A European View on Grid Forming Inverters and Network Codes

Dr. Ralph Pfeiffer, Amprion GmbH, Dortmund, Germany

on behalf of ENTSO-E a.i.s.b.l., Brussels, Belgium

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Who we are …

43 TSOs in
36 countries

300 000 km of
transmission lines

7 times the earth's unconference

3300 TWh electricity
consumption

15% of the global
electricity
consumption

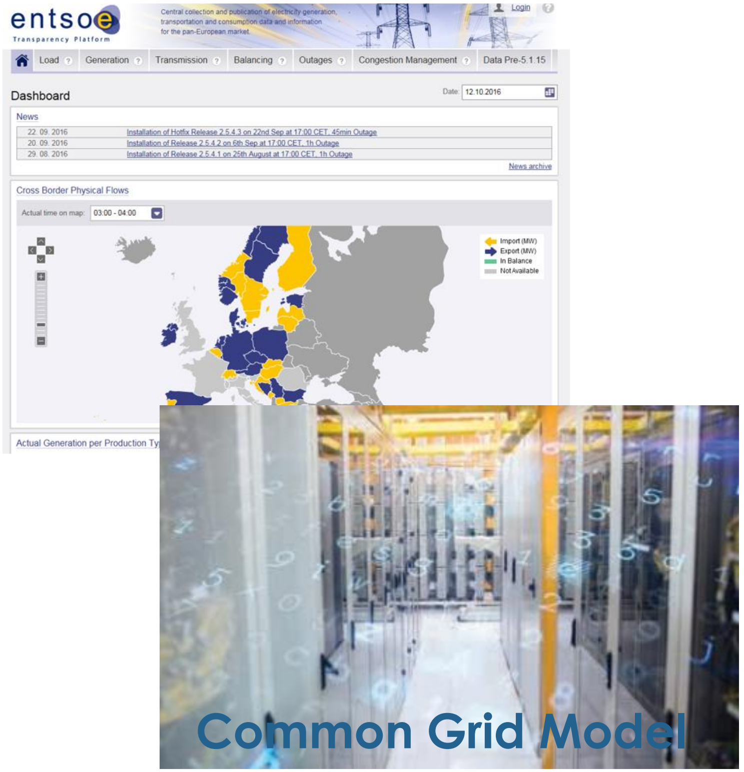
over **500 million**
customers served

What we do …

Contributing to the design and implementation of the Internal Energy Market

Providing regular reporting and recommendations for network development

Developing the necessary IT tools for enabling the implementation



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2. Network codes reconciling system needs with energy policy objectives
3. Power system challenges when moving to a power electronics world
4. Introducing new connection requirements
5. Grid forming inverters – why needed and what can be achieved?
6. Conclusions

EU energy policy framework – The Clean Energy Package (CEP)

Clean Energy Package: Goals and background

Energy transition lead to an increase of complexity

GOALS

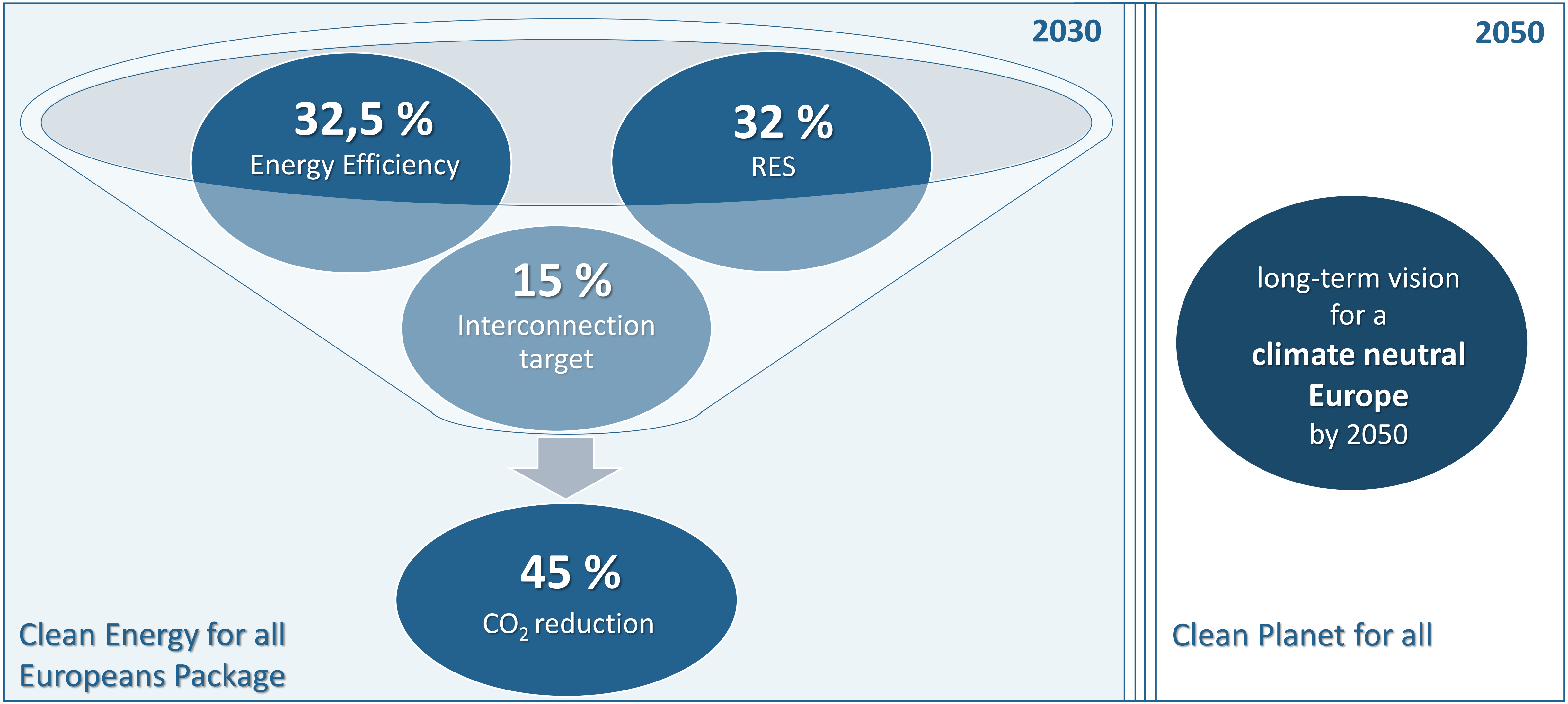
- putting energy efficiency first
- make the market the prime generator of investments
- achieving global leadership in renewable energies
- make the energy cost efficient
- providing a fair deal for consumers

enhancing cooperation and integration ⇄ strengthening the trade

How to tackle this complexity?

- strengthen the grid
- enhance existing cooperation at all levels
- implement EU legislation/ NCs

Figures of the CEP



Network Code (NC) development : Revision changes the dynamics

- Competences of EU Commission (EC) and ACER (Agency for the Cooperation of Energy Regulators) will be expanded with regard to NC development:
  - If ENTSO-E/DSO Entity does not provide a valid proposal for network codes within 12 months, ACER may be mandated by EC to provide its own draft network codes.
  - If ACER does not submit a NC proposal either, the EC can define NC on its own.
- The catalogue of issues on which the EC can issue "delegated acts" or "implementing acts" will be extended.
- **New actor**: involvement of the EU DSO entity where relevant in mutual cooperation with the ENTSO-E

Current legislative framework

ACER drafts framework guideline → ENTSO-E drafts NC → ACER opinion on NC → EC chairs comitology

Clean Energy Package

ACER drafts framework guideline → ENTSO-E or EU DSO entity/ENTSO-E drafts NC + drafting committee → ACER submits revised NC to EC → EC: implementing acts or delegated acts

NCs have a key role in implementing the CEP

Existing network codes

- Network Code implementation is a key priority for ENTSO-E.

Following the CEP:

- review and, where appropriate, revision and alignment with CEP
- Implementation of the already existing NC

Possible new network codes on the topics
"non-frequency ancillary services", "demand response including energy storage and demand curtailment", "cyber security", "Curtailment and Redispatch".

➔ The Electricity Regulation foresees a comprehensive evaluation of existing NC and Guidelines by July 2025

Network codes reconciling system needs with energy policy objectives

The EU network codes:
Made-in Europe rulebook for the smart system of the future

3 Market

- Capacity calculation
- Capacity Allocation and Congestion Management (CACM)
- Electricity Balancing

2 Operation

- Emergency and Restoration
- System Operation

3 Connection

- HDVC
- Demand connection
- Requirements for generators

All approved by Member States

2017

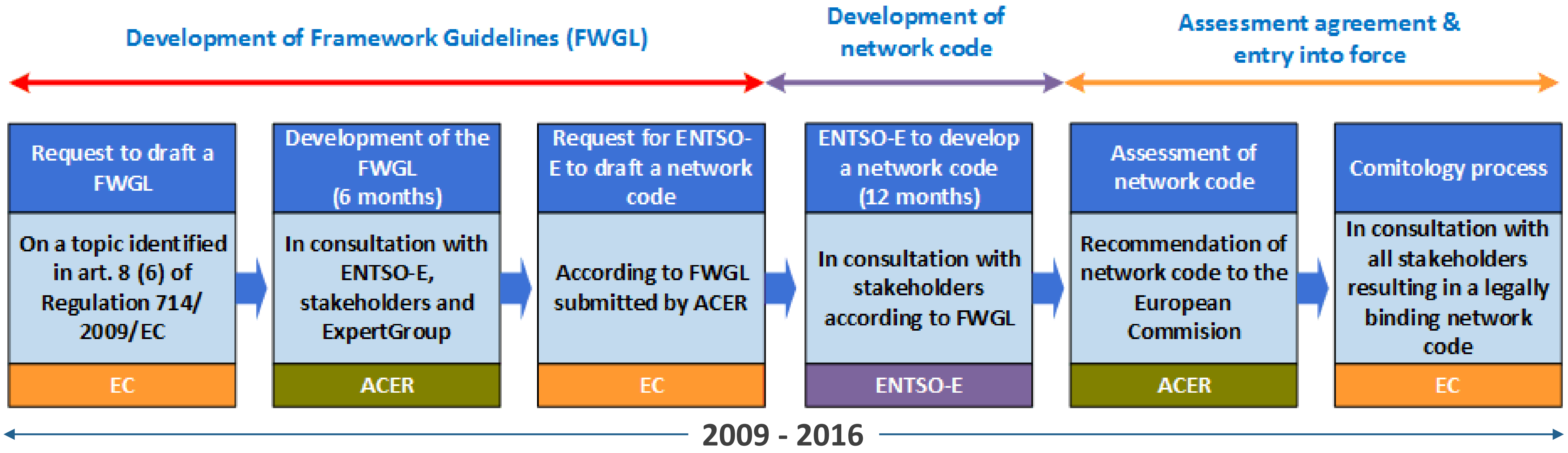
5 years

FULL implementation

2022

CNC development - A 10-year project

Joint effort by EC / ACER / ENTSO-E – with extensive Stakeholder engagement



- **2016 – 2019**
  - National implementation in the 28 EU Member States + aligned countries
  - ENTSO-E implementation guidance by Implementation Guidance Documents (28 IGDs), consultations and workshops
  - Discussions at the Grid Connection European Stakeholder Committee

- **≥ 2019**
  - CNC application
  - Identification of needs for amendments

More information at:
https://www.entsoe.eu/network_codes/

The objective of Connection Network Codes (CNCs)

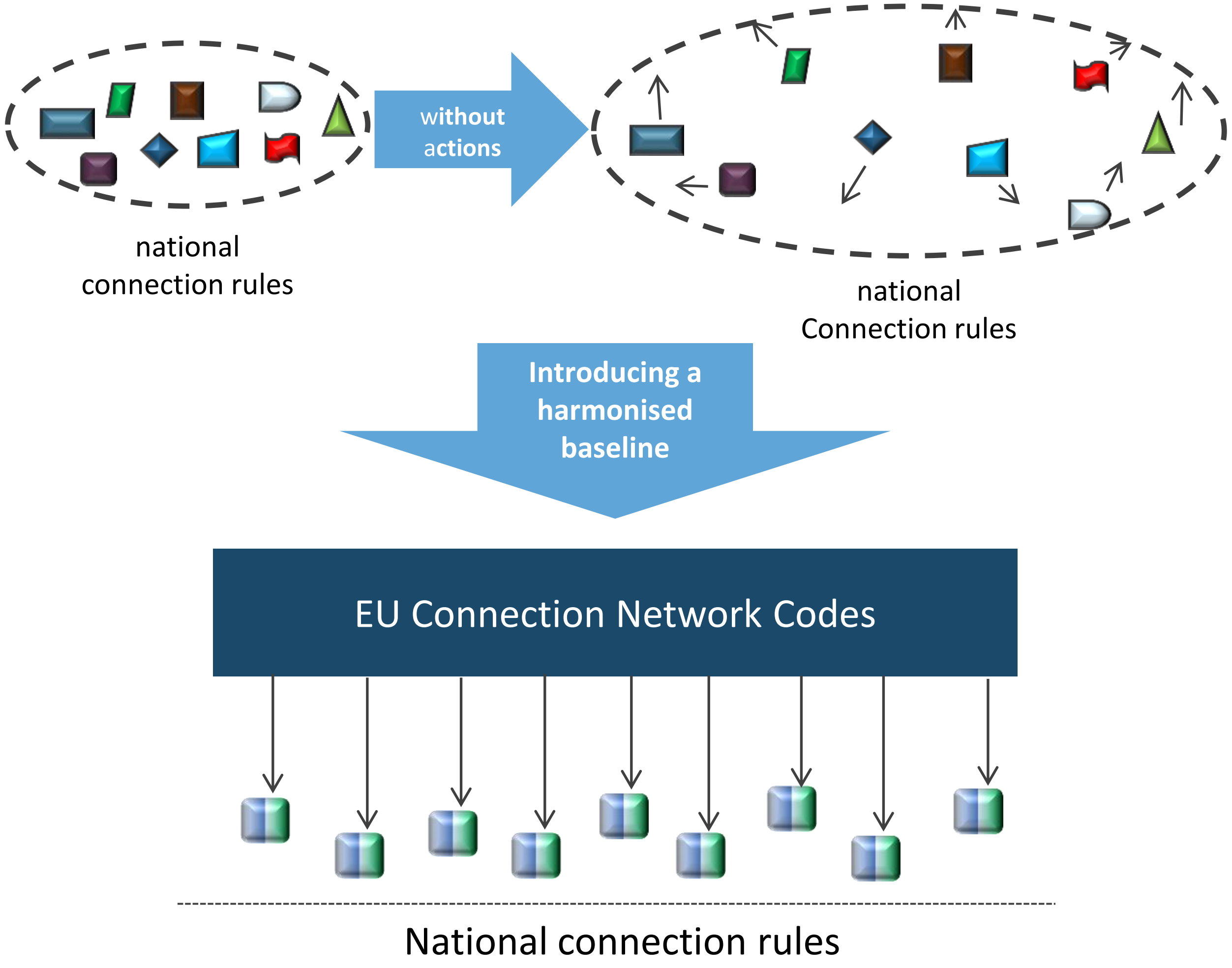
sustainability of connection requirements over equipment life-cycles

Build and maintain transmission networks for long-distance power flows

Implementation of market mechanisms to facilitate a single European electricity market

Continuous evolution and coordination of system operation

Stable operation, robustness of and provision of ancillary services by system users



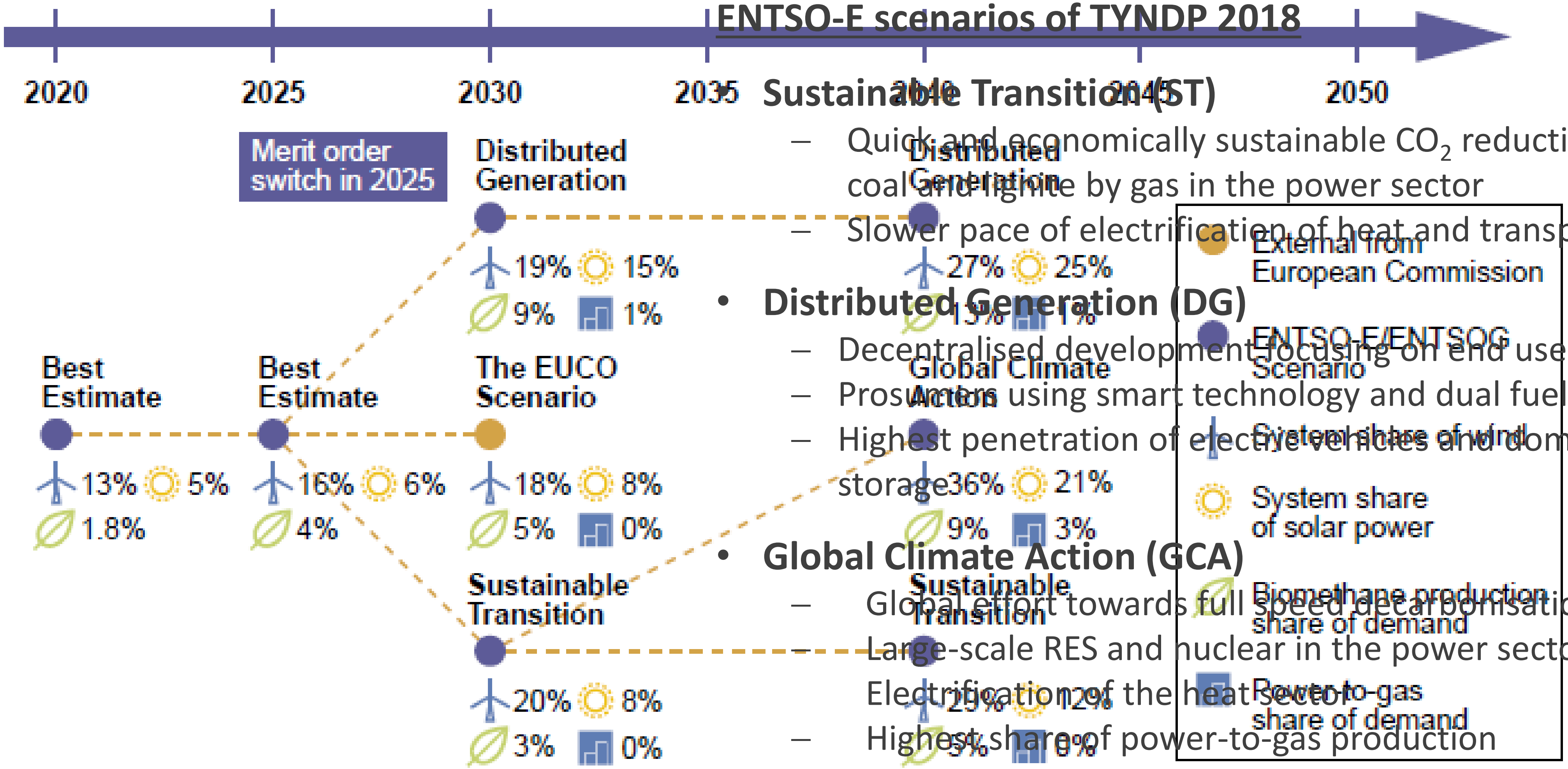
entsoe

Guiding principle of CNCs – non-exhaustive requirements

- To consider adequately regionally varying system needs/characteristics to ensure security of supply, but also to avoid unreasonably onerous requirements.
- A non-exhaustive requirement at European level does not contain all the information or parameters necessary to apply the requirement, but needs to be further specified when implementing the Network Code at national level.
- **Site-specific non-exhaustive requirements** to be considered on a case by case basis.
- **Non-exhaustive requirements of general application** to be specified at either a synchronous area or national level through an established process, e.g. grid code review panel, user group, public consultation, regulatory or ministry approval

Power system challenges when moving to a power electronics world

Scenario framework for system development



ENTSO-E scenarios of TYNDP 2018

- **Sustainable Transition (ST)**
  - Quick and economically sustainable CO_2 reduction by replacing coal and lignite by gas in the power sector
  - Slower pace of electrification of heat and transport
- **Distributed Generation (DG)**
  - Decentralised development focusing on end user technologies
  - Prosumers using smart technology and dual fuel appliances
  - Highest penetration of electric vehicles and domestic PV and storage
- **Global Climate Action (GCA)**
  - Global effort towards full speed decarbonisation
  - Large-scale RES and nuclear in the power sector, and
  - Electrification of the heat sector
  - Highest share of power-to-gas production

Source: ENTSO-E/ENTSO-G - TYNDP 2018 Scenario Report

All scenarios comply with the energy policy targets.

System challenges

Transmission systems in Europe are increasing in complexity

Necessary to identify the challenges in a clear, comprehensive and timely manner

Timely and economical solutions to mitigate the risks identified

Displacement of conventional generation

- Synchronous Generators replaced by mainly converter-connected, non-synchronous RES generation
- Resource-dependent generation patterns

Generation moving to the distribution network

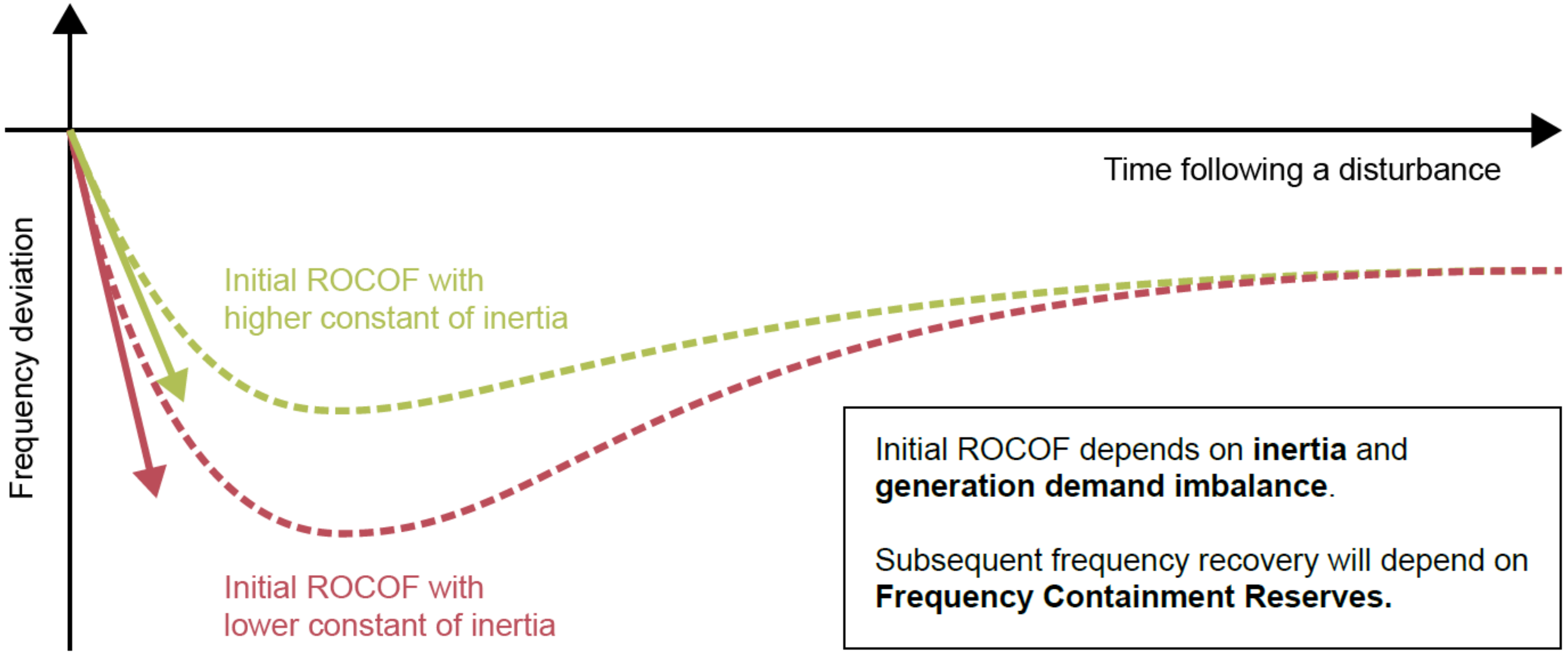
- Less observability and controllability of generation
- Different and more volatile load flow patterns between transmission and distribution networks; fast voltage variations

Increase of interconnection within and across synchronous areas

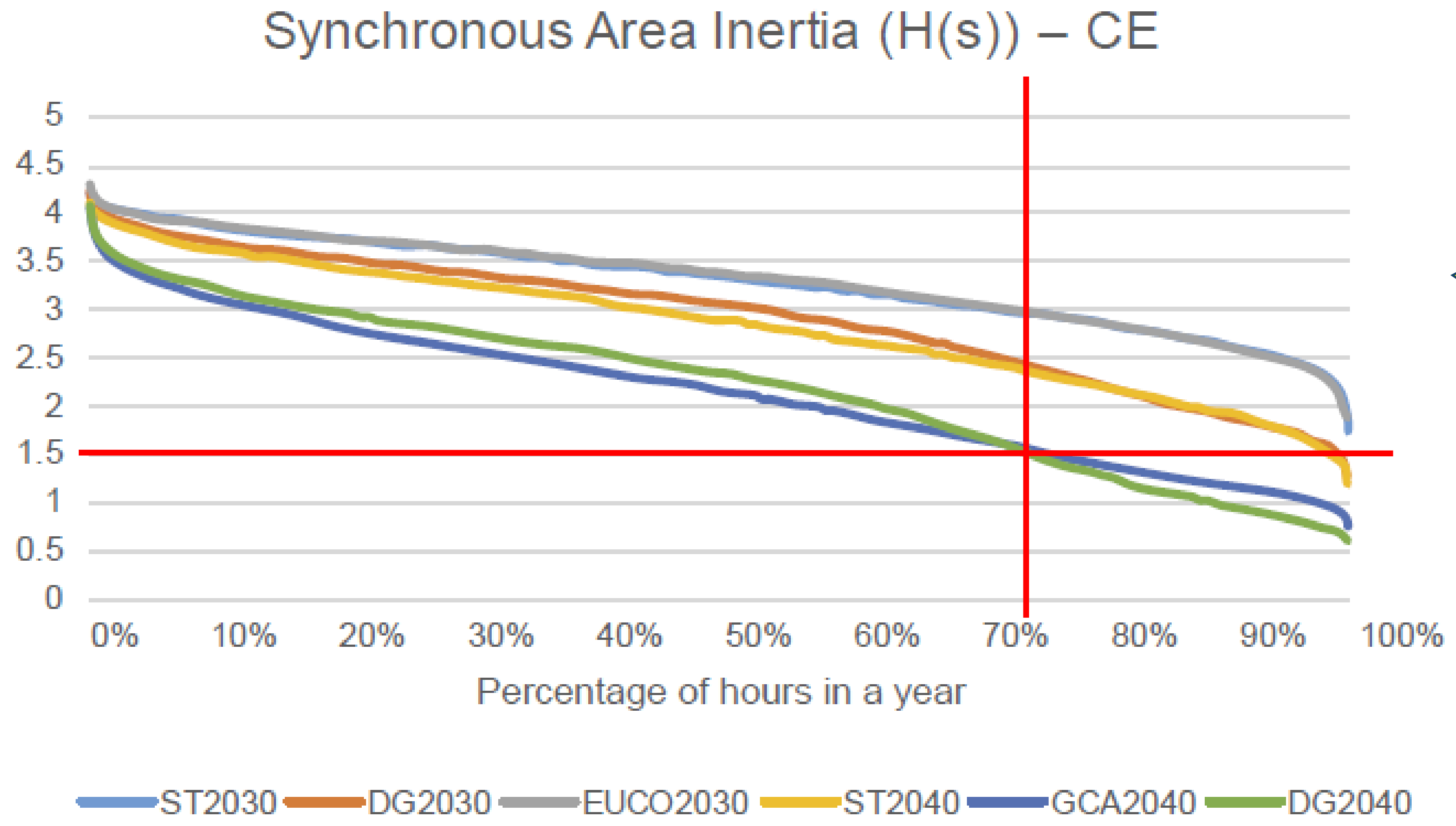
- Higher and more variable power transits across long power corridors
- Increased interdependency of TSOs to operate the system securely and efficiently

Importance of inertia to frequency stability

- A critical aspect in a system with high percentage of non-synchronous generation is the rate-of-change-of frequency (ROCOF) that occurs immediately after a sudden imbalance in generation and demand.
- Concerning the initial ROCOF, the system performance is mainly dependent on the available system inertia.
- **Estimating inertia is used as an assessment proxy.**



System strength 2030/2040 – Inertia indicator

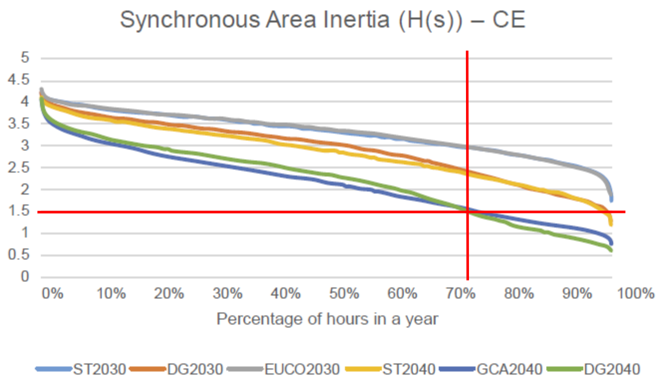


Depending on the scenario assumptions:

H < 1,5 s up to 2.500 h/a

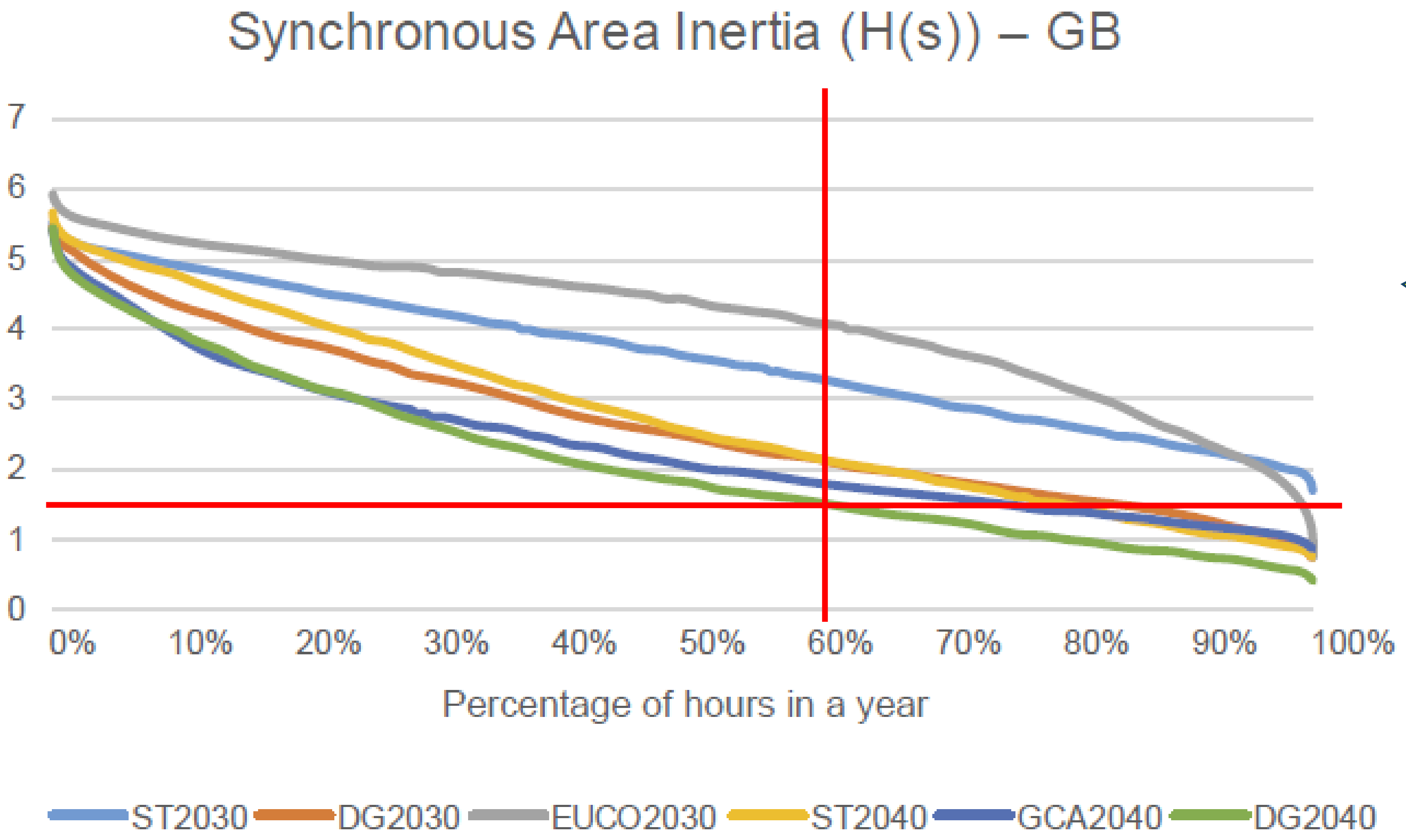
Source: ENTSO-E - TYNDP 2018 System Needs Report: European Power System 2040 – Completing the map

System strength 2030/2040 – Inertia indicator



Source: ENTSO-E - TYNDP 2018 System Needs Report: European Power System 2040 – Completing the map

System strength 2030/2040 – Inertia indicator

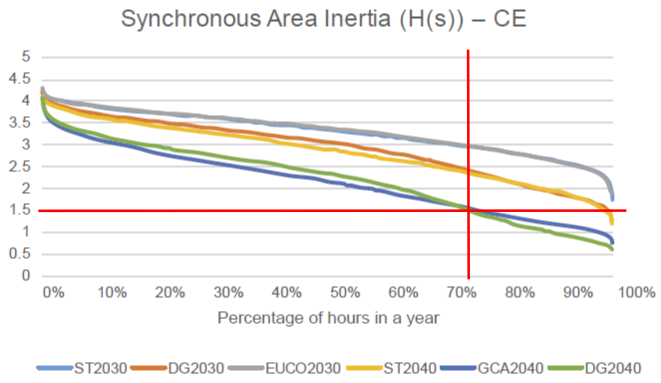


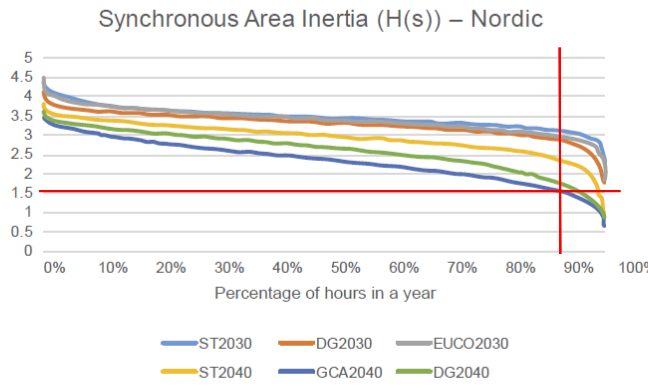
Depending on the scenario assumptions:

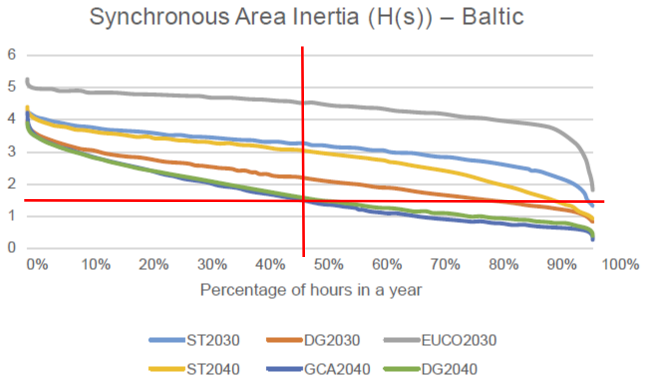
H < 1,5 s up to 3.500 h/a

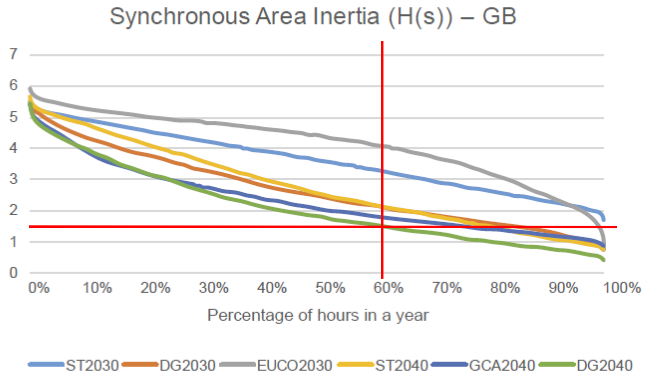
Source: ENTSO-E - TYNDP 2018 System Needs Report: European Power System 2040 – Completing the map

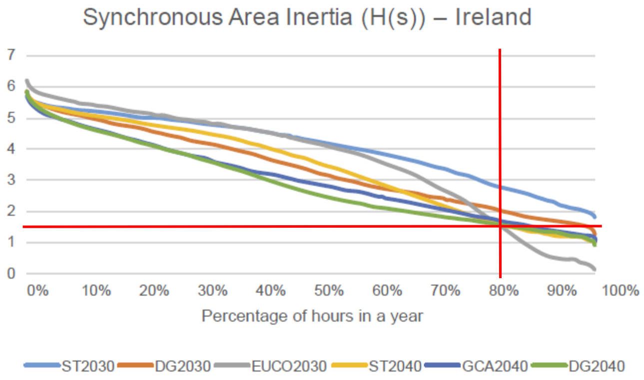
System strength 2030/2040 – Inertia indicator







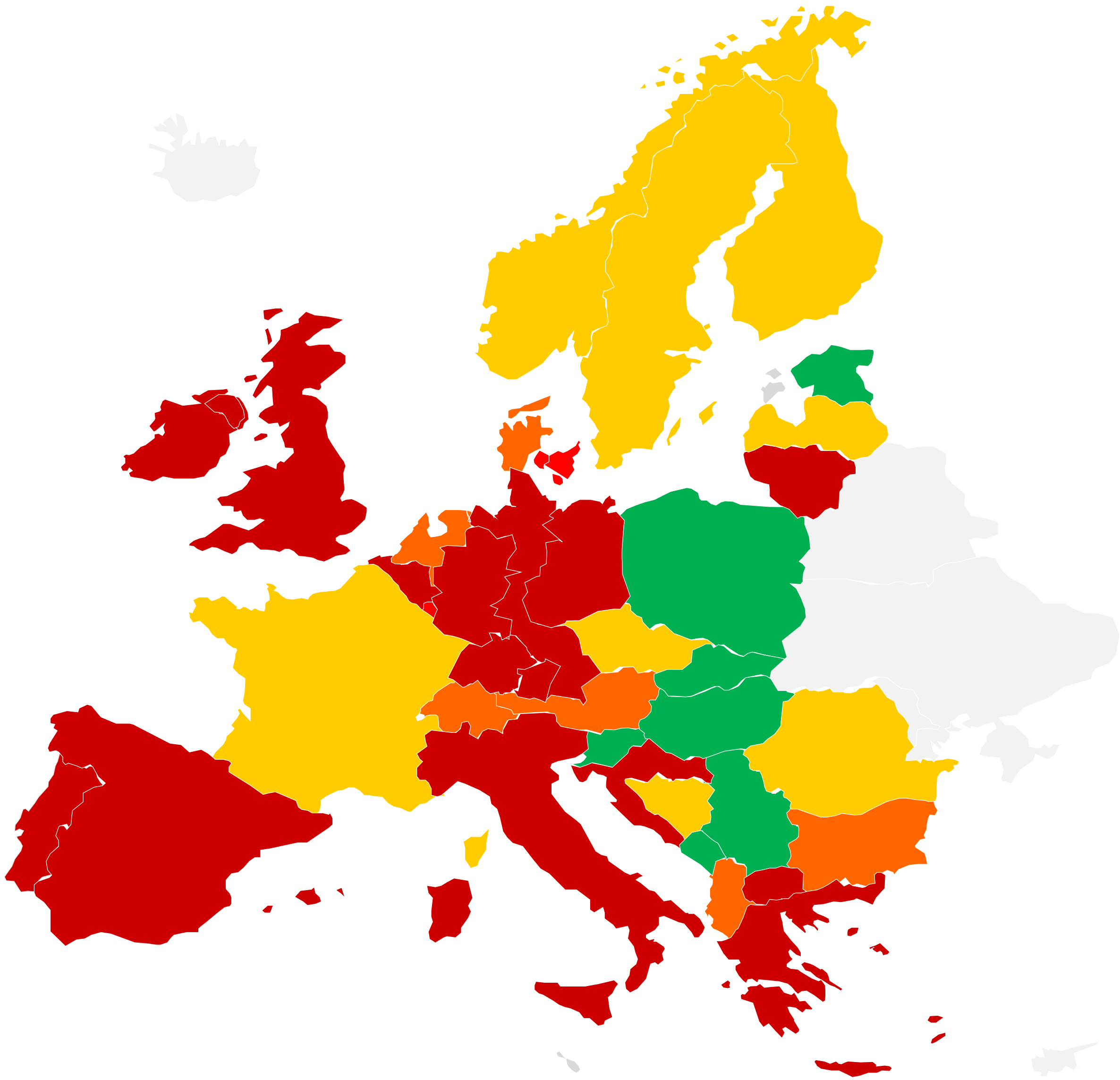




All Synchronous Areas will become prone to a lack of inertia, which will cause large frequency excursions in cases of relatively low mismatches between generation and demand.

Source: ENTSO-E - TYNDP 2018 System Needs Report: European Power System 2040 – Completing the map

National contributions to Synchronous Area system inertia at time of its minimum in 2030 - indicative results



Inertia contribution colouring code:

• Green	$H \geq 4$ s	Very good contribution
• Yellow	$3 \text{ s} \leq H < 4$ s	Good contribution
• Orange	$2 \text{ s} \leq H < 3$ s	Marginal contribution
• Red	$H < 2$ s	Limited contribution

! Action needed !

Other system needs in brief

Flexibility sources

- Highly variable RES generation
- High response (rate-of-change of active power) to be provided by controllable generation and demand

Short-circuit level

- Decrease of short-circuit power due to displacement of synchronous generation, and remote and non-synchronously connected RES sites
- Deeper and more widespread voltage dips in case of network faults
- Lower fault levels to be considered for protection schemes

Reactive power reserves

- Increase of reactive power demand due to highly loaded overhead lines
- Increase of reactive power losses with longer distances between generation and demand
- Generation moving from transmission to distribution networks

Introducing new connection requirements

CNC arrangements for synthetic inertia

COMMISSION REGULATION (EU) 2016/631 … establishing a network code on requirements for grid connection of generators (NC RfG) – Article 21(2):

Type C power park modules shall fulfil the following additional requirements in relation to frequency stability:

(a) **the relevant TSO shall have the right to specify** that power park modules be capable of providing synthetic inertia during very fast frequency deviations;

(b) the operating **principle of control systems** installed to provide synthetic inertia and the associated **performance parameters shall be specified by the relevant TSO**.

COMMISSION REGULATION (EU) 2016/1447 … establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules (NC HVDC) – Article 14:

1. **If specified by a relevant TSO**, an HVDC system shall be capable of providing synthetic inertia in response to frequency changes, activated in low and/or high frequency regimes by rapidly adjusting the active power injected to or withdrawn from the AC network in order to limit the rate of change of frequency. …
2. **The principle of this control system** and the associated **performance parameters shall be agreed between the relevant TSO and the HVDC system owner.**

ENTSO-E recommendation on a process on evaluating the synthetic inertia needs

Step 1 - Define extent of the challenge, by starting data collection on expected instantaneous penetration (IP) of non-synchronous generation at the appropriate level. Establish penetration in relevant the area at least to 2030.

Step 2A - If IP > 75% for the area under consideration for more than 10% of the hours in the year, establish a strategy to make improvements to contributions from non-synchronous generation.

If for the area with a defined challenge from Step 1 the inertia is < 1s for more than 10% of time **consider urgently the possibilities to implement the capabilities defined as Grid Forming.**

If 2A conditions do not apply:

Step 2B - If IP > 50% for your country, regardless of synchronous area (SA) penetration, discuss with other countries in SA. If your country inertia <1s for more than 10% of time consider with your SA TSOs if your limited inertia contribution is acceptable, and your resilience for system splits is adequate. **Consider the possibility of implementing Grid Forming capabilities.**

Step 3 - work out detailed requirements including parameters for the implementation and associated need for models to study the effectiveness as well as compliance tests.
→ introduce new requirements at national level

Source: ENTSO-E – High Penetration of Power Electronic Interfaced Power Sources – ENTSO-E Guidance Document for national implementation for network codes on grid connection

When introducing new connection requirements …

Connection requirements

- aim at solving a specific issue
- define solutions at a functional level
- endeavour to be technology-neutral (to the extent possible)

New/amended/ changed requirements

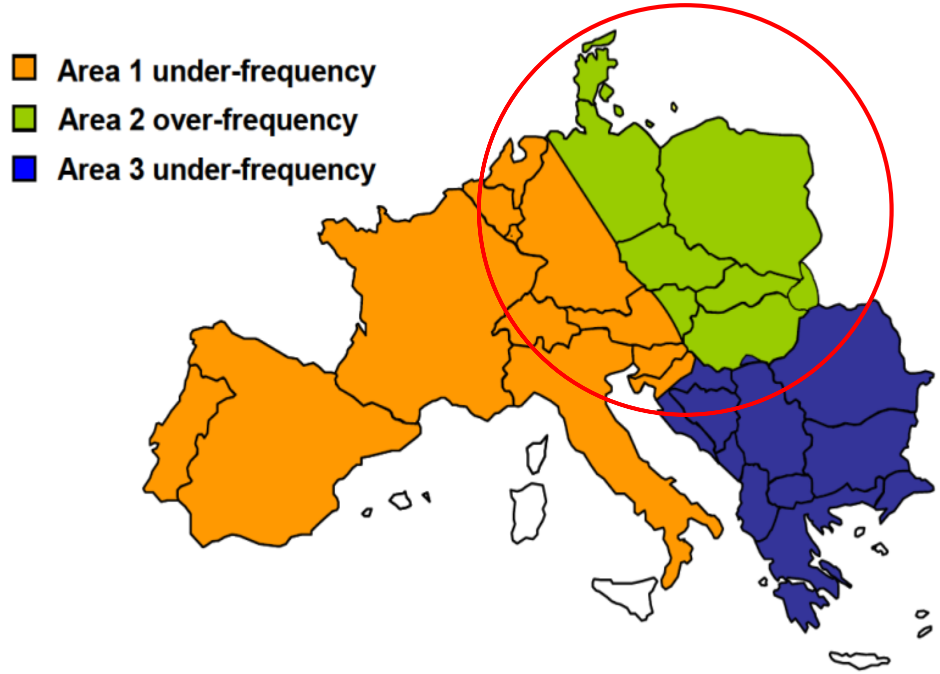
- shall be based on system needs to be concluded from system development scenarios
- are evidenced by system studies
- shall be traded off against alternative solutions
- contribute to energy policy targets (e.g. RES integration while maintaining security of supply)
- need several years from introduction by connection rules to field-application

The challenge is to introduce connection requirements timely with sufficient evidence of system needs

Grid forming inverters – why needed and what can be achieved?

Necessity of grid-forming inverters – Continental Europe (CE)

- Low inertia in case of system split scenarios (in contrast to smaller systems, where the effect occurs already in normal operation and loss of single infeed/demand)
- For such extreme contingencies, automatic emergency control actions are activated in order to secure the system
  - Disturbance leads to situations outside pre-defined limits for frequency containment reserves (primary control: 3 GW in CE)
  - Remedial actions by now: under-frequency load shedding and limited frequency sensitive mode for over-frequency (LFSM-O)
- Frequency stability issues revealed, due to sudden loss of short-circuit power as well as systems' rotating mass of the over-frequency area



04. November 2006 Continental Europe System Split

- **<u>But:</u>** Stability issues in the time-frame of first few periods of grid frequency (<< 100 ms) are **not solely associated** to **frequency gradients** (also: voltage collapse in transient range, harmonic instability, loss of synchronism in transient range, all associated to inverters in current-injecting control mode)

Behaviour of grid-forming inverters

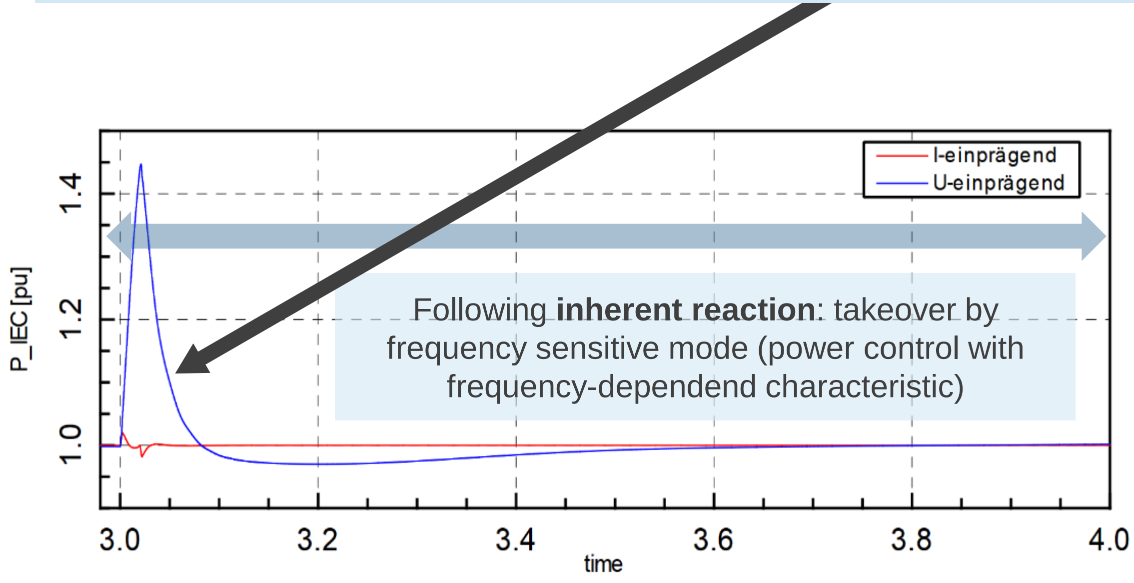
<u>Grid-forming inverters **can contribute to**:</u>

- system inertia and by **instantaneously** taking over active power mismatches **without frequency measurement** (voltage-source behaviour)
- **instantaneous** short-circuit power in the electro-magnetic domain **without frequency measurement**
- **damping sub- and super-synchronous harmonics** (voltage-source behaviour: short-circuit for disturbances outside the fundamental frequency)

<u>Grid-forming inverters **cannot overcome**:</u>

- **Restrictions in inverter current capacities** (However, in total, grid-forming behaviour is achieved over several units although some of them are reaching their current limits)
- The need for **active power reserve** within the steady-state domain (e.g. primary control or fast frequency response).

Inertia (instantaneous power reserve) as inherent reaction (**without** frequency measurement, **without** auxiliary power control)



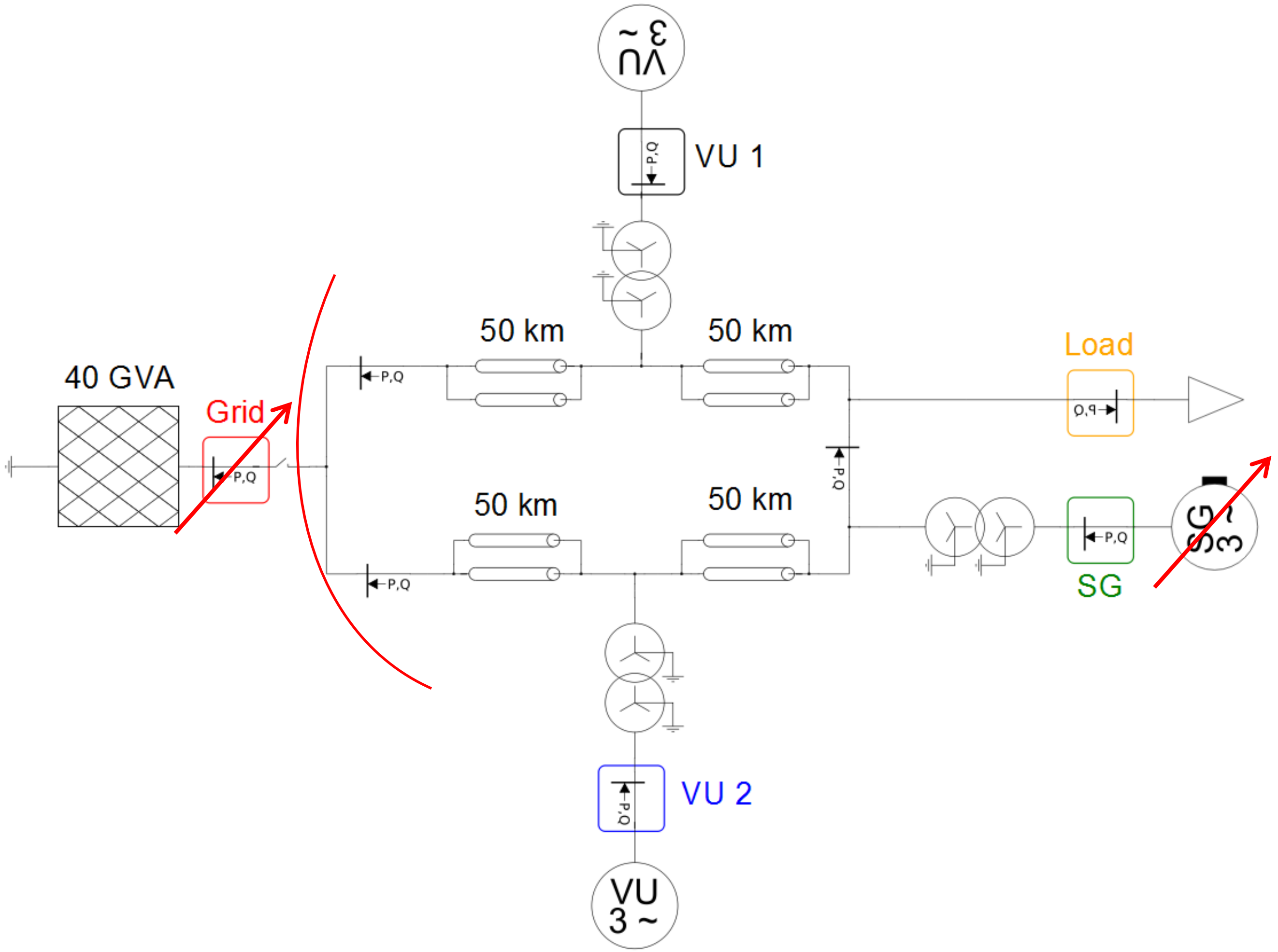
Active power determination according to IEC-61400-27

Grid-forming behaviour can bridge the time, until countermeasures based on frequency measurement can be activated.

System split simulations (I)

- Variation of the share of synchronous generation
- Variation of the power transits
- Variation of the inverter control scheme
- Variation of the control parameters

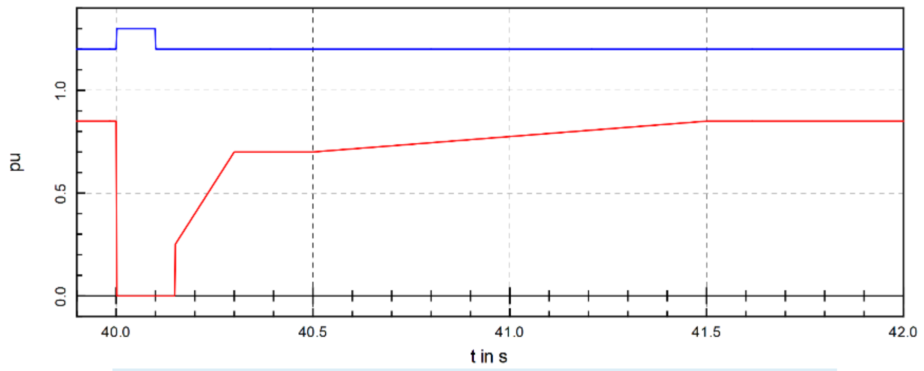
⇒ **Conclusions on criteria for evaluating the controllability of a system split**



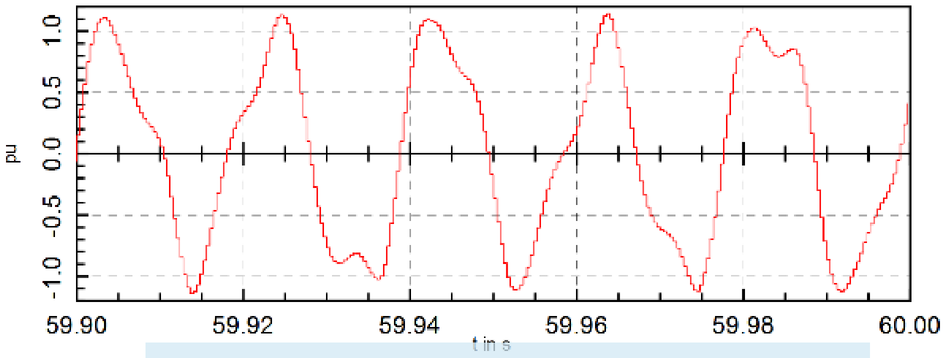
Source: K. Vennemann, T. Hennig, E. Grebe, W. Winter, G. Deiml, J. Lehner, H. Abele, J. Weidner, R. Stornowski, „Systemic Issues of Converter-based Generation and Transmission Equipment in Power Systems“, Wind Integration Workshop 2018, Stockholm, 2018.
(German TSOs system studies on frequency stability)

System split simulations (II)

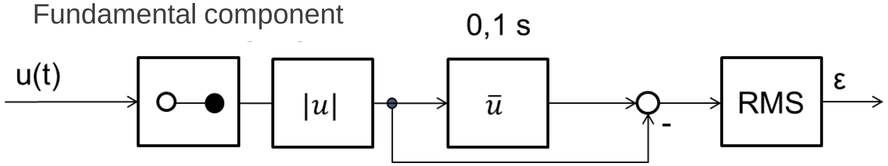
- Stability rate (ε) as a heuristic quantity of the ratio of fundamental component to distortion during a transient event
- LVRT/HVRT voltage-against-time profiles
- Evaluation of min. and max. frequency during a transient event
- Evaluation of rate-of-change of frequency



LVRT/HVRT voltage-against-time profile



Stability rate, ε = 0,018



Source: German TSOs system studies on frequency stability

System split simulations (III)

current-source control with 40% power export before system split

← share of non-synchronously connected generation

Time constant T_1 of determination of frequency / adaptation of active power (PT1-model) →

	f_max				f_min				RoCoF			
↓S_VU/ S_ges →PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
10	51.19	51.19	51.2	51.42	49.98	49.98	49.98	49.98	0.15	0.15	0.15	0.15
20	51.2	51.2	51.21	51.87	49.98	49.98	49.98	49.98	0.3	0.31	0.33	0.34
30	51.19	51.19	51.31	52.31	49.98	49.98	49.98	49.98	0.46	0.49	0.54	0.58
40	51.19	51.19	51.47	52.78	49.98	49.98	49.98	49.98	0.64	0.7	0.8	0.89
50	51.21	51.37	51.78	53.31	49.98	49.98	49.98	49.48	0.9	0.99	1.14	1.31
60	51.69	51.87	52.41	53.95	49.98	49.52	48.66	48.79	1.31	1.4	1.62	1.91
70	52.5	52.55	53.42	54.99	48.58	48.15	45.74	46.9	1.96	2	-3.1	2.88
80	53.58	54.21	55	55	45.92	45	47.51	45.94	-3.4	-4.26	-9.61	-9.87
90	54.85	55	55	55	45	48.03	45	45	5.53	-8.64	-8.81	-8.79
100	54.91	54.93	54.98	55	45.03	45.02	45.02	45.02	-13.62	-14.01	-15.13	-14.77

aggregated results

	Stability indicator ε				U_max				U_min				all information			
↓S_VU/ S_ges →PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
10	0	0	0	0	1.04	1.04	1.04	1.04	1	1	1	1				
20	0	0	0	0	1.04	1.04	1.04	1.04	1	1	1	1				
30	0	0	0	0	1.04	1.04	1.04	1.04	1	1	1	1				
40	0	0	0	0	1.05	1.05	1.05	1.05	0.99	0.99	0.99	0.99				
50	0	0	0	0.0001	1.05	1.06	1.06	1.06	0.99	0.98	0.98	0.98				
60	0	0	0	0.0003	1.06	1.08	1.08	1.08	0.97	0.96	0.96	0.96				
70	0	0	0.0004	0.0006	1.07	1.1	1.1	1.1	0.96	0.92	0.91	0.91				
80	0.0012	0	0.001	0.0399	1.09	1.1	1.1	1.11	0.92	0.59	0.18	0.19				
90	0.0082	0.0022	0.0316	0.0455	1.12	1.11	1.12	1.12	0.73	0.27	0.38	0.38				
100	0.0665	0.0513	0.0212	0.0185	1.12	1.12	1.12	1.12	0.85	0.86	0.88	0.91				

Source: German TSOs system studies on frequency stability

System split simulations (IV)

voltage-source control with 40% power export before system split

Time constant T_1 of determination of frequency / adaptation of active power (PT1-model) →

← share of non-synchronously connected generation

	f_max				f_min				RoCoF			
↓S_VU/ S_ges →PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
10	51.21	51.21	51.21	51.41	49.98	49.98	49.98	49.98	0.15	0.15	0.15	0.14
20	51.21	51.21	51.22	51.77	49.98	49.98	49.98	49.98	0.29	0.3	0.3	0.3
30	51.21	51.21	51.31	52.08	49.98	49.98	49.98	49.98	0.44	0.45	0.46	0.46
40	51.21	51.21	51.42	52.34	49.98	49.98	49.98	49.98	0.59	0.61	0.64	0.63
50	51.2	51.2	51.54	52.58	49.98	49.98	49.98	49.98	0.74	0.78	0.83	0.82
60	51.2	51.21	51.64	52.8	49.98	49.98	49.98	49.98	0.9	0.96	1.03	1.03
70	51.2	51.22	51.73	52.99	49.98	49.98	49.98	49.89	1.03	1.13	1.25	1.25
80	51.19	51.22	51.79	53.14	49.98	49.98	49.98	49.85	1.14	1.28	1.46	1.47
90	51.18	51.22	51.83	53.24	49.98	49.98	49.98	49.98	1.33	1.45	1.62	1.65
100	51.16	51.19	51.81	53.26	49.98	49.98	49.82	49.98	1.48	1.68	-2.35	1.78

aggregated results

	Stability indicator ε				U_max				U_min				all information			
↓S_VU/ S_ges →PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
10	0	0	0	0	1.04	1.04	1.04	1.04	1	1	1	1				
20	0	0	0	0	1.04	1.04	1.04	1.04	1	1	1	1				
30	0	0	0	0	1.04	1.04	1.04	1.04	1	1	1	1				
40	0	0	0	0	1.05	1.05	1.05	1.05	1	1	1	1				
50	0	0	0	0	1.05	1.05	1.05	1.05	1	1	1	1				
60	0	0	0	0	1.05	1.05	1.05	1.05	1	1	1	1				
70	0	0	0	0	1.06	1.06	1.06	1.06	0.99	0.99	0.99	0.99				
80	0	0	0	0	1.06	1.07	1.07	1.07	0.99	0.99	0.99	0.99				
90	0	0	0	0	1.07	1.07	1.08	1.08	0.99	0.99	0.99	0.99				
100	0	0	0	0	1.09	1.09	1.09	1.09	0.99	0.99	0.97	0.99				

Source: German TSOs system studies on frequency stability

System split simulations (V)

current-source control with 40% non-synchronously connected generation

Time constant T_1 of determination of frequency / adaptation of active power (PT1-model) →

↓ ratio of power export to generation

	f_max				f_min				RoCoF			
↓Export[%] → PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
0	50.25	50.25	50.28	50.43	50	50	50	50	0.05	0.05	0.05	-0.06
10	50.48	50.48	50.58	51.08	50	50	50	50	0.23	0.24	0.25	0.26
20	50.7	50.7	50.87	51.63	49.99	49.99	49.99	49.99	0.36	0.38	0.43	0.46
30	50.94	50.94	51.16	52.2	49.99	49.99	49.99	49.99	0.49	0.53	0.62	0.67
40	51.18	51.18	51.46	52.76	49.98	49.98	49.98	49.98	0.63	0.69	0.8	0.88
50	51.43	51.43	51.79	53.32	49.98	49.98	49.98	49.87	0.81	0.86	0.98	1.09

aggregated results

	stability indicator ε				U_max				U_min				all information			
↓Export[%] → PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
0	0	0	0	0	1.02	1.02	1.02	1.02	0.98	0.98	0.98	0.98				
10	0	0	0	0	1.02	1.02	1.02	1.02	0.98	0.98	0.98	0.98				
20	0	0	0	0	1.03	1.03	1.03	1.03	0.99	0.99	0.99	0.99				
30	0	0	0	0	1.04	1.04	1.04	1.04	0.99	0.99	0.99	0.99				
40	0	0	0	0	1.05	1.05	1.05	1.05	0.99	0.99	0.99	0.99				
50	0	0	0	0	1.06	1.06	1.06	1.06	1	0.99	0.99	0.99				

Source: German TSOs system studies on frequency stability

System split simulations (VI)

current-source control with 80% non-synchronously connected generation

Time constant T_1 of determination of frequency / adaptation of active power (PT1-model) →

↓ ratio of power export to generation

↓Export[%] →PT1 f	f_max				f_min				RoCoF			
	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
0	50.54	50.69	51.53	55	50	49.57	47.74	45	0.77	0.91	-2.1	-4.53
10	50.97	51.1	51.84	55	49.22	48.67	46.79	45	1.24	-1.5	-2.69	-4.56
20	51.52	51.61	52.58	55	48.56	47.92	45	45	-1.69	-2.09	-3.74	-4.14
30	52.37	52.71	55	55	47.6	46.1	47.64	45	-2.46	-3.17	-7.97	-9.31
40	53.47	54.16	55	55	46.2	45	47.34	45.91	-3.32	-4.23	-9.82	-9.72
50	54.93	54.11	55	55	45	45	47.4	47.1	-4.02	4.96	-9.84	-9.69

aggregated results

↓Export[%] →PT1 f	stability indicator ε				U_max				U_min				all information			
	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
0	0	0	0.0009	0.0236	1.01	1.01	1.01	1.08	0.89	0.88	0.88	0.68				
10	0.0105	0	0.0008	0.0446	1.02	1.02	1.02	1.09	0.9	0.89	0.89	0.59				
20	0.008	0	0.0009	0.0276	1.04	1.05	1.05	1.1	0.91	0.9	0.87	0.75				
30	0.0071	0	0.0007	0.0041	1.06	1.09	1.09	1.1	0.92	0.86	0.15	0.16				
40	0.014	0	0.0008	0.0429	1.1	1.11	1.11	1.11	0.92	0.62	0.18	0.18				
50	0.0539	0	0.0009	0.0447	1.12	1.12	1.12	1.12	0.92	0.13	0.21	0.21				

Source: German TSOs system studies on frequency stability

System split simulations (VII)

voltage-source control with 80% non-synchronously connected generation

Time constant T_1 of determination of frequency / adaptation of active power (PT1-model) →

↓ ratio of power export to generation

	f_max				f_min				RoCoF			
↓Export[%] →PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
0	50.29	50.29	50.32	50.46	50	50	50	50	0.06	0.06	0.06	0.06
10	50.51	50.51	50.59	50.95	49.99	49.99	49.99	49.99	0.2	0.2	0.2	0.2
20	50.73	50.73	50.85	51.39	49.99	49.99	49.99	49.99	0.33	0.34	0.34	0.33
30	50.96	50.96	51.13	51.86	49.99	49.99	49.99	49.99	0.46	0.47	0.49	0.48
40	51.2	51.2	51.41	52.32	49.98	49.98	49.98	49.98	0.59	0.61	0.63	0.63
50	51.44	51.44	51.7	52.8	49.98	49.98	49.98	49.98	0.71	0.74	0.78	0.78

aggregated results

	stability indicator ε				U_max				U_min				all information			
↓Export[%] →PT1 f	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5	0.02	0.2	1	5
0	0	0	0	0	1.02	1.02	1.02	1.02	0.98	0.98	0.98	0.98				
10	0	0	0	0	1.02	1.02	1.02	1.02	0.98	0.98	0.98	0.98				
20	0	0	0	0	1.03	1.03	1.03	1.03	0.99	0.99	0.99	0.99				
30	0	0	0	0	1.04	1.04	1.04	1.04	0.99	0.99	0.99	0.99				
40	0	0	0	0	1.05	1.05	1.05	1.05	1	1	1	1				
50	0	0	0	0	1.05	1.05	1.05	1.05	1	1	1	1				

Source: German TSOs system studies on frequency stability

Findings from system split simulations

- With **40% installed capacity of non-synchronously connected generation, transits up to 50% of generation** are **manageable with state-of-the-art, current-source inverter control** in case of a system split (today's situation!).

- From ca. **60% installed capacity of non-synchronously connected generation** upwards (depending on the parameters of the current-source inverter control) a system split with **transits ca. 50% of generation** is **no more manageable** with state-of-the-art, current-source inverter control.

- With **80% installed capacity of non-synchronously connected generation, transits from 10% of generation** upwards are **no more manageable with state-of-the-art, current-source inverter control**.

Source: German TSOs system studies on frequency stability

Conclusions

Summary

- The EU has defined ambitious policy targets to decarbonise the energy sector and achieve a climate neutral Europe by 2050.
- The *Clean Energy Package* is expected to enter into force by mid 2019.
- Network codes are the foundation to facilitate the European Internal Energy Market with large-scale RES integration while maintaining security of supply.
- RES integration entails the displacement of bulk synchronous generators by embedded and non-synchronously connected generation.
- Reduction of system inertia increases the frequency sensitivity of the electricity supply system and renders maintenance of frequency stability a major challenge, which requires new technical solutions.
- **Grid forming converters are capable of emulating the intrinsic dynamic behaviour of synchronous generators and are one, but indispensable instrument in the toolbox for mitigating future system needs.**

Thank you for your attention!

Questions?

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