European Network of
Transmission System Operators
for Electricity

FREQUENCY STABILITY IN LONG-TERM SCENARIOS AND RELEVANT REQUIREMENTS

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INTRODUCTION

Through its studies and analysis, ENTSO-E has made important contributions to an open discussion on various power system stability issues, with the goal being to engage with stakeholders and establish a common understanding of the challenges and solutions for the present and future power system. This commitment has led to a project dedicated to assessing and elaborating on the capability of the continental European (CE) interconnected transmission system to sustain out-of-range events, such as system splits, under future scenarios, given the threat of reduced levels of total system inertia and increased power transmission through the electricity system.

Events from the recent past – such as the separation of Italy in September 2003 and the CE synchronous area separation into three parts in November 2006, the East–West separation in January 2021, and the Iberian separation in July 2021 demonstrates that system splits, even if they are out-of-range events that are unlikely to occur, should be considered as serious, challenging, and realistic disturbances that push the interconnected system to the limits of its dynamic stability and incur the risk of large-scale blackouts.

As shown in the TYNDP 2018 scenarios, the energy system is evolving towards a configuration that might lead to the increasing relevance of frequency stability challenges: a variable and renewable energy sources (RES) intensive generation mix, more inverter-based resources, reduced levels of inertia[1] and large and variable power flows. Although a high rate of change of frequency (RoCoF) and frequency excursions are not expected in the CE synchronous area under ordinary contingencies, they can be observed during severe events with high power imbalances and low system inertia, such as system splits, in which the interconnected system is separated into two or more subsystems. The power imbalance, determined by the power flow exchange prior to the split,

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[1] In this report, the term 'inertia' is used to refer in general to the power provided instantaneously in the event of a frequency change, i.e. without any intervention of a control system, and thus it includes the kinetic energy of synchronous generators and synchronous condensers as well as the contribution of converter-based devices with grid-forming capabilities.

and the subsystem inertia, determined by its generation mix, are the key factors that control the initial RoCoF after a system split. Based on the TYNDP 2018 long-term scenarios and market studies, this report investigates, under a set of assumptions, a significant number of combinations of system split cases in the CE synchronous area which separate the interconnected system into two parts. For all combinations, the theoretical initial RoCoF at the centre of inertia is determined at hourly resolution of the year under consideration. This report neither analyses the causes of system splits nor performs grid calculations; instead, it focuses on assessing whether the combinations of subsystems after a split would be able to cope with the relevant initial conditions, in terms of power imbalance and subsystem inertia, under the different TYNDP scenarios.

To assess the RoCoF, the following boundary conditions are assumed:

a) The report refers to a global RoCoF evaluation, corresponding to the rate of change in system frequency at the centre of inertia of the relevant island after the split.

b) The system operation limit, which is currently specified as 1 Hz/s, needs to be clearly distinguished from the robustness of power generation modules (meaning its capability to remain connected to the system), which is specified in the Connection Network Codes as RoCoF withstand capability in 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.

c) 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. As described above, because local phenomena can be more severe than the global RoCoF, the report assumes that the initial RoCoF at the centre of inertia provides an objective indicator of the scale and range of the challenge.

Under these assumptions, for each split case analysed, the study allows the identification of the theoretical initial RoCoF at the centre of inertia at hourly resolution of the year under consideration. The higher the imbalance between load and generation and/or the lower the inertia, the higher the RoCoF. A high RoCoF then reduces the time available for the necessary fast balancing actions to prevent high-frequency excursions exceeding the robustness levels of system users and the remedial capabilities of emergency actions according to system defence plans. This leads to unstable behaviour in the subsystems, unintended shut-off of generation/load or even blackout.

This report helps to create awareness of the challenge related to the achievement of resilience against system splits and aims to guide decision-making on such resilience by indicating which could be the relevant system parameters and how they may be reasonably quantified. In doing this, it takes the first step in enabling a vitally important discussion and setting-up the framework for the needed follow-up studies.

SYSTEM SPLITS AND THEIR IMPACT ON THE ROCOF

According to the report ‘Inertia and rate of change of frequency (RoCoF)’,[2] initial RoCoF values higher than 1 Hz/s can compromise the efficiency of resilience and/or defence plan actions designed to stabilise the grid, and, as such, these RoCoF values are currently regarded as not being manageable. This is because the abovementioned balancing actions are not fast enough to restore the system active power balance before reaching a frequency threshold at which most of the generation begins to disconnect, which in turn leads to blackout. Therefore, this study concentrates on identifying cases of |RoCoF| exceeding 1 Hz/s, and concludes that a significant number of such cases can be observed in all investigated scenarios (Figure 1).

The load ratio reflects the size of a subsystem in relation to the CE system. As the subsystem size increases, the RoCoF value tends to decrease. Moving from the 2025 scenario towards 2040, an increase can be observed in the expected |RoCoF| for subsystems of all sizes as well as in the size of the subsystems exposed to |RoCoF|> 1 Hz/s.

In Figure 1, the discontinuity in RoCoF values, in the load ratio range of 0.15–0.25, is related to subsystems containing countries with a comparatively high share of the entire system load of the CE synchronous area, but still with high RoCoF values due to high load imbalance after a split, low subsystem inertia, or a combination of both.

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[2] ENTSO-E (2020-12-16), *Inertia and rate of change of frequency (RoCoF).*https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/Inertia%20and%20RoCoF_v17_clean.pdf

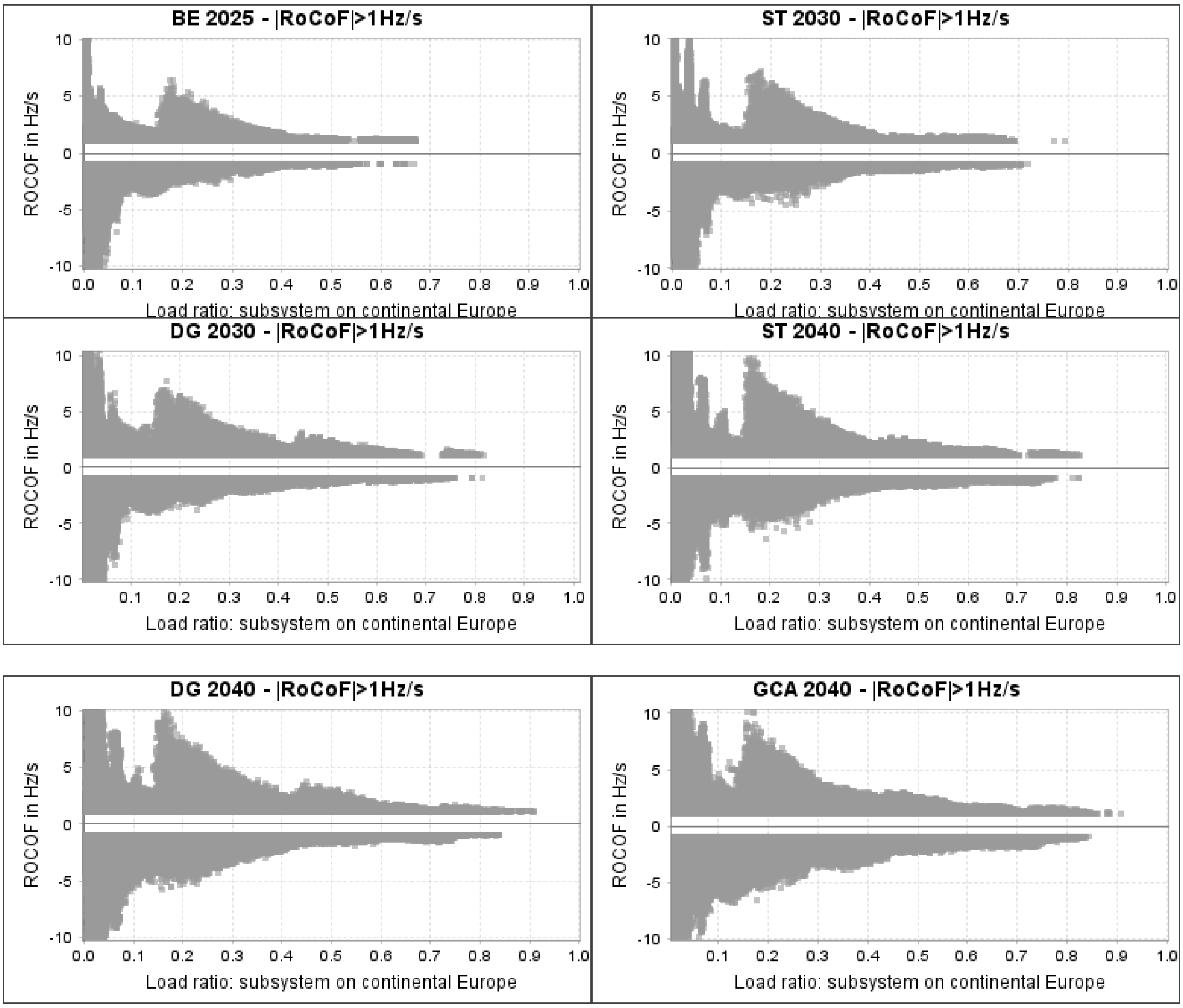

Figure 1: |RoCoF| values above 1 Hz/s for each subsystem of the CE synchronous area (consisting of two subsystems per split combination) plotted against the load ratio of each subsystem with regard to the CE synchronous area for the different TYNDP 2018 scenarios (each dot represents an hour and split combination): 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; and GCA 2040 – Global Climate Action 2040. Values above 10 Hz/s, appearing for small ratios only, are not shown.

It is important to highlight that a clear definition of ‘acceptable risk’, related to a system split and its consequences, is still pending. This report does not aim to propose such a definition because this would be a political as well as a technical decision – the sort of decision that should incorporate the input of all industrial and institutional stakeholders. However, this report may guide decision-making by providing technical indications for the relevant parameters associated with the phenomena of system splits, and how they may be reasonably quantified.

GLOBAL SEVERE SPLITS

In this context, this study focuses on split scenarios with the initial |RoCoF| exceeding 1 Hz/s in both resulting subsystems. Exposure of both resulting subsystems to an |RoCoF| higher than 1 Hz/s incurs the highly possible risk of a blackout of the entire CE. In this case, there is no neighbouring grid ‘alive’ to promptly restore the blacked-out subsystem. Therefore, from a pan-European perspective, these cases are regarded as *global severe splits*. Moreover, although this study calculated the RoCoF at the centre of inertia of the subsystem, it should be noted that local RoCoF values can be significantly higher in reality.

Figure **2** shows these *global severe splits* in colour. Splits for which at least one island exceeds the |RoCoF| limit of 1 Hz/s are shown in grey, whilst splits for which both islands exceed this threshold are shown in other colours. A large number of severe splits are identified, with an increase from 2025 to 2040. In addition to the *global severe splits*, greater challenges and requirements could be present due to severe splits at the national level or between a group of Transmission System Operators (TSOs) (in grey).

Each global severe case is indicated by two dots, and each dot corresponds to one of the two split subsystems showing its load ratio and RoCoF for one specific hour and one system split. From this it can be seen that the two load ratios correspond to 1, whilst the RoCoF values are of the opposite sign.

Figure 2 also shows that for scenarios BE 2025 to GCA 2040, the global severe cases correspond to a larger number of cases, higher RoCoF and split lines that isolate even unequal-sized systems (smaller and bigger load ratios).

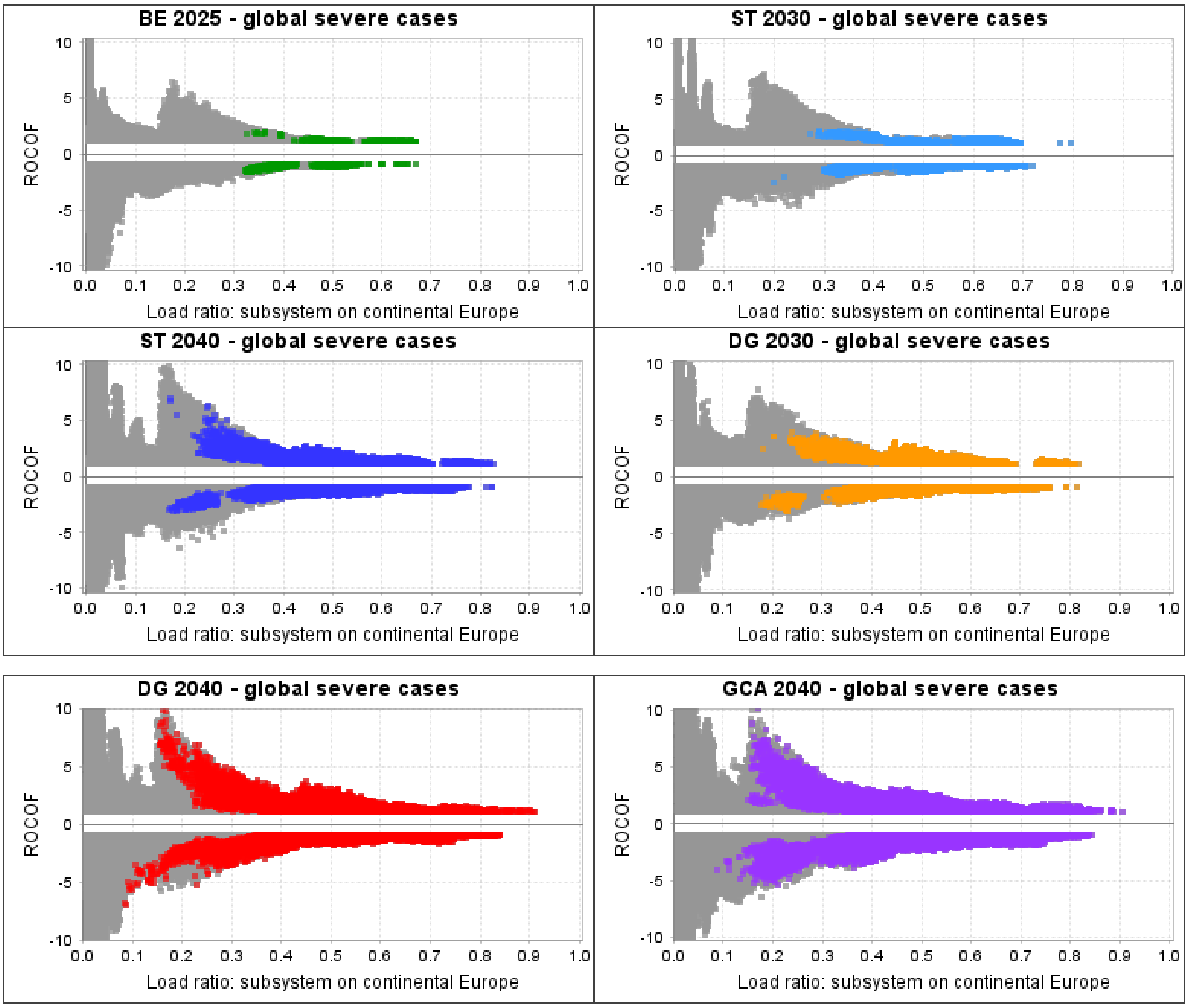

Figure 2: The colours indicate RoCoF (Hz/s) with respect to the load ratio of the subsystem in continental Europe for all cases (hour × split) with an RoCoF higher than 1 Hz/s in both islands under each TYNDP 2018 scenario: BE 2025 – Best Estimate 2025; ST 2030 – Sustainable Transition 2030; ST 2040 – Sustainable Transition 2040; DG 2030 – Distributed Generation 2030; DG 2040 – Distributed Generation 2040; and GCA 2040 – Global Climate Action 2040. Values above 10 Hz/s are not shown.

Due to these global severe splits, as well as other severe splits, countermeasures should be considered to keep them manageable and prevent or at least reduce the risk of potential blackouts. Since there is no single solution to this, several measures for improving the resilience of the future system must be weighed and assessed against each other:

- 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)[3].
- Enhance the total system inertia of the CE synchronous area through assets such as STATCOM with batteries included in the DC circuit and synchronous condensers or through market-based solutions.
- Take measures to avoid a system split, such as by reinforcement of grid assets (in case of non-increasing power flows)[4] and increased use of DC technology instead of AC technology (condition: continuing power flows via the DC system)[5].
- Increase withstand capability[6] of power generation units and establish faster-reacting system protection schemes (further develop the system so that |RoCoF| higher than 1 Hz/s can be handled).
- Develop countermeasures to mitigate the effects of system splits, without influencing the RoCoF but whilst influencing the nadir.[7] (e.g. Special Protection Schemes)
- Impose market restrictions in terms of reduction of the power exchange and deployment of must-run units.

If a subsystem blackout cannot reasonably be mitigated by preventive action, efficient restoration measures, including reassessment of existing restoration plans that may no longer be applicable because of the changing system conditions, must be established.

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[3] In the event of an overfrequency, for example, the chopper of a wind power plant can be used to reduce storage demand. However, it must be ensured that an inherent reaction is first guaranteed by grid-forming behaviour.

[4] Grid reinforcement can only reduce the risk of system splits if the power flows remain the same. If the new grid capacity is used to increase power flows, then the possible power imbalance, and thus the risk of a split, further increase.

[5] Power flows via the DC system are assumed to remain even during a system split.

[6] Considering margins between withstand capability at connection points and the frequency at the centre of inertia.

[7] Use of special protection schemes (SPS) which act in such a way that the imbalance ratio is corrected either by load or generation shedding in order to correspondingly reduce the Nadir.

QUANTIFYING THE CHALLENGE AHEAD

Although this study does not set out to determine the optimum set of solutions to cope with system splits and their potential consequences, an attempt was made to quantify the scale of the challenge through evaluation of the theoretical amount of inertia that should be deployed to keep the |RoCoF| values below the operational threshold of 1 Hz/s.

It is important to note that the specific approach used to evaluate the challenge posed by the system splits does not mean in any way that the installation of additional inertia is the only method, or even the preferred method, to cope with the consequences of such events. As mentioned above, the installation of additional inertia is only one of several measures for improving system resilience that have to be considered and weighed against each other.

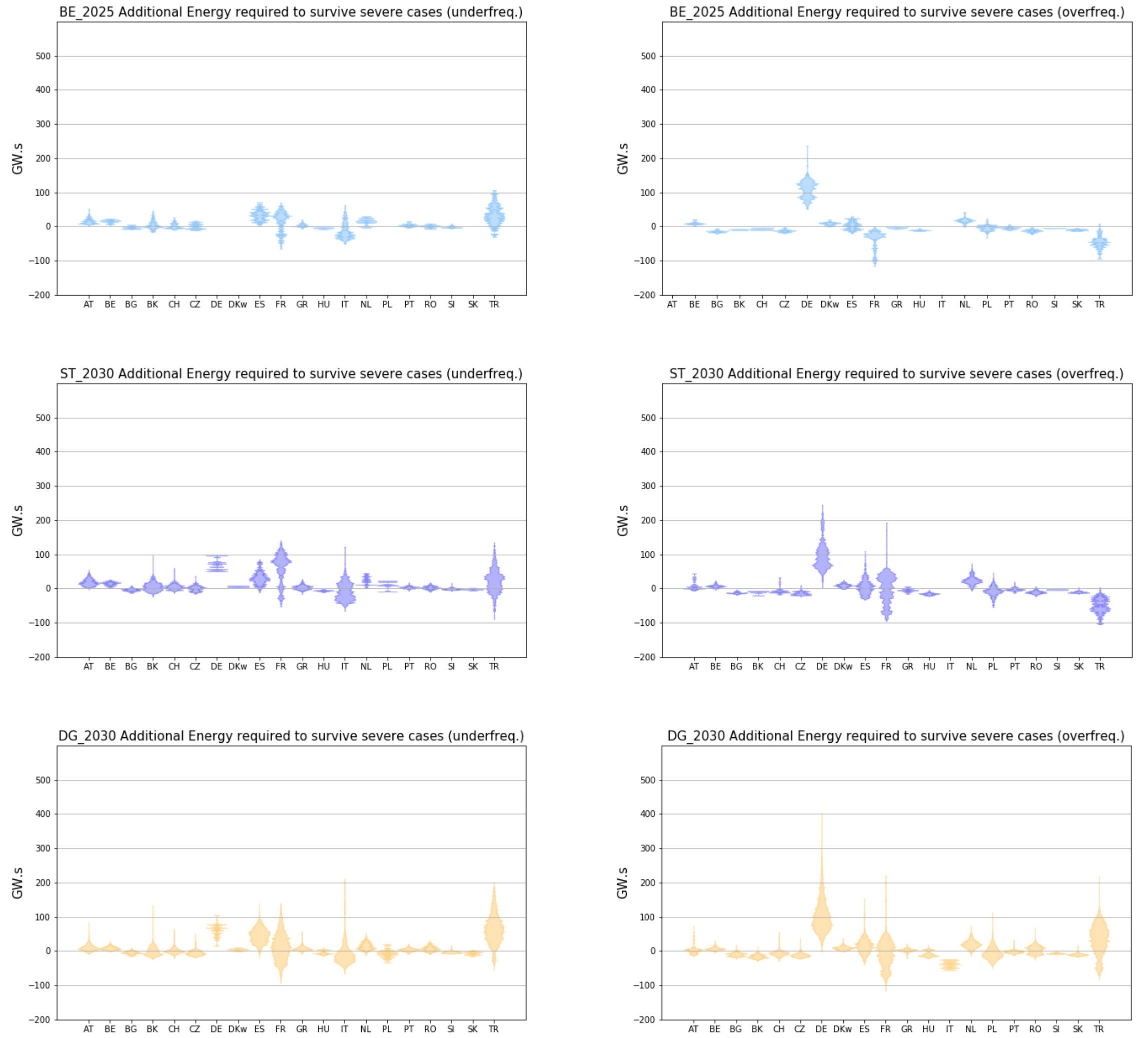
This study, though, focuses only on the solutions related to the instantaneous inertial response and use of initial imbalances (unconstrained market). From this perspective, the available kinetic energy in the system is compared with the necessary kinetic energy values in each hour and scenario to avoid the |RoCoF| exceeding 1 Hz/s in all *global severe splits*.

The theoretical additional inertia required to keep the |RoCoF| below 1 Hz/s in each subsystem is computed for each market zone according to its share in the total generation in the respective hour (proportionally to the sum of the rated power $S_{\max}$ of all running units at the hour; for RES, the actual power output is used instead of the rated power $S_{\max}$). This approach (others could also be considered) is implemented according to the same method for all hours of all scenarios, thus enabling a systematic comparison across all hours and scenarios.

Figure 3 shows the statistical distributions of the theoretical additional inertia $[GW \cdot s]$ required by the subsystems to cope with all *global severe splits*. The additional kinetic energy is computed for each market zone proportionally to its running rated power at each hour.

Note that the reason for the increased need for additional inertia is not solely a high share of inverter-based generation; it is also a result of large power exchange. This is because a large power exchange requires at least one exporting market zone and at least one importing zone.

Furthermore, it is important to note that the *global severe splits* shown in colour in Figure 2 should be understood as a minimum benchmark for defining a manageable split scenario at the CE synchronous area level. Plus, at the national level or between a group of TSOs, greater challenges and requirements could be present due to severe splits (Figure **2**), but these demands are not considered in this study.



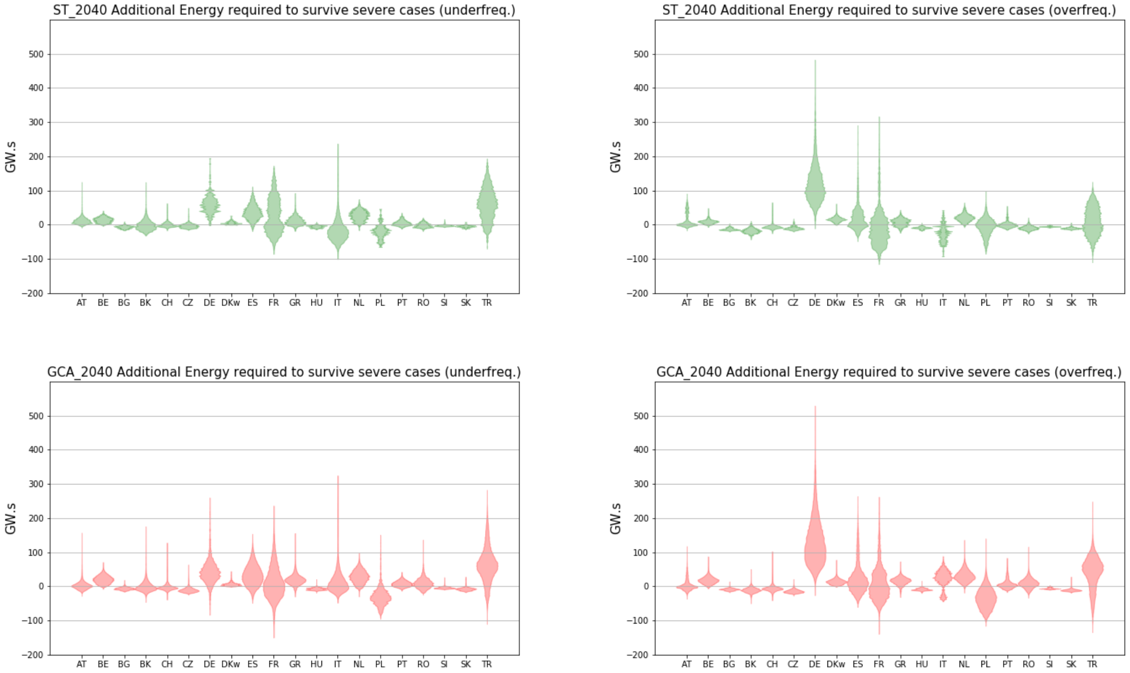


Figure 3: Statistical distributions of the additional kinetic energy (GWs) required by a market zone to cope with all *global severe splits* (overfrequency and underfrequency distinguished). The additional kinetic energy is computed for each market zone[8] proportionally to its running rated power at each hour.

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[8] BK includes the countries AL, BA, HR, ME, MK, and RS, modelled as a single market node.

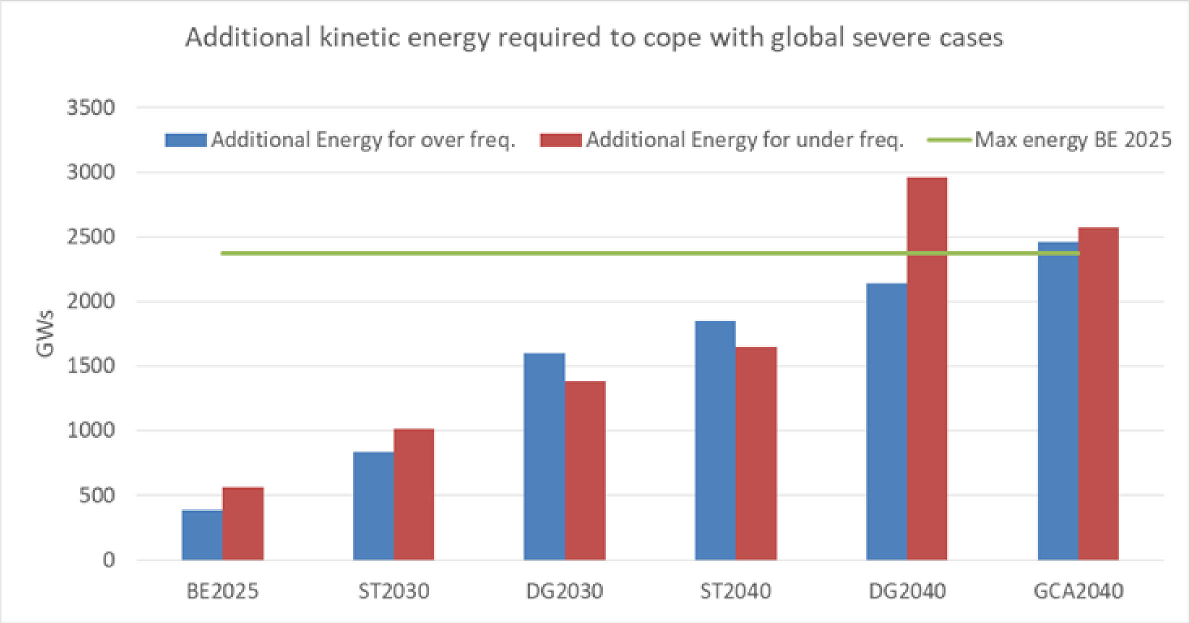

Figure 4: Total kinetic energy demand per scenario to control *global severe splits* in all hours (sum of maxima of Figure 3).

The scenarios from 2025 to 2040, as shown in Figure 3 and Figure **4**, demonstrate that a minimum theoretical additional inertia of more than 500 GWs in 2025 and more than 2500 GWs in 2040 is necessary to be able to cope with all *global severe splits* in all hours.

To provide an indication of the amount of additional inertia needed to cope with the consequences of global severe splits, the inertia values above can be broadly translated into the inertia provided by hypothetical conventional power plants. This would correspond to 400 additional units (100 GW of installed capacity) in 2025 and 2000 units (500 GW of installed capacity) in 2040, each hypothetical unit having an exemplary power of 250 MW and an inertia constant of 5 seconds.

CONCLUSIONS

This study focuses solely on the aspects of inertia involved in the management of all *global severe splits*. It does not assess the possible concrete mitigation measures or the manageability of resistance to system splits, but it does analyse the response of the system in terms of inertia by calculating the |RoCoF| values in the split islands, starting from the market data of TYNDP 2018.

The theoretical amount of additional inertia necessary to improve such a response and limit the |RoCoF| to 1 Hz/s for a set of defined *global severe cases* enables an initial assessment of how challenging it would be to grant sufficient time to implement further frequency control measures and defence plans to prevent a blackout of the entire CE synchronous area.

The *global severe splits* approach focuses on the split cases that might affect all coutries in the CE synchronous area. In addition to problems caused by the *global severe splits*, though, it should be noted that greater challenges and requirements may be present at the national level or between groups of TSOs due to even more severe splits. To manage the consequences of these split events, additional inertia should be provided in the relevant region, or equally effective measures should be put in place. These would then have to be investigated more deeply on a case-by-case basis by the relevant TSOs.

From this analysis and the available results, it is possible to take forward the discussion on managing system splits and related risks in continental Europe and thus determine the most efficient mitigation actions.

Making the system stronger against the impact of these events entails the implementation of additional measures to increase the robustness of the system (infrastructure development and protection systems), even in the current planning phase of the European grid. This includes not only requirements for the corresponding technical capabilities of assets and HVDCs (i.e. connection requirements), covered in the network codes and standards, but also coordinated evolution of Dynamic Security Assessment capabilities, control of flows and national defence plans.

The trends shown in this study also highlight the urgent need to look for no-regret actions as possible improvements of defence plan measures for the increasing RoCoF, which will in any case be necessary to reach whatever is the defined level of resilience against system split.

The challenge posed by the phenomena of system splits cannot be solved by single actions at the national level, however, coordinated efforts from all European TSOs and stakeholders are necessary to ensure the effectiveness of the measures. Indeed, to meet the EU's energy policy objectives, it is necessary to define a viable path that suits all the involved parties and to act urgently.

In this context, it is essential to define a resilience level for managing system splits for a corresponding adequate and robust system design. This report does not propose such a definition but provides important information to create awareness of the complexity of the issue and to guide decision-making about such a resilience level by indicating potentially relevant system parameters and how they are reasonably quantified. For further analyses, it is necessary to determine whether system design should consider system split as an occurrence, and the extent to which it should be accounted for to update defence plans or to define additional measures aimed at improving the resilience of the system. The costs and consequential effects of a severe split are difficult to quantify and must be considered in future assessments.

Finally, TSOs will continue to proactively cooperate with all stakeholders and the industry to facilitate the identification of cost-effective solutions to energy system transition.