Ten-Year Network Development Plan 2020

System dynamic and operational challenges

August 2021 · Final version after ACER opinion

entsoe

ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the **association for the cooperation of the European transmission system operators (TSOs)**. The 42 member TSOs, representing 35 countries, are responsible for the **secure and coordinated operation** of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

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

Our mission

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

Our vision

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

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

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

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

Our values

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

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

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

Our contributions

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

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

› Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;

› Assessment of the adequacy of the system in different timeframes;

› Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);

› Coordination of research, development and innovation activities of TSOs;

› Development of platforms to enable the transparent sharing of data with market participants.

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

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

System dynamic and operational challenges

1. Introduction

Based on the TYNDP scenarios, previous editions of the TYNDP IoSN revealed the trends in which the system is evolving: more RES at all voltage levels, more power electronics either in generation or HVDC connections, a very variable mix of generation and also large and highly variable power flows. This combination of trends, observed in all synchronous areas, translates to technical challenges in several aspects such as in frequency, voltage or congestion management control.

Having in mind the ambitious political goals set out in the Clean Energy Package and the European Green Deal, aiming at making Europe climate neutral in 2050, those trends, and its technical challenges, are becoming more and more evident even in areas where the immediate concerns are more mitigated, such as Continental Europe.

In order to achieve the climate targets adopted by the EU, more and more renewable energy generation plants need to be built. For the optimal integration of renewable generation, increased cross border transmission capacity will be required to accommodate such large amounts of transit flows. On top of that, the grid synchronization/stabilization mechanisms, which up to date have been inherently provided by rotational synchronous generators, will be missing. In future, these tasks will have to be performed by other technical solutions.

As such, beyond all the incremental steps, it is also necessary to shift the perspective into creating today the effective boundary conditions to successfully meet the decarbonisation goals at their full extension.

The challenges are real for the system's security, during the transition and towards a future decarbonized power system. However, for this future decarbonized power system, there are also available technical solutions with different levels of maturity and to be applied at all voltage levels. Hence, there is a need for strong transmission/distribution coordination, to involve all system users and to maintain an aligned cooperation with research and development.

In the midterm, until these new technical solutions are implemented, it may be necessary to take additional measures (e.g. RES or power flow limitations) to ensure system security. As such, there is a need to work decisively on the target solutions and to make them available when necessary so that the midterm and probably costly limitations does not last too long.

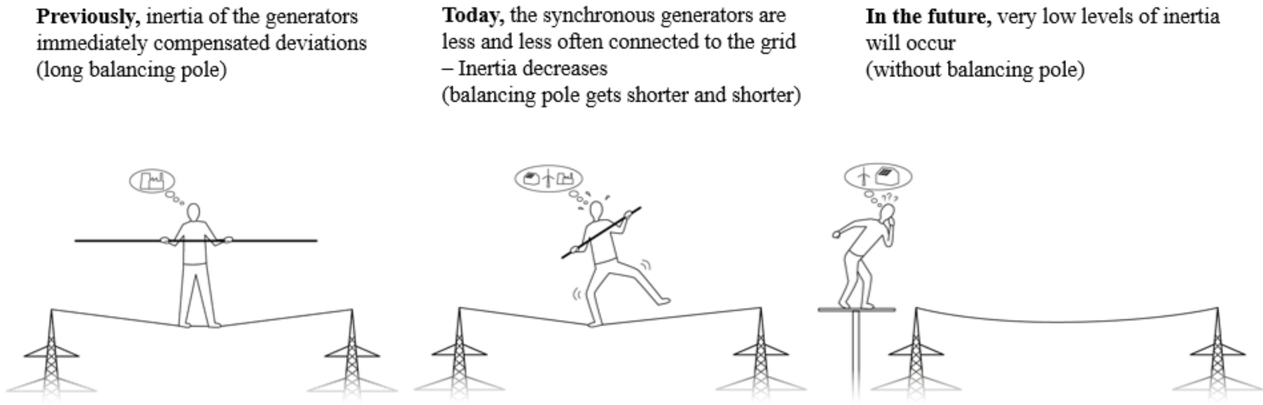
The following chapters illustrate the challenges to maintaining system stability and should enable a clear basis for dialogue with all system users to find the adequate and timely solutions for the system needs.

1.1 Frequency related aspects

Total System inertia and Rate of Change of Frequency

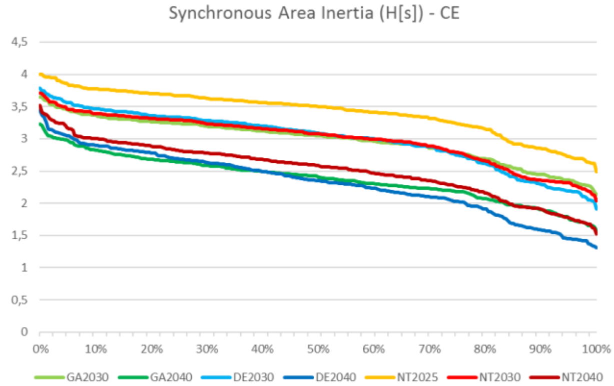
Frequency variations occur in power systems due to mismatches between active power generation and demand. Once a mismatch takes place, the energy stored in the rotating masses of the synchronous generating units, by virtue of their intrinsic mechanical inertia, provides means of instantaneously balancing any mismatch. The immediate inertial response results in a change in rotor speeds and, consequently, the system frequency. Whereas this does not solve the power mismatch problem in a sustainable manner, it is essential for instantaneously balancing this mismatch until frequency reserve response providers are able to respond to the change of frequency and vary the power output of their plants to restore the balance between generation and demand.

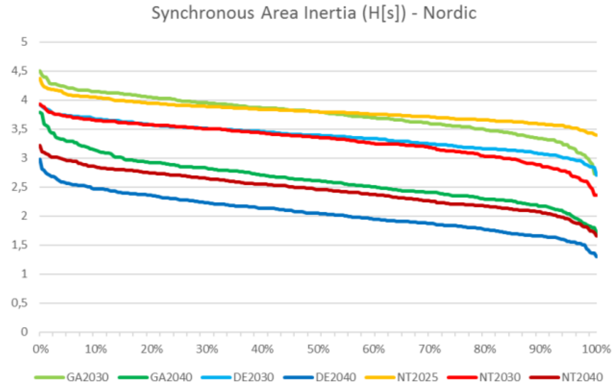
The following analogy provides a description of the problem having in mind the current trend of more and more synchronous generators being replaced by converter connected generators… now from the perspective of a tightrope walker where the balancing pole provides instantaneous inertia support that allows time for his slower stabilising actions after the tightrope swings…

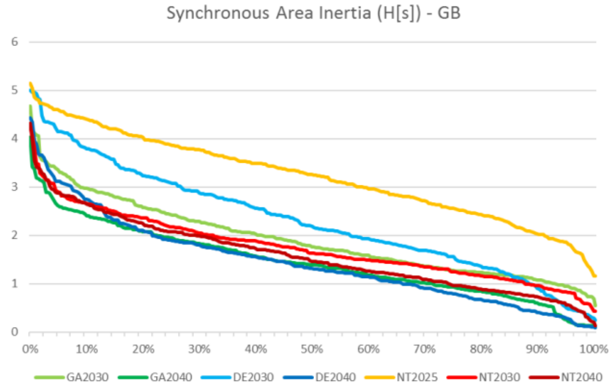


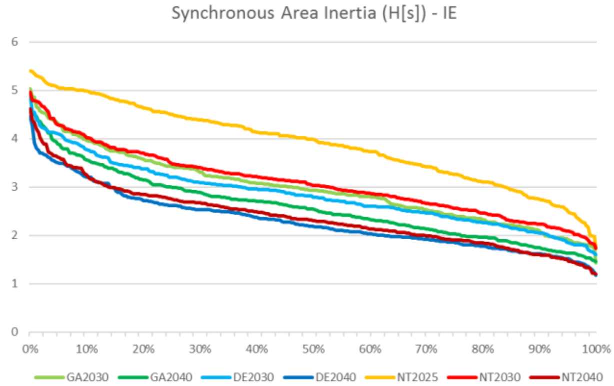
Current trends, and measures to mitigate the consequences on the following pages…

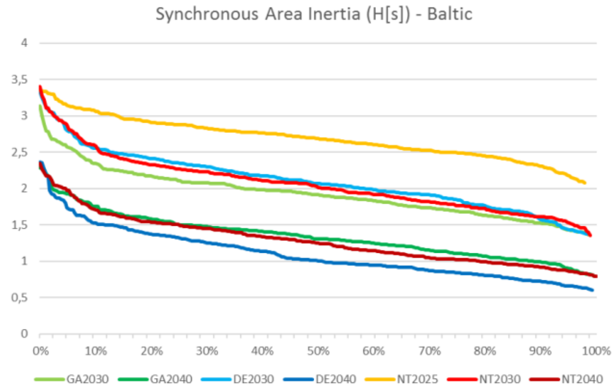
Taking into account the TYNDP 2020 market results, the following duration curves present the percentage of hours in a full year where, for all Synchronous Areas, the intrinsic inertia from generators is above a given value. This estimated equivalent system inertia H[s] is calculated on the basis of an estimated online generators capacity. Inertia contribution from demand is neglected, it has been considered that self-regulating effect of loads is decreasing from the traditional value of 1-2%, which provides a conservative approach without impact on the trend identification and scale of the challenge.









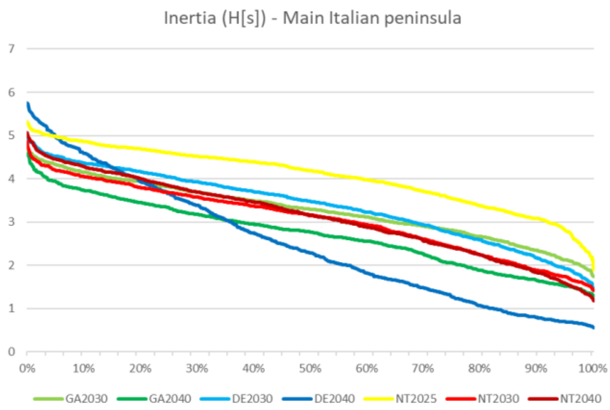


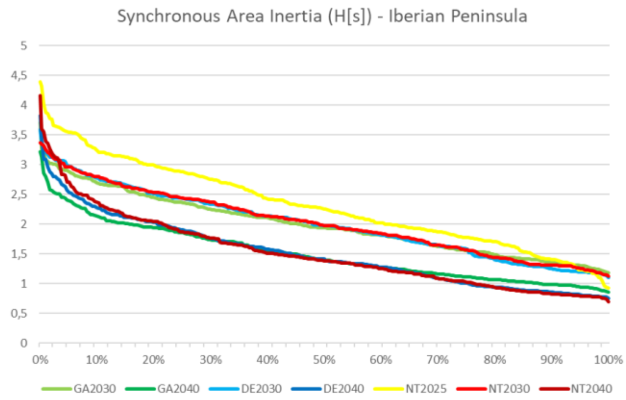
System inertia trends

As we move from the situations in 2025 to 2030 and to the 2040 visions with a higher integration of RES and more distributed generation, inertia in all synchronous areas will decrease. The reduction is noticeable even in large area such as Continental Europe.

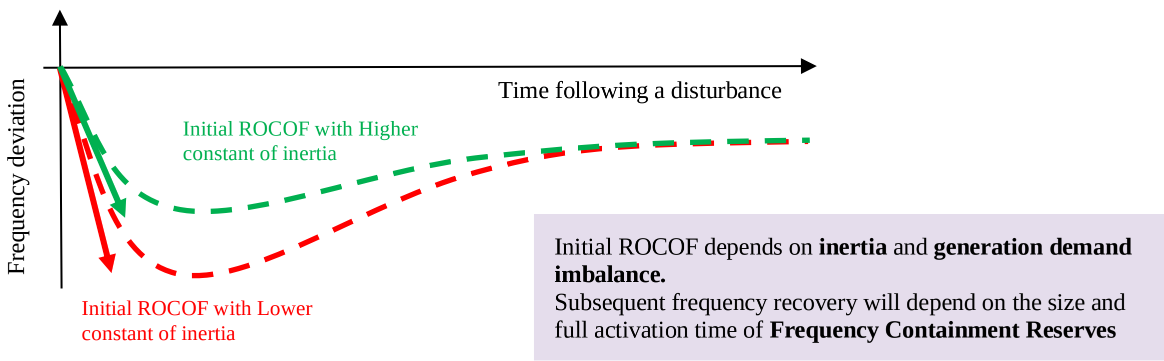
With very low inertia, the system becomes more vulnerable to experience high frequency excursions and even blackout as result of a relatively low mismatch between generation and demand. The impact of this inertia reduction is especially significant in small synchronous areas.

Similarly as above, the following duration curves present the percentage of hours in a full year where the intrinsic inertia from generators, in the main Italian peninsula and the Iberian Peninsula, is above a given value.





The initial rate-of-change of frequency (ROCOF) and the magnitude of the frequency deviation depend on the mismatch between generation and demand compared to the size of the system. The initial ROCOF is also dependent on the total stored kinetic energy (depending on the system inertia) at the time the imbalance took place, as well as on the frequency dependency of the load (self-regulation effect). The higher the imbalance between load and generation and the lower the inertia, the higher the ROCOF is.

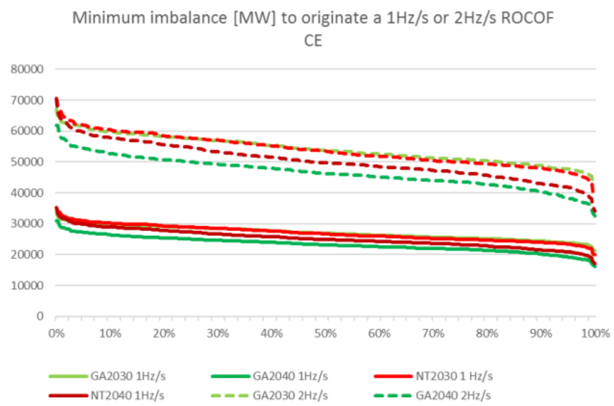


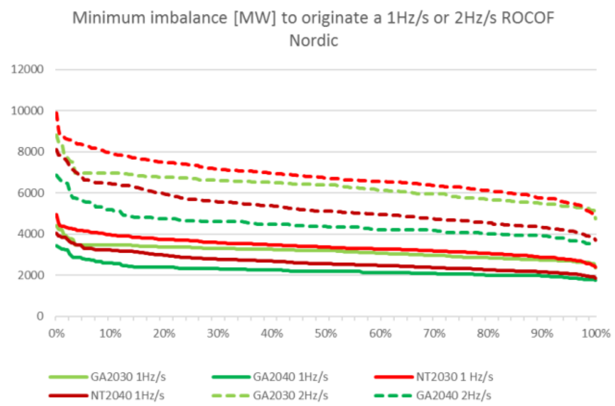
The high ROCOF, which is a system metric that depends on the inertia of the amount of synchronous units in operation and cannot be influenced by means of PPMs, reduces the time available to deploy the necessary fast balancing actions and, additionally, for some units, could lead to disconnection and, therefore, further deterioration of system security. With very low inertia, the system would experience high frequency excursions, which may trigger domestic load-shedding or – in the worst case – lead to a partial or total blackout as result of a relatively low mismatch between generation and demand.

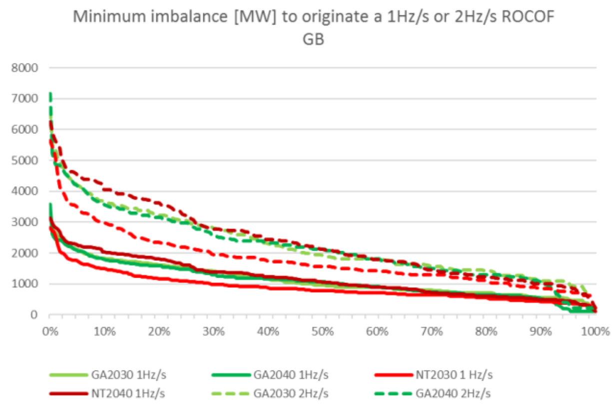
$$ROCOF_{(Hz/s)} = \frac{50_{(Hz)}}{2.Sn_{(MVA)}} \frac{Imbalance_{(MW)}}{H_{(MW.s/MVA)}}$$

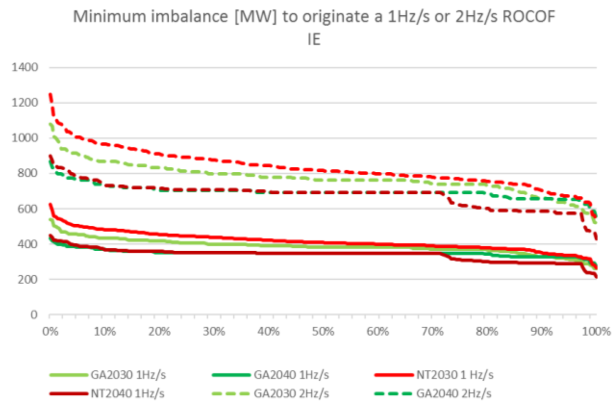
The following figures present the minimum imbalance necessary to trigger a fixed ROCOF for all the hours of the year in the different synchronous areas using the estimated values of inertia. The following assumptions were taken on the illustrative calculations:

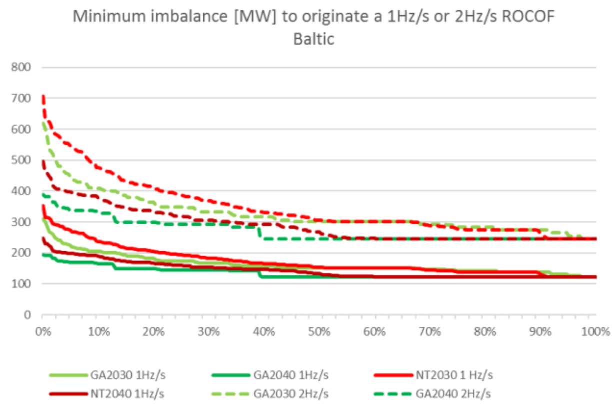
- Three scenarios are used: National Trends (NT), Global Ambition (GA), Distributed Energy (DE)
- Two ROCOF values are used: 1 Hz/s and 2 Hz/s. The higher, 2 Hz/s, representing a typical value for defence plans and RfG withstand capability for generators.











ROCOF trends

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

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

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

The loss of generation necessary to trigger a certain level of ROCOF is higher in large synchronous areas compared to that in small synchronous areas. For example, under certain conditions, a 0.5GW power imbalance in Ireland would be sufficient to trigger the same ROCOF as a 30GW power imbalance in Continental Europe. As a consequence, whereas small synchronous areas would see large and rapid frequency excursions that could last for several tens of seconds after a normal generation loss, large synchronous areas would not see the same size of frequency excursions unless a significant disturbance occurs such as a system split event which would largely exceed the reference incident[1] (3000MW for CE)

System split events

In a system split event the synchronous area splits into separate islands. The exports and imports between these islands, prior to the system split event, turn into power imbalances for the separate islands after the split. The larger the export or import of the island before the split, the greater the imbalance after the split and therefore the greater the need for large and quick adjustment for generation and demand. Not only the resulting imbalances are difficult to predict, but also the resulting equivalent system inertia will differ from island to island. Under those conditions, it is reasonable to consider the existence of large initial ROCOFs exceeding 2Hz/s.

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

Single mass approximation versus local frequency

The inertia and frequency assessment described in this document are performed with the approximation of the single mass: the frequency is assumed to be unique across the system and all machines connected to the system can be aggregated into a single mass equivalent machine. This approach allows to carry out computations based on market data but without a complex grid model.

However, in reality frequency varies from one node to another depending on the grid topology, especially during transients: immediately after and close to the disturbance (for instance a loss of a generating unit or HVDC) the node frequencies vary faster and with greater excursions. After a few seconds, the node frequencies converge to the same value across the synchronous area. The single mass model enables powerful analyses on system-wide trends but locally some machines could see higher frequency deviations.

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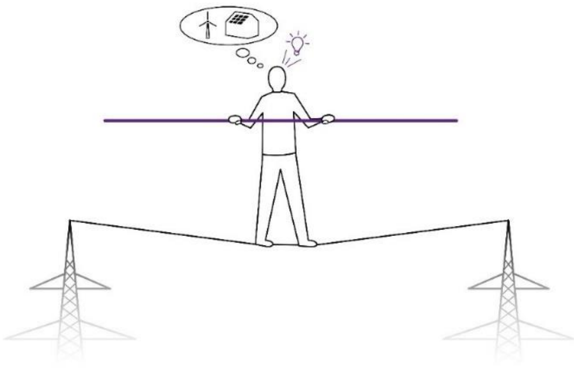
[1] Final Report System Disturbance on 4 November 2006.
https://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/Final-Report-20070130.pdf.

[2] According to the Comission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation: system defence plan means the technical and organisational measures to be undertaken to prevent the propagation or deterioration of a disturbance in the transmission system, in order to avoid a wide area state disturbance and blackout state.

Potential Mitigation Measures

The behaviour of RES units must be further developed so that they react immediately to deviations…



Grid-forming Converters (GFC) are power electronics devices designed in control and sizing in order to support the operation of an AC power system under normal, disturbed, and emergency conditions without having to rely on services from synchronous generators.
Future capabilities of GFC, in order to allow up to 100% penetration of power park modules (PPM) can be classified exhaustively as follows:

1. Creating system voltage,
2. Contributing to Fault Level,
3. Contributing to Total System Inertia (limited by energy storage capacity),
4. Supporting system survival to allow effective operation of Low Frequency Demand Disconnection (LFDD) for rare system splits,
5. Acting as a sink to counter harmonics & inter-harmonics in system voltage,
6. Acting as a sink to counter unbalance in system voltage,
7. Prevent adverse control system interactions.

Their capability relies on the existence of an energy buffer within the DC link (battery storage, headroom on wind or PV inverter based power sources, supercapacitors, or a combination of these, depending on the application).

The technology is still under definition. Research is still ongoing as characteristics are still being shaped in concert with the changing needs of power systems around the world. In this context, ENTSOE established the technical group HPoPEIPS (High Penetration of Power Electronic Interfaced Power Sources) with the purpose of analysing the grid forming capabilities[3] according to the system needs, considering also the existence of current converter technologies, i.e. grid following converters. Other relevant projects, as MIGRATE (https://www.h2020-migrate.eu/) and OSMOSE (https://www.osmose-h2020.eu/) accounted with the collaboration of TSOs.

Different solutions and mitigation measures contribute to securing the power system performance in case of disturbances related to frequency (on top of what is required by current legislation):

- **Technical devices:**

3 High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters - Technical Report https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC High_Penetration_of_Power_Electronic_Interfaced_Power_Sources_and_the_Potential_Contribution_of_Grid_Forming_Converters.pdf

- Presently, immediate inertial response can only be met by synchronous generators. In the future new capabilities, not yet available, such as Grid-forming Converters[3] will be necessary.
- After immediate inertial response, fast frequency response by other sources than synchronous generation are needed: converter-connected generation, demand side response, storage (including batteries).
- Use the contribution of synchronous condensers (SCs): decoupling generators to become SCs under changing operating conditions in real time from generators such as GTs and CCGTs or permanently from decommissioned nuclear power plants (Germany).
- In the case of a System Split, the severity of the fault depends on the exchange of AC power between the grid regions. A solution derived from this would be to limit the power exchange in the AC system between grid regions by increasing the use of direct current transmission. Moreover, the utilisation of grid forming control to HVDC links and especially to assets owned by TSOs – such as FACTS – is the most straightforward and easy way to introduce grid forming capabilities.

❖ **Connection codes and standards:**

- They will be essential to ensure that necessary technical requirements (from generators, HVDC and demand) related to inertia, frequency sensitive mode and robustness against high ROCOF are implemented.
- TSOs, DSOs, manufacturers, research institutes and policy makers must make an effort in establishing the scenarios where GFC are needed and thus, GFC technical requirements must be clearly defined in the future.

❖ **Operation and market:**

- Constraining RES and placing synchronous generation with intrinsic inertia in the unit commitment (must run units). This measure, which is easy to implement as a short-term solution could be less efficient in the long term. This constraint can be in the form of "inertial redispatch".
- Real-time monitoring of system inertia in order to ensure that a minimum level of inertia is available in the system at all times where relevant lack of inertia has been identified [4](already true in Great Britain and Ireland). Current regulations requires minimum inertia investigation for each synchronous area which is updated every two years.
- Procurement of fast control reserves (e.g. "Enhanced Frequency Reserves") as an additional ancillary service and activation when necessary (e.g. during high RES production).
- Reserves shared between synchronous areas using HVDC up to the optimal amount specified by current network codes.
- Large imbalances will become increasingly more challenging to secure and is an issue with cross-border impact: particularly in smaller synchronous areas, constraining cross-border trade with larger synchronous areas, such that the largest secured imbalance does not result in high ROCOF.

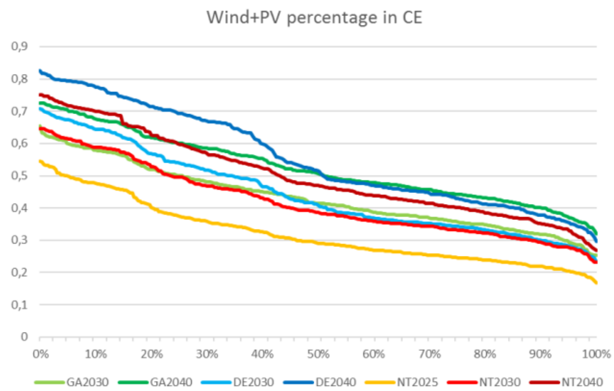
[3] Implementation Guiding Document – High Penetration of Power Electronic Interfaced Power Sources. https://www.entsoe.eu/Documents/Network%20codes%20documents/Implementation/CNC/170322_IGD25_HPoPEIPS.pdf

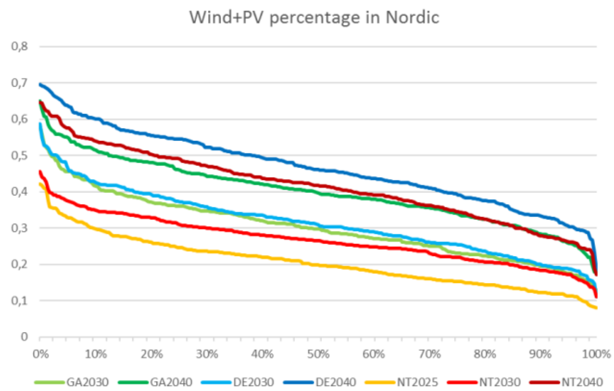
[4] SOGL art. 39 requires each synchronous area to do a study on sufficiency of inertia

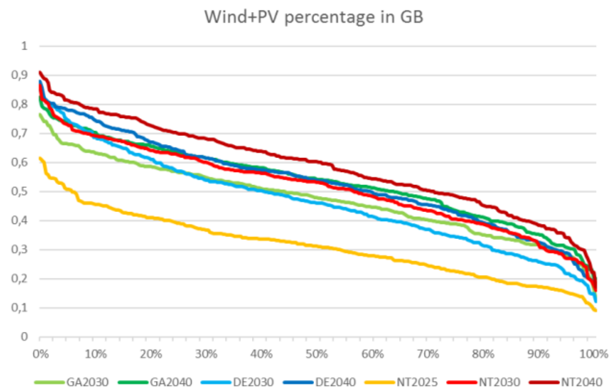
1.2 Flexibility needs

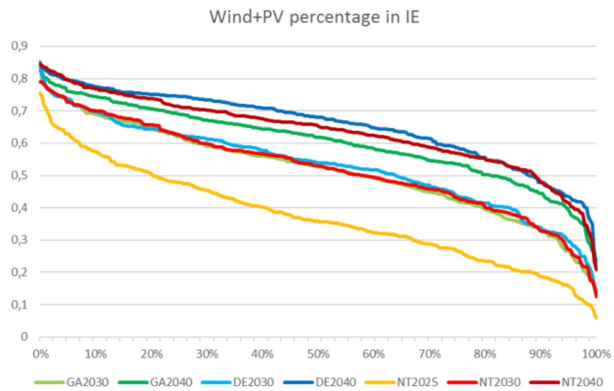
Unlike conventional generation with costly but controllable sources of primary energy, RES utilise primary energy sources that are free but have a variable nature. Hence, the high installed capacity of RES and their close-to-zero marginal costs cause conventional generation to be displaced from the market.

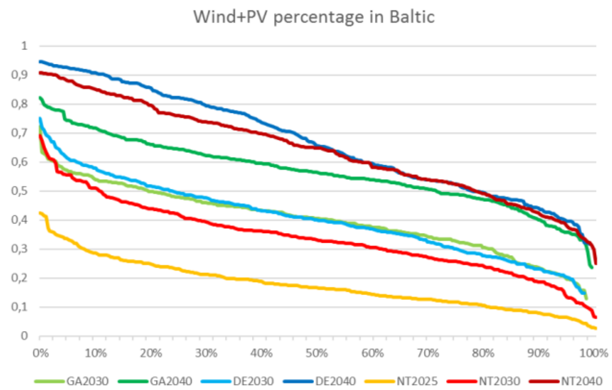
The plots below depict the duration curves of the ratio between the sum of wind and solar photovoltaic generation (not considering all other RES) and total generation. This conservative ratio gives an image of the percentage of variable RES generation over the total generation for all synchronous areas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











Ratio of PV+Wind over total generation

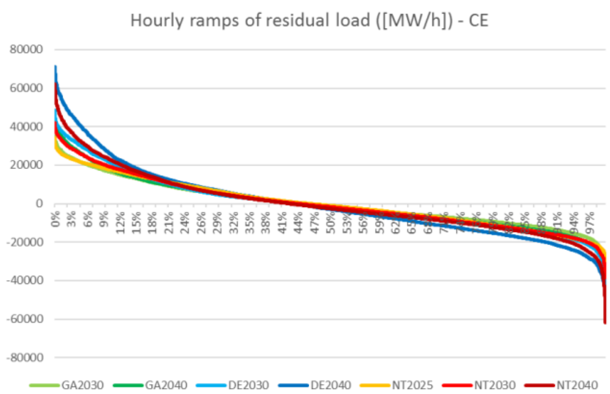
High ratios of variable RES generation over the total generation are reached in all synchronous areas for some hours of the year - above 80% in all synchronous areas for some scenatios, except in Nordic (highest scenario reaching 70%).

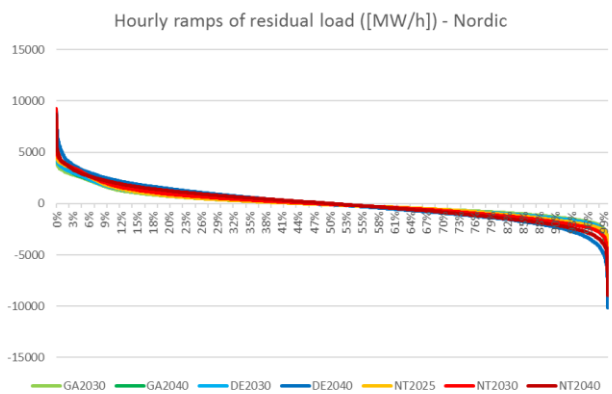
Reduced amount of controllable generating units lead to high flexibility needs in normal operation. This includes new roles for thermal plants, RES participation, demand side response, and storage.

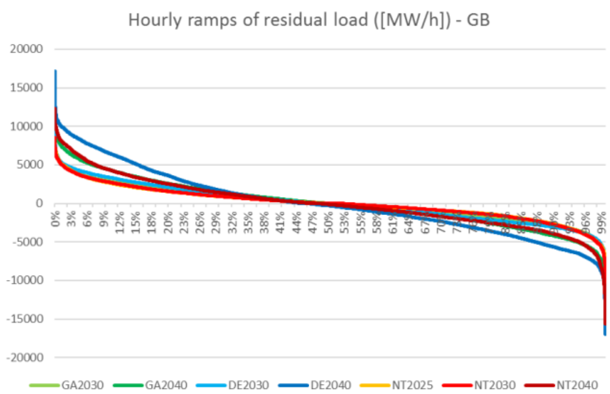
The variability in the power output from RES, which is driven by the variability of the primary energy resource, must be balanced, including forecast output deviations, in order to maintain the frequency equilibrium.

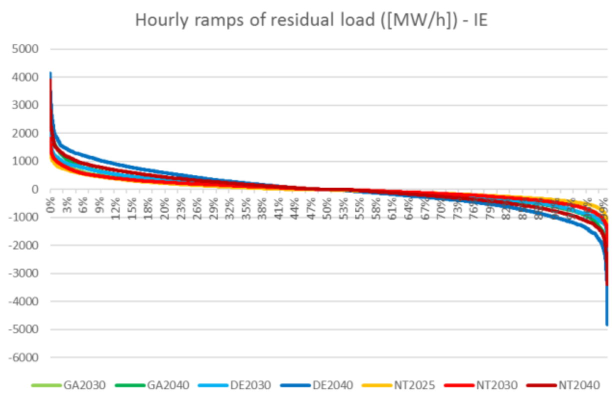
Residual load ramps exhibit the changes of residual load (all demand minus variable RES) from one hour to the following hour. These curves express the response (in MW/hour) that needs to be provided by controllable resources (generating units, demand and storage) in order to maintain balance between generation and demand. They also provide an additional measure into the challenges of operating a system with reduced amount of controllable generating units, high flexibility needs in normal operation, and a requirement to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen imbalances between active power generation and demand.

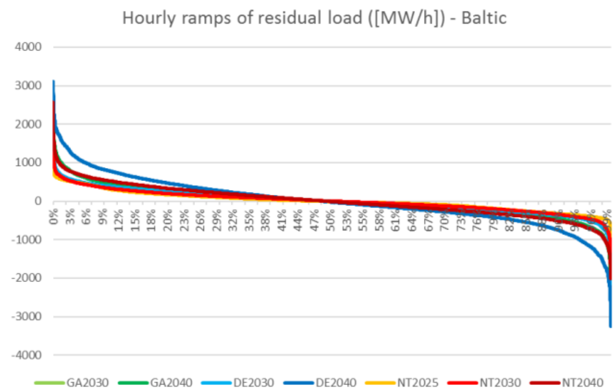
The following plots display the duration curves of residual load ramps as the changes of residual load from one hour to the following one in a synchronous area on a full year. RES includes all RES sources except hydro.











Residual load ramps

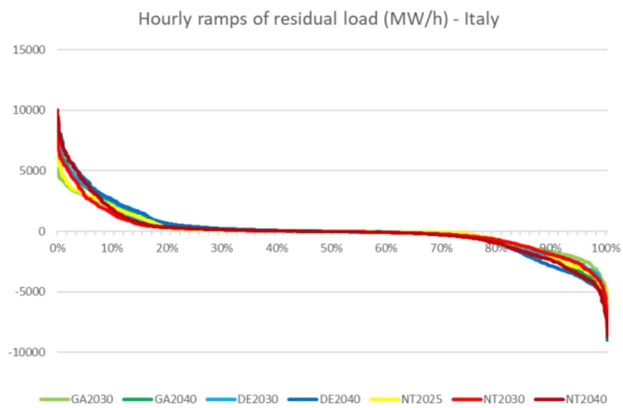
High response (in MW/hour) that needs to be provided by controllable generating units in order to maintain balance between generation and demand is verified in all synchronous areas.

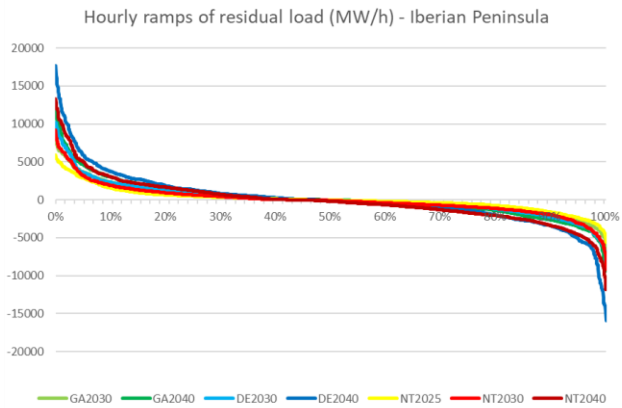
Need to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen generation and demand imbalances

Flexibility sources will be necessary both from the generation and demand side.

Strong interconnection between countries will be essential to exchange the power flows from flexibility sources.

In a more detailed example, the following plots display the duration curves of residual load ramps as the changes of residual load from one hour to the following one in the main Italian peninsula and in the Iberian Peninsula.





In order to cope with this situation new flexibility sources will be necessary both from the generation, storage and demand side. This includes new roles for thermal plants, RES participation, demand side response, and storage. Also from the network side, strong interconnection between areas of production and consumption will be essential to enable the power flows from flexibility sources.

Investments to allow large power flows covering vast distances, flexibility rewards to providers (also at a local level) and innovations in power electronics (inverters) will be central aspects to the solution.

1.3 Transient and voltage stability related aspects

The power flow constraints, in highly meshed areas with an "optimal" distribution of generation units around the consumption areas, are generally based on static limits such as thermal overloads or steady state voltages exceeding operational limits. With the increase of volumes and distance of cross-border energy exchanges, the increase of the static limits of the grid elements and the penetration of power electronic driven and controlled generation and demand, different forms of stability issues – including voltage stability, dynamic stability, and transient stability – are becoming more relevant in defining power flow constraints.

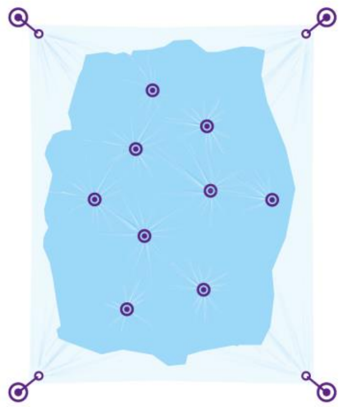
1.3.1 Voltage stability

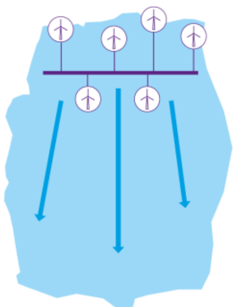
Voltage stability is ensured when each connection point is within a defined voltage band during normal changes in system operation but also in after fault or outage situations.

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

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

However, every situation must be covered…





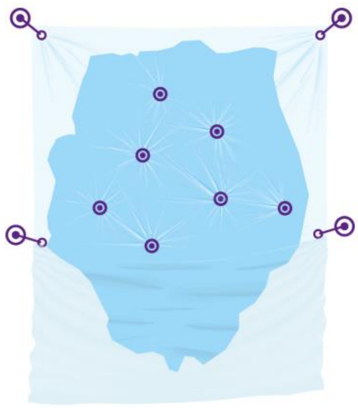
As an example, many RES can be concentrated in a specific zone feeding into another.

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

What happens to the cloth then?

The cloth would hang down and that is exactly what must not happen.

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



As highly volatile converter-connected RES replace synchronous generation, and as the power has to be transmitted over a long distance due to generation being further away from demand centres, the fluctuations in reactive power demand and reactive losses also increase

The electrical system is faced two developments: reduction of available huge generation unit also supporting system voltage and the increase of need for voltage support due to volatile transit situations and higher utilization of the system.

In order to have a deeper view on voltage stability challenges posed by more and more hours without conventional generating units in some zones, a perspective built from market studies results is here presented.

The plots accessible through the link in the final part of this annex depict the duration curves of the number of online synchronous generating for all countries in the ENTSO-E area. The plots for each country show that the potential automatic voltage control sources from conventional generating units vary significantly along the year and tend to be lower in longer-term scenarios, demonstrating that additional sources are necessary to meet the voltage control challenge. On top of that, the location of each of the voltage control sources may also differ significantly within each country.

As seen above, a uniform distribution is the most effective way to control the system voltage. Given the high variability of power transits and generation mix combinations a good mix between network based solutions and generator based solutions will be necessary.

1.3.2 Transient stability

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

As converter-connected RES replaces synchronous generation, and as the power generated has to be transmitted by over a long distance due to generation being further away from demand centres, the short-circuit power will tend to drop to lower level.

This reduction in short-circuit power will result in deeper and more widespread voltage dips in case of network faults. This will have a significant negative impact on the transient stability of generating units. It will also result in an increase in the number of generating units affected by the fault and with risk of disconnection.

The development of short circuit level has to be monitored continuously. If a risk of system stability is revealed, requirements for generating units have to be adapted or other measures to increase short circuit power, e.g. new synchronous condensers have to be taken.

1.3.3 Solution and mitigation needs

The measures envisaged to face the challenges are:

Long- and mid-term measures:

- **Technical devices:**
  - Additional voltage-supporting units are required in the transmission network. These units (synchronous condensers, SVCs, STATCOM, HVDC especially with grid forming capabilities) must be well distributed so that the various situations and faults can be handled.
  - A more frequent use of line and reactors breakers for high voltage management. However, this leads to a faster aging of the switches and thus potentiates more unavailabilities.
- **Connection codes and standards:**
  - Technical requirements implemented in the connection codes will be important as part of the solution measures by providing to relevant generation with capabilities such as fault ride through, voltage support means and grid forming.
- **TSO/DSO coordination:**
  - Reactive support at lower voltages levels: RES at distribution must have reactive support capabilities, it is part of the solution (RES reactive power absorption help reduce high voltages) but there are limitations:
    - RES are not always located where the need for reactive support is (see illustration above)
    - Distribution and transmission don't see the same voltage problems:
      - Possible low voltage at distribution and high voltage at transmission,
      - On load tap changers limit voltage problems at distribution level,
      - Using embedded generation to solve transmission grid problems can cause problems at distribution level…,
      - Cost of losses induced by reactive current at distribution could be an issue (RTE report for the Regulator),
  - Observability and controllability of distributed resources by the TSOs and DSOs as well as strong coordination between both operators.

    - controllability and dependability for transmission grid needs,
    - monitoring the performance and availability of resources/capacities

- The transmission grid flows request reactive support at transmission level (high and low voltages) and a clear range of admissible reactive power exchange at the TSO-DSO interface via coordination with the respective DSOs.

❖ **intermediate short-term measures:**

- Effective use of existing reactive power sources, incl. distribution-connected SGUs (Significant Grid Users)

- Limit RES, limit bulk power flows and or impose must run conventional units to ensure the necessary level of short-circuit power.

1.4 Additional network challenges

The increasing penetration of power electronics (PE) devices and distributed energy sources (DER), the continuous digitalization and the development of emerging technologies in power systems is arising new challenges which requires further investigations and analysis in the near future. The present Section reports a brief overview of these additional network challenges, not fully envisaged in the current design and operation, which could impact the system security and dynamics and need to be monitored to assess the possible impacts and investigate solutions when necessary.

Extensive use of EHV-cables (for AC)	The major sensibility towards the environment and improvements in the technology have leaded in the last decades to an extensive use of **EHV-cables** in the bulk power system, e.g. through overhead line (OHL) replacements. Implementation of EHV cables introduces additional technical challenges in power quality, voltage control and reliability that must be managed to ensure a safe and reliable network operation. EHV cables presents high levels of capacitance compared to the OHL, which implicates the need of **reactive power compensation** to operate within the required limits and possible **resonance** with the inductance of the external system at the power frequency or higher harmonics from PE devices. The different characteristics of EHV cables impose then a practical limitation to long distances and their share in transmission networks to avoid **harmonic resonance** frequencies, large **switching transients over-voltages** and voltage control installations among others. Investigation of solutions and actions to avoid such problems with future increased share of EHV cables will be needed.
Interactions between new devices and controls	The power system dynamic behaviour is changing due to **large-scale integration of AC/DC converters** (in generation, storage, transmission or distribution grids) and the development of smart grids in distribution systems. This change is caused by the different dynamic characteristics of electronic converters (mainly used in the state of the art for renewable generation units and HVDC transmission systems) and the response of smart grids, specified by the implemented control logic in their control and protections systems. A fixed set of predictable and commonly known rules and/or laws of physics that would apply over the whole operating range and during disturbances is not currently available. Furthermore, the control logic applied by power converters and smart grid is generally protected by intellectual property and patents rights and, hence, it is usually not disclosed in the power systems models used by TSOs for grid connection and compliance studies (including large network studies). Another challenge associated with the change of the control nature is the **interaction between the new devices** (control loop interactions, interactions due to non-linear functions, sub-synchronous, near synchronous and high frequency interactions i.e. harmonics and resonances…) or between these devices and the traditional AC grid and components (sub synchronous oscillations, harmonics…). These interactions may lead to power oscillations (observable in voltage, current and power outputs) increasing the stresses to the equipment. Moreover, such oscillation can trigger malfunction in the device protections and they may affect the power system reliability due to the increased probability of inadvertent equipment tripping . Although the stability issue is usually considered as local, concerning the relevant TSO owner of the equipment, the impact could be global, if associated with the tripping of large transmission or generation units (i.e bulk HVDC interconnector). This would also mean an increasing complexity of the real-time system operation. In this context, different challenges need to be faced by the TSOs: – To **identify and prevent the potential adverse interactions**, TSOs need to collect sufficient information from manufacturers (HVDC, wind farms …), distribution system operators or service providers (smart grids). Such information is required to perform dynamic and interaction grid studies to assess the impact on the whole system and to minimise the risk of unwanted interactions. However, manufacturers could be reluctant to share such information, as it is generally protected by intellectual property rights. This would limit TSOs ability to identify all risks. – Hence, simulation methods, simulation models, interfaces, relevant data and signals necessary to be exchanged between the stakeholders in grid connection studies (including large system studies), with main focus on the control interactions for power generation modules, for HVDC systems (including FACTs), for smart grids and other grid users is

	essential. A good practice to reduce this risk is by testing the equipment performance prior to its commissioning and using the test results to validate dynamic models. However, this might not be sufficient, as tests are not likely to include all potential operating conditions. – It is important for TSOs to have access to different types of dedicated models (black-box, open source, generic), representing the real plant (HVDC, synchronous and non-synchronous power generation module) behaviour by implementing/embedding in the models the **real source code**, to enable accurate studies. In this context, well defined signal interfaces in the simulation models for the control and physical layer that need to be observable/accessible from stakeholders in grid connection and compliance verification studies can accommodate such interaction studies. Separation between physical hardware and control is essential to support all kind of interaction studies and allow reproduction of faults/interactions from the field. – The challenge of **mitigation**: once identified, the interactions issues may require changes to the control systems. This includes the specification of the change required to a control logic that is owned by the manufacturer and the establishment of which party carries the liability in case of malfunction.
Cyber-physical systems	Power systems are becoming increasingly dependent on Information and Communication Technologies (ICT) up to the point where the physical system and the IT layer will merge into a **cyber-physical system** where real-time computing and physical systems interact tightly. The cyber layer includes the information hardware, software, data, and the networks. Cyber networks linking different parts of electric power system take a critical role in power system control, dispatching, and other operational affairs. While facilitating and improving the functioning and operation of the power system, at the same time the cyber layer could be a threat for system security, considering possible malware or malicious hacking, which will require rising attention in risk analysis and cyber protection by the TSOs.
Inter-area oscillations	In addition to the function of transferring power, the transmission network binds remote generators' rotors together. The more meshed the network is, the stiffer the link will be. After a disturbance (a loss of generation for instance) distant groups of rotors oscillate against each other. These inter-area oscillations are generally well damped and generators stop oscillating after a few seconds. However, under adverse conditions the oscillations can be sustained and lead to significant power flow oscillations in the transmission lines (hundreds of MW) and to physical damage to generating units. This phenomenon is exacerbated by the weakness of the system (long distances or weakly meshed) and high-power flows. To damp these oscillations, voltage and/or power controls of synchronous machines (Power System Stabilizer), FACTS or HVDC (Power Oscillation Dampers) must be tuned appropriately. The increase of long-distance power flows across Europe could require in some occasions coordinated tuning of the relevant control systems. Otherwise, inter-area oscillations may become a real concern which could notably undermine the profitability of interconnections if power transfer over such interconnections has to be restricted. The tuning of the controllers need to be based on the results of a small signal stability analysis of inter-area oscillations in a synchronous area. This requires a significant amount of work and an accurate and validated dynamic model that represents all relevant devices participating in the oscillations.
Increasing amount of PSTs and internal SA HVDCs	**Embedded HVDC** within a Synchronous Area (SA) and **Phase Shifting Transformers** (PST) are able to control the active power flow on AC transmission lines and thus, to overcome the natural physical load flow distribution according to the branch impedances. Depending on the induced additional voltage (vertical to the grid voltage) PST can achieve an evenly contribution of the power flow transmission lines according to their thermal capacity. As the network impedance is not reduced by PST or HVDC, the physical transmission capacity of the system remains constant. Thus, PST and HVDC can be seen as tool to overcome local overloading due to a smoothly power flow distribution but without increasing the maximum transmissible power of the system which is an image of the angular and voltage stability limits of the system.

	The number of PST and HVDC in the European transmission system is increasing quickly. If local automatic tap changer/set-point controllers are applied, an additional level of coordinated control scheme must be developed, to avoid system security threats due to a massive and uncoordinated shift of power flows after a disturbance.
Energy storage systems	Extensive use of **Energy Storage Systems** (ESSs) will provide new flexibility margins and solutions both from the generation and demand perspective. Energy storage comprises a wide portfolio of technologies for storing electricity, such as flywheels, electrochemical batteries (BESS), super capacitors, compressed air, thermal storage (heat storage) and pumped-hydro storage. ESSs can be used to store excessive RES production avoid congestions and curtailments, improving RES integration and optimizing thermal power plant operation economically and ecologically (significant CO_2 reduction) within the thermal phase-out scenario. Synchronous storage technologies increase system inertia and provide fast fault current infeed (short circuit level) and voltage regulation, whereas non-synchronous can provide synthetic inertia or fast frequency regulation. ESSs can act as a dynamic reactive power source and they can provide black start capability. BESS or hybrid power plants which combine both electrical storage with super-caps could be used to provide grid forming capabilities (at least for large plants in the range 30-100 MW). With the increasing use and integration of ESSs, e.g., in power generating facilities, the technical requirements to be applied by storage technologies must be assessed and updated to cover this new reality.
TSO-DSO cooperation and coordination	Small scale and **distributed energy resources** (DER) are identified today as an emerging reality. Dealing with the variability, unknown reliability, and control of millions of this type of equipment will become relevant issues. Distributed resources, in terms of generation, storage and the increasing share of electromobility is changing the customers in prosumers, leading to possibility of delivering services to the power system, and raising different kind of challenges. DER can have major effect on the power flows, bringing to the need of congestion management and voltage control actions. Consumer active participation can consist in demand side response (DSR), the modification of electricity demand, in response to price signal or a direct sell on the market. An appropriate aggregation of DER can deliver more advanced services such as balancing services and congestion management (mainly aFRR, mFRR, RR). Solving these kind of situations will require special coordination on regional or European level, but also better coordination between local and national level, between TSOs and DSOs. To ensure the security of supply coordinated activation of different type of services (balancing, voltage control, and congestion management) will be required.
Ageing grid facilities and generation units	Reliability of grid elements in a context of a system explored to its limits gains additional emphasis. How to measures the decrease in the level of availability? E.g., as they get older, some generators may show reduced reactive capabilities and be less available during critical times. If this phenomenon is detected it should be monitored to anticipate critical situations; regarding the duty cycle of breakers, stability needs can create further stress on the system. Opening lines on and off and shunt reactors will make the components age faster.
Sector Integration	**Sector integration** is the integration of different sectors (electricity, gas, heat, transport, and industry) in terms of commodity's networks and the conversion of one commodity into another. The aim is to optimize each energy carrier's potential and to achieve an efficient, sustainable, and secure energy system which realize EU climate and energy objectives. Different options for coupling are available: power to heat, power to transport, power to "high value energy", as **power to gas** or **power to X**. The future power system has a greater need for flexible and dependable resources, and sector coupling could provide flexibility sources to face growing congestion and RES integration issues. However, coupling sectors can be difficult, for different balancing timeframe and different products. The main difficulties are related to market design (to recognize each commodity value in different sectors), regulatory, technical and governance, and requires combined efforts between different stakeholder. In this context, TSOs are testing new technologies and business models, which depend on the appropriate regulatory and political framework. Such technologies could impact future power system, as interdependency and more exchange of information are needed, arising at the same time opportunities in terms of new flexibility sources and ancillary services.

1.5 Summary – The system needs

This chapter provides a comprehensive perspective on some of the main dynamic and operational challenges by providing the technical background, an explanation of their impact on the system and focusing on the relevant solutions or mitigation measures. On top of that, new type of phenomena or matters to be monitored and studied are identified.

The analysis computed for all the hours of the long-term TYNPD years and scenarios delivers numerical information on the future trends regarding the system performance and challenges. However, as already mentioned, working solely on an incremental basis is considered an incomplete approach to identify the necessary range of measures to entirely tackle the challenges in a timely manner. As such, this chapter puts also emphasis in forward looking solutions with the potential to meet the European policy goals of decarbonisation at their full extent.

System design challenges are growing:

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

One promising contribute to add into the range of solutions is the Grid Forming Capability of power converters. The constructive dialogue between all involved parties, TSOs, DSOs, research institutes, manufacturers, system users and policy makers, should start now to define the relevant technical requirements for those capabilities, replacing missing capabilities inherent to synchronous generators, and a roadmap to make them available to the system in time.

- Besides network investment solutions, the availability of the necessary technical requirements of grid users and the consistent improvement of Europe’s electricity market to ensure aspects such as reward to system flexibility and incentives for market participants to act in line with system needs remain key priorities.
- Research & Innovation represents an essential building block to meet the challenges. Consistently, during the development period of TYNDP 2020, an extensive work has been performed in the areas of power electronics control and HVDC interoperability and interactions.

Operability challenges are growing.

In alignment with ENTSO-E One System Vision[5], strong cross-border cooperation and strong adaptation to local needs and constraints are necessary:

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

[5] https://vision2030.entsoe.eu/

- Need for distributed flexibilities to contribute to system needs. This will depend on the network, institutional and economic realities of each country, with the drive for automation and decision support that will need to adapt to local constraints, culture and realities, as well as the power electronics solutions and forecasting that will have a strong localised component.

The context is at the same time more European and more local, in order to meet these challenges, TSOs have at the same time:

- The tools and means for increased cross-border cooperation through Regional Coordination Centres with the full range of services that they will provide, as well as with the help of our common association ENTSO-E.
- The in-depth knowledge of local constraints, through our own local footprint and close relationships with institutions, customers, shareholders and the public at large, and through our partnerships with Distribution System Operators.

Additional background information.

This link provides an interactive access to the information presented above and this link additional plots regarding estimated inertia, relative contribution to inertia and automatic voltage control sources from conventional generation in all countries.

Estimated inertia in all countries

The plots represent the estimated duration curve of inertia for each country in the ENTSO-E area. The plots are based on the market study results for all visions of the TYNDP 18. Equivalent inertia for each country, presented as H[s], is calculated on the basis of total online capacity of the respective country for each hour.

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

The plots do not display an assumption of sufficient or insufficient inertia, or even of higher or lower RES integration. They only portray a supplementary insight into the level of the inherent diversity and internal variability of the different countries regarding equivalent inertia.

Relative contribution to inertia for all countries

The plots depict the duration curves of inertia for each country in the ENTSO-E area compared with the respective synchronous area average.

A value of 1 means that the inertia in a given hour is the same as the synchronous area average. Values below 1 do not show insufficient inertia, they only show that the country is below synchronous area average during that number of hours. Similarly, values above 1 show that the country is above synchronous area average during that number of hours.

The plots display the variability of each country regarding the comparison with the respective synchronous area average. Although a trend can be observed in the duration curves, depending on the hour, this comparison can vary significantly and can show values above or below 1.

Automatic voltage control sources from conventional generation

The plots depict the duration curves of the number of online synchronous generating units for each country in the ENTSO-E area. A value of 1 means that the number of generating units is the maximum in the scenarios, all other values are expressed in relation to the maximum value of the respective scenario.

Acknowledgements

ENTSO-E would like to thank all the experts involved in the Ten-Year Network Development Plan 2020 for their commitment and enthusiasm in building this unique coordinated pan-European plan, which is essential to the timely and effective development of transmission infrastructure to deliver long-term European policy and aspirations while keeping the system secure. In particular, ENTSO-E would like to thank the following experts who contributed to this report:

Aluisio Benedetto	Terna
Antonio Conserva	Terna
Bieshoy Awad	National Grid
Carmelo Mosca	Terna
Dante Powell	ENTSO-E
Ettore Elia	Terna
Hans Abele	TransnetBW
Jeff Kelliher	Eirgrid / SONI Ltd.
João Moreira	REN
Jörg-Michael Schmidt	TenneT
Kees Jansen	TenneT
Léa Dehaudt	ENTSO-E
Marvin Kaiser	Amprion
Mikko Koskinen	Fingrid
Olivier Bronckart	Elia
Patricia Labra Francos	REE
Peter Van Roy	Elia
Sergio Martinez-Villanueva	REE
Tobbias Hennig	Amprion
Vincent Sermanson	RTE

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