PROJECT INERTIA – PHASE II: UPDATED FREQUENCY STABILITY ANALYSIS IN LONG TERM SCENARIOS, RELEVANT SOLUTIONS AND MITIGATION MEASURES

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CONTENTS

EXECUTIVE SUMMARY

Building on the conclusions of the report "Project Inertia – Frequency stability in long term scenarios and relevant requirements" [1], the present PROJECT INERTIA PHASE 2 aims to push forward the analysis of the impact of system splits on the future "low inertia" configuration of the Continental Europe (CE) Synchronous Area (SA).

In this first step (present report – first interim report), the project reviews, following similar assumptions and methodology to the aforementioned previous study, a significant 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 Rate of Change of Frequency (RoCoF) at the centre of inertia is determined at hourly resolution of the years under consideration (2030 and 2040). An assessment is made of whether the combinations of subsystems formed after a split would be able to cope with the RoCoF resulting from the relevant initial conditions, regarding power imbalance and subsystem inertia, under the different TYNDP 2022 scenarios. In addition, PROJECT INERTIA PHASE 2 introduced a new methodology for time-domain simulations, delivering a perspective on the frequency performance of the separated subsystems after the split. Having presented the risk of a blackout in the whole SA following a system split, the wider analysis evaluated if a total blackout could occur due to frequencies outside the range 47.5–51.5Hz, even if the initial RoCoF is smaller than 1 Hz/s.

From the updated results, the trends identified in the previous report "Frequency stability in long term scenarios and relevant requirements" are confirmed. Splits for which at least one island exceeds the |RoCoF| limit of 1 Hz/s and splits for which both islands exceed this threshold are identified in a large number and with a visible increase from 2030 to 2040. This demonstrates the progressive decline of system resilience against system splits if no actions are initiated.

Based on the results from the updated calculations and a detailed review of the solution or mitigation measures, in a second step (second interim report), the project will propose a quantified combination of measures to address the identified frequency stability challenges. The following three steps will be taken forward in the second interim report: Define the intended level of resilience against system splits; the resulting minimum level of inertia; and the inertia allocation between countries.

As already defined in the previous phase of the project, the accepted level of reliability of the grid and accepted risk of blackout must involve all the stakeholders and the relevant institutions as it is not for the Transmission System Operators (TSOs) only to define these aspects. PROJECT INERTIA PHASE 2 will focus on making concrete proposals and enabling decision-making.

1. INTRODUCTION

Building on the conclusions of the report "Project Inertia – Frequency stability in long term scenarios and relevant requirements" [1], the present PROJECT INERTIA PHASE 2 aims to push forward the analysis of the impact of system splits on the future "low inertia" configuration of the Continental Europe (CE) Synchronous Area (SA).

In a first step (present report – first interim report), the project will update and improve the existing methodology to assess system split cases based on pan-European market studies for long-term future scenarios (TYNDP 2022 scenarios). The methodology will include systematic analytical calculations and, for a selected number of cases, new "system balance model" (SBM) time-domain calculations.

Based on the results from the updated calculations and a detailed review of the solution or mitigation measures, in a second step (second interim report) the project will propose a quantified combination of measures to address the identified frequency stability challenges.

As already defined in the previous phase of the project, the accepted level of reliability of the grid and accepted risk of blackout must involve all the stakeholders and the relevant institutions as it is not for the TSOs only to define these aspects. PROJECT INERTIA PHASE 2 will focus on making concrete proposals and enabling decision-making.

2. INVESTIGATION CONTEXT

System splits, also called system separations, present a rare but major challenge for the stable operation of an SA. During a system separation, an SA splits apart into at least two asynchronous electrical islands. Five major system splits affected CE in the last 20 years and are highlighted below.

1. 2003-09-28: Italy was separated from the Union for the Coordination of Transmission of Electricity (UCTE) [2]
2. 2006-11-04: CE was split into three separate islands [3]
3. 2015-03-31: Turkey split into two islands followed by a blackout of the Turkey power system[4]
4. 2021-01-08: South-East of CE (Balkan Peninsula) was separated from the rest of CE [5]
5. 2021-07-24: the Iberian Peninsula was separated from the rest of CE [6]

In the following subsections, details about the past system splits, including causes, consequences and learnings, are given. In all cases, before the system separations, the power systems were highly loaded.

2.1 Separation of Italy (2003)

Cause: [2, p. 59]:	1. tree flashover on highly loaded line 2. unsuccessful reclosing of line (phase angle difference too large) 3. a lack of urgency from operators concerning overloading of parallel lines and initiation of countermeasures 4. trip of second highly loaded line due to enduring overloading and subsequent islanding of Italy (power imbalance of approx. 6.4 GW) 5. angle instability and voltage collapse in Italy
Consequence: [2, pp. 43,72]	• blacking out of Italy (ranging from 3 hours to more than 10 hours in different parts of Italy) • overfrequency and overvoltages in UCTE caused various grid elements to trip • approx. 2.4 GW of generation tripped in rest of CE

Learnings/Recommendations (excerpt): [2, p. 89]	• acceleration of Wide Area Monitoring System (WAMS) installation program • synchronisation of rules (N-1…) between TSOs and improvement of real-time data exchange • extensions of national regulations & update of emergency procedures • …

The root causes are manifold, including large phase angles due to power flows and network topology, human factor and a general tendency towards grid use close to its limits [2, p. 63].

2.2 System Separation of 2006

Cause: [3, p. 48]	1. non-fulfilment of the N-1 criterion (only an empirical assessment of the grid state was conducted before some switching actions instead of necessary numerical calculations) 2. insufficient coordination between neighbouring TSOs after outage rescheduling 3. cascaded tripping of lines due to overloading
Consequence (excerpt): [3, p. 25]	• approx. 17 GW of load was shed in the Western island (15 million people were affected by local blackouts [7, p. 3]) • approx. 10.9 GW of generation tripping in the Western island • approx. 6.2 GW of wind generation tripped in the North-East island • trip of the interconnection between Morocco and Algeria
Learnings/Recommendations (excerpt): [3, p. 58]	• review TSO “N-1 criterion” applications • “Master Plan” for emergency operations • new standards for regional and inter-regional coordination and adaption of regulatory and legal frameworks • implement a real-time system to enable the monitoring of the UCTE system state • …

The root cause is a combination of a high transit over long distances and human error, more specifically the neglect of official operational guidelines and insufficient communication between TSOs.

2.3 Turkey System Separation followed by blackout of Turkey power system (2015)

Cause: [4, p. 8]	1. multiple important 400 kV lines were out of service due to construction and maintenance work 2. all series capacitors in Turkey were out of service 3. incorrect evaluation of system transmission capability (no (N-1) dynamic security compliance) 4. lack of awareness of importance of series capacitors, which were mostly out of service 5. insufficient protection relay settings 6. tripping of generators, which were not compliant with the grid code
Consequence (excerpt): [4, p. 7]	• approx. 4.8 GW of load was shed • loss of synchronism and subsequent disconnection of the CE system • widespread blackout in Turkey which left more than 70 million people without electrical power.
Learnings/Recommendations (excerpt): [4, pp. 9,44]	• improve outage- and maintenance-planning • install online contingency analysis and angle observation in the control centre • adapt load shedding scheme • improve grid operator training and awareness • …

The root cause is a combination of a high transit over long distances and human error, more specifically a lack of awareness of the system transmission capability during an extraordinary system topology.

2.4 Separation of Balkan Peninsula (2021)

Cause: [5, p. 134]	1. unforeseen high load-flow from South-East to North-West of CE, especially on a specific busbar coupler in Croatia (also, unknowingly operation of the system on the verge to angular instability) 2. trip of mentioned busbar coupler and cascading trip of parallel lines due to overcurrent protection

Consequence: [5, pp. 57,65,69]	• approx. 5.25 GW of generation tripped • approx. 0.3 GW of load was shed • local power outages in Romania • High Voltage Direct Current (HVDC) between RTE and REE tripped due to erroneous protection parametrisation
Learnings/Recommendations (excerpt): [5, p. 65]	• Correct and monitor non-conform disconnections of loads and generation • adapt substation topologies to reduce load flow on busbar couplers (also include relevant devices in security calculations) • adapt set points of protection devices • revise margins for power flows • improve intra-day forecast to better match real-time operations • monitor and assess angular stability margin of critical transmission system corridors in operational planning and real-time operations (WAMS into EAS integration project). • …

The root cause was the CE system being operated close to the stability limit and the unexpected overcurrent tripping of a neglected part of the transmission chain (in this case a busbar coupler).

2.5 Separation of Iberian Peninsula (2021)

Cause: [6, p. 111]	1. a forest fire broke out close to a two-circuit line 2. for more than 3 hours, the respective TSO was not informed by local authorities of a fire close to a transmission line to be able to disconnect the lines 3. the fire caused a short circuit on one system without successful automatic reclosure 4. after 2 minutes, the second system of the two-circuit connection tripped as well, again without successful automatic reclosure 5. this double-outage led to a redistribution of power flows following a cascaded tripping of parallel lines due to overloading 6. separation of Iberian Peninsula due to loss of synchronism
Consequence: [6, p. 93]	• approx. 3.8 GW of generation tripped • approx. 4.9 GW of load was shed

Learnings/Recommendations (excerpt): [6, p. 112]	• improve data collection and monitoring of generation tripping, especially on the Distribution System Operator (DSO) level • improve TSO–DSO coordination on protection relay settings to avoid excessive distributed generation shedding • investigate possible additional Special Protection Scheme (SPS) on transit corridors • enhance Low Frequency Demand Disconnection (LFDD) monitoring and settings • improve investigation into weather-related risks • review settings for resynchronisation devices on tie-lines • …

The root cause was insufficient awareness of weather-related risks (wildfires) in combination with a lack of communication between local authorities and TSOs about these risks.

2.6 Conclusion of Past Events

System splits can and already have led to blackouts (local outages in 2006 and wide-area outages in Italy in 2003 and in Turkey in 2015). Power outages can have severe consequences for the population and economy of a country. In the past, system splits led to blackouts only in some parts of the CE system and not the whole CE area. System restoration time is significantly reduced if a blacked-out system has a good connection to an energised power system. The healthy, energised power grid can support and stabilise the blacked-out system during the restoration phase. Due to the increase in system restoration time (compared to an only partly blacked-out system), blackouts of complete SAs are expected to be much more critical. Prolonged outages are expected to lead to national catastrophes in the affected areas within days [8], [9].

In light of the root causes of the system splits, which were summarised in the previous sub-sections, the following statements can be made:

- From the technological perspective, all system splits could have been avoided. The necessary technologies and tools to mitigate the risks in highly loaded grids with high transits were, from the technological standpoint, already available.

- Improved situational awareness, preparation and coordination of involved parties could have prevented all past system separations.

- All system split events have followed on a heavy loaded transmission system state and power transfers over large distances. The closer a transmission system is operated at its stability limit, the higher the risk of large-scale consequences (e.g. system splits) after unforeseen events such as faults or trips. Given the trend of operating the transmission system close to its limits, it is plausible in the future to expect increasingly heavy loading conditions characterising the grid.

Examining the amount of energy distributed and used, the CE power system is one of the largest man-made technological achievements and is inherently complex. Avoiding human error in such complex systems which contain millions of assets, interfaces and stakeholders cannot be guaranteed. Reference [10] shows a collection of large disturbances worldwide and also analyses the causes and evolution of events. It is also demonstrated here that human error contributes to a large portion of past disturbances [10, p. 15]. Because of this complex interplay, system splits, even though their probability is very low, will also remain an unpredictable risk in the future. A quantitative assessment of very low-probability, very high-risk events can only under- or overestimate the effectiveness of mitigation measures. As the causes of system splits are always unique, precautions against them can only be made generally, and the similarities of events are of a qualitative nature.

On the one hand, the continuous optimisation of equipment, settings and processes will reduce the chance of future system splits, even with unexpected human intervention or unforeseen equipment interactions. On the other hand, increasing power flows and grid utilisation in future power systems increases the risk of large incidents due to the grid being operated closer to its limits and with increasing amount of power exchanges. In the future, other boundary conditions can also increase the risk of large-scale events if not mitigated properly:

- Reduction in system inertia, which can lead to faster and higher frequency excursions;
- As yet uncertain behavior of new generators and consumers (such as power to gas demand facilities, prosumers);
- increase in extreme weather events (such as severe storms, droughts, wildfires, …); and
- supply change challenges and other unforeseen unavailability of assets.

2.7 Scope of Investigation

The previous Project Inertia report "*Frequency Stability in Long-Term Scenarios and Relevant Requirements*" [1] provided an initial overview on the role of inertia when considering system splits in CE. It serves as a basis for continuing the discussion on efficient mitigation measures in this report. Hence, the goal of this report is to update the previous overview and assess the system resilience towards system splits from a frequency stability perspective. Furthermore, necessary measures to increase system resilience to the desired level are investigated, which will help to make informed decisions on system reinforcement.

It is worth noting that frequency stability is not the only stability challenge the system faces. Frequency stability issues are a direct consequence of power imbalances and sudden strong shifts in power flows. Even if closely linked to voltage stability issues, which can arise from changing load flow conditions, other stability issues, beyond frequency disturbances, are nonetheless out of the scope of this report and require examination in other investigations. However, by tackling frequency stability challenges, a necessary foundation for the system's resilience is established without restricting any solutions that might also be required to tackle other system stability issues.

As system splits can lead to blackouts with catastrophic consequences, reducing the likelihood of their occurrence should always be pursued by implementing the learnings from previous events or by reinforcing the grid in the face of increasingly large and variable power flows, onshore and offshore, across Europe. A preventive perspective remains a central aspect to tackling the system split challenge. Nevertheless, a minimum level of inertia, which is required to limit the RoCoF during system split events, in addition to reliable system defence plans are fundamental requirements to avoid blackouts during unforeseen major disturbances. This minimum level of inertia should not be understood as a limitation to RES but rather an enabler to large RES integration.

3. CALCULATION METHODOLOGY AND ASSUMPTIONS

3.1 Analytical calculations

The analytical or algebraic calculations are based on the same assumptions as for the phase I of the project: the initial conditions of a system balance model after a system split. Given the equivalent inertia (or kinetic energy E_{k}) and the power imbalance (ΔP) created by the system split, the instantaneous Rate of Change of Frequency (RoCoF) at the centre of inertia or $\mathrm{d}f/\mathrm{d}t$ can be calculated.

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{f_0}{2}\frac{\Delta P}{E_{\mathrm{k}}}$$

From this equation, the minimum kinetic energy required to keep the RoCoF below 1 Hz/s can be deduced:

$$MinEnergy(hour, split) = \frac{f_0}{2}|\Delta P|$$

The data are derived from the market data of the TYNDP 2022. The imbalance (ΔP) following a system split is computed from the hourly exchange data. The Kinetic Energy E_{k} is computed from the hourly generation mix and assumptions on the inertia constant (in MWs/MVA) by fuel type in addition to the assumption on the loading factor ($P/P_{\max}$) of generating units.

The system split analysis is based on a simplified graph of the system which connects clusters of market zones called nodes. Nodes usually correspond to countries but can aggregate countries for the sake of simplification of the graph.

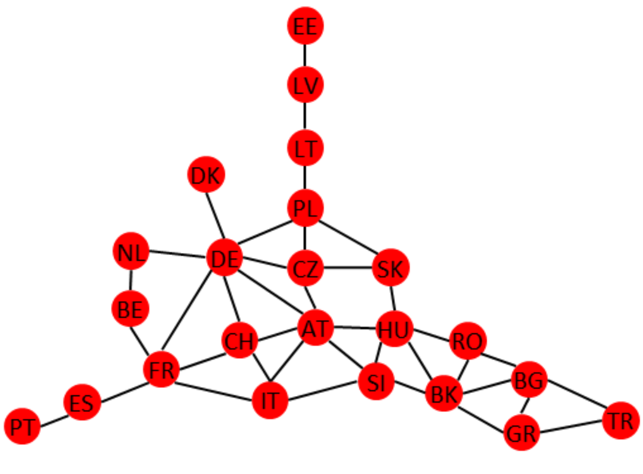


Figure 1 - Simplified graph of the system which connects clusters of market zones called nodes

An efficient algorithm has been developed to search for all possible partitions of the graph in two and only two parts: the system splits configurations. This simplification enables the computational effort to be tackled and also captures more complex split configurations: for a given subsystem, there is no difference as to whether the rest of the synchronous area remains in one or more parts.

3.2 Time-domain calculations

The purpose of time-domain calculations is to verify that a power system will not become unstable or even collapse during major disturbances and to determine the operating limits of the system. There are many commercially available tools for detailed frequency stability simulations. These tools enable the entire interconnected network to be modelled. However, such models are typically very complex. A much simpler representation of a power system can be done by means of SBM. Therefore, it was decided to perform the subsequent time-domain calculations based on a proven SBM developed by ENTSO-E Sub Group System Protection & Dynamics (SG SPD) [12], [13].

The SBM is based on an aggregation of all synchronous generators, non-synchronous generators and loads. This aggregation enables the calculation of the time dependent frequency (with respect to the centre of inertia) considering all modelled relevant frequency control mechanisms in the range of 47.5 Hz and 51.5 Hz which have an impact on the dynamic behaviour and the frequency:

- Self-regulating-effect of loads
- Frequency containment reserve (FCR)
- LFSM-O provided by inverter coupled generators
    - When the frequency overpasses 50.2 Hz, inverter coupled generators (e.g. wind offshore, wind offshore, photovoltaic) can quickly decrease their active power injection according to a pre-defined droop.
- LFSM-UC provided by inverter coupled loads
    - When the frequency drops below 49.8 Hz, inverter coupled loads (e.g. batteries in charging mode, EVs, electrolysers) can quickly decrease their active power consumption according to a pre-defined droop.
- Frequency support by HVDC interconnectors
- Pump and industrial load shedding
- LFDD
- Tripping of non-conform RES (RES without the capability to withstand the full frequency range of 47.5 Hz to 51.5 Hz)

The parameters of the dynamic simulation are derived from the requirements from Network Code Emergency and Restoration for the LFDD, or from the SG SPD data collection on other disconnection criteria (non-conform RES, industrial loads, pumping units disconnection). The data are collected and aggregated by node to match the system split graph.

4. CALCULATION RESULTS

The analysis focuses on the risk of blackout in the whole synchronous area following a system split. This event is referred to as a total blackout.

Each island created by the system split can blackout either due to a RoCoF higher in absolute value to 1 Hz/s or by a frequency exceeding the frequency band of 47.5–51.5 Hz. The first criterion can be checked with algebraic calculations (see 3.1); the second requires a dynamic simulation (see 3.2).

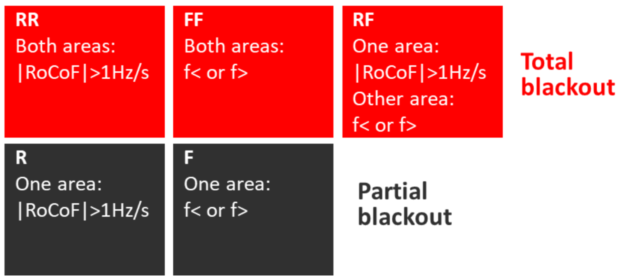


Figure 2 – Conditions for blackout due to RoCoF higher in absolute value to 1 Hz/s or by a frequency exceeding the frequency band of 47.5–51.5 Hz

When the |RoCoF|>1 Hz/s, the frequency is not checked: we assume the situation is unacceptable, whatever the frequency trajectory. The frequency is checked only when the |RoCoF| is below 1 Hz/s.

The first result is the initial RoCoF, which is calculated by $\frac{df}{dt} = \frac{f_0}{2}\frac{\Delta P}{E_k}$.

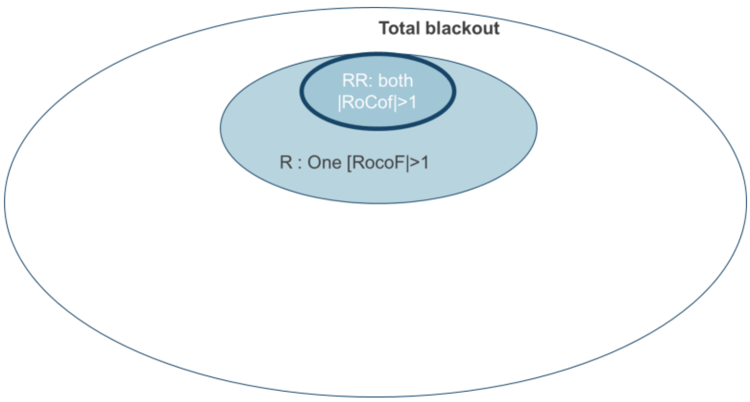
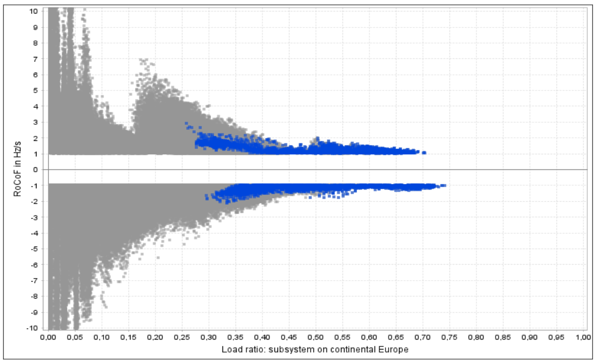


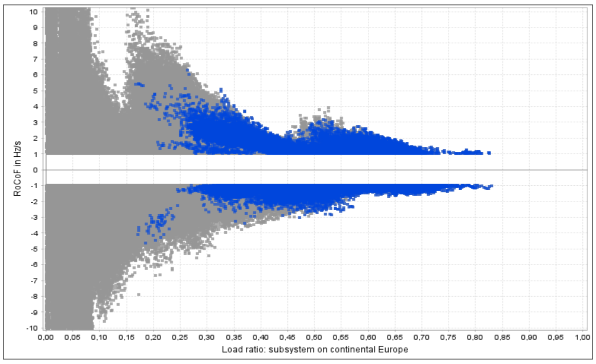
Figure 3 – Subset of total blackout cases due to both areas experiencing an absolute RoCoF value greater than 1 Hz/s

In the graphs below, each dot corresponds to an island created by a system split at a given hour. The x-axis is the ratio of the island (or area) load with respect to the load of CE. The blue dots correspond to cases when both islands experience |RoCoF| > 1 Hz/s.

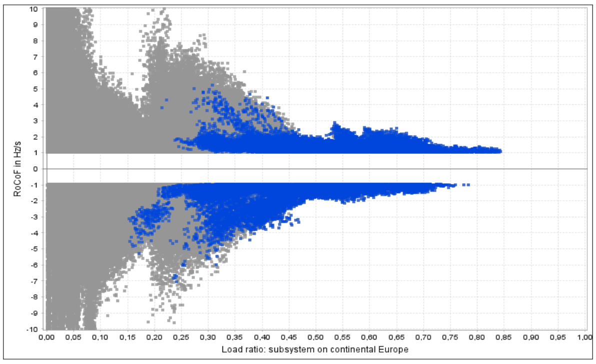
NT 2030



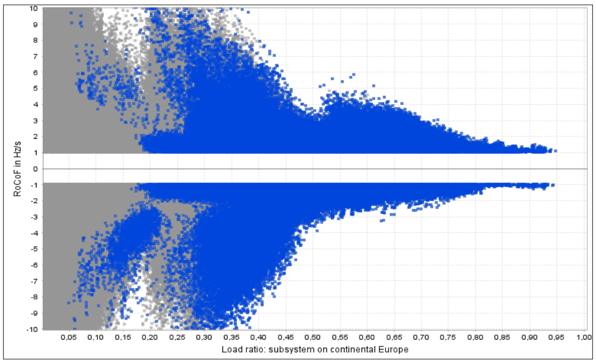
NT2040



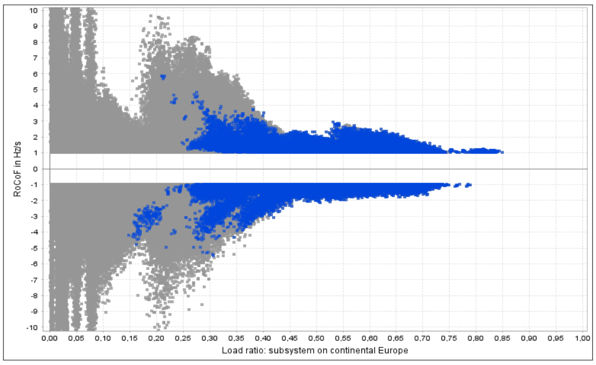
DE2030



DE2040



GA2030



GA2040

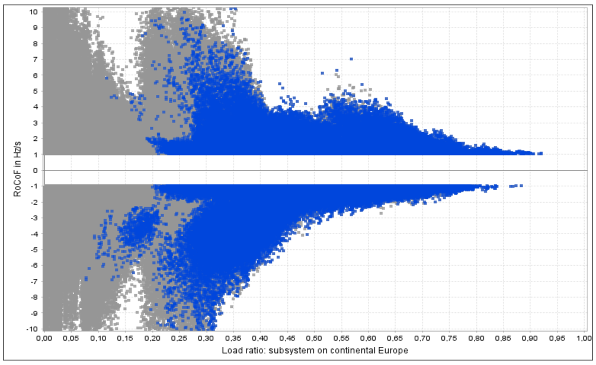
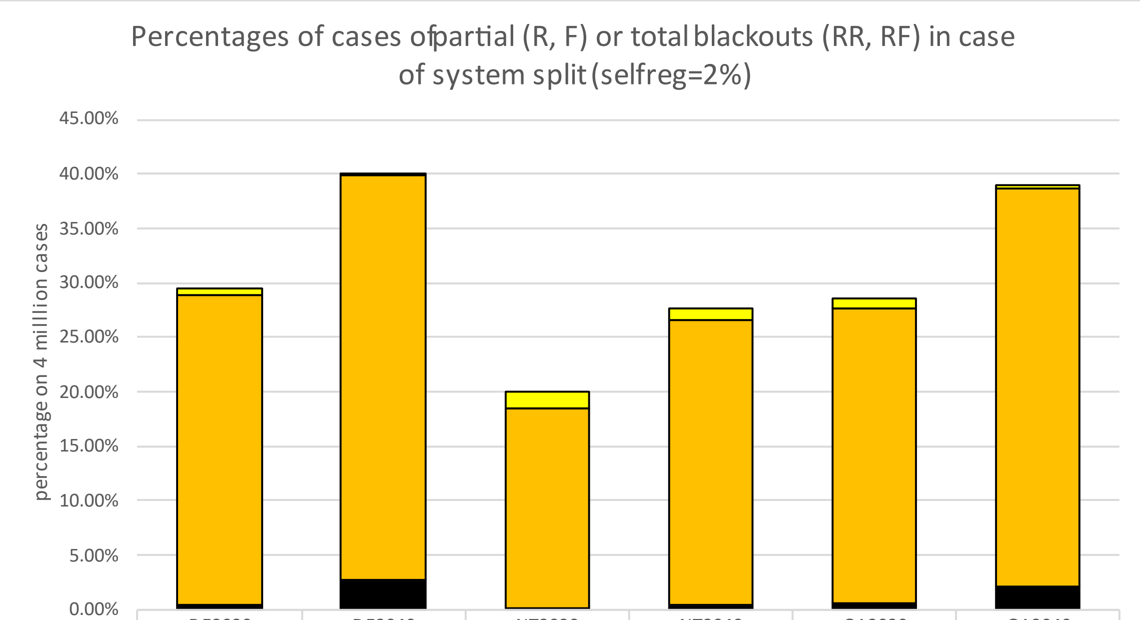


Figure 4 – Subset of total blackout cases due to both areas experiencing an absolute RoCoF value greater than 1 Hz/s |RoCoF| values above 1 Hz/s for each subsystem of the CE SA (consisting of two subsystems per split combination) plotted against the load ratio of each subsystem with regard to the CE SA for the different TYNDP 2022 scenarios (each dot represents an hour and split combination): NT 2030, NT 2040 – National Trends 2030, 2040; DE 2030, DE 2040 – Distributed Energy 2030, 2040; GA 2030, GA 2040 – Global Ambition 2030, 2040. Values above 10 Hz/s, appearing for small ratios only, are not shown.

There are 452 ways to split the graph of CE (system split configurations) which, multiplied by the number of hours in a year, represents almost 4 million systems splits cases for each of the six scenarios. 358 split configurations may create a total blackout due to the RoCoFs (both |RoCoF| > 1 Hz/s) at least in one hour.

The analysis below refers to all possible 452 system split configurations and dynamic simulations with 2% self-regulation, 200 ms load shedding delay and a generalised LFDD scheme with 6 stages (49.0 Hz: 5%, 48.8 Hz: 8%, 48.6 Hz: 8%, 48.4 Hz: 8%, 48.2 Hz: 8%, 48.0 Hz: 8%).



	DE2030	DE2040	NT2030	NT2040	GA2030	GA2040
F	0.7%	0.1%	1.5%	1.1%	1.0%	0.4%
R	28%	37%	18%	26%	27%	36%
RF	0.001%	0.000%	0.002%	0.000%	0.000%	0.001%
RR	0.50%	2.72%	0.06%	0.35%	0.63%	2.18%

Figure 5 – Percentages of cases of partial or total blackouts in the event of system split.
RR: both |RoCoF|>1 Hz/s, RF: on one side |RoCoF|>1 Hz/s and on the other side frequency exceeding the band of 47.5–51.5 Hz, R: on one side |RoCoF|>1 Hz/s and the other side is ok, F: frequency exceeding the band of 47.5–51.5 Hz and the other side is ok.

The simulations show that the scenarios with greater occurrences of total blackouts are DE2040 and GCA2040.

As mentioned before, when the |RoCoF| > 1 Hz/s, the frequency trajectory is not checked as the situation is already considered unacceptable. The cases where the frequency trajectory is checked are only the cases when the |RoCoF| is below 1 Hz/s. Existing studies show that frequency estimation is not a trivial task, particularly under high RoCoF conditions and at locations with a low short-circuit power (high measurement noise, harmonics,…) where the majority of RES – and perhaps also LFDD-relevant feeders – is/will be installed. Hence, the simplified SBM will be unable to capture all possible large frequency deviations that may exist in real grid conditions.

According to the study results, most of the total blackouts are due to high RoCoF (RR) and not due to frequency excursions beyond the limits (FF or RF).

A closer examination of acceptable cases regarding RoCoF (|RoCoF| < 1 Hz/s) of the scenario DE2040, in the subsequent dimensions of min /max frequency, shows that there are only a few frequency thresholds issues (frequency exceeding the band of 47.5–51.5 Hz) and those are entirely due to over-frequency situations (frequency > 51.5 Hz).

Within the over-frequency situations, only a few cases correspond to an initial negative RoCoF situation.

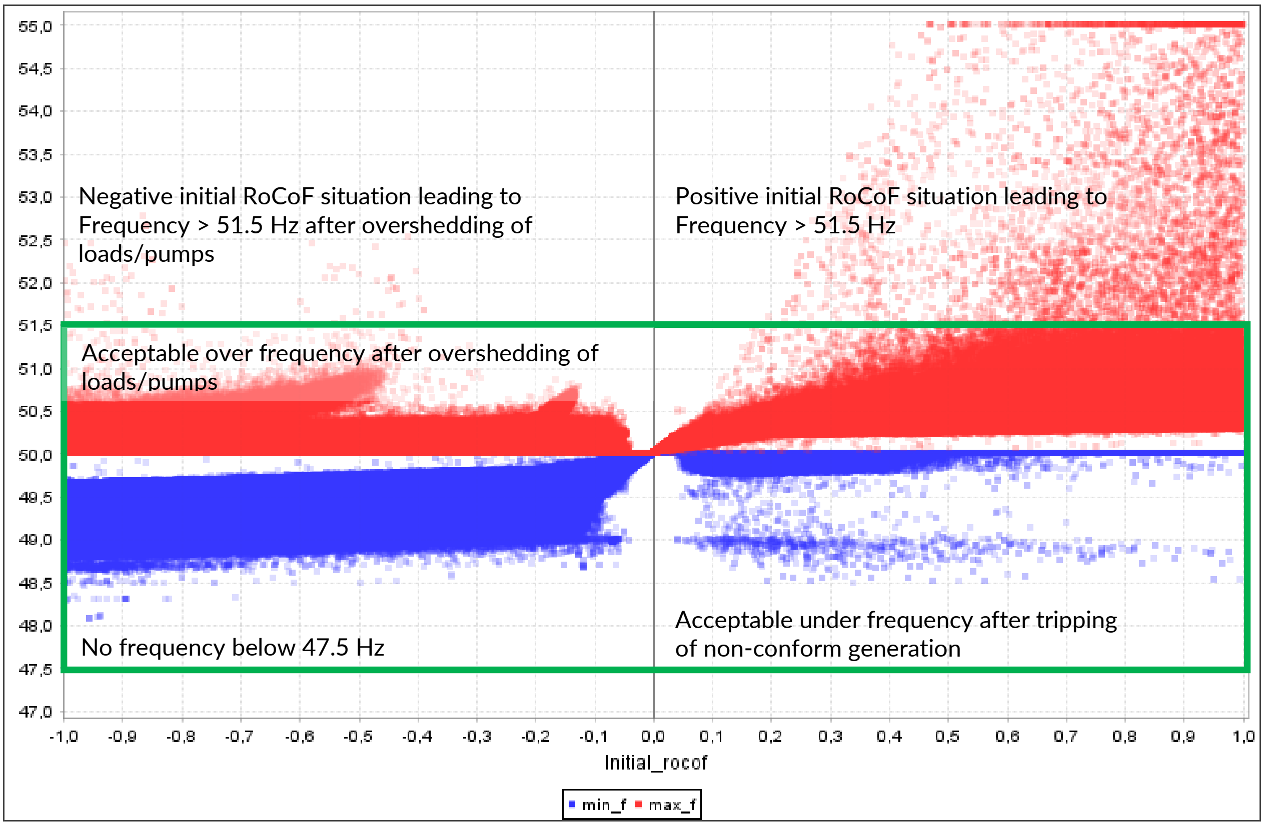


Figure 6 – DE 2040: all cases with a |RoCoF|<1 Hz/s with load self-regulation of 2%, 200ms load shedding delay and a generalized LFDD scheme with 6 stages (49.0 Hz: 5 %, 48.8 Hz: 8 %, 48.6 Hz: 8 %, 48.4 Hz: 8 %, 48.2 Hz: 8 %, 48.0 Hz: 8 %).

Considering the initial RoCoF experienced by the split subsystem, the red dots in Figure 6 represent the maximum frequency such subsystem reached during the time-domain simulation and the blue dots the minimum frequency reached during the time-domain simulation.

As can be seen in Figure 7, different frequency trajectories occur in the analysed cases:

- Case A: positive initial RoCoF leading to a frequency increase and a remaining over-frequency state (in the event the remaining frequency is below 51.5 Hz, it is considered acceptable);
- Case B: positive initial RoCoF leading to a frequency increase and a remaining under-frequency state due to a large volume tripping of non-conform generation (e.g. disconnection at 50.2 Hz);
- Case C: negative initial RoCoF leading to a frequency drop and a remaining under-frequency state; and
- Case D: negative initial RoCoF leading to a frequency drop and a remaining over-frequency state due to overshedding of loads or pumps (in the event the remaining frequency is below 51.5 Hz, it is considered acceptable).

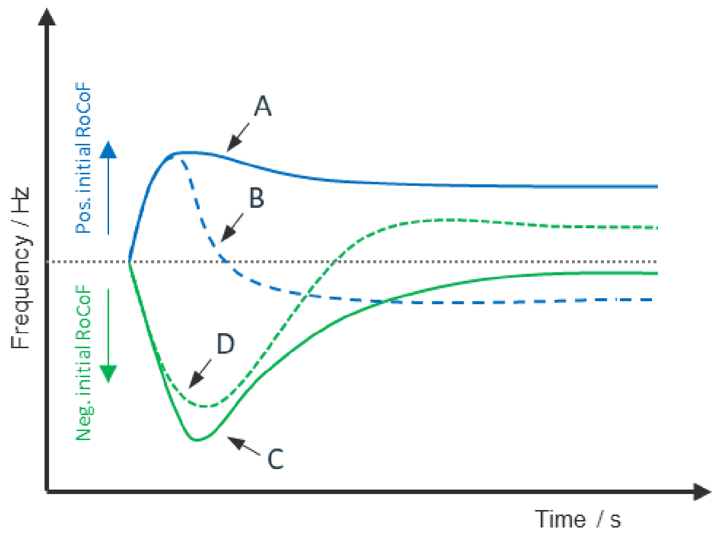


Figure 7 – Illustration of 4 time-domain trajectory cases

The analysis of total blackout can focus on the RoCoF and the indicators derived from the algebraic equations, notably the available and additionally needed kinetic energy per subsystem (split area) required to keep the initial RoCoF below 1 Hz/s. This additionally needed kinetic energy is well defined at the synchronous area level for a given point in time and is exemplarily shown in Figure 8 as a sorted curve for all *Global Severe Splits* in the NT20230 scenario. This additional kinetic energy could be potentially scaled down due to simultaneity factors and potential synergy effects of the individual nodes (countries).

Furthermore, the additional kinetic energy per node (country) can subsequently be fed into an optimisation function (e.g. minimisation function via linear programming or mixed integer linear programming) to ensure the most efficient solution from a global perspective.

As a contribution to further considerations about sizing and allocating additional kinetic energy, this approach allows, on the one hand, a top-down approach, where the optimal (i.e. minimum) additional kinetic energy allocation for each node (country) needed to satisfy all *Global Severe Splits* is calculated. On the other hand, it also enables a bottom-up approach where the total additional amount of kinetic energy that can be allocated is constrained by an upper limit and the optimal allocation per node (country) is calculated such that the number of unsatisfied *Global Severe Splits* is minimised.

At this point, it should be mentioned that the choice of approach (top-down vs. bottom-up) is ultimately subject to a common risk assessment, i.e. how many potential *Global Severe Splits* should actually be covered.

Finally, the definition of a detailed and transparent framework for the calculation of the required additional energy by node and the fundamental principles (e.g. additional inequality constraints required to fairly allocate the kinetic energy between nodes) are currently under development and will be outlined in the final report of this project.

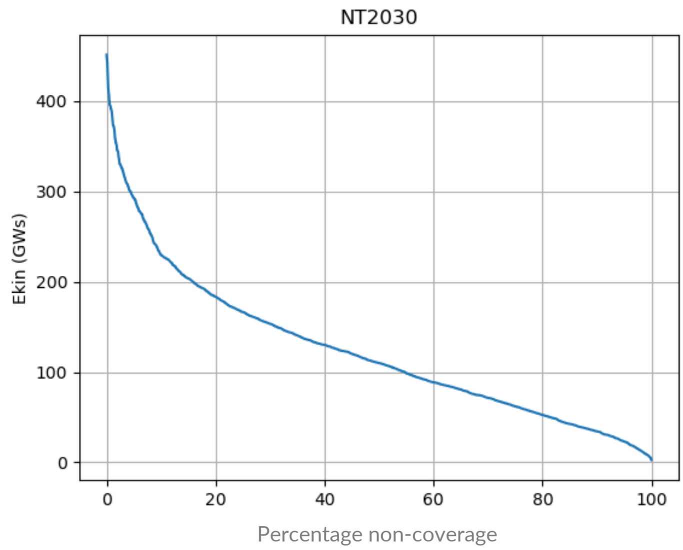
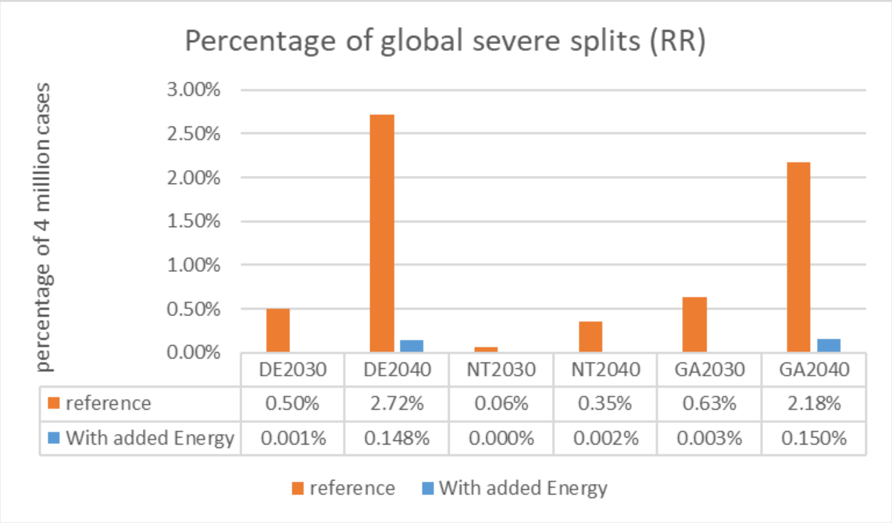


Figure 8 – Sorted additionally needed kinetic energy per synchronous area for all *Global Severe Splits* in the NT20230 scenario (global view)

<u>Simplified example:</u>

If all *Global Severe Splits* were to be solved for the scenario NT2030, the following maximum additional kinetic energy would be required on the RGCE synchronous area level (Figure 8): 445 GWs, which corresponds to an equivalent of 255 synchronous condensers (SCs) of 250 Mvar and H=7 MWs/MVA.

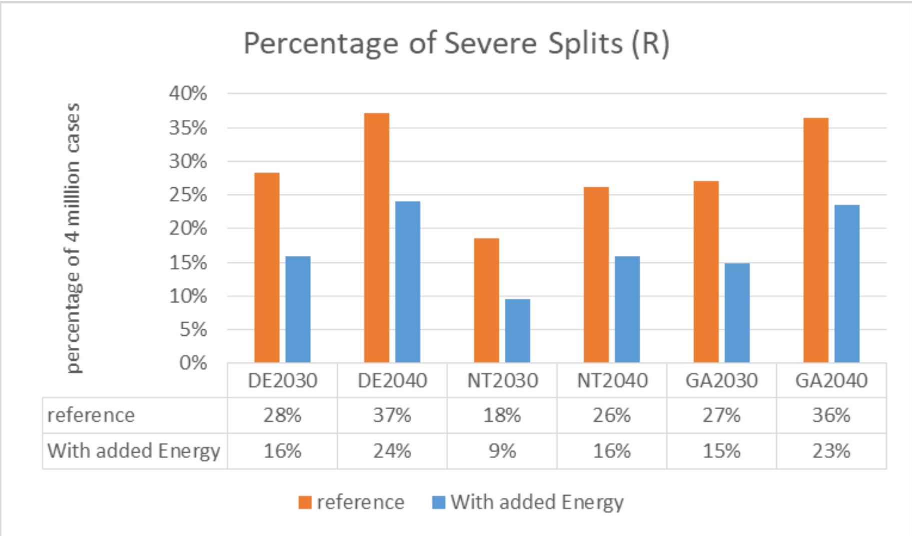
With this permanently available additional kinetic energy and an exemplary allocation with respect to the total generation running capacity (without applying any further optimisations), the number of *Global Severe Splits* ("RR" means both |RoCoF|>1 Hz/s) is null for scenario NT 2030 as expected and also drastically decreases for other scenarios:



	DE2030	DE2040	NT2030	NT2040	GA2030	GA2040
reference	0.50%	2.72%	0.06%	0.35%	0.63%	2.18%
With added Energy	0.001%	0.148%	0.000%	0.002%	0.003%	0.150%

Figure 9 – percentage of *Global Severe Splits* with added energy sized such to reduce Global Severe Splits to zero for the NT 2030 scenario.

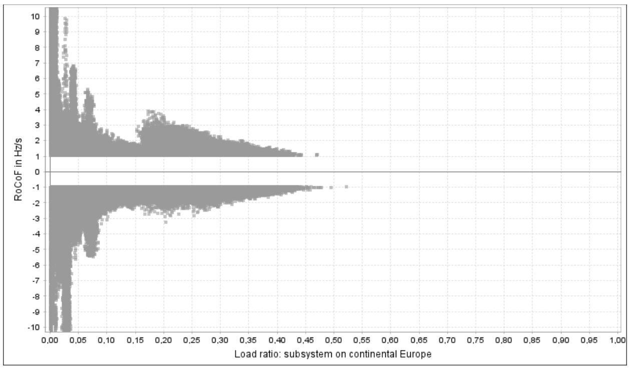
The number of severe cases ("R" means |RoCoF| > 1 Hz/s on one side only) is also significantly reduced:



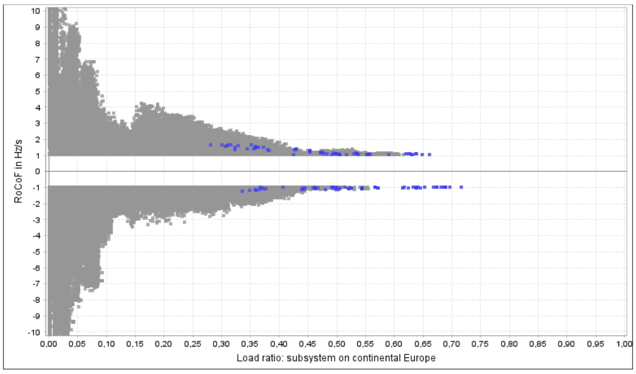
	DE2030	DE2040	NT2030	NT2040	GA2030	GA2040
reference	28%	37%	18%	26%	27%	36%
With added Energy	16%	24%	9%	16%	15%	23%

Figure 10 – percentage of severe splits with added energy sized such to reduce Global Severe Splits to zero for the NT 2030 scenario.

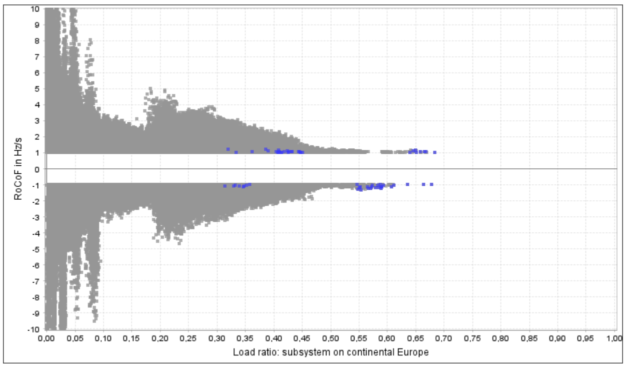
NT2030



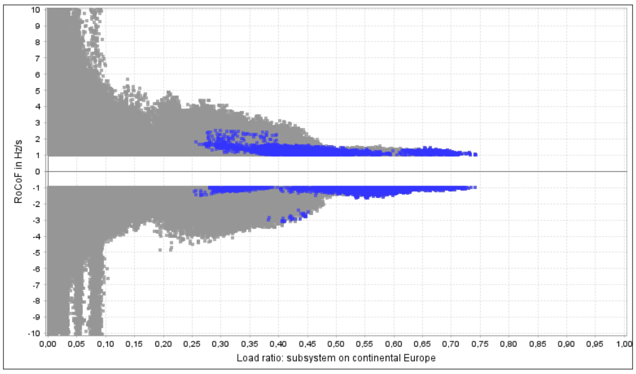
NT2040



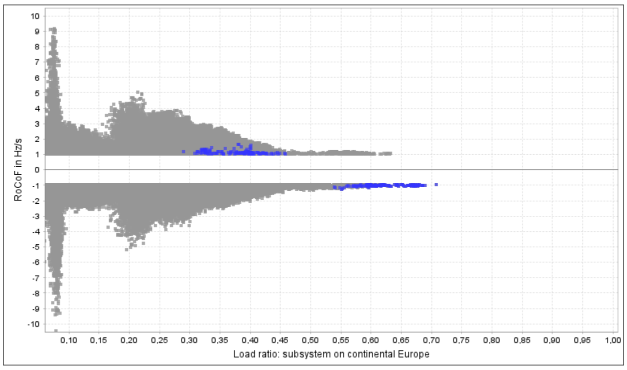
DE2030



DE2040



GA2030



GA2040

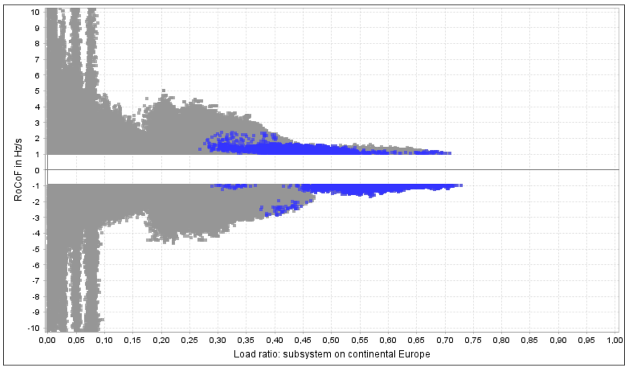


Figure 11 – Subset of total blackout cases due to both areas experiencing an absolute RoCoF value greater than 1 Hz/s after additional kinetic energy in the simplified example.
|RoCoF| values above 1 Hz/s for each subsystem of the CE synchronous area (consisting of two subsystems per split combination) plotted against the load ratio of each subsystem regarding the CE synchronous area for the different TYNDP 2022 scenarios (each dot represents an hour and split combination): NT 2030, NT 2040 – National Trends 2030, 2040; DE 2030, DE 2040 – Distributed Energy 2030, 2040; GA 2030, GA 2040 – Global Ambition 2030, 2040. Values above 10 Hz/s, appearing for small ratios only, are not shown.

5. SOLUTION OR MITIGATION MEASURES

To prevent or at least reduce the risk of potential blackouts for *Global Severe Splits*, or other splits also deemed as severe, solution or mitigation measures to render them manageable must be established. Within the frame of the project, the initial list of measures from PROJECT INERTIA PHASE 1 has been updated and refined.

5.1 General aspects

As there is no single solution, several categories of measures for improving system resilience have to be considered and weighed against each other. Assuming the importance of limiting the likelihood of system splits, the following actions can be categorised and listed:

- **Foundational measures**
  - Tackle the root cause. Keep inertia (rotational energy) above a certain limit.

- **Enhanced response measures (necessary in addition to the foundational measures)**
  - Enhanced withstand capabilities for stable grid operation during high frequency gradients
  - Frequency containment support to limit the nadir/zenith of the frequency

- **Restrictions to market (last resort measures)**
  - reduction of the power exchange and deployment of must-run units

In addition to the development of adequate solution or mitigation measures, the question arises of how they should be efficiently introduced in an SA. From a high-level perspective, different methods for achieving the required system behavior exist. As described in detail in Chapter 5 section 2, this can be done either by amending and/or establishing new grid code requirements, operational codes, ancillary service markets, bilateral agreements with grid users or targeted TSO/DSO actions.

Regarding the foundational measures to achieve the required system behavior, beyond the setup of synchronous condensers and STATCOM to keep inertia above a certain limit, two additional approaches should be considered.

- Mandatorily require the necessary technical capabilities and their availability from new or substantially modified grid users (PGMs, EVs, etc.). This can be achieved with the introduction of new or extended connection requirements in dedicated Connection Network Codes (CNC 2.0). The implementation of this option does not require additional market rules. The agreement on harmonised connection requirements for the entire SA will be an important task which needs to be well-organised. In addition, the future CNC legislation should also require the system operators to validate the compliance of new or substantially modified grid users in the course of the connection process.

- Market-based procurement of inertial response – based on new markets (e.g. inertia certificates) or similar to already existing markets (e.g. for FCR). To organise a market, several aspects have to be considered, in particular the product design (maximum/minimum bid size, product period, conditional products, indivisible/divisible products, activation trigger, settlement, penalties, etc.), the prequalification of providers and the monitoring of activation. In addition, the necessary regulatory framework (including respective market rules) has to be established. Experiences with existing frequency control reserves have shown that such development processes require adequate time and comprehensive cooperation between the relevant TSOs and stakeholders. For example, if a new ancillary service is intended to be used in an entire SA, TSOs need to compile several aspects, such as common technical requirements, dimensioning rules for the total required amount, allocation keys and possible restrictions for the distribution. Furthermore, market participants would most likely request that TSOs organise a single market for the entire SA, which introduces additional challenges (e.g. establishment of a central tendering/optimisation platform, effectiveness of cross-border procurement to tackle system split situations, settlement, harmonisation of boundary conditions, etc.).

  While markets potentially have the advantage that TSOs are able to constantly procure and monitor the necessary amount and quality of ancillary services, they may also introduce cost-inefficiencies if the respective product design and remuneration system are not well suited. In addition, an illiquid market could potentially lead to severe operational challenges due to missing bids and hence insufficient amounts.

For all possible aspects and combinations, there is a need to consider a balance between the system needs, the capability of different technologies, the expectations from decision-makers, system operators, grid users, market participants and social welfare. The challenge posed by the phenomena of system splits cannot be solved by single actions at the national level. Coordinated efforts from all European TSOs are necessary to ensure the effectiveness of the measures.

Considering that a high initial RoCoF generally reduces the available time for deploying the necessary fast balancing actions for preventing high frequency excursions, as described above, it is important to focus on introducing measures that actually tackle the foundation of the problem, which is the lack of inertia of the system. According to the "Inertia and Rate of Change of Frequency (RoCoF)" report, initial RoCoF values higher than 1 Hz/s can compromise the efficiency and/or resilience of defence plans actions aiming to stabilise the grid.

It is important to add that measures that enhance withstand capabilities or support frequency containment will definitely upgrade the efficiency and robustness only if they are implemented in addition to a system for which RoCoFs ≤ 1 Hz/s and the frequency remains inside the permissible limits (47.5 Hz and 51.5/52.5 Hz). Without the foundational measures, solely relying on such frequency withstand and support capabilities would lead to significant (cost) inefficiencies and a system that is still not robust.

From a system perspective, it is therefore important to develop a transparent implementation roadmap of solutions or mitigation measures that is based on keeping inertia (rotational energy) above a certain limit as an indispensable pillar. Due to the fairly formal process of changing the relevant regulatory framework, it is furthermore necessary to begin the necessary initiatives on a European level sufficiently early.

5.2 List of measures

In this section, several categories of measures are further evaluated regarding practicability and relevant aspects. The results of the qualitative analysis are summarised in the following tables.

Category		Measure	GC	OC	AS	BA	TD	Relevant aspects
Foundational measures	**Keep inertia (rotational energy)** above a certain limit	Grid forming capable grid users (e.g. Power Park Modules [PPMs] or storages) with inertial response	x		x	x		Effective measure for new grid users (given that they can comply with the requirements) Requires compliance verification and harmonised minimum technical requirements May require specific requirements for certain technologies (e.g. additional storage for PPMs to provide underfrequency inertial response)
		Grid forming capable STATCOMs with inertial response			x		x	Effective and easy controllable measure as it is usually part of TSO/DSO assets Requires additional storage
		Setup of synchronous condensers			x	x	x	Effective and easy controllable measure as it is usually part of TSO/DSO assets
		Incentive grid users with inertial response			x			New and existing grid users could benefit from new ancillary services Very complex task that might require considerable time for implementation Requires several actions from TSOs/DSOs, grid users and regulators to setup an "inertia market" (e.g. with certificate trading) and adequate performance monitoring could lead to non-uniform distribution or lack of inertia across an SA if the market or regulatory framework turns out to be inadequate, which could be critical in case of system splits.

	Limit the likelihood of system splits and potential imbalances	Reinforcement of grid assets on weak corridors					x	Reduced likelihood of system splits; Long-lasting, very complex and costly task
		Reinforcement of grid assets using DC technology (Condition: continuing power flows via the DC system)					x	Reduced imbalance in the event of a system split Long-lasting, very complex and costly task

Category		Measure	GC	OC	AS	BA	TD	Relevant aspects
Enhanced response measures	**Enhanced withstand capabilities** for stable grid operation during high frequency gradients	Increase RoCoF and over-/under frequency withstand capability for new and substantially modified PGMs, DFs and HVDCs	x					Enhanced grid response; simple measure for new grid users (given that they can comply with the requirements) Does not directly tackle the root-cause of the problem and may only "delay" its effects
		Retrofit of RoCoF and frequency protection settings of existing PGMs, DFs and HVDCs		x		x	x	Enhanced grid response Does not directly tackle the root-cause of the problem and may only "delay" its effects; long-lasting and very complex task; requires several actions from TSOs/DSOs and grid users; for some installations the settings may not be changed
	Frequency containment support to limit the nadir/zenith of frequency	Setup of faster acting system protection schemes (e.g. LFDD including RoCoF criteria)	x	x			x	Enhanced grid response Long-lasting and very complex task; requires several actions from TSOs/DSOs (change of thousands of relays), relay manufacturers and grid users; requires harmonised rules for frequency/RoCoF estimation and filtering; shift of LFDD points to lower voltage levels could further complicate robust frequency/RoCoF estimation
		Setup of additional special protection schemes		x		x	x	Enhanced grid response Long-lasting and very complex task; requires several actions from TSOs/DSOs, relay manufacturers and grid users; requires even distribution of SPS across the synchronous area and coordination between TSOs/DSOs

		Fast frequency/active power control provision by existing and new PGMs, DFs and HVDCs	x	x	x	x	x	Effective measure for new and potentially existing grid users Requires compliance verification and harmonised minimum technical requirements Does not reduce the risk of system splits caused by high RoCoFs
		Setup of additional frequency stabilising functions provided by new grid users (e.g. LFSM-UC)	x					Effective measure for new grid users Requires compliance verification and harmonised minimum technical requirements

6. CONCLUSIONS AND NEXT STEPS

PROJECT INERTIA PHASE 2 updated the analysis performed in the report "Frequency stability in long term scenarios and relevant requirements"[1].

Based on the most recent TYNDP 2022 long-term scenarios and market studies, the present report reviews, under a set of similar assumptions and methodology, 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 years under consideration (2030 and 2040) and an assessment is made of whether the combinations of subsystems after a split would be able to cope with the RoCoF resulting from the relevant initial conditions regarding power imbalance and subsystem inertia under the different TYNDP 2022 scenarios.

In addition, PROJECT INERTIA PHASE 2 introduced new time-domain simulations to enable a perspective on the frequency performance of the separated subsystems after the split. Having present the risk of a blackout in the whole synchronous area following a system split, the wider analysis evaluated if a total blackout could occur due to frequencies going outside the range 47.5–51.5Hz, even if the initial RoCoF is smaller than 1 Hz/s.

6.1 Conclusions of the first interim report

From the updated results in Chapter 4, the trends identified in the report "Frequency stability in long term scenarios and relevant requirements" are confirmed. Splits for which at least one island exceeds the |RoCoF| limit of 1 Hz/s and splits for which both islands exceed this threshold are identified in a large number and with a visible increase from 2030 to 2040. This demonstrates the progressive decline of system resilience against system splits if no actions are initiated.

The time-domain analysis shows that when the initial RoCoF is smaller than 1 Hz/s, the frequency threshold issues can be limited in number. As such, to define a baseline where all other frequency related mechanisms shall properly work, the analysis of total blackout can focus on the RoCoF and the indicators derived from the algebraic equations, notably the kinetic energy (of synchronous machines) required to keep the initial RoCoF below 1Hz/s. This kinetic energy is well defined at the

[1]https://eepublicdownloads.azureedge.net/clean-documents/Publications/ENTSO-E%20general%20publications/211203_Long_term_frequency_stability_scenarios_for_publication.pdf

split area level for a given point in time, but the definition of the required energy by node (usually country) requires further analysis.

Given the reduction of system resilience against system splits, it is necessary to define which level of resilience is desired for the CE synchronous system. This report outlines the basis for such a discussion and definition.

According to Chapter 5, the solution measures should be divided into foundational measures and enhanced response measures. The latter builds on the commonly agreed minimum level of resilience intended for the system. Independent of all necessary and important preventive measures to limit the likelihood of a system split, it must be assumed that a system split can always happen and, consequently, a minimum level of inertia must be defined.

6.2 Next steps of the project

The accepted level of grid resilience and accepted risk of blackout must involve all the stakeholders and the relevant institutions as it is not for the TSOs only to define these aspects.

To define exact proposals for implementation, it is necessary to discuss and agree on the supporting assumptions. The following three steps will be taken forward:

1. Define the intended level of resilience against system splits;
2. Determine the resulting minimum level of inertia; and
3. Determine the inertia split between countries.

Intended level of resilience – Eliminate *Global Severe Splits* in 2030 NT scenario

The analysis is based on the TYNDP 2022 scenarios, which define the conditions in which system splits are assessed. Those conditions include the hourly changing generation mix and the imbalances experienced by the split subsystems.

Global Severe Splits are split scenarios with the initial |RoCoF| exceeding 1 Hz/s in both resulting subsystems. The exposure of both resulting subsystems to a |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 the most severe and are used as the criteria for assessing the system resilience.

PROJECT INERTIA PHASE 2 considers that the approach towards recovering the level of resilience against system splits should be taken step-by-step and pursue non-regret and adaptable solutions.

As such, the TYNDP 2022 scenario selected to define the minimum level of resilience is 2030 National Trends. According to the results described in Chapter 4, a minimum level of inertia can be calculated to eliminate all *Global Severe Splits* in this scenario.

Under this approach, the following aspects must be highlighted:

- Although *Global Severe Splits* are reduced, there are situations where other severe splits, which are not global, will remain, with very high values of RoCoF. Hence, even after recovering the resilience against system splits, there is still a need to maintain withstanding capability to RoCoF in all Power Generating Modules.

- SCs, STATCOMS with Grid Forming Capability and storage and PPMs with Grid Forming Capability and storage will be necessary.

    - In the short-term, SCs and STATCOMs with storage will be necessary. Those short-term solutions will also bring added benefits to system stability concerning, for example, voltage control and short-circuit power.

    - PPMs with Grid Forming Capability and Storage are necessary and should be deployed as soon as possible to build a volume that can effectively support the system. According to the 2023 revision of the network code on requirements for grid connection of generators, and subsequent implementation timeline, a wide deployment of Grid Forming Capabilities (with and without storage) is not expected before 2028. Only then will the availability of such capabilities start to increasingly grow, together with new PPMs. This means that from today until at least 2028, large volumes of PPMs without any Grid Forming Capabilities will continue to enter the system.

    - Measures to anticipate Grid Forming Capability with storage should be considered such as market incentives.

  The initial 'non-regret' assessment based on defined TYNDP scenarios should be reviewed every two years using the TYNDP regularly updated scenarios. Checks should be made to establish whether the TYNDP Investigation of System Needs can support this regular assessment.

Minimum level of inertia

Chapter 4 provides an insight into the minimum level of inertia necessary to eliminate all *Global Severe Splits* in the 2030 NT scenario.

- All countries must ensure their agreed minimum level of inertia. This means additional energy in addition to that estimated using the TYNDP scenarios. The best selection of means to reach the minimum level of inertia will depend on the country-specific decision.

- A methodology for estimating online inertia at all times must be developed and agreed by all TSOs of SA CE. This information will allow the process to be continually improved and enable more precise knowledge about the actual system needs.

- Following the SOGL principles, every two years the minimum levels of inertia can be reassessed.

Determine the inertia allocation between countries

Building on the above steps, a methodology to determine the optimal inertia split between countries will be discussed in the following stage of the Project**.**

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GLOSSARY

Abbreviation	Meaning
AS	New Ancillary Services
BA	Bilateral Agreements with Grid Users
CE	Continental Europe
CNC	Connection Network Codes
DE	Distributed Energy (TYNDP Scenario)
DSO	Distribution System Operator
EAS	ENTSO-E Awareness System
EV	Electric Vehicles
FCR	Frequency Containment Reserve
GA	Global Ambitions (TYNDP Scenario)
GC	Grid Connection Codes
Global Severe Splits	Global Severe Splits are split scenarios in which the initial |RoCoF| exceeds 1 Hz/s in both resulting subsystems.
HVDC	High Voltage Direct Current
LFDD	Low Frequency Demand Disconnection
LFSM-U/O	Limited Frequency Sensitive Mode (Under- and Over-Frequency)
NT	National Trends (one of the TYNDP scenarios)
OC	Operational Codes
PGM	Power Generation Module
PPM	Power Park Module
RES	Renewable Energy Source
RGCE	Regional Group Continental Europe

RoCoF	Rate of Change of Frequency (also $\dot{f}$)
SA	Synchronous Area
SBM	System Balance Model or Single Busbar Model
SC	Synchronous Condensers
SG SPD	SubGroup System Protection and Dynamics (under ENTSO-E RG CE Group)
SOGL	System Operation Guideline
SPS	Special Protection Scheme
STATCOM	Static Synchronous Compensator
TD	TSO/DSO Actions
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
UCTE	Union for the Coordination of Transmission of Electricity
WAMS	Wide Area Monitoring System