates the challenges related to maintaining a stable European transmission system. It aims to supply a clear basis for a wider discussion involving all system users and to identify adequate and timely solutions to meet system needs in terms of voltage and frequency support.

Given the scale of the energy transition, it is essential to acknowledge the challenges related to the evolution of the generation pool. As the transmission system is one of the main enablers of the integration of the RES potential of the European energy system, its configuration must adapt to the system's new characteristics.

Connection codes will be essential to ensure that necessary technical requirements related to grid-forming, inertia, frequency sensitivity, robustness against high RoCoF and voltage support are implemented by generators, HVDC and demand. Flexibility sources will be necessary from both the generation and demand sides and strong exchange capacity will be essential to enable power flows from these sources.

The system will face highly variable flows, with frequent changes of magnitude and direction. This will cause the grid to experience very high and very low loading conditions in rapid succession. In addition, the time needed for grid development and expansion is much longer than the time needed for RES deployment, which makes it challenging for TSOs to use the grid to its limits. Non-wire solutions can enhance the utilisation of existing and future infrastructure and complement the standard infrastructure development. Therefore, such solutions should be part of the optimal network development strategy.

The present report emphasizes that TSOs are already studying the new stability challenges and corresponding mitigation measures. TSOs are willing and ready to play their part in solving these challenges and this report points to system trends and recommendations for effective action.

Introduction

Based on the TYNDP scenarios, previous editions of the TYNDP Investigation of System Needs revealed trends in the system's evolution: more RES at all voltage levels; more power electronics, either in generation or high-voltage-direct-current (HVDC) connections; a highly variable mix of generation; and large, highly variable power flows. This combination of trends was observed in all synchronous areas, and it translates to technical challenges in several aspects of system operation such as frequency, voltage and congestion management control.

Given the ambitious political goals set out by the European Union, which aim at making Europe climate neutral by 2050 at the latest, these trends, and its technical challenges, have become evident even in areas where the immediate concerns are mitigated, such as Continental Europe (CE).

In order to achieve the European Union's climate targets, more renewable energy generation plants, both onshore and offshore, must be built at a rapid pace. For the optimal integration of such renewable generation, increased cross border transmission capacity, including wide-meshed offshore grids, will be required to accommodate such high volumes of transit flows. In addition, grid synchronisation/stabilisation mechanisms, which till today have been inherently provided by rotating synchronous generators, will be missing. In the future, other technical solutions will have to fulfil these functions.

Beyond these incremental steps, it is necessary to shift the overall perspective into creating today the effective boundary conditions to successfully meet the decarbonisation goals at their full extension.

The system security challenges, posed by the energy transition and a future decarbonised power system, are significant. However, to realize this future decarbonized power system, technical solutions with different levels of maturity are available and can be applied at all voltage levels. Hence, there is a need for strong transmission/distribution coordination, to involve all system users and to maintain cooperation with research and development.

In the medium term, until these new technical solutions are implemented, it may be necessary to take additional measures (e. g., RES or power flow limitations) to ensure system security. As such, there is a need to work decisively on the target solutions and to make them ready and available when necessary to limit the duration of the (probably costly) medium-term limitations.

The following chapters illustrate the challenges to maintaining system stability. They will enable a clear basis for dialogue with all system users to find the adequate and timely solutions for the system needs.

Frequency Related Aspects

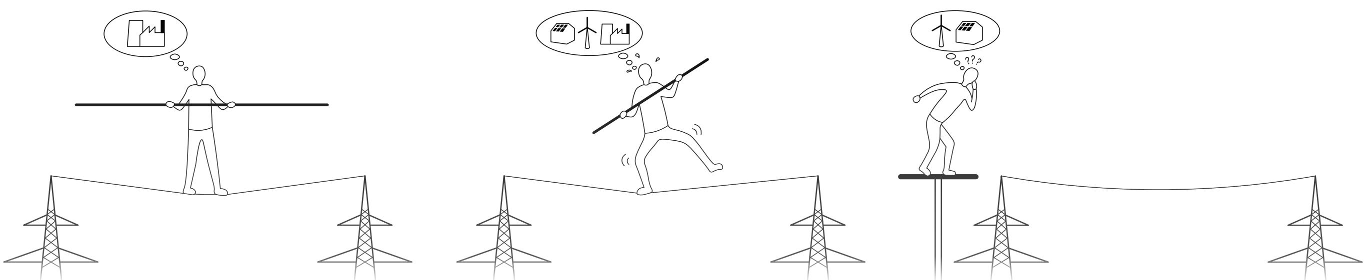
Total System Inertia and Rate of Change of Frequency

As the European electricity system is synchronous, the value of the frequency measured in Warsaw at any given time during the normal state of operations is, in theory, the same as the value measured in Lisbon. However, the electricity system is constantly exposed to a variety of events at different scales that change the local frequency values. The consequences of these changes can ignite a reaction chain that propagates their effects over very large distances, sometimes even at the continental level.

Frequency variations occur in power systems due to **mismatches between active power generation and demand**. In the event of a mismatch, the energy stored in the rotating masses of the synchronous generating units can instantaneously balance the mismatch by virtue of the units' intrinsic mechanical inertia. This immediate inertial response results in a change in rotor speeds and, consequently, the system frequency. Whereas this mechanical response of the machine does not solve the power mismatch problem in a sustainable manner, it is essential for instantaneously balance mismatches until frequency reserve response providers can respond to the change of frequency and vary the power output of their plants, thus restoring the balance between generation and demand.

The following analogy provides a description of this balancing problem in light of the current trend – thanks to efforts related to the energy transition – of more and more synchronous generators being replaced by generation interfaced with the grid through power electronics. From the perspective of a tightrope walker, the balancing pole provides instantaneous inertia support that gives the walker time to stabilise after actions on the tightrope. However, the walker's pole gets shorter and shorter over time, making it harder for him to remain stable and balanced on the rope.

Taking into account the results of TYNDP 2022 market simulations, the following duration curves present **the intrinsic inertia from generators plotted over the ordered hours of a full year for all Synchronous Areas**. This estimated equivalent system inertia H(s) is calculated based on estimated online generator capacity. Inertia contribution from demand is neglected, as the self-regulating effect of loads is decreasing from the traditional value of 1 – 2 %. This provides a conservative approach that does not affect trend identification or the scale of the challenge.

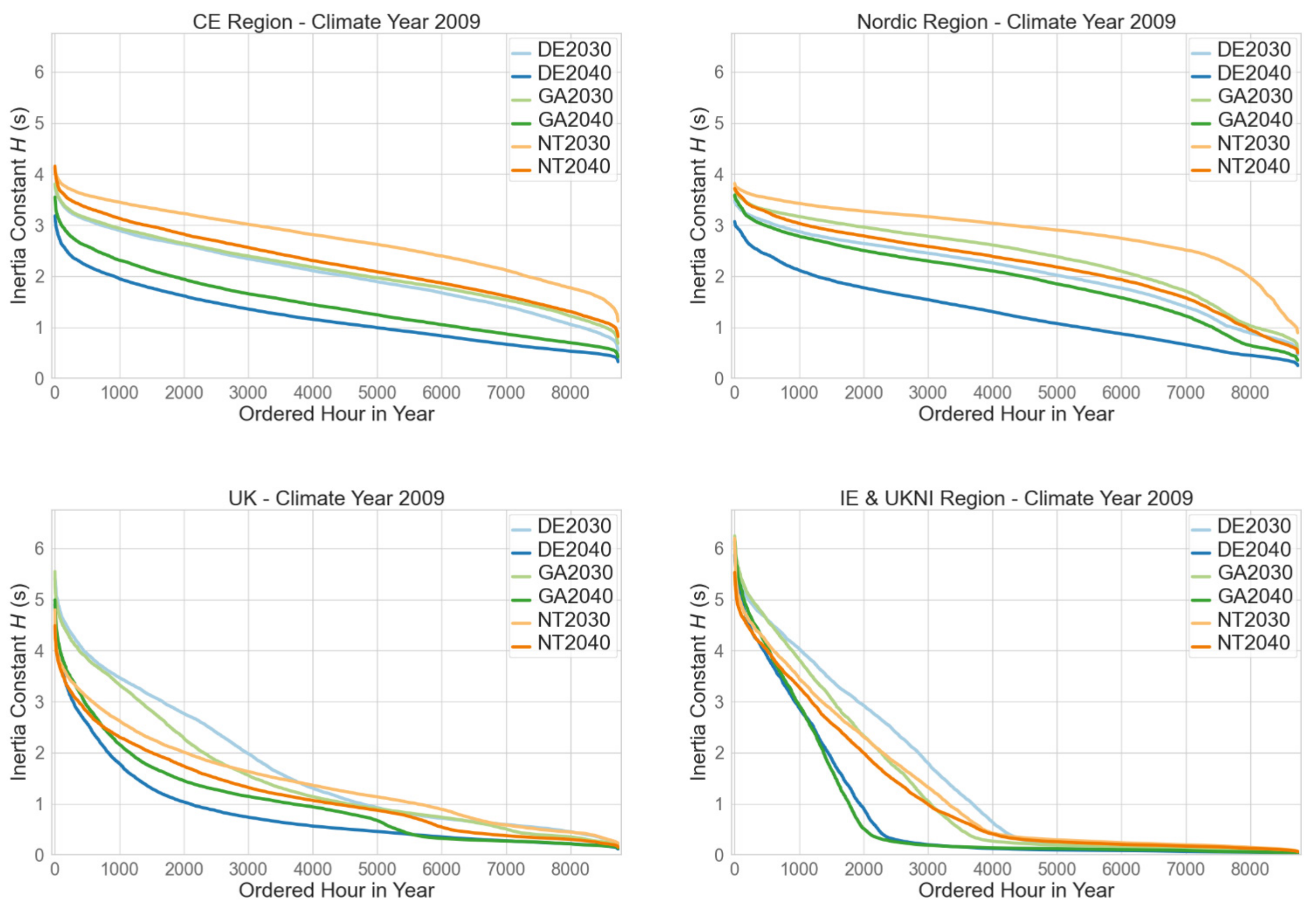


PREVIOUSLY
Inertia of the generators immediately compensated deviations (long balancing pole)

TODAY
the synchronous generators are less and less often connected to the grid – Inertia decreases (balancing pole gets shorter and shorter)

IN THE FUTURE
very low levels of inertia will occur (without balancing pole)

The figures below show six different outlooks. They include three different scenarios – Distributed Energy (DE), Global Ambition (GA) and National Trends (NT) – at two timeframes: 2030 and 2040.



System inertia trends

Trend

From 2030 to the 2040 scenarios inertia in all synchronous areas will decrease. The reduction is noticeable even in large area such as Continental Europe.

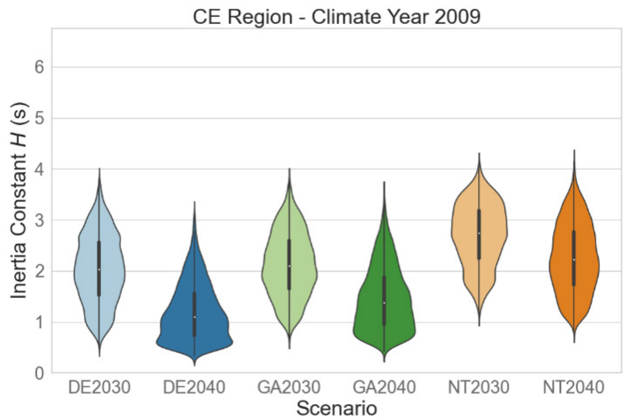
Challenge

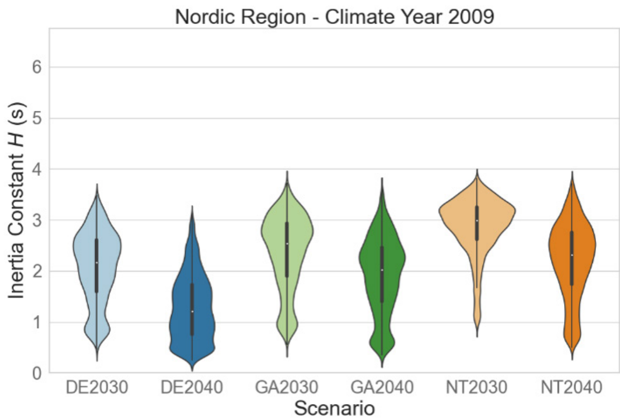
With very low inertia, the system becomes more vulnerable to experience high frequency excursions and even blackout. Within small areas the impact of this inertia reduction is already a challenge. In larger systems such as CE only a major incident like a system split could lead to a high frequency excursion or even a blackout.

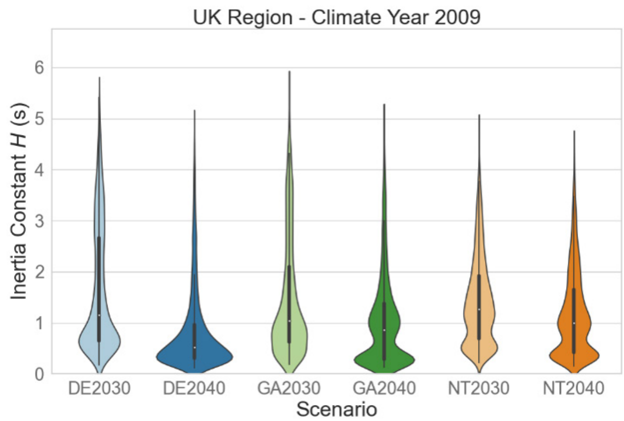
Solutions

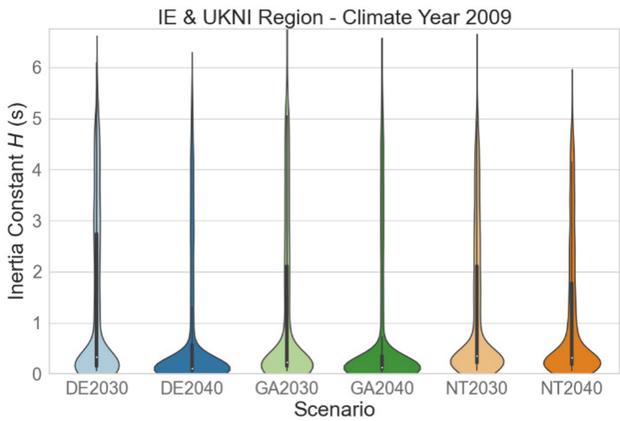
Provide inertia by inverter-based RES and enhance the system inertia through assests such as STATCOM and synchronous condensers. To keep up with the pace of the energy transition, network codes shall be updated in a fast and harmonised process.

For each scenario, the trend of falling inertia over time becomes especially apparent in so-called violin plots of the different synchronous areas. The violin plots below aggregate the number of hours during which the system inertia is at a certain value and represent this as the thickness of the violins. Larger plots indicate more hours during which a certain value of the inertia constant in a synchronous area is shown.



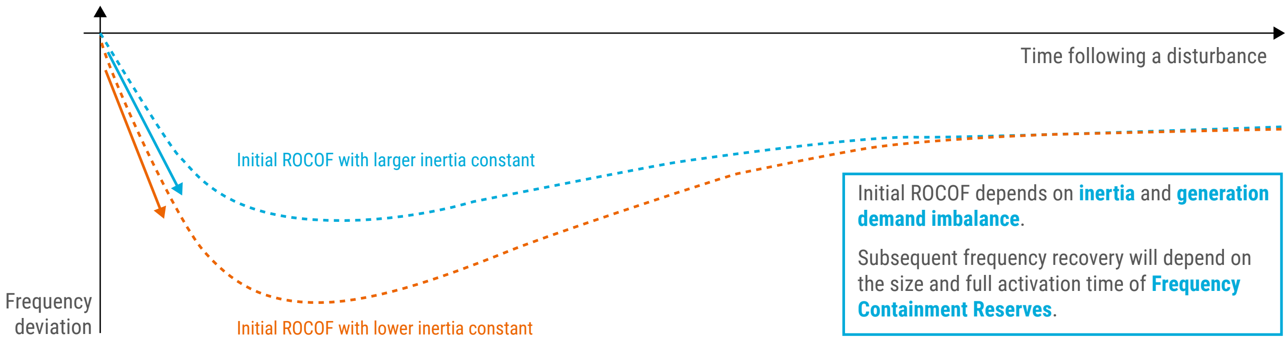






The graphs above show that, no matter the scenario considered, the trend is for the inertia to decrease. This trend was already individuated in the past TYNDP editions. Interestingly, in the updated data from 2022 Scenarios, **the decrease in the inertia of the system is even bigger than the one highlighted in the 2020 edition of the IoSN**. Taking the Continental Europe Synchronous Area as an example, the inertia constant rarely reached 1.5 s and never reached 1 s. The updated simulations show that the average value of the inertia constant throughout the year is lower, and the minimum is around 0.5 s.

The available inertia (shown in the figures above) is one of the two primary factors that influence the initial rate of change of frequency (RoCoF) at the time the imbalance takes place. The other important factor is the mismatch between generation and demand. The initial RoCoF also depends on the load's frequency dependency (self-regulation effect). The higher the imbalance between generation and demand and the lower the inertia, the higher the RoCoF.

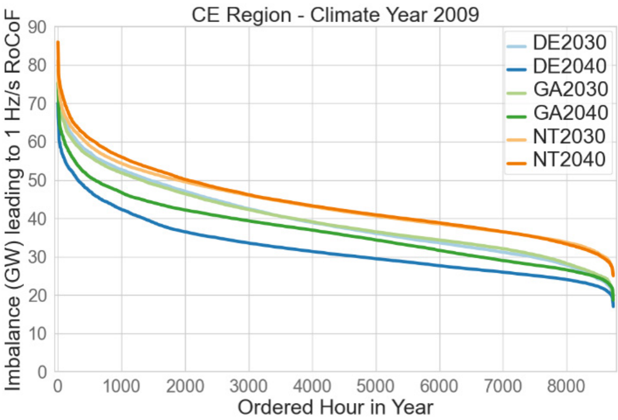


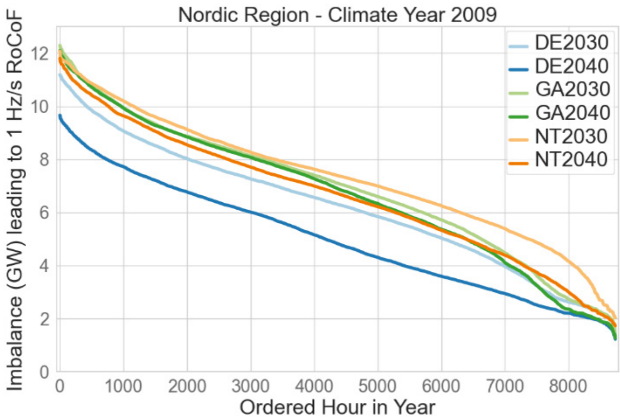
The high RoCoF, is a system metric that depends on the inertia of synchronous units in operation and cannot be influenced by means of Power Park Modules (PPM). High RoCoFs reduce the time available to deploy the necessary fast balancing action. In addition, for some units, high values could lead to disconnection and, therefore, further deterioration of system security. With very low inertia, the system would experience high frequency excursions, which may trigger domestic load-shedding or – in the worst case – lad to partial or total blackouts after relatively small mismatches between generation and demand.

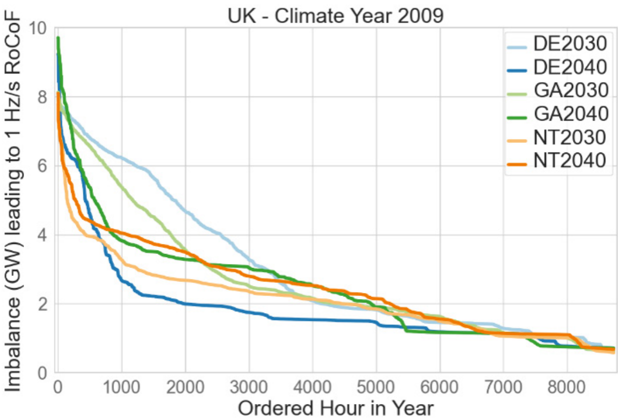
$$RoCoF_{(\mathrm{Hz/s})} = \frac{50_{(\mathrm{Hz})}}{S_{\mathrm{n}(\mathrm{MVA})}} \frac{Imbalance_{(\mathrm{MW})}}{2 \cdot H_{(\mathrm{MWs/MVA})}} Hz/s$$

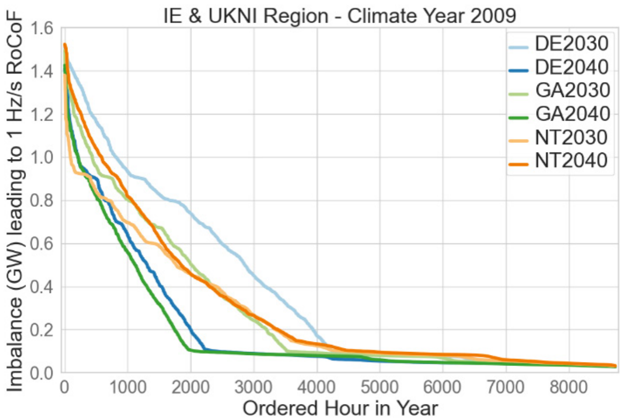
The formula above calculates the minimum imbalance necessary to trigger a RoCoF of 1 Hz/s for all the hours of the year in the different synchronous areas using the estimated inertia values. The following assumptions were made for the illustrative calculations:

- The report refers to a global RoCoF evaluation corresponding to the rate of change in system frequency at the centre of inertia.
- The system operation limit, which is currently specified as 1 Hz/s, needs to be clearly distinguished from the robustness of power generation modules and HVDC converters (meaning their capability to remain connected to the system) The latter is specified in the Connection Network Codes as a RoCoF withstand capability in the range of 2 – 2.5 Hz/s. Consequently, because local phenomena can be more severe than the global RoCoF, a sufficient margin between these two values is consistently shown.
- The report considers the initial RoCoF value, whilst the operational limit and withstand capability are usually determined in a 500 ms time window. The initial value can be significantly higher than the average value of 500 ms. Since local phenomena can be more severe than the global RoCoF (as described above), the report assumes that the initial RoCoF at the centre of inertia provides an objective indicator of the scale and range of the challenge.









ROCOF

Trend

Given the trend of more non-synchronous sources without intrinsic inertia, frequency sensitivity (ROCOF and frequency excursion) to generation-demand imbalance will increase. This is emphasized in scenarios with high integration of RES.

Challenge

Small synchronous areas would see rapid and large frequency excursions following a normal generation loss, large synchronous areas would not see the same size of frequency excursions unless a significant disturbance occurs such as a system split.

Solutions

Enhance the total system inertia of synchronous areas, Increase withstand capability for power generation units, setup faster-reacting system protection schemes.

Given the trend of more non-synchronous sources without inertia, higher frequency sensitivity (RoCoF and frequency excursion) to incidents implying generation-demand imbalances is expected to increase. Furthermore, a high penetration of inverter-supplied loads also increases the frequency independence of the demand. A decrease of the self-regulation effect of demand increases the balancing effort required to address the power imbalances.

This means that the more the energy mix is dominated by inverter-interfaced generation, the easier it is for an imbalance to trigger potentially dangerous changes in the frequency value if adequate support is not implemented in time.

Additionally, it is important to note that the loss of generation necessary to trigger a certain level of RoCoF is higher in large synchronous areas than in smaller ones. For example, in certain hours, a 100 MW power imbalance in Ireland (Ireland and Northern-Ireland) would already be sufficient to trigger the same RoCoF as a 16 GW power imbalance in Continental Europe. Consequently, whereas small synchronous areas would see large, rapid frequency excursions that could last for several tens of seconds after a normal generation loss, large synchronous areas would not see the same size of frequency excursions without a significant disturbance (e. g. a system split event) drastically exceeding the reference incident[1] (3,000 MW for CE).

1 Final Report System Disturbance on 4 November 2006.
https://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/Final-Report-20070130.pdf (last checked on 2022-06-16)

System Splits Events

Events from the recent past – such as the separation of Italy in September 2003, the separation of the CE Synchronous Area into three parts in November 2006, the East–West separation in January 2021 and the Iberian separation in July 2021 – demonstrate that system splits, though unlikely and out of range, should be considered serious, challenging, and realistic disturbances. System splits push the interconnected system to the limits of its dynamic stability and may result in large-scale blackouts.

During a system split event, a synchronous area splits into separate islands. Pre-split, exports and imports between the islands become power imbalances after the split. The larger the export or import of an island before the split, the greater its imbalance after the split and, therefore, the greater the need for a large and rapid adjustment of generation and demand. Not only are the resulting imbalances difficult to predict, but the resulting equivalent system inertia will also differ from island to island and from one period of time to another one.

A system split is more likely to occur across congested transit corridors, thus interrupting these transits. Since transits are increasing in magnitude, distance, and volatility, the power imbalance following a system split event is likely to increase. This would consequently lead to larger, longer, and quicker frequency excursions in subsequently formed islands. The increased imbalance has to be compensated by fast frequency response (FFR) including fast control reserves or frequency related defence measures e. g. Limited-Frequency-Sensitive-Mode Over-frequency (LFSM-O) or Low Frequency Demand Disconnection (LFDD). System splits will make the system reach the emergency state (as defined in the System Operations Guidelines), as a result of out of range contingency. TSOs will not act preventively to mitigate the impact of out of range contingencies but will react by activating their defence plan. Defence plans[2] are designed to help during and after those severe disturbances but cannot stabilize all system split scenarios with extreme imbalances. Potentially needed restoration plans will employ adequate resources to stabilize the islands and to re-synchronize them later the system.

The report "Frequency Stability in Long-Term Scenarios and Relevant Requirements"[3] investigates, under a set of assumptions, a very large number of combinations of system split cases in the CE Synchronous Area, separating the interconnected system into two parts. For all combinations, the theoretical initial RoCoF at the centre of inertia is determined in an hourly resolution of the year under consideration.

Initial RoCoF values higher than 1 Hz/s can compromise the efficiency of the resilience and/or defence plan actions that aim to stabilise the grid. As such, these RoCoF values are currently considered unmanageable. This is because the aforementioned balancing actions are not fast enough to restore the system's active power balance before reaching a frequency threshold at which most of the generation disconnects, leading to a blackout.

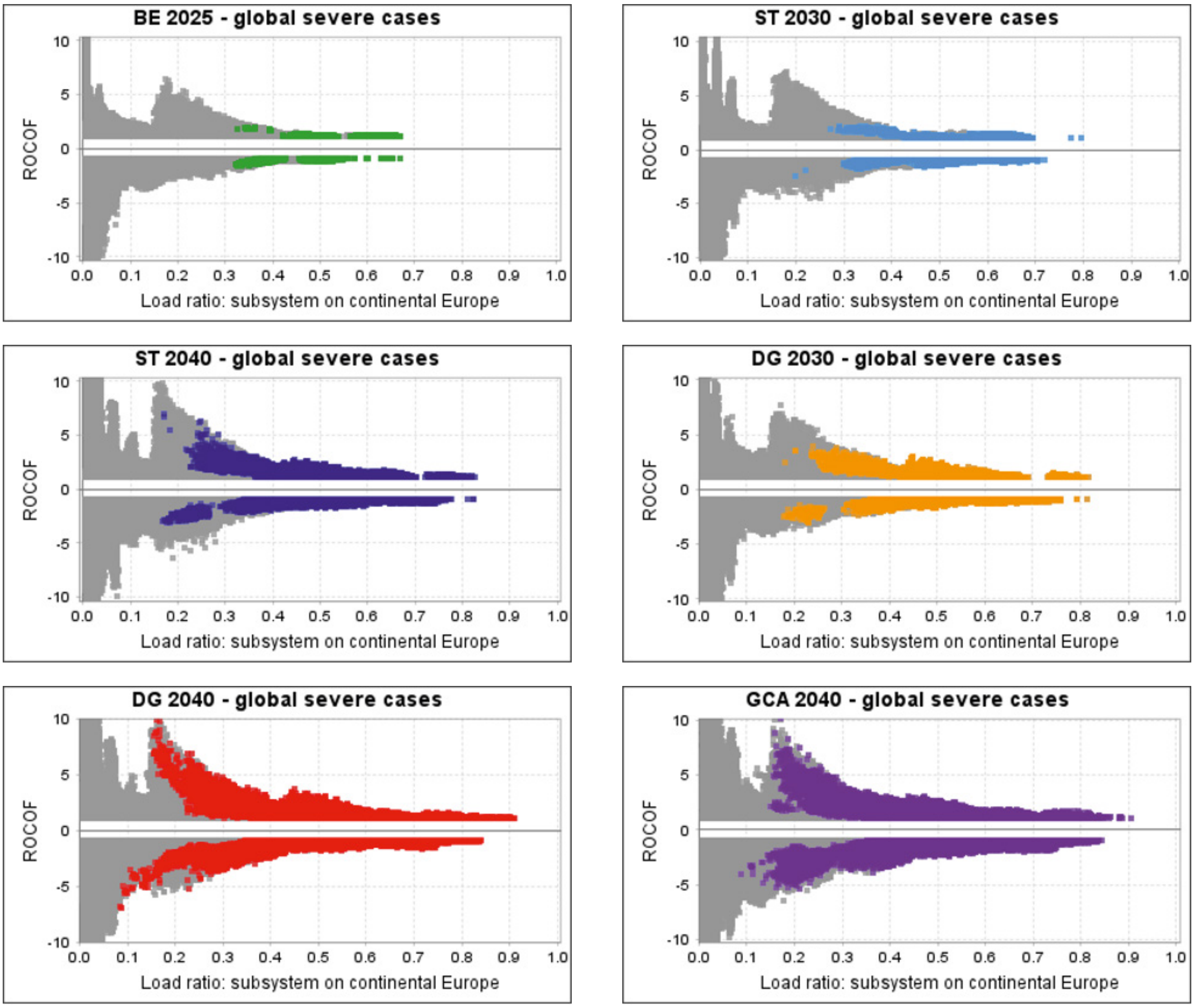
The study observed many cases of RoCoF exceeding 1 Hz/s in all investigated scenarios. In the cases of split scenarios in which the initial RoCoF exceeds 1 Hz/s in both resulting subsystems, there is a possible risk of a blackout of the entire CE. In this case, there is no neighbouring grid left alive to restore the blacked-out subsystem. From a pan-European perspective, these cases are therefore considered as global severe splits.

The following figures show the RoCoF values above 1 Hz/s for each subsystem of the CE Synchronous Area. Splits in which one island exceeds the RoCoF limit of 1 Hz/s are shown in grey, and splits for which both islands exceed this threshold are coloured. A large number of severe splits are identified, with an increase from short- to long-term scenarios. In addition to the global severe splits, severe splits could create greater challenges and requirements at the national level or between a group of TSOs (in grey).

Each global severe case corresponds to two dots, each of which relates to one of the two split subsystems. Each dot shows the subsystem's load ratio and RoCoF for one specific hour and one system split. Obviously, the two load ratios are complementary to 1 and the RoCoF values are of opposite signs.

2 According to the Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation: system defence plan means the technical and organizational measures to be undertaken to prevent the propagation or deterioration

3 https://eepublicdownloads.azureedge.net/clean-documents/Publications/ENTSO-E%20general%20publications/211203_Long_term_frequency_stability_scenarios_for_publication.pdf (last checked: 2022-06-16)



The plots above are taken from the aforementioned report "Frequency Stability in Long-Term Scenarios and Relevant Requirements", whose analysis at the time was based on the data extracted from the TYNDP 2018 (page 8). The plots present the RoCoF values above 1 Hz/s for each subsystem of the CE Synchronous Area (consisting of two subsystems per split combination) plotted with respect to the load ratio of each subsystem with regard to the CE synchronous area[4]. Values above 10 Hz/s, which appear for small ratios only, are not displayed in the plots.

Even though the consideration of the updated values from the TYNDP 2022 scenarios may impact the absolute values in the plots above, the trends shown are confirmed as relevant even in the updated scenarios.

In order to prevent, or at least reduce, the risk of potential blackouts for these identified global severe splits or other severe splits, countermeasures to manage the splits must be considered. Since the challenge posed by system splits cannot be solved by isolated actions at the national level, coordinated efforts from all European TSOs and Stakeholders are necessary to ensure the effectiveness of the measures.

Although the trends and the scale of the challenge are clearly identified in the studies, allowing to conclude on the multiple solution needs, the analysis of the behaviour of the future transmission system is a large-scale challenge. ENTSO-E is committed to further expanding its methodological and analytical tools to incrementally improve the quality of the insights provided by the TYNDP. The information delivered is – and will continue to be – open to be discussed within the framework of the stakeholder engagement process. This process will feed the overall discussion of the adequate levels of reliability during the energy transition process.

4 BE 2025 – Best Estimate 2025, ST 2030 – Sustainable Transition 2030, ST 2040 – Sustainable Transition 2040, DG 2030 – Distributed Generation 2030, DG 2040 – Distributed Generation 2040, GCA 2040 – Global Climate Action 2040.

Potential Mitigation Measures

Various solutions and mitigation measures contribute to securing power system performance against frequency-related disturbances (on top of what is required by current legislation). Since there is no single solution to this issue, several measures for improving the resilience of the future system will have to be weighed and assessed against each other:

Technical devices:

- Presently, an immediate inertial response can only be met by synchronous generators. In the future new capabilities, such as Grid-forming Converters[5] will be necessary.

  - Provide inertia by inverter-based RES generators (i. e. power park modules) and battery storage systems (the precondition is the availability of grid forming control[6]).

- Enhance the total system inertia of the synchronous area through assets such as STATCOM with batteries included in the DC circuit, synchronous condensers (through installation of new machines e. g., Italy), or through market-based solutions.

- Use the contribution of synchronous condensers (SCs): decoupling generators to become SCs under changing operating conditions in real time from generators such as gas turbines (GTs) and combined cycle gas turbines (CCGTs) or from decommissioned power plants (e. g., Germany). The inertia contribution from the existing assets can be optimized through the connection of rotating masses to the SC

- After the immediate inertial response, a fast frequency response from sources other than synchronous generation is needed, such as converter-connected generation, demand-side response and storage (including batteries).

- Increase withstand capability for power generation units and set up faster-reacting system protection schemes; further develop the system to handle RoCoF values higher than 1 Hz/s.

- In the case of a System Split, the severity of the fault depends on the exchange of AC power between the grid regions. A solution derived from this would be to limit the power exchange in the AC system between grid regions by increasing the use of direct current transmission. Moreover, the utilisation of grid forming control from HVDC links and especially from assets owned by TSOs – such as flexible alternating current transmission system (FACTS) – is the easiest and most straightforward way to introduce grid forming capabilities.

- Implement measures to avoid a system split: for example i. e. reinforcement of grid assets (in case of non-increasing power flows), increased use of DC technology instead of AC technology (condition: continuing power flows via the DC system).

- Develop countermeasures to mitigate the effects of the system splits (no influence on the RoCoF but on the nadir) (e. g. Special Protection Schemes).

5 Grid-forming Converters (GFC) are power electronics devices designed in control and sizing in order to support the operation of an AC power system under normal, disturbed, and emergency conditions without having to rely on services from synchronous generators
Technical Report (ENTSO-E et. al.) – High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters. https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/2022/High_Penetration_of_Power_Electronic_Interfaced_Power_Sources_and_the_Potential_Contribution_of_Grid_Forming_Converters.pdf

6 In the event of an over frequency, for example, the chopper of a wind power plant can be used to reduce the storage demand. However, it must be ensured that an inherent reaction is first guaranteed by grid forming behavior.

Connection codes and standards:

- Connection codes and standards will be essential to ensure that necessary technical capabilities (from generators, HVDC and demand) related to inertia, frequency sensitive mode and robustness against high RoCoF are implemented.

- To assure future system stability given the lack of synchronous generation, some Grid-forming Converters capabilities should be implemented as mandatory requirements in the Connection Network Codes at latest after a certain transition period. Those are:
  - Creating system voltage
  - Contributing to fault level
  - Providing inertia within the design limits
  - Preventing adverse control system interactions

For further information see the following position paper on GFC requirements[7].

Operation and market:

- Constraining RES and placing synchronous generation with intrinsic inertia in the unit commitment (deployment of "inertial redispatch"). This measure, which is easy to implement as a short-term solution may be less efficient in the long term from an economical and environmental point of view (for the thermal generation).

- Market restrictions in terms of reduction of the power exchange, and deployment of inertial redispatch.

- Real-time monitoring of system inertia in order to ensure that a minimum level of inertia is available in the system at all times where relevant lack of inertia has been identified (this is already common practice in Great Britain and Ireland). Current regulations require minimum inertia investigation for each synchronous area which is updated every two years[8].

- Procurement of fast control reserves (e. g. "Enhanced Frequency Reserves") as an additional ancillary service and activation when necessary (e. g. during high RES production).

- Reserves shared between synchronous areas using HVDC up to the optimal amount specified by current network codes.

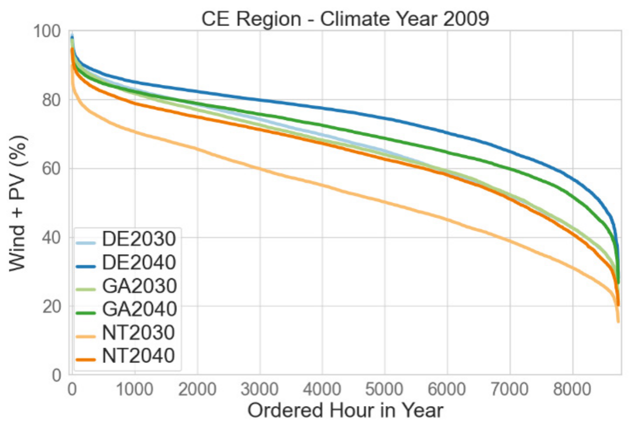
7 https://eepublicdownloads.entsoe.eu/clean-documents/RDC%20documents/210331_Grid%20Forming%20Capabilities.pdf

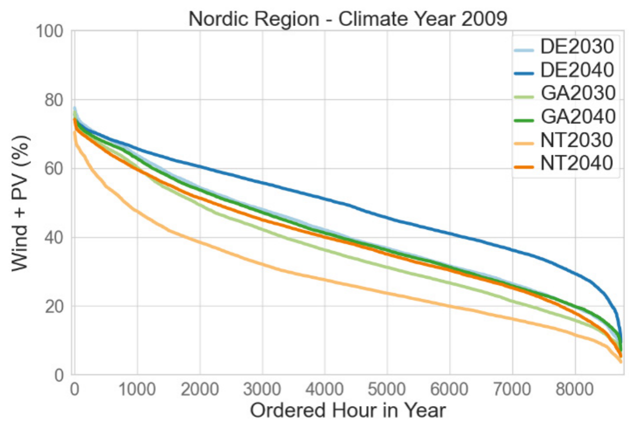
8 SOGL art. 39 requires each synchronous area to do a study on sufficiency of inertia

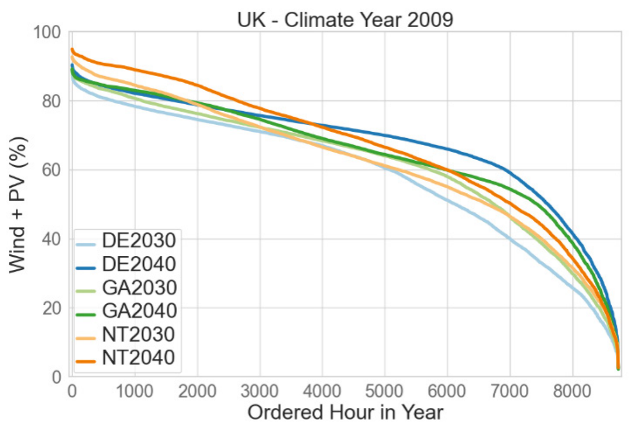
Flexibility Needs

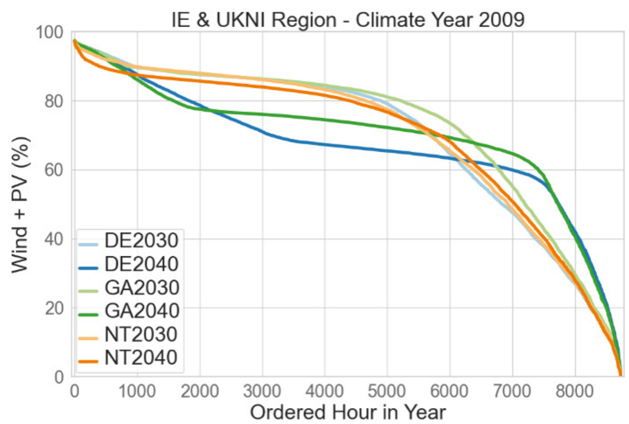
Unlike conventional generation, which provides costly but controllable sources of primary energy, RES utilise primary energy sources that are free but have a variable nature, that is largely weather dependent. Hence, an increasingly decarbonized system with high installed capacity of RES will have to stop relying on the dispatchable fossil fuel generation that provides most of the flexibility and ancillary services in today's system.

The plots below depict the duration curves of the **ratio between the sum of wind and solar photovoltaic generation (not considering all other RES) and total generation**. This conservative ratio gives a snapshot of the percentage of variable wind and solar photovoltaic RES generation over the total generation for all synchronous areas and TYNDP scenarios over a full year.









Ratio of PV+Wind over total generation

Trend

High ratios of variable RES generation over the total generation are reached in all synchronous areas for some hours of the year – above 80 % in all synchronous areas for some scenarios, except in Nordic (highest scenario close to reaching 80 %).

Challenge

Reduced amount of controllable generating units lead to high flexibility needs in normal operation.

Solutions

This includes new roles for thermal plants, RES participation, demand side response, and storage.

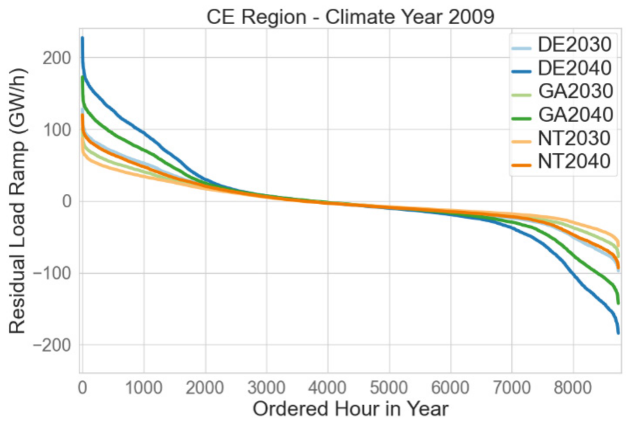
In order to maintain the frequency equilibrium, the variability in the power output from RES, which is driven by the variability of the primary energy resource, must be balanced, including forecast output deviations.

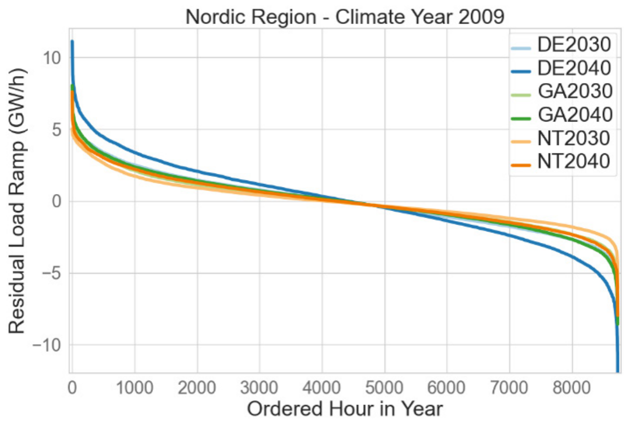
Residual load ramps exhibit the changes of residual load (total demand minus variable RES) from one hour to the following hour These curves express the (in GW/hour) that needs to be provided by controllable resources (generating units, demand and storage) in order to maintain balance between generation and demand. They also provide an additional measure into the challenges of operating a system with

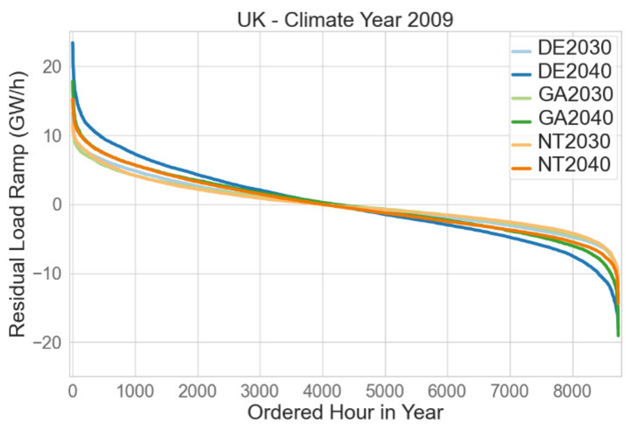
1. reduced amount of controllable generating units,
2. high flexibility needs in normal operation, and
3. a requirement to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen imbalances between active power generation and demand.

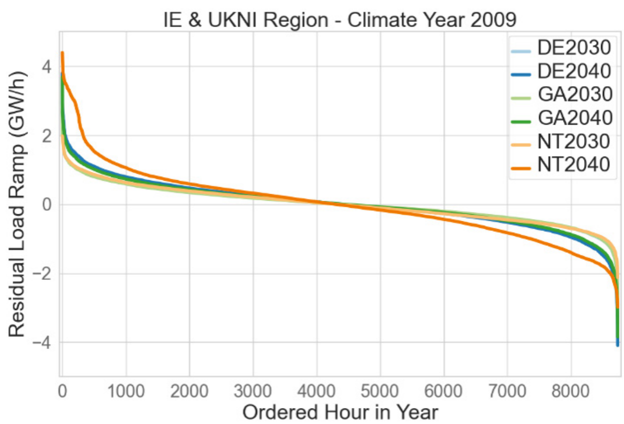
The analysis included in the plot below does not take into account that faster fluctuations in the load (happening in the domain of the minutes) might still happen in the real-time operations, due to change in the schedule of the generation or sudden changes in the weather conditions. This can result in higher load and generation gradients that can only be captured through a higher time granularity than hourly data.

The following plots display the duration curves of the residual load ramps as the changes of residual load from one hour to the next in a synchronous area over a full year. RES includes all RES sources except hydro.

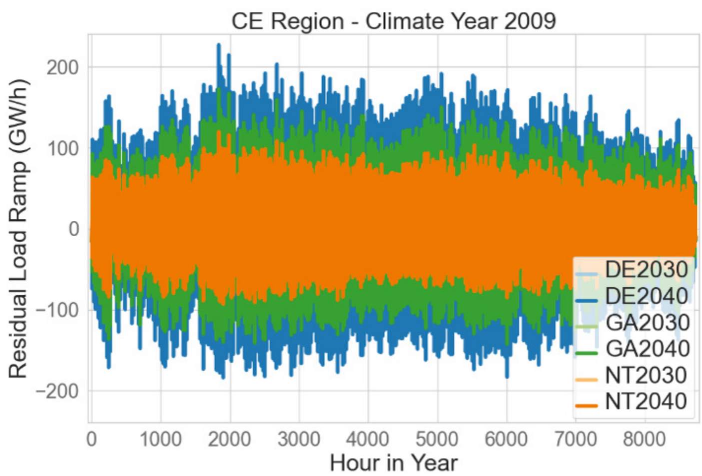








The following plot displays the time-sequential residual load ramp curve of the CE system, indicating volatility over short time durations and an increasing trend to later timeframes. The data shown in the plot below is the same as the plot above, without being ordered from the highest ramp to the lowest, but showing the distribution of the ramps throughout the different hours of a year.



Residual load ramps

Trend

Increasing high response (in MW/hour) that needs to be provided by controllable generating units in order to maintain balance between generation and demand is verified in all synchronous areas.

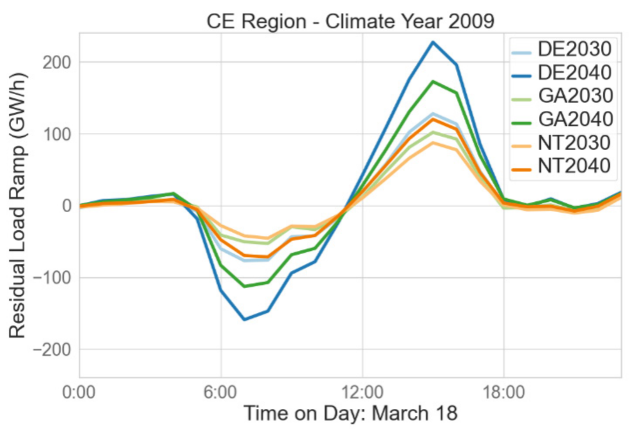
Challenge

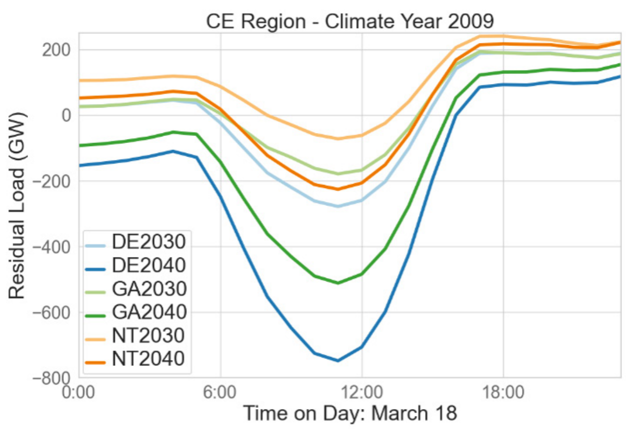
Need to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen generation and demand imbalances

Solutions

Flexibility sources will be necessary both from the generation and demand side.
Strong interconnection will be essential to exchange the power flows from flexibility sources.

In more detail, the following plots shows for one extreme day in the CE system, the residual load ramps (gradient of the residual load) and the residual load itself in that hour.





In order to cope with this situation new flexibility sources will be necessary both from the generation, storage, demand side, and across sectors. This includes new roles for thermal plants, RES participation, small and large demand side response, smart charging EVs, battery storage and electrolysers. From the network side, transmission network reinforcements will remain essential to enable power flows between production, consumption and flexibility sources.

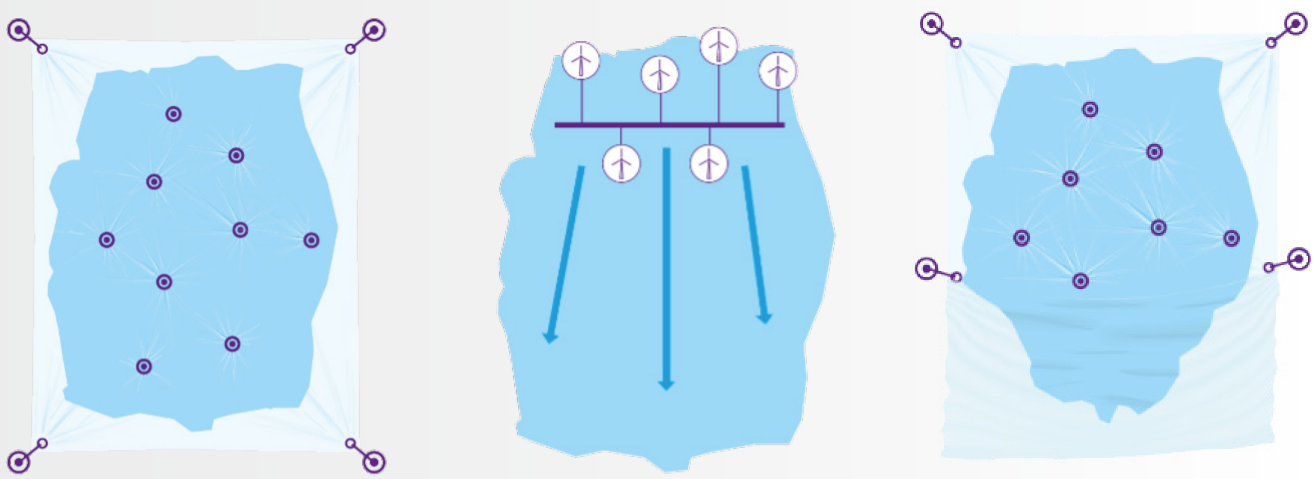
Investments to allow either local or long-distance power flows, covering the exchanging areas, flexibility rewards to providers (also at a local level) and innovations in power electronics (e. g. inverters) will also be central aspects of the solution.

Transient and Voltage Stability

Power flow constraints in highly meshed areas with an "optimal" distribution of generation units around the consumption areas are generally based on static limits. These may include thermal overloads or steady state voltages exceeding operational limits. Various stability issues have become more relevant when defining power flow constraints, given the increase of volumes and distance of cross-border energy exchanges, the increase of the static limits of the grid elements and the penetration of power electronic driven and controlled generation and demand. This issues include voltage stability, dynamic stability, and transient stability.

Voltage Stability

Voltage stability is ensured when each node of the network remains within a defined voltage band during normal changes in system operation but also in post-fault or outage situations.



In the tablecloth analogy the voltage level is represented by the height profile of the table cloth. Actors, (e. g. power plants) stretch the cloth in "optimal" locations and maintain a uniform height profile. Historically the power generating units have been built close to the load centers. This distribution came along with an appropriate distribution also in terms of voltage stability.

The challenge is that, depending on the power infeed situation, the market situation or the weather situation for RES, the voltage support units can be distributed very differently.

As an example, many RES can be concentrated in a specific zone feeding into another.

On days or hours when the feed-in is dominated by RES generation concentrated in a specific zone (here in the north), there are hardly any units left in the south.

What happens to the tablecloth then?

The tablecloth would hang down which is exactly what must be avoided.

In the grid, the units for voltage support must be demand-oriented so that each of these different feed-in situations can be handled.

The electrical system is faced with two developments: the reduction of available synchronous generation units also supporting system voltage and the increase of need for voltage support due to volatile transit situations and higher utilization of the system. As highly volatile converter-connected RES replace synchronous generation, and as the power has to be transmitted over a longer distance due to generation being further away from demand centres, there is an increase in the fluctuations in reactive power demand, to maintain an adequate voltage profile and to ensure voltage stability, as well as in the reactive losses.

The potential automatic voltage control sources from conventional generating units will tend to be lower in longer-term scenarios, demonstrating that additional sources are necessary to meet the voltage control challenge. On top of that, the location of each of the voltage control sources may also differ significantly within each country. Typically, a uniform distribution is the most effective way to control the system voltage. Given the high variability of power transits and generation mix combinations a good mix between network based solutions and generator based solutions will be necessary.

Transient Stability

Short-circuit power has been commonly used as an indicator of the system strength and, consequently, the ability of a synchronous generating unit to ride through a large disturbance and remain in synchronism with the system. A strongly meshed system with enough synchronous generation running at all times will have a high short-circuit level.

As converter-connected RES replaces synchronous generation and generated power must be transmitted over long distances between generation units and demand centres, the short-circuit power will tend to drop to a lower level.

This reduction in short-circuit power will result in deeper and more widespread voltage dips in the event of network faults. This will significantly impair the transient stability of the generation units. It will also result in an increase in the number of generation units affected by the fault and with a risk of disconnection.

The development of short circuit level has to be monitored continuously. If a risk of system stability is revealed, the relevant capabilities of generating units defined in terms of connection requirements have to be improved, or measures to increase short circuit power, e. g. new synchronous condensers have to be taken.

Solutions and Mitigations Needs

The following measures are envisaged to face the challenges discussed above:

Medium- and long-term measures:

- **Technical devices:**
  - Additional voltage-supporting units are required in the transmission network. These units (synchronous condensers, SVCs, STATCOM and HVDC converters, especially with grid-forming capabilities) must be well distributed to handle the various possible situations and faults.

- **Connection codes and standards:**
  - Technical requirements implemented in the connection codes will be important as part of the solution measures by defining relevant technical capabilities for power generating modules such as fault ride through, voltage support means and grid forming.
  - Large loads such as power to gas plants can also provide an important contribution to a stable system with appropriate grid-serving capabilities.

- **TSO/DSO coordination:**
  - Reactive support at lower voltage levels: RES at distribution must have reactive support capabilities. Though this is part of the solution (RES reactive power absorption helps reduce high voltages), there are several limitations:
    - RES are not always located where reactive support is needed (see illustration above).
    - Distribution and transmission do not suffer the same voltage problems:
      - Possible low voltage at distribution and high voltage at transmission,
      - On load tap changers limit voltage problems at distribution level,
      - Using embedded generation to solve transmission grid problems can cause problems at distribution level,
      - Cost of losses induced by reactive current at distribution level could be an issue,
  - Observability and controllability of distributed resources by the TSOs and DSOs as well as strong coordination between both operators.
    - controllability and dependability for transmission grid needs,
    - monitoring the performance and availability of resources/capacities
  - The transmission grid flows request reactive support at transmission level (high and low voltages) and a clear range of admissible reactive power exchange at the TSO-DSO interface via coordination with the respective DSOs.
- **Intermediate short-term measures:**
  - Effective use of existing reactive power sources, including distribution-connected users
  - Limiting RES, limiting bulk power flows and/or imposing must-run conventional units to ensure the necessary level of short-circuit power.

Challenge of using the grid to its limits

As described in the chapter “Flexibility Needs”, there is an increasing need for new flexibility sources (or non-wire solutions) in the grid. The system will face highly variable flows, with frequent changes of magnitude and direction. This will cause the grid to face very high loading conditions at one moment and very low ones at the next. Moreover, the time needed for grid development and expansion is much longer than the time needed for RES deployment As a result, it is challenging for TSOs to use the grid to its limits. However, non-wire solutions can enhance the utilisation of the existing infrastructure and complement the standard infrastructure development. Therefore, non-wire solutions should be part of the optimal strategy.

Before building new lines, it is important to analyse whether the optimisation of the existing grid can be a sound technical and economic solution. In Germany this principle is called the NOVA-Prinzip (NetzOptimierung, Verstärkung, Ausbau). The principle means that grid optimisation should take place first, then reinforcement and lastly the construction of new lines.

The following solutions are part of the portfolio to be considered:

Grid reinforcement focuses on increasing the transmission capacity in existing corridors, for example by adding an additional circuit or by replacing lines by lines with a higher capacity.

Increased line capacity (Dynamic Line Rating, DLR)

The ampacity of an OHL is temperature dependent and therefore strongly affected by its ambient conditions. In certain weather conditions the capacity of existing OHL can be significantly increased (more than 150 %). Although several projects on DLR are in everyday operation already, it is still challenging to determine the present and future current carrying capacities and integrate these results in the operational processes while keeping an adequate security margin of the power system stability limits. DLR creates some challenges to stability, which need to be taken into consideration when determining the maximum current. By increasing the flows, the reactive power needs of the lines increase in both normal operation and during contingencies. Sufficient (dynamic) reactive power sources have to be in place to avoid voltage stability problems. There is also an increased risk of transient stability problems when applying DLR. The increase in power flow increases the angle difference, bringing the system closer to its transient stability limit.

(reference: Dynamic Line Rating (DLR) – ENTSO-E (entsoe.eu))

Power flow control devices

Phase Shifting Transformers (PST) and Static Synchronous Series Compensators (SSSC) are devices which enable the control of active power flows in three-phase electric transmission networks. A PST is a specialized type of transformer that controls power flows by regulating the difference in the voltage phase angle between two nodes of the system. A SSSC consists of a Voltage Source Converter (VSC) and a transformer, that is connected in series with a transmission line. The resulting serially injected voltage leads or lags the line current by 90° and emulates a controllable inductive or capacitive reactance. This enables the reduction or increase of the equivalent line impedance to enhance the line's active power transfer capability. Power control devices increase the flexibility and capacity of the system if operated in a coordinated way. In contingency analysis it should however be taken into consideration that the trip of such a device can cause a large power swings due to the sudden change in voltage phase angle.

(reference: Phase Shifting Transformers – ENTSO-E (entsoe.eu) / Static Synchronous Series Compensator – ENTSO-E (entsoe.eu))

Voltage control devices

Of the various voltage control devices, the most relevant for transmission systems are variable shunt reactors (VSR), STATCOMS and synchronous condensers.

The VSR uses a tap changer, of the same type used in power transformers, to vary the inductance of the shunt reactor by changing the number of electrical turns in the reactor windings. Thus, controllability for grid operators in reactive power management is provided by the possibility to continuously adjust the compensation according to the load variation.

A synchronous condenser is a DC-excited synchronous machine without any driving equipment attached to its shaft. Therefore, it has similar benefits for grid stability as a synchronous generator and provides inertia (assuming it is equipped with a flywheel), short-circuit current, and voltage control capabilities. These capabilities help to improve the frequency, transient and voltage stability.

A Static synchronous compensator (STATCOM) is a FACT device based on VSCs with semi-conductor valves in a modular multi-level configuration. It is capable of dynamically providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. This will reduce voltage volatility and improve the voltage stability. When equipped with energy storage, STATCOMS can also support the damping of local or inter-area active power oscillations.

(reference: (Variable) Shunt Reactor – ENTSO-E (entsoe.eu), Synchronous Condenser – ENTSO-E (entsoe.eu), Static Synchronous Compensator (STATCOM) – ENTSO-E (entsoe.eu))

Extensive use of **Energy Storage Systems** (ESSs) will provide new flexibility margins and solutions from both the generation and demand perspective. Energy storage comprises a broad portfolio of technologies for storing electricity, including flywheels, electrochemical batteries (BESS), super capacitors, compressed air, thermal storage (heat storage) and pumped-hydro storage.

ESSs can be used to store excessive RES production avoiding congestions and curtailments. They can thus improve RES integration and optimising thermal power plant operation economically and ecologically (achieving a significant CO_2 reduction) within the thermal phase-out scenario. Synchronous storage technologies increase system inertia and provide fast fault current infeed (short-circuit level) and voltage regulation, whereas non-synchronous devices can provide synthetic inertia or fast frequency regulation.

ESSs can act as a dynamic reactive power source and they can provide black start capability. BESS or hybrid power plants, could be used to provide grid forming capabilities (at least for large plants in the range 30 – 100 MW). With the increasing use and integration of ESSs, e. g., in power generating facilities, the technical requirements to be applied by storage technologies must be further assessed.

System storage

There are different kinds of storage which can be used to store energy, either on a short term or long term basis. Short term energy storage can be achieved by using battery storage, whilst mechanical storage, thermal storage, chemical storage (power to gas) can provide long term storage.

Battery storage

Battery storage consists of utilizing the fast and versatile nature of batteries to provide ancillary services to DSOs and TSOs. The primary services are frequency balancing, voltage support and congestion management. It is also possible to address adequacy by adjusting charging and discharging to peak in an hourly perspective so the demand curve is more stabilized.

Battery storage can help both conventional generation and wind and solar plants to provide frequency balancing services and voltage control. However, algorithms can enable wind and solar to provide fast active power control, automatic voltage control and automatic generation curtailment, even without the use of storage systems.

Mechanical storage

Mechanical storage includes storage methods such as compressed air energy storage (CAES), liquid air energy storage (LAES) and flywheel.

These solutions can provide frequency balancing by producing electricity with a rapid response time. Flywheels have the most rapid response time and can provide inertia as well as other immediate frequency balancing products, supporting the frequency stability. CAES involves compressed air, which can be expanded and used to drive a turbine that creates electricity. LAES entails cooling down air until it becomes liquid, which also can expand and be used to drive a turbine that creates electricity. CAES and LAES can provide both frequency balancing, congestion management and adequacy, whereas flywheel is suitable only for frequency balancing.

As an example Liquid Air Energy Storage (LAES) is a solution that can increase the flexibility of power plants or absorb production peaks from RES, reducing the need for curtailment.

Thermal Energy Storage

Thermal storage uses heat to store energy so that when demand peaks, the heat can produce electricity directly by initialising a steam turbine. Thermal energy storage can offer frequency balancing for steam power plants and open- cycle power plants or help with adequacy or congestion management for variable generation.

Chemical storage

Electricity can be stored in chemical products such as hydrogen and methane. These production facilities can adjust their consumption of power to imbalances between consumption and production in the power grid, the goal being to produce hydrogen or methane in a sustainable manner. Their electricity consumption is therefore tailored to renewable resources and has to be able to adapt quickly and frequently with a large capacity. The facilities use this ability to provide frequency balancing, adequacy and, in some cases, congestion management. This type of chemical storage is also a method of storing renewable energy. The hydrogen or methane can participate with balancing the power grid directly by powering a gas plant or indirectly by powering hydrogen cars instead of electric vehicles (EVs).

(reference: Battery Technology, Flexible Generation, Hydrogen and Methane Production, LAES/CAES + Flywheel – ENTSO-E Technopedia (entsoe.eu/Technopedia))

Voltage Uprating

An increase of the voltage level allows for a significant increase of the transmission capacity. The feasibility of voltage upgrade depends on the detailed assessment of the existing right of ways, air clearances, required tower adaptation, the further use of existing conductors and also permissible electromagnetic emissions (E- and H-Feld and audible noise).

(reference: Voltage Uprating – ENTSO-E Technopedia (entsoe.eu/Technopedia))

Where system need cannot be satisfied by grid optimization and grid reinforcement, those measures are not feasible from a technical or economical perspective, the construction of new lines will have to be considered.

Additional network challenges

The increasing penetration of power electronics (PE) devices and distributed energy sources (DER), the continuous digitalization and the development of emerging technologies in power systems create new challenges which require further investigations and analysis in the near future. The previous edition of the TYNDP system needs study[9] reported an overview of these additional network challenges, which remain valid. They can impact the system security and dynamics and need to be monitored to assess the possible impacts and investigate solutions when necessary. Those challenges are:

- Extensive use of EHV-cables (for AC)
- Interactions between new devices and controls
- Cyber-physical systems
- Increasing amount of PSTs and HVDC lines
- TSO-DSO cooperation and coordination
- Ageing grid facilities and generation units
- Sector Integration
- Energy Storage Systems

Given their relevance, the following topics are highlighted.

Inter-area oscillations

In addition to its function of transferring power, the transmission network binds the rotors remote generators together. The more meshed the network is, the stiffer the link will be. After a disturbance (a loss of generation for instance) distant groups of rotors oscillate against each other. These inter-area oscillations are generally well damped and generators stop oscillating after a few seconds.

However, under adverse conditions the oscillations can be sustained and lead to significant power flow oscillations on the transmission lines (hundreds of MW) and to physical damage to generating units. This phenomenon is exacerbated by the weakness of the system (long distances, weakly meshed portions of the grid or low inertia) and high-power flows.

To damp these oscillations, voltage and/or power controls of synchronous machines (Power System Stabilizer), FACTS or STATCOM/HVDC (Power Oscillation Dampers) must be tuned appropriately. The increase of long-distance power flows across Europe could require in some occasions coordinated tuning of the relevant control systems. Otherwise, inter-area oscillations may become a real concern which could notably undermine the profitability of interconnections if power transfer over such interconnections has to be restricted.

The tuning of the controllers need to be based on the results of a small signal stability analysis of inter-area oscillations in a synchronous area. This requires a significant amount of work and an accurate and validated dynamic model that represents all relevant devices participating in the oscillations.

9 Link

Summary – the system needs

This chapter provides a comprehensive perspective on some of the main dynamic and operational challenges by explaining the technical background, their impact on the system and the relevant solutions or mitigation measures. In addition, it identifies new phenomena or matters of interest to be monitored and studied.

The analysis carried out for all the hours of the long-term TYNDP time horizons and scenarios delivers quantitative information on the future trends of the system performance and related challenges. However, an incremental approach will be insufficient for identifying the range of measures necessary to tackle the challenges in a timely and thorough manner.

As such, this chapter also emphases forward looking solutions with the potential to meet the full extent of the European policy goals of decarbonisation.

System Design Challenges

Without further action, intermediate solutions are needed to maintain system stability (limiting RES, limiting flows and imposing the need to operate must-run units). To avoid these limitations, it is essential to introduce more sustainable and efficient measures, such as the integration of synchronous condensers.

One indispensable part of the solutions is the grid forming capability of power converters. The constructive dialogue between all involved parties, TSOs, DSOs, research institutes, manufacturers, system users and policy makers, which has been started already, needs to be accelerated now to define the relevant technical requirements for those capabilities, to replace the diminishing contribution inherent to synchronous generators, and set up a roadmap to make them available to the system in due time.

- The availability of the necessary technical capabilities of grid users and the consistent improvement of Europe's electricity market to ensure a reward system for system flexibility solutions and incentives for market participants to act in line with system needs remain key priorities.
- The so-called "non-wire solutions" can enhance the utilization of the existing and future infrastructure and complement the infrastructure development. Therefore, "non-wire solutions" should be part of the optimal strategy.
- Research & Innovation represents an essential building block to meet the challenges. Consistently, significant RD&I efforts and stakeholder collaborations are needed to accelerate the uptake of new technologies for stability management. TSOs are ready to take on the challenge on facing growing stability phenomena.

Operational Challenges

In alignment with ENTSO-E "System of Systems" vision, strong cross-border cooperation and strong adaptation to local needs and constraints are necessary:

- New market models will be closer to the system's physical reality requiring closer operational coordination, to meet challenges that may span different countries. Moreover, the models will combine resources to develop solutions for a system with high level of power electronics, and the need to include multiple countries in our forecasting.

- The need for distributed flexibilities to contribute to system needs is imperative. This will depend on the network, institutional and economic realities of each country, with the drive for automation and decision support that will need to adapt to local constraints, culture and realities.

The context is simultaneously more European and more local. In order to meet these challenges, TSOs have several resources:

- The tools and means for increased cross-border cooperation through Regional Coordination Centres with the full range of services that they will provide, as well as with the help of our common association ENTSO-E.

- The in-depth knowledge of local constraints, through their own local footprint and close relationships with institutions, customers, stakeholders and the public at large, as well as through partnerships with Distribution System Operators.

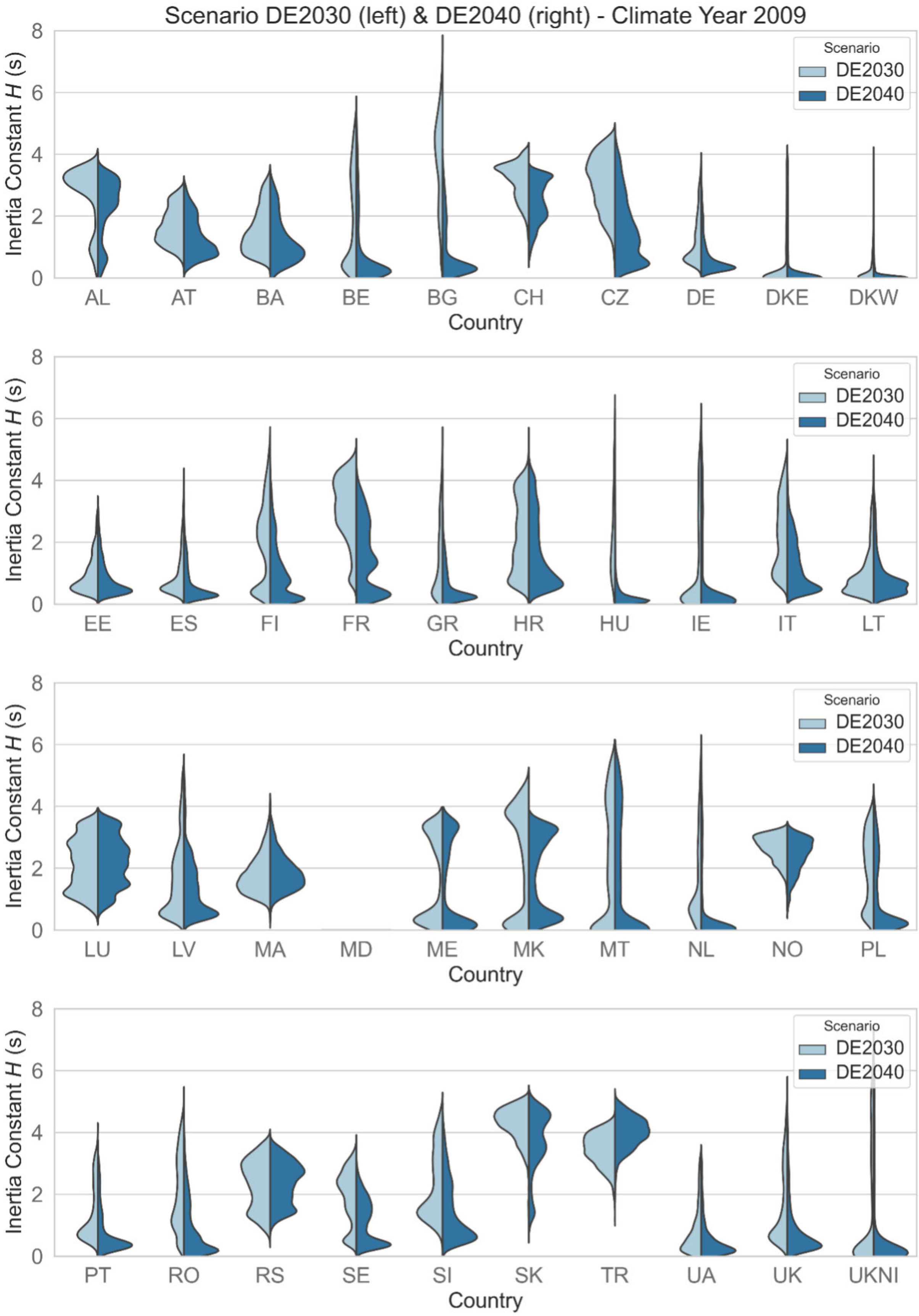
Additional Background Information

Estimated Inertia in All Countries

The following plots represent the estimated inertia for each country in the ENTSO-E area. The plots are based on the market study results for all visions of the TYNDP 2022. Equivalent inertia for each country, presented as H(s), is calculated on the basis of the total online capacity of the respective country for each hour. The figures show a split violin plot (analogous to the inertia plots above), where, for each country, the left side of each violin presents the inertia of the 2030 timeframe of a scenario and the right side shows the inertia of the 2040 timeframe of the same scenario. Hence, the trend of inertia development can be seen very clearly for each country.

The estimation provides an abstract image of the equivalent inertia resulting from the generation mix in each country for all the hours of the year. In general, countries with higher inertia values have a generation mix with higher share of synchronous generation (which may also include RES from hydro). Conversely, countries presenting lower values of inertia have a generation mix with higher share of converter connected RES.

The plots do not allow a conclusion on sufficiency of inertia, or even on the level of RES integration. Instead, they only portray a supplementary insight into the level of the inherent diversity and internal variability of the different countries regarding equivalent inertia.


Scenario DE2030 (left) & DE2040 (right) - Climate Year 2009
Inertia Constant H (s)
Country
Scenario
DE2030
DE2040
0
2
4
6
8
AL
AT
BA
BE
BG
CH
CZ
DE
DKE
DKW
EE
ES
FI
FR
GR
HR
HU
IE
IT
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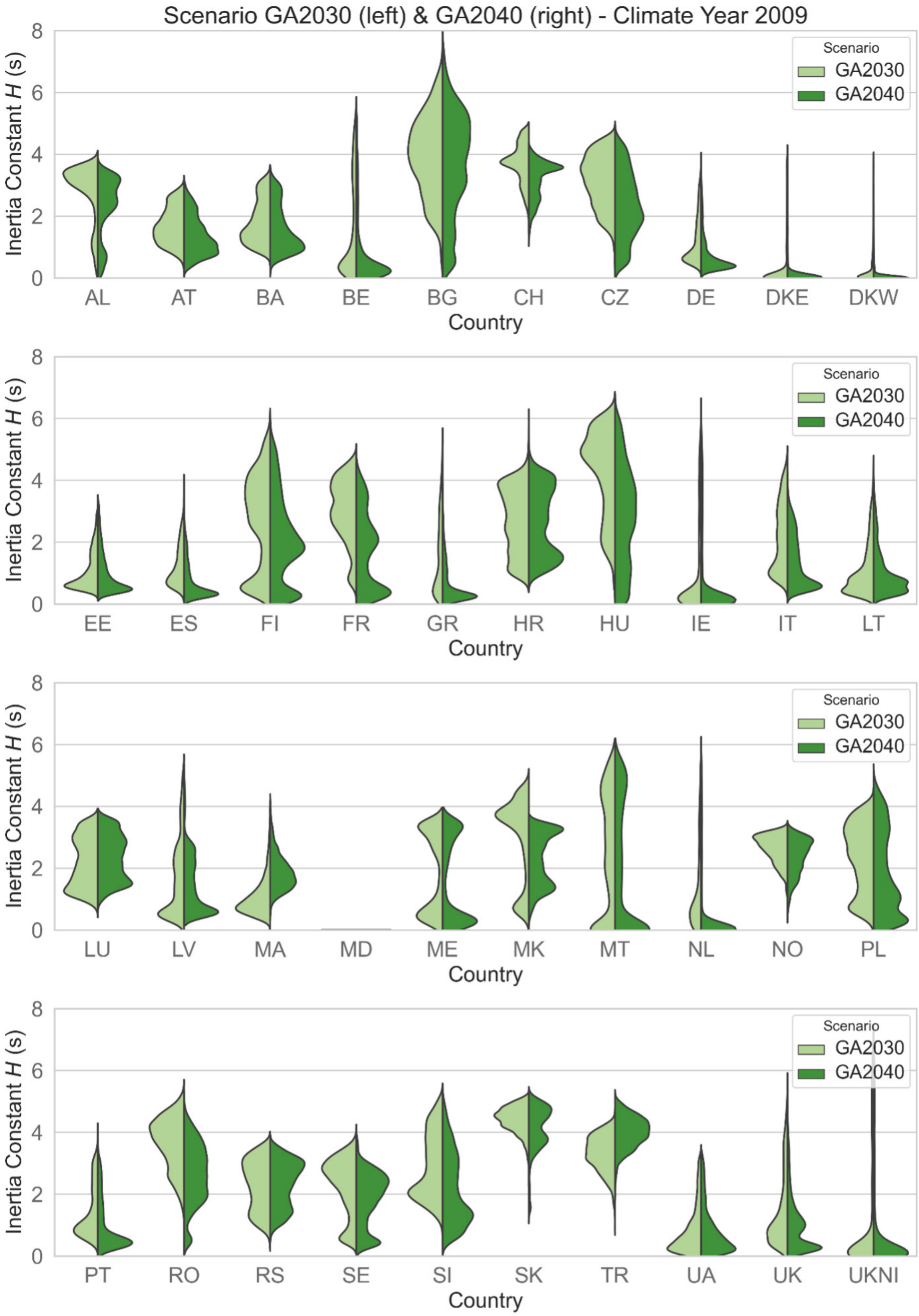
Scenario GA2030 (left) & GA2040 (right) - Climate Year 2009
Inertia Constant H (s)
Country
Scenario
GA2030
GA2040
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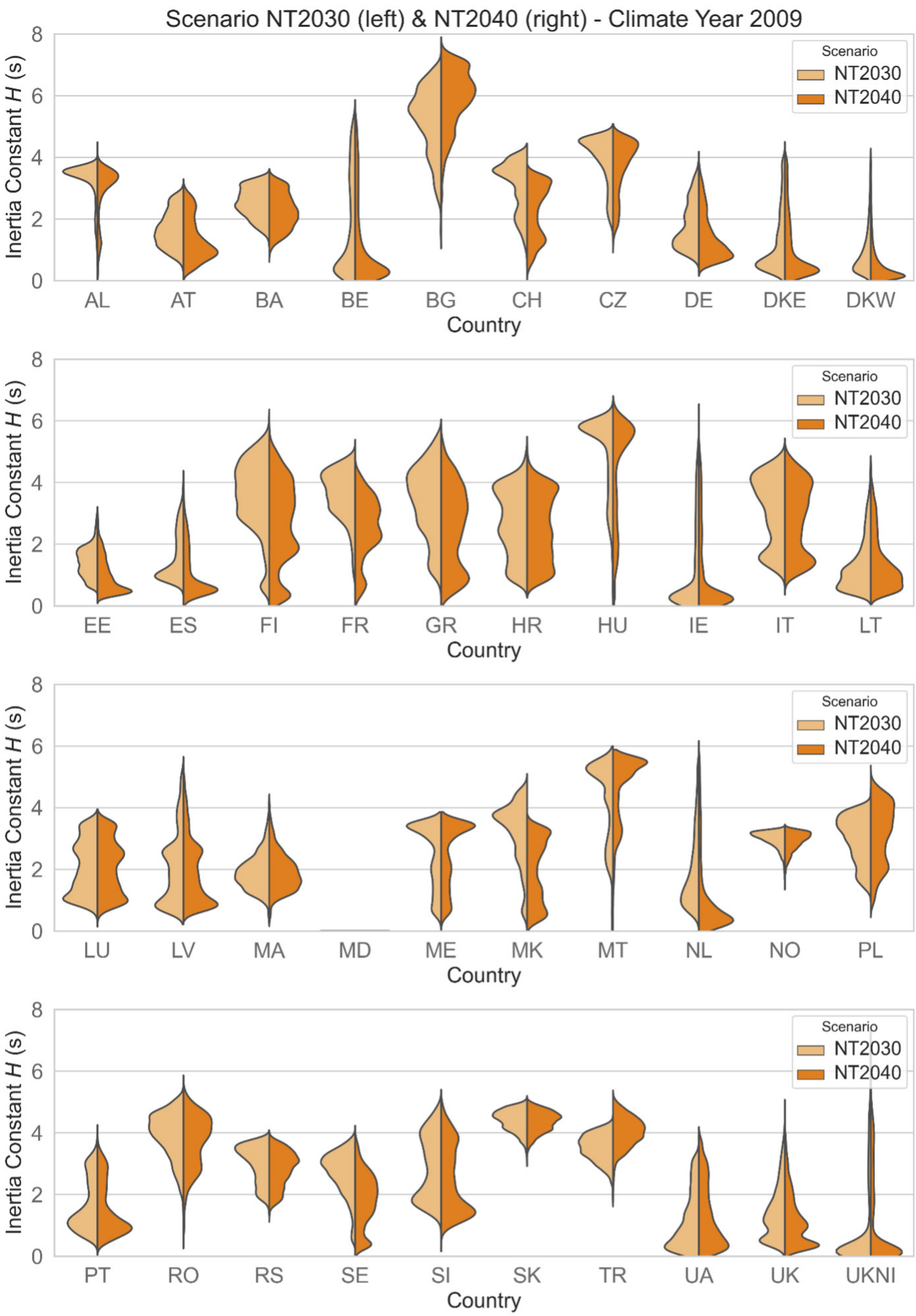
EE ES FI FR GR HR HU IE IT LT
LU LV MA MD ME MK MT NL NO PL
PT RO RS SE SI SK TR UA UK UKNI


Scenario NT2030 (left) & NT2040 (right) - Climate Year 2009
Inertia Constant H (s)
Country
Scenario
NT2030
NT2040
AL AT BA BE BG CH CZ DE DKE DKW
EE ES FI FR GR HR HU IE IT LT
LU LV MA MD ME MK MT NL NO PL
PT RO RS SE SI SK TR UA UK UKNI
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