Federal Ministry
for Economic Affairs
and Climate Action

System Stability Roadmap

Roadmap for achieving the secure and robust operation of the future power supply system with 100% renewable energy sources

bmwk.de

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Contents

List of abbreviations

AS	Ancillary services
BMWK	Federal Ministry for Economic Affairs and Climate Action
BMBF	Federal Ministry of Education and Research
BNetzA	Federal Network Agency
dena	German Energy Agency
DKE	German Commission for Electrical, Electronic & Information Technologies
DSA	Dynamic Stability Assessment
DSO	Distribution system operator
EnWG	German Energy Industry Act
FGW	Federation of Wind and other Decentralised Energies
FINC	Fully integrated network components
GEP	Grid Expansion Plan
LFSM	Limited Frequency Sensitive Mode
NDP	Network Development Plan
RE	Renewable energies
SCR	Short circuit ratio
SDS	System development strategy
SO	System operator
TCR	Technical Connection Rules
TSO	Transmission system operator
VDE	Association for Electrical, Electronic & Information Technologies
VDE FNN	VDE Forum Network Technology/Network Operation

1 Abstract

On the way to a climate-neutral electricity system, the grid will increasingly be operated with electricity generated entirely from renewable energies. The System Stability Roadmap outlines a path for achieving the secure and robust system operation with 100% renewable energy sources. It is anchored in the 2021 coalition agreement and was drawn up by the Federal Ministry for Economic Affairs and Climate Action (BMWK).

The transformation in the generation structure towards renewable energies represents a far-reaching change in the power system. This also affects the provision of ancillary services and other measures required to ensure system stability for the secure operation of the electricity grid. For example, the retirement of conventional fossil-fuelled power plants means that their inherent stabilising properties will no longer be available. This means that, in future, these properties will have to be provided by alternative means. This System Stability Roadmap is dedicated to the issues that result from this system change and the overarching question of how a secure and robust operation of the electricity system is also possible using only renewable energy sources.

“Who does what and when?”: The System Stability Roadmap shows, at a procedural level, which steps must be taken to ensure the continued stable operation of the grid, when they should take place, and which actors are responsible for each process.

The System Stability Roadmap identifies all processes and process enhancements that are relevant to system stability and shows who is responsible for each process. A distinction is made between the role of the process initiator and the actors involved implementing it. The implementation period as well as the main dependencies of the processes are also described.

The System Stability Roadmap was developed by the BMWK with the participation of the Federal Network Agency (BNetzA), transmission and distribution system operators, manufacturers, associations, standardisation bodies and the scientific community.

The project steering group consisting of the BMWK, BNetzA, German Energy Agency (dena) and ef.Ruhr GmbH was supported by an advisory board consisting of all stakeholders. Experts from the institutions represented were delegated to topic-specific working groups. The content of the work of the four working groups was recorded in corresponding accompanying papers, which formed the basis for the development of the roadmap. All in all, more than 150 people from more than 80 institutions were involved. The expertise and commitment of all the stakeholders were and are the decisive factors to achieving the goals.

As a basis for the roadmap, a common vision with the functionalities of the future power system was initially developed. With the aid of this vision, challenges regarding the stable and robust system operation with 100% renewable energy sources are described.

When looking at the vision of the future power system, two changes in particular stand out when compared to the current system: 1) Besides the contributions from the transmission grid, system stability will, in future, also be largely determined by the characteristics of the renewable energy sources and loads connected to the distribution grid. 2) These primarily inverter-based grid users will replace the stabilising properties of the conventional power plants that will no longer be available in the future.

The experts in the working groups identified relevant issues and corresponding needs for action based on the vision. On this basis, processes that need to be adapted or newly established on the way to ensuring the secure and robust operation of the system with 100% renewable energy sources were derived. These processes form the core of the System Stability Roadmap.

In dialogue with the advisory board and the working groups, the responsibilities, the actors involved, along with the time aspects of the processes identified, were determined.

A total of 41 stability processes and 10 overarching processes were identified in the System Stability Roadmap.

With regard to the topics of

- Frequency,
- Voltage,
- Resonance stability, short-circuit current, angular stability,
- System control as well as grid and supply restoration

topic-specific stability processes were identified in each case. Overarching processes relating to system stability are processes that can be assigned to several topics. In other words, they are processes that address the adjustments, further developments or specifications that are required across all topics. As a result, responsibility for these processes is, in some cases, spread across several institutions. The implementation of all the processes must be coordinated and will be accompanied by monitoring.

The roadmap takes various perspectives on the secure and robust system operation using 100% renewable energies.

The core element of the roadmap, i.e. the concrete milestone plan, was drawn up against the background of the overarching objective of the secure and robust system operation using only renewable energy sources. Here, the focus was on the perspectives of fields of action, sub-goals and responsibilities (Figure 1.1).

Seven key fields of action for ensuring the secure and robust system operation using only renewable energy sources were identified.

In addition to analysing the processes according to the aforementioned topics, they were additionally grouped according to fields of action.

The fields of action are as follows:

- Overarching system requirements and framework
- Determining the system demand
- Covering the system demand
- Technical rules, regulations and instructions
- System resilience
- Grid-forming inverters
- Research, field testing and piloting.

Each of these fields of action is a key building block to assure the secure and robust system operation with 100% renewable energies.

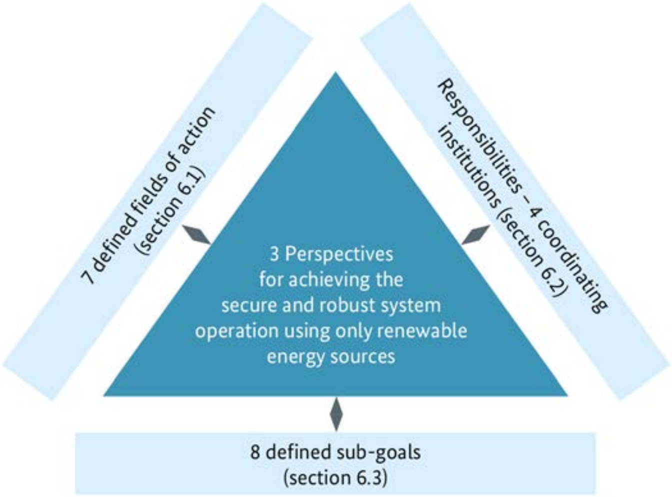
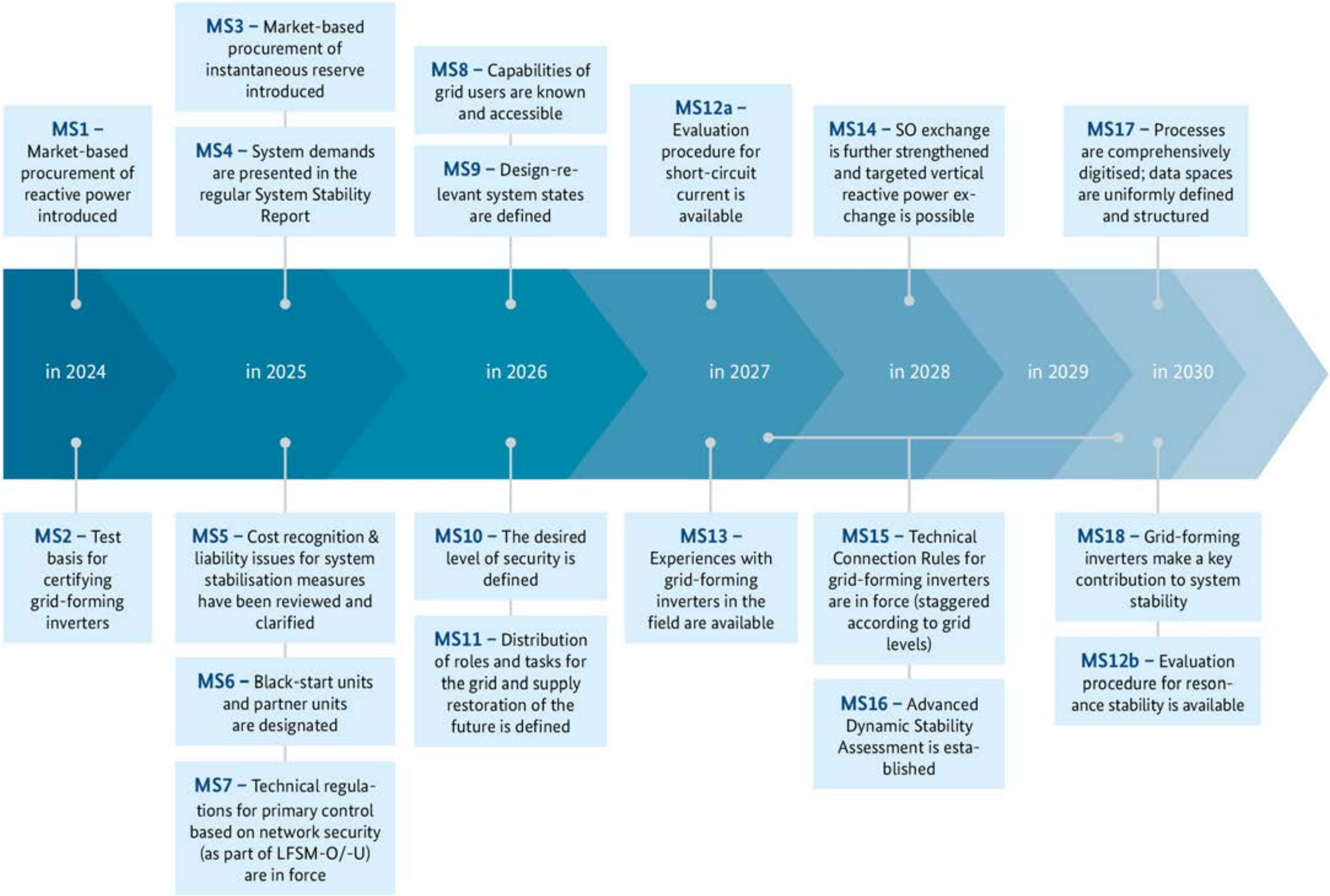


Figure 1.1: Roadmap perspectives

For the implementation of the System Stability Roadmap, 18 key milestones have been identified (Figure 1.2). The individual milestones, in turn, can be assigned to three central paths with high urgency for action.

First path – defining the level of security and determining the system demand: Where it is not yet clear, the target level of security for the power system must be defined. Based on this, so-called design-relevant system states can then be defined. Design-relevant system states describe predictable and unpredictable events which may confront the system and which must be managed. They are required because it is neither technically possible nor economically viable to cover all conceivable events. The design-relevant system states defined make it possible to quantify the demand for ancillary services and other measures for system stability and thus to display them transparently. In some cases, assessment procedures need to be further developed in order to display system demands (e.g. for the required short-circuit current contribution from inverter-based grid users). In part, completely new evaluation criteria will also have to be derived and established (e.g. for resonance stability). The identification of system demands should include both known and potentially additional future ancillary services and measures for system stability.

Second path – covering the system demands: The second central path is the coverage and structured procurement of system demands. To this end, suitable procurement procedures must be introduced and technical connection rules and regulations supplemented and adopted. Grid assets and HVDC[1] converter stations can and should also contribute to meeting demand. An additional building block is the further expansion of information and data exchange between system operators (SOs) and renewable energy sources and loads as well as between the system operators themselves. Among other things, this should also enable the targeted vertical exchange of reactive power. Comprehensive process digitisation and standardised data spaces are prerequisites for this increased coordination.



MS1 – Market-based procurement of reactive power introduced

MS2 – Test basis for certifying grid-forming inverters

MS3 – Market-based procurement of instantaneous reserve introduced

MS4 – System demands are presented in the regular System Stability Report

MS5 – Cost recognition & liability issues for system stabilisation measures have been reviewed and clarified

MS6 – Black-start units and partner units are designated

MS7 – Technical regulations for primary control based on network security (as part of LFSM-O/-U) are in force

MS8 – Capabilities of grid users are known and accessible

MS9 – Design-relevant system states are defined

MS10 – The desired level of security is defined

MS11 – Distribution of roles and tasks for the grid and supply restoration of the future is defined

MS12a – Evaluation procedure for short-circuit current is available

MS13 – Experiences with grid-forming inverters in the field are available

MS14 – SO exchange is further strengthened and targeted vertical reactive power exchange is possible

MS15 – Technical Connection Rules for grid-forming inverters are in force (staggered according to grid levels)

MS16 – Advanced Dynamic Stability Assessment is established

MS17 – Processes are comprehensively digitised; data spaces are uniformly defined and structured

MS18 – Grid-forming inverters make a key contribution to system stability

MS12b – Evaluation procedure for resonance stability is available

Figure 1.2: Key milestones of the System Stability Roadmap (The introduction of the Technical Connection Rules for grid-forming inverters is to be staggered according to grid levels, which is why a time period is shown here as a horizontal line).

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[1] High-voltage direct current

Third path – establishing grid-forming inverters: The third central path concerns the penetration of grid-forming inverters in the transmission and distribution grids. Grid-forming inverters are a key technology for maintaining system stability in the future system. What, however, is lacking is experience with their widespread use. This must be gained in pilot tests and the technical requirements have to be defined. Furthermore, technical connection rules (differentiated according to voltage levels or power classes) have to be drawn up for grid-forming inverters. This will ensure that the potential of grid-forming inverters (e.g. for providing inertia) can be utilised safely and appropriately in order to make a significant contribution to system stability.

The System Stability Roadmap is the starting point for the transformation in the area of system stability. Implementation requires a great deal of commitment from all stakeholders. The BMWK and the BNetzA will support the enactment of the roadmap.

The System Stability Roadmap provides a structured overview of the requisite adjustments and further development of the processes needed to maintain system stability. Implementation must now be coordinated and demands a high level of commitment from all stakeholders. Without any additional human resources, it will probably not be possible to implement many of the processes at all or at the required speed. There is great pressure to act and this pressure makes it necessary to carry out processes in parallel. Secure, yet swift action is required here.

The exchange structures and cooperation between all the stakeholders, as established for the development of the roadmap, serve as the basis for the further implementation of the System Stability Roadmap. This should thus make it possible to anticipate and resolve any ambiguities or conflicts. The BMWK will jointly oversee the implementation of the roadmap with the BNetzA and provide support as needed to counteract potential delays. For this purpose, targeted monitoring is also planned.

The System Stability Roadmap and the System Development Strategy are pillars of the transformation of the energy system.

System stability includes compliance with all technical and operational limits during normal operation and the ability to reliably return to the normal state after a fault has arisen. As well as operating the system and maintaining system stability, the transformation of the way energy is generated and consumed as well as of the infrastructure itself is also crucial to achieving a climate-neutral energy system. For the latter areas, the System Development Strategy (SDS) defines an overarching framework that provides guidance for subsequent processes such as the network development plans for electricity and gas or hydrogen. The System Stability Roadmap and the SDS are, therefore, complementary pillars of the transformation of the energy system. More information on the SDS is available in German at https://www.bmwk.de/Redaktion/DE/Dossier/ses.html.

2 Task of the System Stability Roadmap

2.1 Background

The power supply system is undergoing profound structural change. In order to achieve a climate-neutral electricity system, what is required is a strong and rapid expansion of renewable energies. At the same time, conventional power plants are being phased out. While the decommissioned large controllable power plants feed into the transmission grid, the feed-in of wind energy and PV[2]-systems largely takes place at the distribution grid level. On the load side, the change is typified by increasing electrification, e.g. through electric mobility , the expansion of the use of heat pumps, in industrial processes or through electrolysers for producing hydrogen. The aforementioned changes on the load side also take place primarily at the distribution grid level. These developments raise the question of how the security and reliability of the power supply can be assured in the future.

System stability as part of supply security: Generation adequacy as well as grid adequacy are necessary to ensure supply security. At all times, the amount of electricity demanded by consumers must be able to be balanced by the corresponding generation capacity and the availability of the requisite transport capacity in the grid. Besides adequacy, system stability is another key element of security of supply. System stability includes compliance with all technical and operational limits during normal operation and the ability to reliably return to the normal state after a fault has arisen. The understanding of system stability in the context of the System Stability Roadmap is, therefore, based on a systemic approach. Thus, it goes beyond the widespread understanding of stability as a collective term for polar wheel angle, frequency and voltage stability. The system stability aspects are directly linked to the diverse changes in the supply system.

Every power plant influences the electrical properties at the grid connection point and thus the overall power system characteristics. Conventional power plants are directly connected to the grid via synchronous generators (the electrical frequency of the rotor in the generator corresponds to the frequency of the voltage in the grid: normally 50 Hertz). In addition, with their drive train consisting of a turbine and generator, they have an inherent large rotating mass, which is accompanied by a certain inertia. In contrast to conventional power plants, wind and PV systems and battery storage systems are connected to the grid via inverters. These inverters are necessary to enable the power feed-in into the 50 Hertz grid. The majority of these inverter-connected grid users that have been connected to the grid so far only make a limited contribution to system stability due to the Technical Connection Rules in force. Instead, the focus has been on maximising the power feed-in.

System change: With the further expansion of renewable energies, particularly wind and PV, and the upcoming phase-out of coal, the consideration of system stability is of particular importance. The inherently stabilising properties of power plants with synchronous generators must be provided alternatively. This means that the range of tasks of renewable and distributed energy resources, loads and grid assets, must be developed further. The further development of these grid users for the provision of stabilising ancillary services (AS) and further measures for system stability will be required in the future. Ensuring stability is crucial for the energy transition so as to guarantee supply security even when using only renewable energy sources. This requires adjustments to the requirements to be met by grid users.

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[2] Photovoltaics

Moreover, much closer co-operation between system operators will be necessary in the future, both at the same as well as between the different voltage levels. Overall, the paradigm shift in the energy supply from synchronous generators to inverter-based resources makes new solutions for grid operation and for ensuring system stability both possible and necessary.

The question thus arises as to what measures are necessary to ensure system stability even when using only renewable energy sources. In order to answer these questions for the first time in a broad process involving all stakeholders, the development of the System Stability Roadmap was anchored in the 2021 coalition agreement.

2.2 Objectives

What: The aim of the roadmap is to present a blueprint for achieving the secure and robust operation of the system using only renewable energy sources. The roadmap is intended to show which functionalities and processes are required for this, which existing processes need to be accelerated or adapted, and how they can be bundled holistically in a transformation path. The concept of process is broadly interpreted in this roadmap and encompasses all activities aimed at ensuring system stability.

Who: Besides the question of which processes need to be initiated or adapted, the question of who is responsible in each case is a key component of the roadmap. Above all, the process coordinators must ensure that the respective processes are initiated. Depending on the process, the involvement or performance of other stakeholders may be required. Identifying these other stakeholders is also part of the project.

When: Due to the ambitious implementation schedule to achieve a climate-neutral energy system, the System Stability Roadmap also focuses on the time-related aspects of the need for action identified, i.e. the question of when. It is, therefore, particularly important to enable the early and timely initiation of processes and the identification of significant process dependencies over time.

Reaching a consensus: Stability in the electricity grid is complex and influenced by activities of a large number of stakeholders. At the same time, a high level of supply security must be assured at all times. One key part of the project is, therefore, also to develop the System Stability Roadmap, taking into account and with the aid of all the stakeholders involved. The results are intended to emerge from a holistic system perspective and be based on the broadest possible foundation of expertise. In addition, the industry process for reaching a consensus is of great importance. Particularly with a view to the subsequent implementation phase, the roadmap aims to organise cooperation with and between the responsible stakeholders in a cooperative and efficient manner.

Who does what and when? The aim of the roadmap can be summed up by the following question: who does what and when to ensure system stability on the way to a climate-neutral energy system? However, putting the processes into practice is not the aim of the roadmap. The roadmap fulfils a necessary coordination function in order to create clarity regarding responsibilities and to enable the timely start of all the requisite processes. Once the roadmap has been published, the BMWK and the BNetzA will support its implementation. There will continue to be scope for dialogue and coordination with and between the stakeholders. As part of this implementation phase, the processes identified are to be readjusted wherever necessary. The implementation phase for individual processes has already begun and ongoing processes have already been reprioritised and accelerated.

2.3 Procedure

The creation of the System Stability Roadmap was led by the BMWK and carried out by a project steering group consisting of the BMWK, BNetzA, ef.Ruhr GmbH and dena. Stakeholder management was primarily carried out by dena, while ef.Ruhr GmbH acted as the technical expert and moderator of the expert groups. The BNetzA supported the project in an advisory capacity. Work on the roadmap was carried out in six steps, as shown in Figure 2.1.

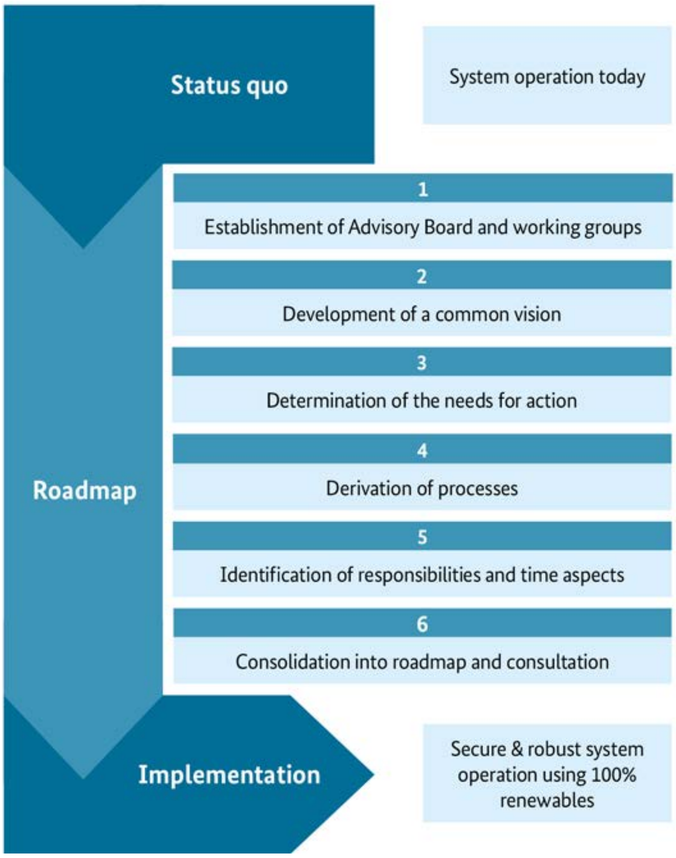

Figure 2.1: Creation of the roadmap

1. Establishment of Advisory Board and working groups: In an initial step, representatives of transmission and distribution system operators, manufacturers, associations and scientific institutions in management positions were invited to take part in developing the roadmap as part of the Advisory Board. At the first meeting of the Advisory Board in October 2022, the project was explained by the project steering group and the representatives on the Advisory Board were asked to delegate experts from their institutions to working groups. While the Advisory Board served as a consultative body, detailed exchanges on individual topics took place within the working groups. A total of four topic-specific working groups were set up:

- **WG1:** Frequency
- **WG2:** Voltage
- **WG3:** Angular stability, resonance stability and short-circuit current
- **WG4:** System control as well as grid and supply restoration

A total of around 50 people from 35 different institutions were represented on the Advisory Board. The 4 working groups and 11 core groups comprised around 110 people from 70 institutions. A total of 5 advisory board meetings and 24 working group meetings as well as over 40 core group meetings took place while the roadmap was being developed. Figure 2.2 shows the organisational structure that was established to develop the System Stability Roadmap.

2. Development of a common vision: The starting point for the collaboration was the development of a common vision. The vision includes a description of the functionalities of the future power system and, derived from this, the challenges for the secure and robust operation of the system using only renewable energy sources. The vision served to create a common understanding among the stakeholders and thus formed the basis for cooperation. The result is presented in chapter 4.

3. Determining the needs for action: This step comprises the procedure to determine the needs for action as a basis for information in order to derive the necessary processes or process adjustments. With each aspect of stability, three questions took centre stage:

- What are the triggering events?
- What impact do they have on the system demand?
- What are the options for meeting demand?

Besides the collaborative work done in the working group meetings, more profound issues were discussed between meetings in so-called core groups.

The third step resulted in topic papers in which the status of the discussion and the technical interconnections were documented for each of the four working groups. The four accompanying papers are accompanying documents to this roadmap document and take up the various directions that the expert discussion took. In this phase, greater space was deliberately given to discussion and technical details so as to obtain a broad starting point for the subsequent derivation of the processes.

Chapter 3 of the roadmap describes the technical background to the stability aspects.

4. Derivation of the processes: Based on the discussions in the working groups, the experts from ef. Ruhr GmbH derived the processes and process adjustments that are needed to ensure a stable electricity system. They were confirmed by the Advisory Board and the working groups. With regard to the overarching target question “Who does what and when?”, the result of this step is the answer to the question of “What?”.

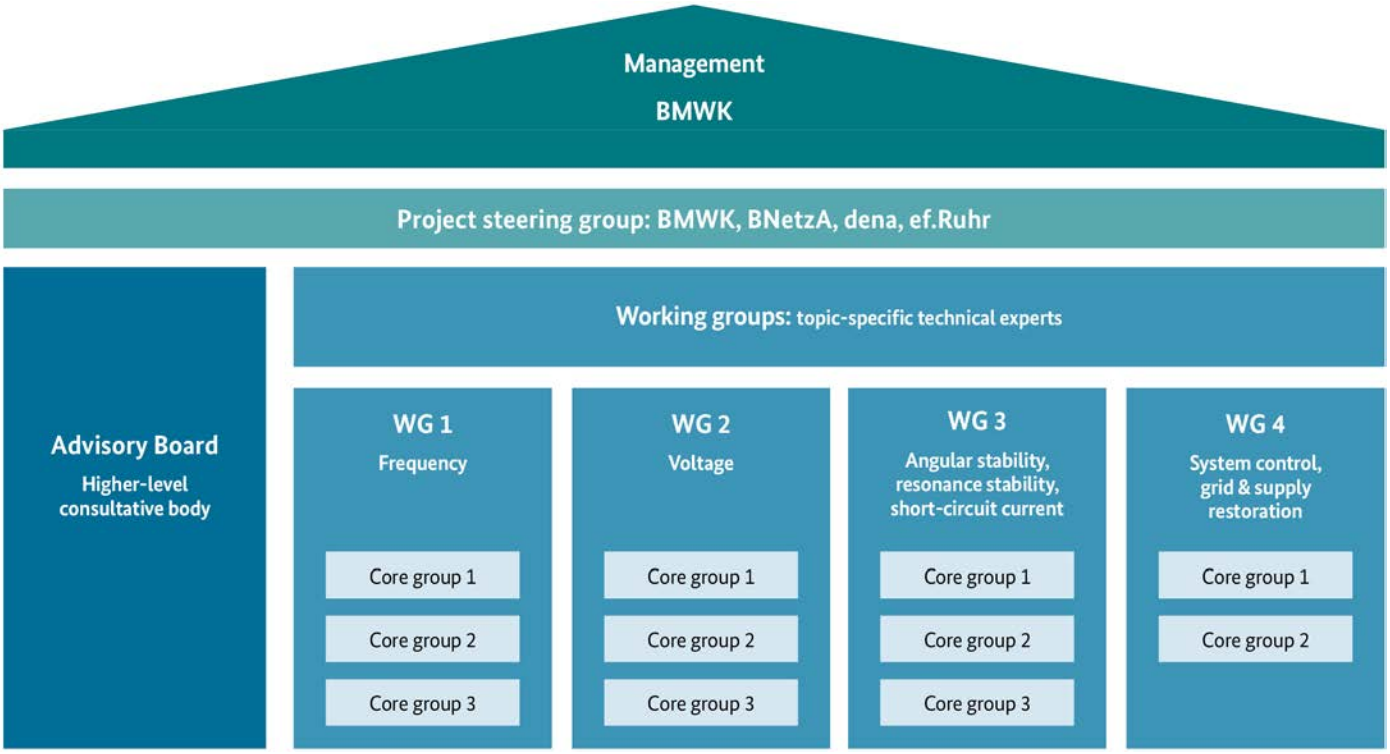

Figure 2.2: Organisational structure of the System Stability Roadmap

5. Identification of responsibilities and time aspects: Further working group meetings were held to determine who the process coordinators and further necessary stakeholders for each of the processes were. The experts also explained their assessment of the time aspects. One important part of this step was the consultation with and confirmation of the results by the Advisory Board.

6. Consolidation into the roadmap and consultation: In the final step, the processes agreed by the Advisory Board and working groups were brought together by the experts from ef.Ruhr GmbH to form the System Stability Roadmap. The results are explained in this document in chapters 5, 6 and 7.

Chapter 5 describes the individual processes in greater detail. Furthermore, the process dependencies are described in the context of the respective topic, along the lines of the categorisation of the working groups.

Chapter 6 presents the processes from different perspectives. This includes sub-goals, fields of action and responsible institutions. Moreover, a description from an overarching perspective with the help of a milestone plan is provided in chapter 7.

When finalising this document, the feedback from a two-week commenting phase, which was open to all participants from the Advisory Board and the working groups, was taken into account.

The System Stability Roadmap is a key step on the way to achieving the secure and robust system operation using only renewables. Collaboration on the roadmap between the various stakeholders is a good basis for implementing the processes identified. The expertise and commitment of all the stakeholders were and are the decisive factors to achieving the goals. Chapter 8 takes a closer look at the implementation of the roadmap.

3 Technical background

The objective of the System Stability Roadmap, i.e. to draw up a holistic roadmap for maintaining the secure and robust operation of the system when using 100% renewable energy sources, means that the various aspects of system stability must be considered together. This is a very complex task, since each aspect in itself involves a large number of complex issues.

The categorisation of the topics is based on the current categories in the field of stability analyses. In order to do justice to the broad range of topics from an overall perspective, this chapter contains brief descriptions of the relevant aspects of stability. The focus is on making it easier to understand the processes identified in Chapter 5, without going too deeply into technical or physical details.

3.1 Frequency

To ensure stable system operation, electricity generation and consumption must be in balance at all times. The frequency of the voltage in the grid serves as a central indicator and reacts directly to deviations between generation and consumption. In simplified terms, frequency stability can be visualised as a balance between generation and consumption, which can become unbalanced in the event of disturbances, as illustrated in Figure 3.1.

In order for the frequency to be considered stable, it must be kept within a defined range of tolerance of 200 mHz around the rated value of 50 Hz. This rated frequency means that the fundamental oscillation must repeat exactly 50 times per second. This also means that a period must not be longer or shorter than 0.02 seconds. Since consumption and generation fluctuate continuously, the frequency in real operation also oscillates within the range of tolerance of 200 mHz and is not constant at precisely 50 Hz.

In Figure 3.2, the range of tolerance and a frequency deviation are visualised in simplified form by the arrows. There are various technical options for counteracting a deviation from the rated value. The time range required for a reaction is a key distinguishing feature.

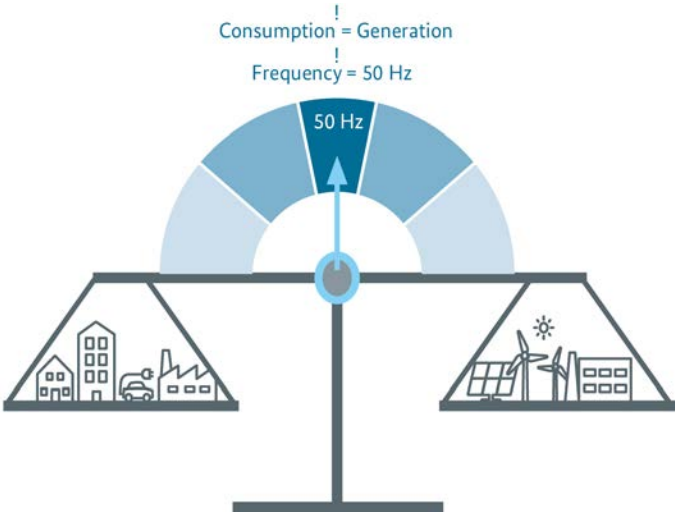

Figure 3.1: Frequency stability as a balance between generation and consumption

As part of the System Stability Roadmap, the focus of the analyses is primarily on the short term. Specifically, the frequency phenomena ranging from a few milliseconds to a few seconds after a change are relevant because they are particularly affected by the transformation in the generation structure.

What is particularly important is the inertia, which represents an instantaneous, i.e. undelayed, reaction to a power imbalance. To date, the required amount of inertia has been provided by synchronous machines in conventional power plants. The rotating components of these large generators act as a buffer against frequency deviations due to their rotational energy. This grid-stabilising property can also be provided by renewable energy sources and battery storage systems when they are equipped with new, so-called grid-forming inverters. Grid users with these new properties are already being installed in some countries. Section 5.2.1 describes the processes that were identified in the course of developing the System Stability Roadmap to ensure frequency stability.

3.2 Voltage

To ensure stable system operation, the voltage in the grid must be kept within the technical limits of, usually, ± 10% at all times so that grid users such as large industrial plants and household electrical appliances are not disrupted or damaged. This is shown in simplified form in Figure 3.2, in which the arrows delimit a certain range for the level of the voltage amplitude. Furthermore, grid users must be designed in such a way that they remain safely and stably connected to the grid for a certain period of time should there be a sudden voltage deviation due to a fault.

Analogous to the frequency aspects, in the case of voltage, a distinction must also be made between phenomena with different time horizons. On the other hand, a key distinguishing feature between the frequency and voltage aspects is regionality. While frequency deviations spread almost equally throughout the entire Continental Europe Synchronous Area, voltage deviations generally only affect limited grid areas and levels.

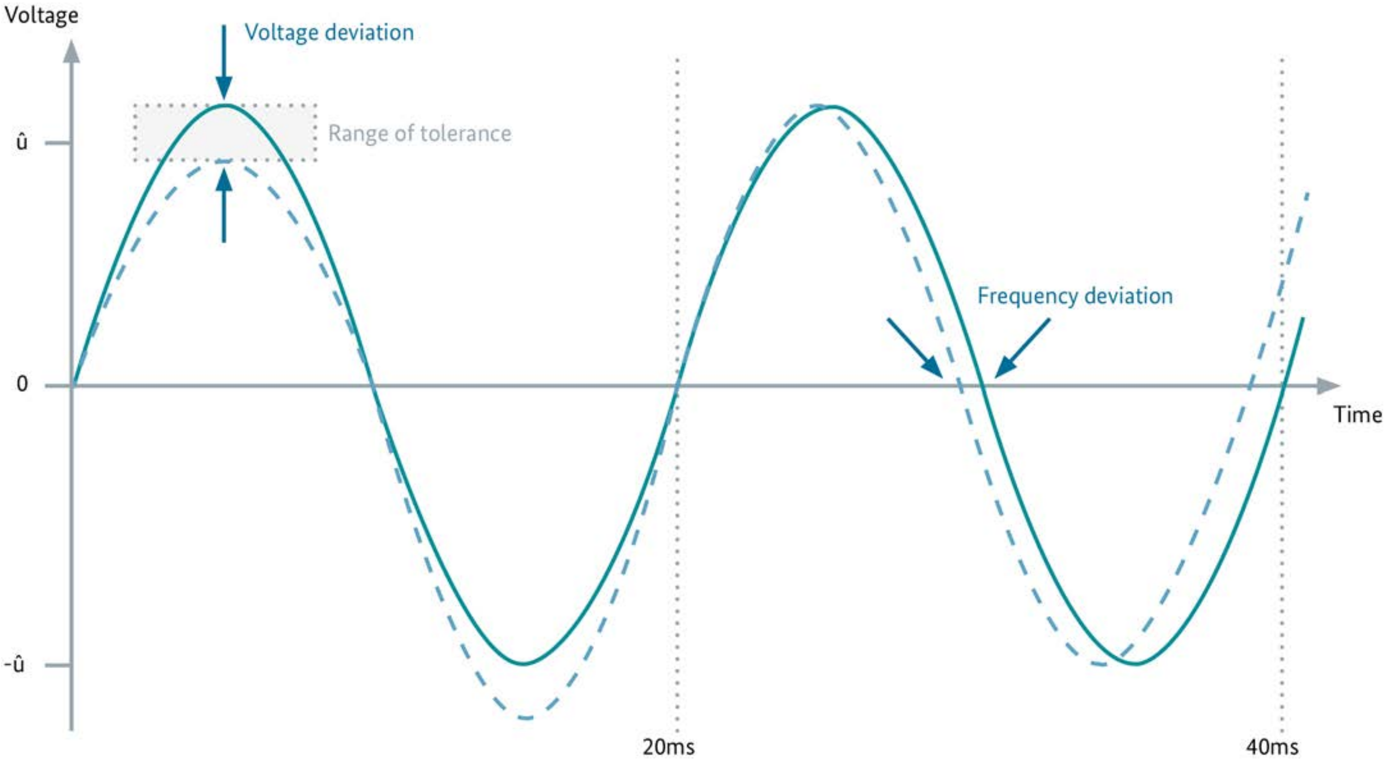

Figure 3.2: Voltage and frequency deviation

In principle, there are various ways to maintain voltage stability. Depending on the characteristics of the afore-mentioned temporal and spatial dimensions, the options differ in terms of their operating principles and economic efficiency.

As part of the System Stability Roadmap, the main focus is on the influence on voltage stability asserted by the altered generation and load structure. In the transmission grid, voltage stability is mainly ensured by the reactive power balance. In the distribution grid, on the other hand, the voltage also depends on the active power feed-in or consumption. Thus, the change in the generation and load structure has a particular influence on both the provision of reactive power and the local active power balance in the distribution grid.

In the past, voltage stability was largely maintained by conventional power plants. As they will be phased out of the system in the future, the new grid users integrated into the grid must be upgraded accordingly. In addition, considerable coordination measures are required on account of the very different spatial requirements for voltage stability. The processes identified as part of the System Stability Roadmap that need to be carried out to ensure voltage stability are described in section 5.2.2.

3.3 Resonance stability

In an alternating current system, various oscillating circuits can arise from different grid components: between installed inductors and capacitors, between the rotating masses of generators and the grid, and between inverters. In an oscillating circuit, a signal, e.g. the current, oscillates back and forth. If this oscillation is stimulated at a certain rate, it will increase continuously over time. Put simply, resonance is the amplification of an oscillation. This may result in overloading.

A comparison with a mechanical vibration helps to better visualise this phenomenon. If a person swings a rope in a certain rhythm or with a certain frequency, for example, the movement of the rope becomes stronger and stronger (see Figure 3.3). After a short time, the oscillation can become so strong that the rope becomes uncontrollable. This frequency, which causes the system to resonate, is called the resonance frequency.

Figure 3.3: Example of an oscillating system

This phenomenon can occur analogously (unintentionally) in electrical circuits. If, for example, the circuit consisting of inductor and capacitor is excited with a current at a certain frequency, this can lead to a significant amplification of the current and, ultimately, to damage to the components. Keeping the voltages and currents within the defined technical limits and stable in relation to these amplifications is called resonance stability. Any resonances that occur should be damped as well as possible. With the increase of inverter-based grid users, the possibilities for such interactions to occur are on the rise. The precise effects in the grid cannot be fully assessed yet. Power electronic components that have a damping effect can be used as countermeasures, for example. A higher short-circuit power also has a positive effect on resonance stability. Additional control mechanisms can also be applied to avoid any destabilising interactions between the controllers.

The processes identified with regard to resonance stability are explained in section 5.2.3.

3.4 Short-circuit current

The short-circuit current is the current that flows in a system in response to a short circuit. In the case of a short circuit, two normally insulated live elements are connected with a resistance close to zero. As a result, the voltage in this circuit also drops to almost zero and a very high current flows, which is, at first, many times the rated current. For a simplified illustration, the relationships between current, voltage, and resistance are depicted in Figure 3.4: In the event of a short circuit, there is no resistance, which means that the current can flow unhindered through the conductor.

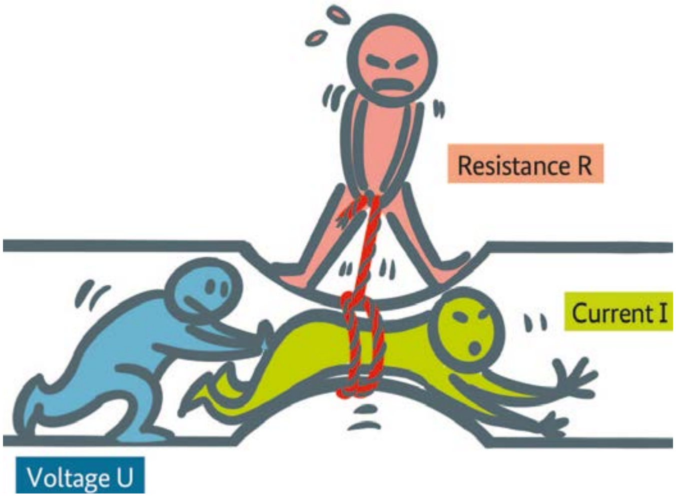

Figure 3.4: Relationship between voltage, current and resistance

In today's electricity system, short-circuit current is supplied by the generators of conventional power plants. If the voltage drops locally in the grid owing to a short circuit, then the voltage at the connection point of a generator also drops. Due to the inertia of its rotating mass, in a generator a consistently high voltage is induced with less resistance, resulting in a significantly higher current (short-circuit current).

On the one hand, the strong current can lead to heating and, in the worst case, to the destruction of the components. On the other, the increased currents in the event of a short circuit form the basis of the grid protection concept. Protective devices can detect the higher current flow and disconnect the fault from the grid. Doing so restricts the short-term voltage dip locally. For this reason, the short-circuit current must have a minimum threshold value so that the circuit breakers can trip, while, at the same time, the maximum threshold which protects grid assets from damage must not be exceeded.

The inverters typically connected to the grid so far have so-called grid-following characteristics. Their control is designed to feed in a constant[3] current and to disconnect from the grid if the voltage drop becomes too large or lasts too long.

[3] The term 'constant' here refers to the constant amplitude of a sinusoidal alternating quantity.

In contrast, grid-forming inverters apply a constant voltage. They can inertly adjust the voltage in the event of deviations and thus have a voltage-stabilising effect. An integrated storage unit can provide the buffer required to instantly feed energy in or out in order to mitigate frequency and voltage changes in the event of any imbalances. In the future system, in contrast to few large synchronous generators, the system-stabilising properties are taken over by many smaller grid-forming inverter-based grid users with small energy storage units. A short-circuit event is a special case of a drop in the voltage. In contrast to synchronous generators, which can feed in short-circuit currents of a multiple of their rated current, inverters only have a limited current carrying capacity and can normally only supply short-circuit currents equal to their rated current.

The climate-neutral electricity system (according to the vision described in chapter 4) will be dominated by inverter-coupled grid users and the proportion of synchronous generators will decrease. That is why the issue of whether short-circuit current contributions from alternative sources are required must be checked. For example, transformers or rotating phase shifters can be used to amplify the contribution of grid-forming inverters.

In actual practice, the term “short-circuit power” is often used instead of “short-circuit current”. The short-circuit power is a notional value and a measure of the strength of a grid.

In section 5.2.4, the processes identified in the development of the System Stability Roadmap regarding the short-circuit current contribution are described.

3.5 Angular stability

The synchronous generators of conventional power plants rotate at the same speed as the changing of the alternating voltage in the grid: the mechanical rotation frequency of the generators and the grid frequency are synchronised (50 Hz). Put more precisely, the electromagnetic torque of a generator's stator is in the opposite direction equal in magnitude to the mechanical torque of the rotor. If the load changes, the generator accelerates or decelerates, thereby altering the pole angle (i.e. the angle between the magnetic rotating fields of the stator and rotor). If the angle becomes too large, the machine gets out of sync and cannot be brought back to a stable operating point. If several generators accelerate together in a certain area, they remain in sync with each other but lose synchronisation with the system. Synchronism can, therefore, be lost between one generator and the system or between groups of generators.

Angular stability in a conventional power system describes the ability of the synchronous generator to maintain synchronism with the grid under normal operating conditions (static stability) or to restore it after faults (transient stability). Faults can, for example, be large load changes or short circuits.

Analogue to resonance stability, angular stability can be illustrated in a simplified way using an example from mechanics: If one hitches a carriage with a spring to a horse, the spring stretches when the horse starts moving (Figure 3.5). If the weight of the carriage increases, e.g. due to the addition of passengers, the spring stretches further apart when the horse pulls on it. Similarly, the angle between the rotor torque and the stator torque increases as the load increases. Like the spring, the synchronous generator can only absorb a certain additional load. The pole wheel angle is, consequently, the limiting variable for the provision of inertia by synchronous generators.

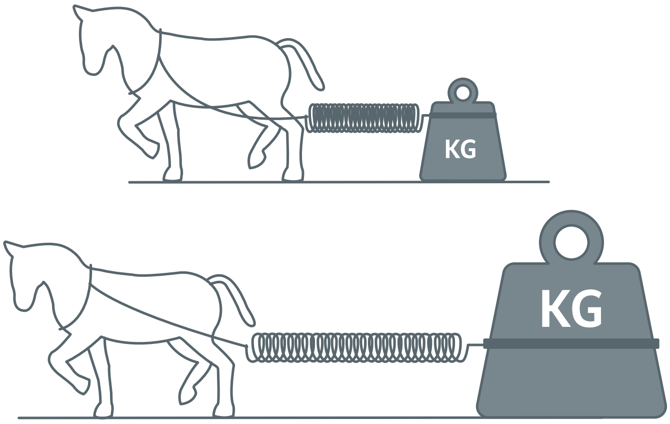

Figure 3.5: An analogy for angular stability

Inverter-coupled grid users are not directly mechanically coupled with the grid. With the decline of synchronous generators, the damping torque previously provided by their rotating masses has to be replaced by other grid users and grid assets so that currently manageable fault and load situations do not result in a loss of synchronism in the future. As with synchronous generators, inverters also have a maximum angle between the internal inverter voltage and the clamping voltage at a remote reference point which must not be exceeded. Furthermore, the current that can be endured by the semiconductors is a limiting factor.

Thus, the challenge for the future electricity system consists, on the one hand, of the ability to maintain angular stability through inverters, and, on the other, of maintaining the angular stability of the remaining generators and loads.

Section 5.2.5 deals with the processes for angular stability that were identified as part of the System Stability Roadmap.

3.6 System control and grid and supply restoration

The electricity system can be described as resilient if the fundamental structure and functionality of the grid are preserved, and in the event of an extreme disruption, such as a weather catastrophe, can be restored. Figure 3.6 depicts a schematic representation of the grid states along a fault path. According to this definition[4] of the Association for Electrical, Electronic & Information Technologies (VDE), resilience can also be described using three components.

1. Robustness: The first component is robustness. This includes the resistance of grid assets in the normal state in compliance with the so-called (n-1)-criterion. According to this principle, a safety margin for possible faults is taken into account in the normal state ((n-0)-state), so that one grid element may fail without any direct consequences. The state after a failure is then referred to as the (n-1)-state. This redundancy in the system design means that the functionality of the power system is not unduly impaired if, for example, an overhead line fails.

2. Adaptability: The second component of resilience is adaptability. If an (n-1)-case occurs, i.e. if one grid asset fails, the system switches to the alert state. As in the normal state, all technical limit values are still met in the (n-1)-case. Nevertheless, measures must be immediately taken to restore the original level of security, i.e. the normal state. If this is not possible due to the severity of a fault and technical limit violations occur, e.g. due to another failure of a grid asset, the system then enters an emergency state. To reduce the risk of uncontrolled, cascading supply failures, protection measures for the emergency state are defined as part of the system defence plan and activated when they occur. If, for example, generation and consumption become significantly imbalanced despite the use of balancing energy, resulting in a critical drop in frequency, consumers will be disconnected from the grid as a final counter-measure. Precisely which consumers will be switched off is decided according to where the reduction in electricity consumption is most effective.

3. Ability to recover: The third component is the ability to recover. Should the measures in the system defence plan not be sufficient to keep the system in a stable equilibrium, this may lead to a regionally limited or a complete collapse of the grid (blackout). These cases are extremely rare and should be avoided by the use of all reasonable means available. However, should such an event occur, it must be possible to carry out the restoration in a controlled and coordinated manner. Corresponding restoration plans exist for this purpose.

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[4] https://www.vde.com/resource/blob/2032350/0a72402482510621ee1096baa8586490/resilienzversorgungsnetze-etg-dvgw-data.pdf

Grid and supply restoration
The procedure for restoring power after a blackout is roughly divided into the two phases of grid restoration and supply restoration: In the first phase, the prioritised goal is to restore voltage to the transmission grid and to make sufficient ancillary services available (grid restoration). In the second and subsequent phase, generation and load are successively switched back on (supply restoration). This requires taking a coordinated approach between the system operators and the control of generation and load in the distribution grid. Section 5.2.7 describes the processes identified in the System Stability Roadmap that must be established in the area of grid and supply restoration in the future.

System control
In particular, the organisational and operational aspects and tasks that system operators must take into account to ensure secure and resilient grid operation are assigned to the area of system control. In practice, system control applies the requirements of the Energy Industry Act (EnWG) for the operation of energy supply grids (section 11 EnWG). This explicitly includes the coordination functions that are necessary to fulfil the aspects of system security and stability as described in this chapter. The system control processes identified in the System Stability Roadmap are described in section 5.2.6.

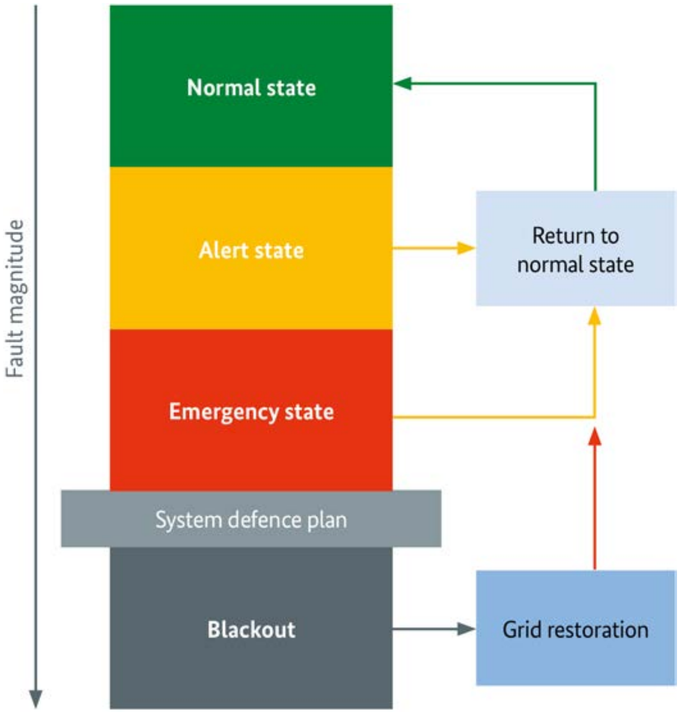
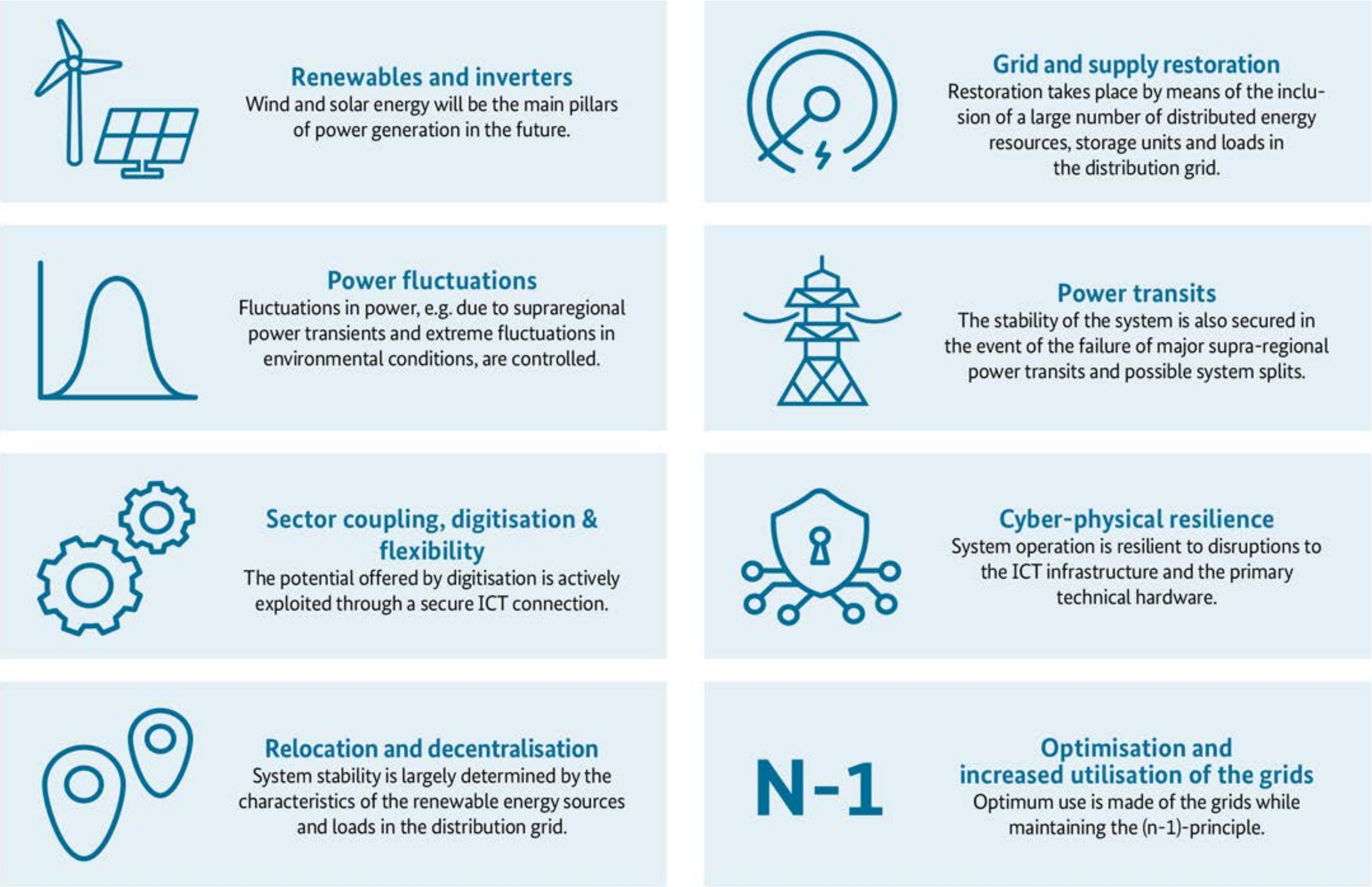


Figure 3.6: System states depending on the magnitude of a fault

4 Vision and challenges

The vision of the System Stability Roadmap generically describes the future power system and the challenges for the secure and robust grid operation using only renewable energy sources. Due to the large number of forecast uncertainties, this should be understood independently of the precise future composition of the power plant portfolio. Although issues relating to the market supply security and grid expansion are also essential for the future electricity supply, the System Stability Roadmap focuses on technical stability issues as well as the secure operation of the grid. The vision is, therefore, not intended to make any quantitative statements on technology-specific generation or storage capacities.

In this vision, the requisite functionalities of the power system and so-called “triggers” for ancillary services are determined. Moreover, the fundamental grid user characteristics required to maintain system stability are discussed. In the following, the target aspects for the relevant areas are first described in general terms and they are then followed by a list of the associated challenges. A compact and simplified representation of the vision is shown in Figure 4.1.



Renewables and inverters
Wind and solar energy will be the main pillars of power generation in the future.

Grid and supply restoration
Restoration takes place by means of the inclusion of a large number of distributed energy resources, storage units and loads in the distribution grid.

Power fluctuations
Fluctuations in power, e.g. due to supraregional power transients and extreme fluctuations in environmental conditions, are controlled.

Power transits
The stability of the system is also secured in the event of the failure of major supra-regional power transits and possible system splits.

Sector coupling, digitisation & flexibility
The potential offered by digitisation is actively exploited through a secure ICT connection.

Cyber-physical resilience
System operation is resilient to disruptions to the ICT infrastructure and the primary technical hardware.

Relocation and decentralisation
System stability is largely determined by the characteristics of the renewable energy sources and loads in the distribution grid.

Optimisation and increased utilisation of the grids
Optimum use is made of the grids while maintaining the (n-1)-principle.

Figure 4.1: Vision in a nutshell

Renewables and inverters

Wind and solar energy will be the main pillars of power generation in the future. They are connected to the grid via inverters. The system can be operated stably using only renewable energy sources, even without conventional power plants. Inverter-based grid users make a vital contribution to maintaining system stability. Sufficient inertia, short-circuit current and short-circuit power[5] are available at all times from grid-forming grid users. Dynamic voltage control or the dynamic provision of reactive power to maintain voltage stability is assured.

The power quality criteria in terms of height, waveform, frequency and symmetry are all met in order to maintain the voltage quality at a high level.

The challenges associated with this area:

- The decline in power plants with synchronous generators and the increase in inverter-based renewable and distributed energy sources require the adaptation of the Technical Connection Rules (TCR) as well as new concepts, processes and tools for grid operation. The focus here is on system stability in normal operation and the management of defined grid faults.
- Although inverters have different hardware limits compared to synchronous generators, they offer greater scope for control because their behaviour is determined by software. In order to achieve system-stabilising inverter behaviour, the use of these freedoms must be explicitly defined and the correct implementation made verifiable.
- A key challenge here is system stability (in a short time range), taking into account a reduction in system inertia (inertia of conventional power plants and synchronously operated loads) and the rise in potentially critical system states (e.g. system splits in times of high transits).
- Due to the decreasing system inertia and the decreasing frequency dependency of loads and the simultaneous rise in demand, all available sources must be considered to provide inertia. The contribution of inverter-coupled grid users in particular will play a decisive role here. The parameters of energy resources and loads need to be realigned.

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[5] The short-circuit power is a measure of a grid's strength or voltage sensitivity. Sufficiently high short-circuit power is necessary, among other things, so that faults and short-circuits in the grid can be clearly identified by protection devices. On the other hand, however, the short-circuit power must not be too high so that circuit-breakers can still switch safely.

- The operation of inverter-based renewable energy sources and loads with grid-following control is based on the regional presence of a stable voltage and a sufficiently large short-circuit ratio (SCR) at the grid connection point. To ensure this SCR, the availability of a sufficiently large short-circuit power is mandatory at all times. The requirements for dynamic voltage control and the dynamic provision of reactive current to maintain voltage stability must be defined. Furthermore, it is also necessary to check whether new concepts for grid protection are required and/or to ensure that the existing grid protection concepts are not impaired. Under certain circum-stances, excessive short-circuit power may also become critical if too many grid-forming inverters are active at a grid node.

- In the future, a variety of sub aspects must be considered for short-circuit power, such as the strength of the grid connection point, protec-tion tripping, a sink for harmonics and the propagation of faults (discharge voltage pattern). Suitable assessment parameters must be defined for them.

- The technical potential of grid users connected via inverters for the provision of ancillary services must be further developed in all sub-sectors.

- When providing ancillary services, an economically efficient development of procurement concepts for capacity, provision and call-off must be found, taking into consideration system security and system demands. This can take place either on a mandatory basis, e.g. via minimum requirements, through market elements or through fully integrated network components (FINC), as well as in a suitable combination of all options, even across voltage levels. Depending on the design and availability of cost-effective alternatives, appropriate incentive systems must be designed. This means, for example, that additional potential can be tapped for grid users that are connected via inverters. What must be taken into account here is that, depending on the allocation of the grid users in the various grid levels, follow-up costs may arise for upgrading the grids, which must be included in the economic analysis.

- Potential instabilities due to e.g. power oscillation of many decentralised controls or inverters must be avoided by means of appropriate con-trol schemes or damping measures.

SYSTEM SPLIT

In continental Europe, power grids are electrically connected to form a synchronised area. A serious disruption can lead to the splitting of the interconnected grid into sub-grids – a so-called system split. The last time such an event occurred with widespread consequences was on 24 July 2021, and before that on 8 January 2021 and 4 November 2006. The system split in 2006, known as the Emsland fault, resulted in the unintentional formation of three sub-grids, as shown in Figure 4.2.

Imbalances between generation and consumption occur abruptly in the resulting sub-grids. The respective imbalance depends on how high the power exchange with the other sub-areas was before the incident and where the interconnected grid splits up. In order for the sub-grids to reach safe and stable operating points, sufficient inertia must be available.

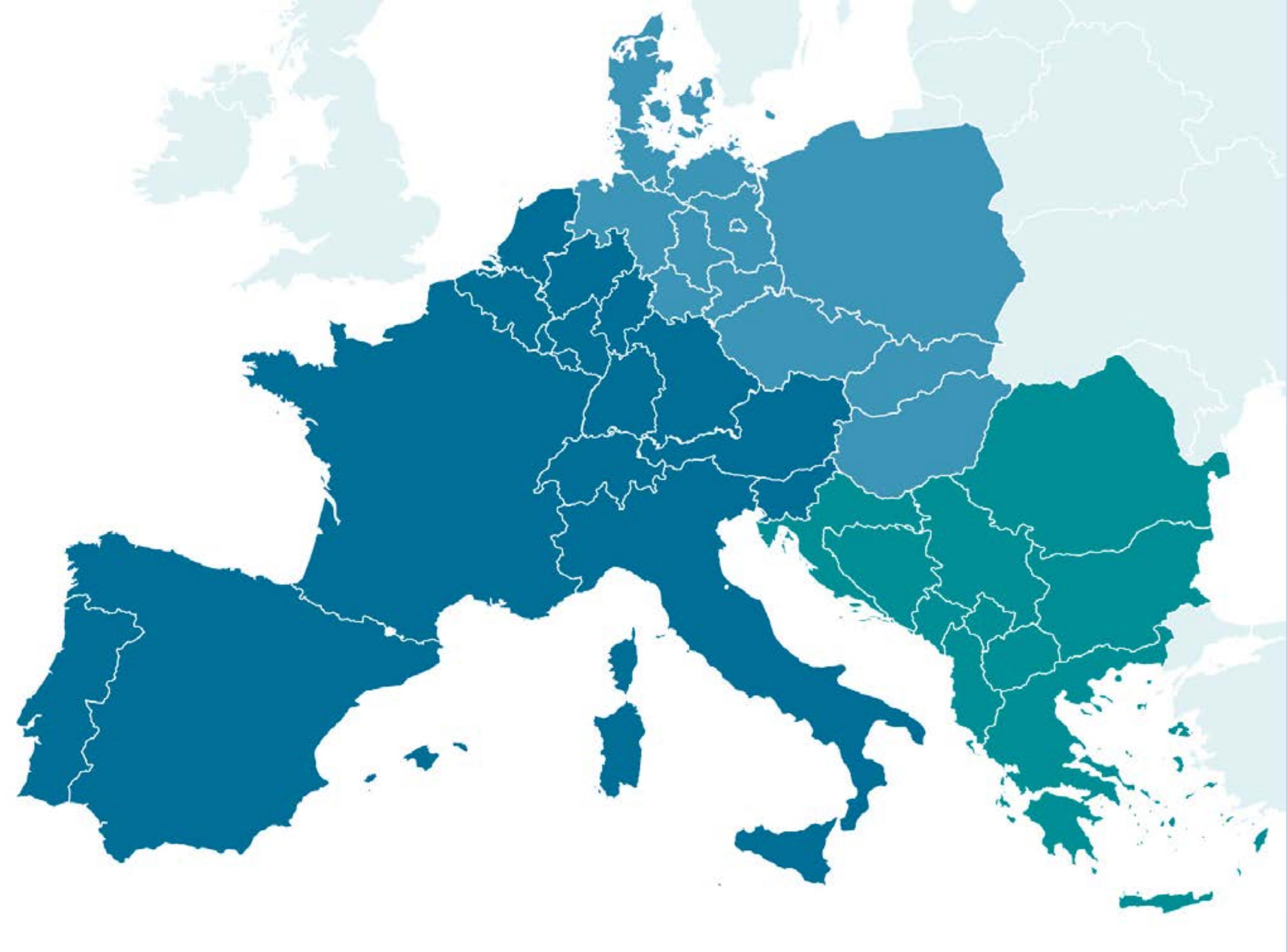

Figure 4.2: 2006 system split

Relocation and decentralisation

In the transmission grid, the central generation capacities and their potential for the provision of ancillary services are no longer available to the previous extent. System stability is, therefore, largely determined by the characteristics of the renewable energy sources and loads in the distribution grid. Potentially required ancillary services can or must be efficiently provided by the high number of renewable and distributed energy resources, storage units and loads in the distribution grid.

The challenges associated with this area:

- Due to the increasing number of grid users and the need to provide ancillary services from the distribution grid, the complexity of system control and the requirements for co-operation between the system operators and, in particular, for (automated) communication are rising.

- Decentralising the system structure can result in changes to the static and dynamic characteristics of the grid. Interactions can potentially occur due to a high number of inverters at a short electrical distance. Local limitation and damping of interactions through robust system and grid user design and the detection of interactions must be ensured.

Grid and supply restoration

Restoration will involve a large number of distributed energy resources, storage units and loads in the distribution grid. The verification and testing of component characteristics and subsystem behaviour as well as the practising of processes and procedures with the cooperation of all stakeholders under the new framework conditions of restoration ensure stakeholders' ability to act if need be and are implemented as an integral part of regular operation. Synergies of processes between normal operation and restoration have been established.

At transmission level a national core grid will be set up by the national transmission system operators (TSO) to enable the supra-regional transport of energy and to reintegrate the German transmission grid into the European interconnected grid as early as possible after a blackout. In order to resupply customers in the initial (sub-)national supply restoration, secured generation capacity and energy are available in the required volume sufficiently quickly, even in times of unfavourable weather conditions. There are clear guidelines for prioritising supply and solidarity in supply between regions as soon as grid and system requirements are no longer dominant.

The challenges associated with this area:

- A suitable procurement concept makes it possible for each TSO to have an adequate number, distribution and redundancy of black start-capable resources available for grid restoration. The black start-capable resources store energy in adequate quantities.

- Due to the fluctuating power supply of renewable energy sources, suitable defined requirements are necessary in order for them to be integrated into restoration concepts.

- Blackout-proof communication and coordination between certain energy resources and loads and system operators must be ensured.

- The roles and tasks of the TSO and distribution system operators (DSO) during the grid and supply restoration must take into consideration the increasing decentralisation of generation and must be developed further. The rapid restoration of supply in all distribution grids is coordinated by the TSO. A suitable interface to the downstream DSO exists. The TSO is kept informed about the current situation and potential in the distribution grids.

- Renewable energy resources that feed into the distribution grid via grid-forming inverters must make an essential contribution to system stability. Their ability to operate sub-grids can be utilised to achieve the robust operation of island grids in the distribution grid in the event of disruptions. This requires, among other things, sufficient frequency and voltage control capabilities in the grid islands. In the distribu-tion grid, what must be established are aggregation systems that enable the large number of distributed energy resources and storage units to participate in active power management (e.g. grid controller in the distribution grid, areal power plant, etc.), particularly in grid and supply restoration.

Power fluctuations

Fluctuations in output, such as those caused by transregional power transits and extreme variations in environmental conditions, as well as jumps in output due to market behaviour, are kept under control. In the future, they will primarily be caused by a greater fluctuation and regionality in production, but also by changes in consumer behaviour.

The challenges associated with this area:

- The high photovoltaic and wind capacity results in large gradients at sunrise and sunset as well as wind fronts, which can lead to large demands for control reserve given today's time resolution of market products (1/4 h).

- The potentially high simultaneity of power surges of inverter-based grid users at the beginning and the end of the market feed-in ("hourly surges") must be controlled. Any simultaneity of power surges can also be caused by starting up and shutting down wind turbines, e.g. due to immission control requirements. They must be avoided or limited in advance. Additional demands arise for effective ramp specifications for permissible power gradients.

- Higher power fluctuations result in additional local demands for dynamic reactive power for voltage stabilisation. At the same time, the proportion of conventional power plants pro-viding dynamic reactive power is declining.

Power transits

Despite increasing regional and supra-regional power transits, system stability is guaranteed even in the event of serious disruptions such as system splits. Representative system states are defined for the large number of possible grid faults. They can be used to determine the system demands for maintaining system stability.

The challenges associated with this area:

- The handling of an outage of higher, Europe-wide power transits leads to a significantly greater demand for inertia than the normative outage. The demand for inertia for such a case must be determined. What must also be determined is the issue of which stabilisation mechanisms will then replace the inertia. In this case, a sensible mix of fast control reserve, LFSM[6] and load shedding should be determined.
- The requirements for ensuring stability affect the entire European interconnected system. This requires the harmonisation of system parameters such as inertia, time to control the active power output, voltage control, protection and control concepts, as well as a system of overall coordination.
- The importance of the primary control of frequency-dependent generation and loads in the event of overfrequency and underfrequency is becoming increasingly important.

Optimisation and increased utilisation of the grids

The transport demand in the electricity grids is increasing and becoming more volatile on account of market-based supra-regional power transits, sector coupling and decentralisation. Besides accelerating the requisite expansion of the grid, the existing grid will be utilised to a greater extent and, at the same time, safely (e.g. through load flow management, curative grid operation, weather-dependent overhead line operation, dynamic stability analyses, etc.).

The challenges associated with this area:

- It is necessary to examine the target to be pursued by long-term grid planning as well as what proportion of, for example, expected bottlenecks can or should be covered by system control approaches while maintaining system security and robustness.
- The static and dynamic reactive power demand of the grids is increasing significantly due to the increased utilisation. Coordinated reactive power control is, therefore, becoming increasingly important. Static and dynamic reactive power sources must be available at all times.
- The requirements for system control as well as the requirements for co-operation across grid levels and balancing areas are increasing significantly.
- Curative system control is to be introduced in stages and at different grid levels and will supplement the existing congestion management processes.

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[6] Limited Frequency Sensitive Mode – overfrequency or underfrequency control

Sector coupling, digitisation and flexibility

All relevant energy resources and (controllable) loads, storage units and grid assets at all voltage levels are connected via a secure ICT infrastructure and can be used to serve the grid. Coupling with other energy sectors is supported and synergies enabled. The potentials offered by digitisation and flexibilisation is being actively exploited.

The challenges associated with this area:

- The operation of the electricity grid requires use to be made of flexibility, particularly in the distribution grids. To achieve this, as much flexible power as possible must be made controllable. Suitable and secure IT communication must be available for this purpose.

- The use of grid-supporting flexibility can support grid operation and optimise the use of grid capacities in the distribution grid. To this end, planning and regulatory conditions must be created and conflicts of interest with the energy market resolved.

- In order to be able to call up flexibility preventively and curatively (re-dispatch), the complexity of system control is on the rise. This increases the need for communication between the grid levels, particularly in fault situations.

- New loads can lead to high power peaks locally, particularly in the case of pure market optimisation.

- In order to be able to make use of loads such as electric vehicles and power-to-X-facilities, further technical specifications are required for the provision of ancillary services.

- Both the grid connection point and the properties of electrolysers must be designed in such a way that system stability is ensured at all times.

Cyber-physical resilience

System operation is resilient to disruptions to the ICT infrastructure and the primary technical hardware and the protection systems. Robust control and communication concepts protect against cyber attacks and other disruptions in the IT systems.

The challenges associated with this area:

- Robustness in the event of disruptions to the ICT infrastructure is becoming more important in all areas of the energy system. To manage the consequences of cyberattacks and large-scale IT problems, the system must be able to handle the loss of communication with a large number of grid users (security by design). The energy system must be highly resilient.

- In the event of a fault (e.g. communication failure), fallback levels are required for all system-relevant processes as well as tools that temporarily allow minimum but still stable system operation. The minimum scope of supply to be ensured for this restricted system operation mode determines the type and magnitude of the reserves and ancillary services.

5 Stability processes identified

The stability processes identified are presented below. They were derived along the topics of frequency, voltage, resonance stability, short-circuit current, angular stability, system control and grid and supply restoration. Furthermore, overarching processes of system stability were derived, which address fields of action that can be categorised as cross-cutting and interlinking.

Process

In this document, the term “process” refers either to a new process to be established or the further development or adaptation of an existing process. The roadmap does not provide any details or specifications for how the processes should be carried out. Rather, it focuses on the structured description of who the process coordinator is, i.e. the initiator of the process, when the process is to be started, its expected duration and which field of action the process is to address.

The processes were derived from relevant issues and the corresponding need for action in the individual topics. They were developed by experts in topic-specific working groups. The questions and needs for action on which the processes are based can be found in the accompanying papers (see section 2.3). The accompanying papers outline the discussion status of the working groups in preparation for the creation of the roadmap.

Process coordination

Besides the institution that is coordinating the process, i.e. the initiator, other stakeholders may also be involved in the process in question. Depending on the process, it may even be possible that they will have to do most of the content-related work. In addition, other stakeholders may take on responsibilities for sub-processes. The content design and structuring of the actual processes are not the subject of this roadmap, but are the responsibility of the participating institutions.

In principle, the process coordinator is responsible for ensuring that all the stakeholders involved in the process fulfil their tasks in a coordinated manner and that the results are made available to the relevant stakeholders. He or she initiates and controls the sub-processes, but does not necessarily bear the main responsibility for all sub-sections. The role of the process-coordinating institutions can take a variety of forms. For example, processes within the responsibility of the BMWK and the BNetzA are often characterized by the fact that they can be shaped further after an initial impulse or the definition of framework conditions by other actors. The BNetzA may commission the TSO to develop a procurement concept for an ancillary service, or the BMWK may initiate a platform in which experts define system resilience requirements.

The content of the examples would then be organised by the TSO or the experts. Thus, the responsibility here primarily relates to the start of the process as well as the monitoring and ensuring that the required result is achieved. Processes in the area of responsibility of system operators or the VDE’s Forum Network Technology/Network Operation (FNN), for example, are often of a much more operational nature, so that (large) parts of the content-related work are also carried out by these institutions. For example, the VDE FNN is responsible for adapting the Technical Connection Rules.

The TSO are responsible for system stability, meaning that many of the processes in their area of responsibility are inherently dealt with by them. This, however, explicitly does not mean that no other stakeholders can or must play an active role in these processes. However, the clear aim of the System Stability Roadmap is to appoint a process-coordinating institution that will initiate and lead the process and involve other institutions as and when required. Here, explicit partial responsibilities can and must be transferred to the stakeholders involved, according to their territories.

Process duration

For each process, the expected process duration is specified by the start and end time. This was based, on the one hand, on the known duration of established or comparable processes and, on the other, on the time at which the process result is required. This results in a natural area of tension that needs to be resolved.

This also means that, in selected cases, established processes will have to be accelerated. The start time indicates when a process should be started at the latest. In principle, the aim here is to parallelise and closely interlink processes wherever this makes sense. Therefore, there are, in some instances, time windows in which a process should start, since the process directly depends on one or more upstream processes and corresponding partial results must first be available.

The same applies to the expected end time of processes, since, in some cases, partial results that serve as input for processes downstream must already be available at earlier points in time, or because the process duration cannot yet be clearly predicted. During implementation, all the processes are monitored so that any deviations and delays can be identified at an early stage and appropriate adjustments made.

Regular cycle

Moreover, a cycle is specified for recurring processes, i.e. when they are to be carried out regularly. A clear distinction must be made between the process as such and process adaptation.

Processes directly affected

The processes identified in the System Stability Roadmap are at least indirectly interdependent, since they all contribute to system stability. In some cases, however, processes are directly dependent on each other. This is particularly the case whenever the results or partial results of a process are required input for some other process. Furthermore, topic-specific stability processes also contribute to overarching processes for system stability and vice versa. They are listed under “processes directly affected” and require particularly close coordination with the respective process.

The process dependencies are also described in more detail in section 5.3 and chapter 6.

Result of the process

The desired result is presented for each process. The process coordinator is responsible for the path to achieving results and defining interim results. This requires, in particular, a dialogue with the institutions responsible for the adjacent processes. In the case of recurring processes, the description of results refers to the first process run, i.e. to the minimum viable product to be further developed on a regular basis. This is the case, for example, with minimum technical requirements, which are revised cyclically as and when more knowledge is gained. Consequently, it is not necessarily a matter of the final product, but about a good initial result that serves as a basis for subsequent processes and can be further developed.

National and international implementation

Germany is part of the European interconnected grid and the European electricity trade. The interconnected concept offers major advantages that make it easier for all nations to operate “their” system in a stable manner. To this end, European network codes that define a common framework are issued. They then need to be transposed into national requirements and, if need be, supplemented with specific national features. In Germany, for example, this is done through the Technical Connection Rules. The European harmonisation process takes a relatively long time.

Interconnected operation is a key element of the energy supply. However, Germany is also a pioneer of the energy transition. This means that national solutions should be developed and initiated at an early stage and, at the same time, proposals should be actively incorporated into the design of European requirements. The System Stability Roadmap is, therefore, also meant to drive forward the further development of system stability in Europe. Taking this approach offers the advantage of being able to act fast and carry out the necessary processes to ensure the secure and robust system operation in good time, even when using 100% renewable energy sources in Germany.

Strongly divergent national requirements are an obstacle to the rapid further development of the technical characteristics of grid users to stabilise the system. What should be aimed for here is a high degree of international standardisation. This area of tension should be taken into account when applying the processes.

To leverage synergies and avoid redundant parallel activities, ongoing national and international activities should be included in all processes and synchronised as far as possible. This is carried out by the process coordinators.

Resources

Setting up and implementing the processes sometimes involves a considerable amount of effort. The process and sub-process coordinators must, therefore, plan the resources at the start of the processes. The process dependencies, especially with upstream and downstream processes, are of paramount importance here. Particularly for processes whose results form the basis for many other processes, it is vital that they are completed on schedule. The pressure to act is high in all processes. Sufficient resources must, therefore, be allocated. It can be assumed that the current structures will not always be suitable and the human resources will not always be sufficient to address the new tasks. All process and sub-process coordinators must, therefore, provide additional staff as required when planning resources and adapt or expand their structures to the new tasks. Prioritisation across processes may also be required if sufficient resources cannot be allocated in good time.

The tight schedule of the System Stability Roadmap will also make it necessary to start processes in parallel, even though dependencies exist (this also impacts on resource planning). Classic “sequential” processing will not always be possible in this case. Appropriate resources must, therefore, also be planned for this in parallel.

The structured categorisation of the processes for each individual topic is presented in section 5.3. As described in section 2.2, the processes were derived from the relevant issues and the corresponding needs for action in the individual topics. They were developed by experts in topic-specific working groups.

Research and piloting

When designing and implementing the processes, issues may arise for which there are currently no established solutions. Researchers are already working on important building blocks for the electricity grid of the future and are testing new solutions, e.g. as part of the German government’s energy research funding programme. The results of this work are incorporated into the processes at the appropriate points. If there is any need for further research or testing, processes should be accompanied by appropriate research or field trials.

5.1 Overarching processes for system stability

Overarching processes for system stability are processes that are not exclusive to one topic, but can be assigned to several topics. Specifically, they are processes that address cross-topic adjustments, further developments or specifications. Overarching processes are generally much more complex than topic-specific stability processes and are usually iterative processes requiring a great deal of information. These pieces of information are sometimes compiled in different sub-processes or these sub-processes are also dependent on the input from the respective overarching process. That is why close co-operation between the institutions involved is, therefore, essential. Depending on the overarching process, the various institutions have different roles to play. As a result, process coordination is, from time to time, spread across several institutions, since overarching processes bring together several individual stability processes with individual responsibility.

V1. Definition of overarching resilience requirements of the system in an industry-specific process

It is necessary to define a general framework for system demands. To this end, an industry process led by the BMWK will be used to work out what resilience requirements (also in normal operation) are placed on the system. Once these requirements have been defined, design-relevant system states can be derived and system demands quantified. The TSO, but also the DSO, have a key role to play here. They must show whether and where higher-level requirements still need to be defined so that these system demands can be clearly quantified. The question “How safe is safe?” is also of concern. Considerations must always be made against the background of the cost-benefit ratio. Thus, the

BNetzA also has an important role to play, since it examines and authorises the demands of the system operators. As mentioned in the introduction, close cooperation with the relevant topic-specific stability processes is necessary. The information gained there regarding the resilience requirements is requisite input for this process.

- Process coordinators: BMWK, BNetzA, TSO
- Time (expected): immediately (start) until 2026 (end)
- Cycle: initial setting, adjustment as needed
- Further stakeholders involved: DSO, associations
- Processes directly affected: F1, F4, S1, NVWA1, NVWA2, NVWA4
- Result: A list of resilience requirements to be defined for the system has been created. The respective requirements have been determined.

V2. Enabling and piloting broad field testing of advanced capabilities to maintain system stability

The further development of the system necessitates trialling and testing. This applies in particular – but not exclusively – to pilot tests of grid-forming inverters in the distribution grid or extended functions and tests in the context of grid and supply restoration. Among other things, it is important to clarify, with legal certainty, which costs can be recognised for system operators and who has to bear liability risks or how costs for any damage incurred are treated in regulatory terms. The aim is to enable pilot tests that are required for the safe and robust system operation using only renewable energy sources. To this end, costs and liability risks that cannot be influenced must be moderated and distributed appropriately. In the future, it will not only be necessary to carry out individual pilot tests in small grid areas, but also large-scale field trials with existing grid users. The German government's energy research funding programme can support such research and demonstration projects. As part of the BMWK's research funding programme, for example, a large-scale demonstration of stable grid operation with a high penetration of renewables is being planned over the next five years. Irrespective of this, however, pilot tests (possibly in the short term) carried out on the system operators' own initiative are also required. Existing research projects could also be built upon, e.g. a co-demonstration platform is being developed as part of the Kopernikus project ENSURE, funded by the Federal Ministry of Education and Research (BMBF), which can be used to validate solution modules for the energy system of the future. These findings can be used as the basis for piloting system stability.

There is a particularly high demand for pilot and field tests in the area of resonance stability (R5) and the integration of grid-forming inverters (F7). There are still unanswered questions regarding the execution of such broad pilot projects. This applies with regard to coordination and realisation (system operators), but also with regard to regulatory issues such as cost recognition and liability for tests with customer facilities in the field (BNetzA). For example, in the case of tests for restoring the grid and supply, besides cost recognition for measures to enable the DSO to restore the grid, cost recognition for operational tests and renewable energy resources with grid-supporting behaviour must also be clarified. An iterative approach is planned for this overarching process. System operators must set up appropriate field trials, including large-scale ones, and harmonise the technical framework conditions. This is the case in particular in processes F7, R5, B6 and NVWA3. The field tests will necessarily include grid users with different connection rules. They could be renewable and distributed energy resources and loads. The aim should be to carry out tests in a real grid environment, e.g. in an island. In the event of damage, consumers should be adequately compensated.

If regulatory issues or obstacles are identified by the system operators when the field tests are being designed, e.g. with regard to liability risks and cost recognition, they must be pointed out to the BNetzA or the BMWK. They must then be minimised as far as possible so that the field tests and pilot trials required to ensure the safe and robust operation of the system can also be carried out. Incorporating the experience gained from previous research projects into the planning and scientific monitoring of the field tests is advisable.

Note: This does not mean that all costs should basically be categorised as "permanently uncontrollable costs".

- Process coordinators: TSO/DSO (field test concept), BNetzA (regulatory issues)
- Time (expected): immediately (start) until 2025 (end)
- Cycle: recurring, if new requirements arise that necessitate field tests
- Further stakeholders involved: BMWK, research facilities
- Processes directly affected: F7, R5, B6, NVWA3
- Result: Field tests are carried out and regulatory issues such as cost recognition and any liability issues are identified and clarified with legal certainty.

V3. Transparent definition of system demands and examination of a joint specification of demands and their establishment across all topics, in particular at the TSO level

To be able to cover the system demands, they have to be known. To this end, the demands for ancillary services and measures for system stability must be identified transparently and with sufficient lead time. This is to take place, in particular, in the System Stability Report, which was adopted by the cabinet in the Solar Package on 16 August 2023 (see box). System stability measures can also be measures that limit the demand for ancillary services. For example, effective ramp specifications for permissible power gradients at the start and end of market-based active power consumption/feed-in ("hourly jumps") can be useful (cf. V4, F4). This structured approach allows the participation of all grid users, stimulates investment and enables potential bottlenecks to be pinpointed and addressed at an early stage. On the one hand, demand should be identified in as aggregated a manner as possible, since a larger field of suppliers can be expected in the event of market procurement. On the other, demand should only be aggregated to the extent that it makes sense for coverage. This applies to both the spatial and the temporal dimension. The degree of aggregation of demand per ancillary service and system stability measure should be determined individually by the TSO. This requires a techno-economic assessment process to determine where providing the service makes sense. Determining demand also involves identifying and recognising potential demand for new ancillary services or system stability measures so that they can be specified and procured in downstream processes.

- Process coordinators: TSO
- Time (expected): ongoing (start) until 2024–2026 (end); should be coordinated with the Network Development Plan (NDP)
- Cycle: System Stability Report: for the first time in 2025, then every 2 years.
- Additional designation if necessary.
- Further stakeholders involved: DSO, BMWK, BNetzA
- Processes directly affected: V4, F1, F4, F8, S1, S2, S5, K1, K3, K4, K5, K6, R1, W1, B1, B6, NVWA1
- Result: System demands are clearly and transparently identified in a System Stability Report.

SYSTEM STABILITY REPORT

Basis: On 16 August 2023, the Cabinet adopted the draft law for a regular System Stability Report as part of the “Solar Package”. With the System Stability Report, the Federal Government is already responding to the processes and requisite fields of action identified during the creation of the System Stability Roadmap and is laying an important foundation stone for its execution.

Who, what and when: With the System Stability Report pursuant to section 12i Energy Industry Act, operators of transmission grids that have balancing area responsibility are obliged to report on the security, reliability, stability and performance of their supply system every two years, and must do so for the first time on 1 January 2025. The existing obligation of TSO under section 12 (3b) Energy Industry Act to report on the security, reliability and performance of their supply system at the request of the regulatory authority will be further developed and concretised by the new section 12i Energy Industry Act (System Stability Report). In the System Stability Report, the TSO must present the current status for all areas of system stability and identify the need for action in the individual areas with regard to secure grid operation, even when all the electricity is generated using renewable energies. The system demands for the next ten years must also be quantified.

Concrete options for action must be derived for the system demands. All suitable options must be identified, and their impact quantified and evaluated. In addition, the respective implementation period, the costs and the suitability of the options must all be taken into account and at least one suitable transformation path with concrete measures must be presented. DSO or third parties are obliged to participate in the drawing up of the System Stability Report at the request of a TSO with balancing area responsibility. The regulatory authority may also provide further information on the form and content of the report.

Evaluation, monitoring and recommendation for action: The regulatory authority (or a third party commissioned by it) evaluates the System Stability Report and makes recommendations for action. This includes, in particular, the demands, the possible covering of those demands and concrete measures for further action. In addition, the regulatory authority continuously monitors the status of the implementation of measures in the area of system stability. TSO, DSO and third parties shall provide the regulatory authority with the information required for monitoring in a suitable form. The evaluation of the report and a monitoring report must be submitted to the BMWK no later than six months after receipt of the System Stability Report. They must also be published.

Role in the roadmap: The System Stability Report is a tool and already a result of the implementation of the System Stability Roadmap. With the System Stability Report, there will be a legal obligation on the one hand and a coordinated medium on the other, in which several of the identified processes can already be dealt with (in particular, process V3). Thus, these processes will also be documented as part of the System Stability Report. In addition, the results of the System Stability Report serve as input for further processes, e.g. with regard to the derivation of procurement systems of ancillary services, the further development of technical connection rules or the need to revise or develop new stability assessment procedures.

V4. Structured procurement of the system demands following the three pillars of minimal technical requirements, markets or fully integrated network components

What must be ensured is that the necessary system demands are covered at all times. This can be achieved through combinations of minimum technical requirements, through markets and through dedicated grid assets of the system operators. The aim is to establish suitable procurement and covering for all system demands. Both the spatial and temporal dimensions of system demands must be taken into account here. The various options for meeting demand result in different responsibilities for this overarching process. This also explicitly involves developing a structured procurement process for potential system demands for new ancillary services and system stability measures, even if there is no clear responsibility for this in the current system. This would mean first determining whether there is a need for technical adjustment, i.e. the need for new or the adaptation of existing ancillary services or system stability measures (TSO and DSO). One such extension will be the specification for effective ramps for permissible power gradients. The TSO coordinate this sub-process and analyse which gradients could occur and what impact this would have on grid operation, control reserve, etc. Based on this, they then develop a proposal for corresponding ramp specifications. The development of the ramp specifications must be closely coordinated with the definition of design-relevant system states (F4), which are also within the scope of coordination of the TSO. These ramp specifications must then be sensibly integrated into the energy system. This can be achieved through minimum technical requirements or market specifications. It is to be expected that minimum technical requirements for recovery after faults (e.g. return of voltage) are suitable and that limits on the gradients in regular market operation ("hourly jumps") should generally be specified by the market.

If there is also a demand for additional ancillary services or other measures to ensure system stability, it is necessary to examine how these demands can be met. The demands can be covered in various ways, which must be tailored to the respective ancillary service and the system stability measure. What must be checked is whether there is a corresponding legal basis for procurement and whether any adjustments need to be made to this (BMWK). This could, for example, be the extension of section 12h Energy Industry Act. This would then be followed by an assessment of whether market-based procurement (in full or in part) is efficient (BNetzA). A corresponding procurement concept must then be developed (BNetzA), whereby appropriate minimum technical requirements (VDE FNN) can also form part of the structured procurement. Besides ancillary services and system stability measures, which can, in principle, be procured on the market, there are also properties that must be permanently provided by grid users to maintain system stability. To this end, it is necessary to check whether existing properties need to be adapted through revised minimum technical requirements or whether new or additional properties need to be developed (VDE FNN).

- Process coordinators: BNetzA, BMWK, VDE FNN, TSO
- Time (expected): immediately (start) until 2026 (end)
- Cycle: regularly upon/with adjustment of system demands
- Further stakeholders involved: DSO
- Processes directly affected: F1, F2, F3, F5, F8, S4, S5, S6, S7, S8, K2, K4, K5, R2, R3, R4, W1, W2, B2, NVWA5
- Result: Structured procurement procedures are available for all system demands. Procurement can be achieved via minimum technical requirements, markets, fully integrated network components or combinations thereof.

V5. Monitoring of grid user capabilities and the enabling of reasonable access to system capabilities

An overview of the capabilities and master data of grid users must be comprehensively documented and be available in the future, especially at distribution grid level. Furthermore, access to the grid user capabilities and needs-based parameter changes by the system operators must be assured. This requires the development of a standardised platform and the definition of the necessary data formats and communication standards. During initial implementation, this process will focus on monitoring grid user capabilities. Later on, this process will focus on enabling reasonable and secure access to the grid user capabilities (depending on whether and which accesses are necessary to cover system demands).

- Process coordinators: BNetzA, DSO
- Time (expected): immediately (start) until 2026 (end)
- Cycle: initial implementation, further development as required
- Further stakeholders involved: TSO
- Processes directly affected: S5
- Result: In the initial step, the capabilities of grid users can be called up. There will then be subsequent expansion to demand-based parameterisation of grid users, depending on the performance class or grid level.

V6. Process digitisation

Standardised interfaces and exchange formats must be established in order to enable the exchange of information, data and operating statuses required for the processes mentioned in this roadmap. The aim is to break down data silos and make information accessible and usable in a reasonable way. The expansion of renewable energies and sector coupling should be flanked by the digital process transformation. To this end, a framework is to be created that provides the requisite guidelines but gives the stakeholders the freedom to organise them according to their individual requirements. One example of such a framework is the VDE FNN's “Digital Twin for Electrical Energy Systems”. These frameworks are to be developed in the VDE FNN and German Commission for Electrical, Electronic & Information Technologies (DKE). To this end, the system operators should identify processes and, in particular, the necessary data exchange that necessitates standardised exchange formats. In addition, suitable data spaces that enable a standardised database for different processes and workflows should be defined. Exchange formats are already being used or being introduced in other countries, which, in Australia and California, are based on IEEE 2030.5. Whether such existing approaches can be built upon should be examined.

- Process coordinators: VFE FNN, TSO, DSO
- Time (expected): immediately (start) until 2035 (end)
- Cycle: continuous further development
- Further stakeholders involved: Manufacturers, DKE
- Processes directly affected: V5, S3, S6, K5, B3, B4
- Result: A framework for process digitisation is in place. Processes were digitised within these guidelines.

V7. Further development of stability analyses and Dynamic Stability Assessment systems

For comprehensive Dynamic Stability Assessments (DSA) in the grid, so-called DSA-systems are already being developed and used. In order to gain an overview of the grid status in real time in the future, with increasing complexity of the overall system, and in order to be able to take suitable countermeasures during grid operation, these systems must be developed further. On the one hand, the changing framework conditions and system demands must be taken into account. On the other, decision support for operators will become increasingly important. Stability phenomena occur quickly and (partially) automated countermeasures need to be initiated within a few seconds. Not all stability aspects can be integrated to the same depth in the DSA-system. The depth of integration, the degree of automation of the countermeasure and the lead time (short-term planning to real time) result in particular from the needs of the TSO and should therefore be determined by them.

- Process coordinators: TSO
- Time (expected): immediately (start) until 2028 (end)
- Cycle: initial comprehensive revision, continuous adjustments and extensions
- Further stakeholders involved: DSO
- Processes directly affected: S5, B2, B3
- Result: System operators can use the DSA-system to carry out reliable stability analyses and operators have an overview of the grid status and can initiate (counter)measures quickly and in a targeted manner.

V8. Support of the system by “all” grid users

The demand for ancillary services and system stability measures should be satisfied efficiently. The aim is to open up a wide range of providers and to enable all grid users to contribute. This is to be achieved through needs-based and individualised minimum technical requirements as well as by means of suitable markets and product specifications. Consequently, there is a close content-related connection to structured procurement (V4). When designing the procurement systems (BNetzA) and minimum technical requirements (VDE FNN), it is vital that as many grid users as possible are included, provided they can make an efficient contribution. This must be balanced with the level of demand so that requirements are only placed on as many and those grid users that are needed to cover demand. This relationship must be taken into account when defining the product and specifying the requirements. The process time is based on the international adjustments to the network codes and the downstream national implementation as well as the development time of market procurement concepts. The process must be run through cyclically as required.

- Process coordinators: VDE FNN, system operators, BNetzA
- Time (expected): immediately (start) until 2027–2030 (end)
- Cycle: one-off implementation, needs-based customisation
- Further stakeholders involved: BMWK, manufacturers
- Processes directly affected: F1, F2, F3, F5, F7, S6, S7, S8, K3, R2, R3, W3, NVWA4
- Result: All grid users contribute to supporting system stability to the best of their ability.

V9. Enabling grid-forming properties in the distribution grid

In the future, the major part of the generation capacity will be located at distribution grid level. In order to be able to continue to assure stable and robust grid operation, at least some of these systems must have grid-forming properties (in addition to selected grid users in the transmission grid). In this process, these properties are to be enabled and promoted across all topics so as to provide, e.g. inertia, short-circuit power and other measures for system stability from the distribution grid in the future. The process is, therefore, a subset of the overarching processes for system stability V2, V3, V4 and V8. However, since grid-forming properties are a key technology for ensuring the secure and robust system operation using only renewable energy sources and represent an essential field of action in the above-mentioned overarching processes for system stability, enabling them should be bundled as this separate process.

To introduce these grid-forming properties in the distribution grid, technical requirements and corresponding verifications must be defined in the grid connection rules (VDE FNN). Also, technical hurdles resulting from today’s protection or operational aspects, for example, must be removed, particularly in the distribution grids (system operators), insofar as this is possible while maintaining secure operation. In particular, the effects of grid-forming properties on grid operation must be investigated and tested in pilot plants (system operators and BNetzA, see V2).

To reduce the complexity of these steps and provide the fastest and most targeted support possible through grid-forming facilities, it is recommended to differentiate between voltage levels or power classes. It is also necessary to clarify up to which voltage level grid-forming properties will be required.

- Process coordinators: VDE FNN
- Time (expected): immediately (start) until 2026 (HV and HV/MV), 2029 (MV), 2033 (LV) (end)[7]. Wherever possible, earlier completion should be aimed for. There are various ideas within the industry regarding timing. This discrepancy should be resolved at the start of the process.
- Cycle: one-off implementation, continuous adjustments and extensions
- Further stakeholders involved: System operators, manufacturers, BNetzA
- Processes directly affected: F1, F5, F6, F7, S7, S8, K3
- Result: In the distribution grid, grid users with grid-forming properties are established in the wholesale business, depending on the voltage level. Ancillary services and measures for system stability are also provided from the distribution grid.

V10. Accompanying studies and the need for research

As needed, open questions will be addressed through accompanying studies and research projects. The studies and projects can also be used to increase the efficiency of measures or to reduce the demand for ancillary services as well as for iterative optimisation. The processes described in this roadmap should be scientifically accompanied according to the needs. The German government's energy research funding could also be utilised for this purpose.

- Process coordinators: needs based
- Time (expected): as required
- Further stakeholders involved: -
- Processes directly affected: all (depending on requirements)
- Result: Any questions that may arise are clarified.

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[7] Voltage levels: low voltage (LV), medium voltage (MV), high voltage (HV), transformation high voltage/medium voltage (HV/MV)

5.2 Topics

The topic-specific stability processes are described below.

5.2.1 Frequency

F1. Definition of the technical specifications of inertia

Inertia must be clearly specified by a technical requirement description. It must also be clearly qualifiable. This requires appropriate measuring and testing procedures.

- Process coordinators: VDE FNN
- Time (expected): immediately (start) until 2024 (end)
- Cycle: one-off, recurring audit
- Further stakeholders involved: BMWK, BNetzA
- Processes directly affected: F5, F6, F7, V1, V3, V4, V8, V9
- Result: The technical specification of inertia as well as corresponding measurement and test procedures are available.

F2. Market-based procurement of “inertia for local grid stability” – development of a procurement concept including procurement horizons and, if applicable, regionality

Due to the continuous decline in conventional power plants, the inertia inherently available in the system is decreasing. The market-based procurement of the ancillary service “inertia for local grid stability” (abbreviated as inertia) serves, therefore, to accelerate the implementation of these properties in renewable energy sources, loads and storage units in order to ensure that future demands of the system can (continue to) be covered in good time. In the process, the procurement system should enable the involvement of different technologies as well as technology development (system readiness level). See also the overarching process V4. The Federal Network Agency (BNetzA) has already initiated the process of defining a procurement concept.

- Process coordinators: BNetzA
- Time (expected): immediately (start) until 2024–2025 (end)
- Cycle: one-off, needs-based adaptation
- Further stakeholders involved: TSO, DSO
- Processes directly affected: V4, V8
- Result: The procurement concept for inertia has been introduced and is being implemented.

F3. Adaptation of the requirements for over/underfrequency control (Limited Frequency Sensitive Mode – LFSM-U/O)

In the event of frequency deviations from normal operation, the overfrequency/underfrequency control intervenes as an emergency measure in the system defence plan. These control measures are known as LFSM (Limited Frequency Sensitive Mode) in the Network Code Requirements for Generators (NC RfG) on the European level. The national implementation of LFSM in Germany is known as “primary control based on network security”, which additionally considers certain loads. A distinction must be made between overfrequency (LFSM-O) and underfrequency (LFSM-U). In the process for LFSM-O, the following must be taken into account: the stability requirement for inverter-based grid users must be redefined; for LFSM-U: the selectivity and, presumably, also the non-discrimination of underfrequency load shedding decrease dramatically.

As part of an extended concept within the system defence plan, the replacement of activated inertia must be achieved much more reliably than before (in a frequency range to be defined in grid areas with falling frequency, e.g. after a system split). To this end, renewable and distributed energy sources and storage units (including feed-in from electric vehicles during bidirectional charging) must adhere to the requirements of the primary control based on network security (as part of the LFSM), which defines a continuous control based on adequate stability criteria. For non-controllable loads, such as heat pumps and unidirectional charging stations, a frequency-dependent cut-off in the underfrequency range must be established. At present, primary control based on network security is currently being incorporated into the Technical Connection Rules for low voltage level up to extra-high voltage level for the 2025 amendment.

- Process coordinators: VDE FNN
- Time (expected): immediately (start) until 2026 (end)
- Cycle: initially one-off, needs-based revision as with all FNN instructions and connection rules
- Further stakeholders involved: covered via VDE-FNN composition
- Processes directly affected: V4, V8
- Result: revised note and/or application guideline for LFSM-U and LFSM-O for system support of (selected) inverter-based grid users

F4. Analysis of system demands – definition of design-relevant system states, in particular system splits and identification of demands including locality

Design-relevant system states (in particular system split cases) must be defined in coordination with the specification of higher-level robustness and resilience requirements and their implementation. They must take particular account of the increasing power transits and power gradients. This can be done, for example, in the System Stability Report. Based on this, the demands for ancillary services and measures for system stability, such as inertia and their quantity structures and, if need be, their temporal, situational and regional provision must be determined, taking into account safety margins. In the context of covering the demands, measures which decrease the demand in the first place should be considered as well. Cases relevant to the system design should, therefore, also take into account any necessary limitations of power ramps or similar (see also V4).

- Process coordinators: TSO
- Time (expected): immediately (start) until 2026 (end)
- Cycle: one-off, revision as required
- Further stakeholders involved: BNetzA, BMWK, ENTSO-E[8]
- Processes directly affected: F5, F6, V1, V3
- Result: Design-relevant system states are defined and system demands, especially the demand for inertia, can be quantified.

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[8] European Network of Transmission System Operators for Electricity

F5. Progressive adjustment of minimum technical requirements for inertia from power inverters

To cover future system demands for inertia, the introduction of the grid-forming properties of renewable energy sources, loads and storage units is required. To this end, corresponding minimum technical requirements must be further developed and applied in the grid connection code. The requirements should be developed at least in a staggered manner according to voltage levels, see also overarching stability process V9.

- Process coordinators: VDE FNN
- Time (expected): 2024 (start) until 2027–2030 (end)
- Cycle: initially one-off, needs-based revision as with all FNN instructions and connection rules
- Further stakeholders involved: -
- Processes directly affected: V4, V8, V9
- Result: Minimum technical requirements for inertia from inverters are available.

F6. Test basis for the certification of grid-forming inverters

The conformity of a renewable energy source, load or storage unit with the applicable grid connection code is verified by a certificate that authorises it to be connected to the grid. Appropriate verification procedures and test processes must, therefore, also be developed for newly introduced requirements, such as grid-forming properties, with which the accredited certification bodies can check the conformity of the grid user with the grid connection code. When developing test procedures, international processes, e.g. at CENELEC level, must be observed in order to achieve the international harmonisation of requirements as far as possible.

- Process coordinators: FGW[9], DKE[10]
- Time (expected): immediately (start) until 2024 (end)
- Cycle: one-off, needs-based adaptation (e.g. for minimum requirements in TCR following the national implementation of RfG 2.0)
- Further stakeholders involved: VDE FNN
- Processes directly affected: V9
- Result: Test basis for the certification of grid-forming inverters

F7. Rapid piloting of grid-forming inverters to gain experience and refine technical rules

Before any possible mass rollout of grid-forming inverters, pilot test are required in order to identify any potential problems, e.g. in the distribution grid, and to refine requirements for grid users in good time if necessary. The pilot users and field tests are to be designed and coordinated by system operators in particular. For this purpose, the necessary financial and legal framework conditions must also be clarified and, if need be, further developed (V2). The focus here is on gaining knowledge in the context of grid-forming inverters. This is a sub-process of overarching process V2.

- Process coordinators: TSO, DSO
- Time (expected): immediately (start) until 2024–2028 (end)
- Cycle: as required
- Further stakeholders involved: Manufacturers, research facilities, BNetzA
- Processes directly affected: V2, V8, V9
- Result: Experience gained from field testing grid-forming inverters

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[9] Federation of Wind and other Decentralised Energies (FGW)

[10] German Commission for Electrical, Electronic & Information Technologies (DKE)

F8. Additional or further developed ancillary services such as a fast(er) frequency containment reserve

Depending on the future development of the electricity grid, there may be demands for additional ancillary services or the further development of established ancillary services, e.g. in order to manage future power gradients. Therefore, a process should be established to define technical requirements as well as the procurement of these additional or enhanced ancillary services. See also overarching processes V3 and V4.

- Process coordinators: BNetzA
- Time (expected): as required (start) until as required (end)
- Cycle: whenever action is required
- Further stakeholders involved: TSO, DSO, VDE, FNN
- Processes directly affected: V3, V4
- Result: when required

5.2.2 Voltage

S1. Expansion of considered contingencies for “worst-case” scenarios like system splits, including different observation years and grid utilisation cases

What is required is to clarify which operating scenarios are relevant to the future system design with regard to covering the reactive power demands (including n-1 and exceptional contingencies) of the individual system operators. Of particular importance here is the demand that must be covered for upstream or downstream system operators. This process must be carried out in close coordination with the definition of the overarching robustness and resilience requirements (V1) and can be addressed as part of the System Stability Report.

- Process coordinators: TSO
- Time (expected): immediately (start) until 2025 (end)
- Cycle: regularly when the scenarios are updated (e.g. in the rhythm of the grid development plan of the TSO)
- Further stakeholders involved: DSO, BNetzA, BMWK
- Processes directly affected: V1, V3, S7
- Result: Addition of the design-relevant faults for determining the reactive power demand

S2. Establishment of a standardised procedure for determining ancillary service demands at DSO level as part of the grid expansion plans

The demand required for reactive power and alternative or supplementary measures to maintain voltage stability must be determined by each system operator for its own grid area. The criteria to be observed by each individual system operator in this task with regard to the stability of the overall system must be compiled. Moreover, a procedure is to be developed for the exchange of grid planning data relating to the planning of reactive power demands and alternative or supplementary measures for voltage stability. In the process, close coordination with the System Stability Report of the TSO must be ensured (V3). This topic can also be addressed as part of the System Stability Report.

- Process coordinators: DSO
- Time (expected): immediately (start) until 2024 (end)
- Cycle: one-off setup, adaptation as required
- Further stakeholders involved: TSO, BNetzA
- Processes directly affected: V3
- Result: Reactive power demands are shown in a structured manner in the grid expansion plans of the DSO.

S3. Permanent exchange format for planning at TSO/DSO and DSO/DSO interfaces

Procedures must be established for the exchange of planning and operational data regarding the provision of reactive power, both between grid users and the grid and between system operators, as well as the sensible utilisation of extra-high voltage/high-voltage transformers for maintaining voltage stability in the high-voltage grid. This includes information on demand planning, operational call-offs and, if applicable, billing.

- Process coordinators: TSO and DSO
- Time (expected): immediately (start) until 2024 (end)
- Cycle: one-off setup, with regular exchange of information, adaptation as required
- Further stakeholders involved: plant operators
- Processes directly affected: V6
- Result: Procedures for exchanging information have been further developed and established.

S4. Implementing a procurement concept in accordance with s12h Energy Industry Act, which addresses, among other things, exchange between system operators, including “pass-through billing”

As part of section 12h EnWG, the BNetzA is currently conducting an implementation procedure for the market-based procurement of reactive power (BK6-23-072). The corresponding procurement concept is expected to be published in the first quarter of 2024. It must be examined whether, in particular, the exchange of reactive power across grid levels or other relevant topics are already covered by the current regulation in section 12h EnWG and the BNetzA’s stipulation or whether corresponding extensions should be made. See also overarching process V4.

- Process coordinators: BNetzA
- Time (expected): immediately (start) until 2024 (end)
- Cycle: one-off, needs-based adaptation
- Further stakeholders involved: TSO, DSO, BMWK, when amendments to the law are necessary
- Processes directly affected: V4
- Result: Procurement concept for reactive power has been introduced and is being implemented. A possible need for adjustments to the procurement concept as regards the exchange of reactive power between system operators has been examined and will be implemented depending on the outcome.

S5. Increasing observability in distribution grids

More data on reactive power exchange are required for the efficient use of reactive power sources across all voltage levels. The scope of measured values at connection points in the distribution grids must, therefore, be optimised and retrofitted where necessary. The recognition of costs for such measures must be clarified and the time required for structural realisation taken into consideration.

- Process coordinators: DSO
- Time (expected): immediately (start) until 2026–2030 (end)
- Cycle: one-off setup, adaptation as required
- Further stakeholders involved: TSO
- Processes directly affected: V3, V4, V5, V7, B1, B3
- Result: Grid states and system behaviour in the distribution grid are known to a sufficient extent (depending on the voltage level).

S6. Process for automated call procedures and coordination of reactive power exchange at the SO-SO interface

System operators (SO) requiring reactive power from third parties must design and apply efficient procedures for requesting available reactive power capacity and calling up reactive power. In addition to specification BK6-23-072 for the market/grid interface, an FNN connection rule for coordination between system operators may need to be drawn up.

- Process coordinators: TSO and DSO
- Time (expected): 2024 (start) until 2028 (end)
- Cycle: one-off setup, adaptation as required
- Further stakeholders involved: VDE FNN
- Processes directly affected: V4, V6, V8
- Result: Procedures for requesting reserve power and calling up reactive power are designed so that they can be recorded in an application rule (2024) and then implemented (by 2028) if required.

S7. Development of further protection measures to prevent a voltage collapse (system defence plan, implementation of NC-ER, counterpart in the distribution grid)

Besides the provision of reactive power during normal operation, measures that are to be taken if system security is ever jeopardised or disrupted must be described. The existing regulations, e.g. those of the VDE FNN, must be revised and supplemented with regard to the requirements according to S1 (expansion of considered contingencies for “worst-case” scenarios).

- Process coordinators: TSO, DSO
- Time (expected): immediately (start) until 2024–2025 (end)
- Cycle: cyclical
- Further stakeholders involved: -
- Processes directly affected: V4, V8, V9
- Result: Protection measures to prevent a voltage collapse have been developed and fixed.

S8. Further development of the VDE application rules on the interfaces between the system operators

For an efficient provision of reactive power, both informational communication processes and formats for coordination, as well as processes and formats for the operational provision, retrieval, and billing procedures, need to be standardised.

- Process coordinators: VDE FNN
- Time (expected): 2024 (start) to 2028–2030 (end)
- Cycle: initially one-off, needs-based revision as with all FNN instructions and connection rules
- Further stakeholders involved: TSO, DSO, manufacturers
- Processes directly affected: V4, V8, V9
- Result: Technical connection rules have been further developed, especially in line with the communication requirements.

5.2.3 Resonance stability

R1. Study to develop standardised criteria and assessment methods for resonance stability

The causes and effects of resonance stability are currently being investigated solely in project-specific interaction studies and, in some cases, in harmonic studies. For this reason, the TSO, in close cooperation with manufacturers, DSO, research facilities and tool manufacturers, will develop standardised procedures (e.g. simulation/ measurement procedures) and evaluation criteria in order to quantify resonance stability on a systemic basis. The process is to be initiated by the VDE FNN and will take place under its guidance. Here, in particular, the identification of critical grid areas and frequency ranges and the handling of high modelling uncertainties must be taken into account. The criteria and procedures may then be published in the form of a white paper or guideline.

- Process coordinators: VDE FNN
- Time (expected): immediately (start) until 2027–2030 (end)
- Cycle: one-off implementation to develop criteria, then revised as required
- Further stakeholders involved: system operators, manufacturers, research facilities
- Processes directly affected: V3, R2
- Result: A document on standardised criteria and assessment procedures for resonance stability

R2. Defining systemic and grid user-specific requirements, especially for the wholesale business

Based on the standardised assessment procedures developed in (R1), the TSO develop system requirements to ensure resonance stability with the support of manufacturers, DSO and research facilities, e.g. in the form of limit values or system characteristics (if required). With the participation of all stakeholders involved, minimum technical requirements for grid users, which can also be used explicitly for the wholesale business, are derived in the VDE FNN from the systemic requirements. In the course of this, a subdivision between minimum requirements and further requirements, e.g. in the form of ancillary services, may be developed. The minimum requirements identified are then transferred to an FNN instruction, TCC[11] or TCR.

- Process coordinators: VDE FNN
- Time (expected): 2025–2026 (start) to 2028–2029 (end)
- Cycle: initially one-off, needs-based revision as with all FNN instructions and connection rules
- Further stakeholders involved: system operators, manufacturers, research facilities
- Processes directly affected: V4, V8, R5
- Result: System requirements as well as requirements for grid users to ensure resonance stability are available.

R3. Certification and test procedures for grid user properties

In order to ensure the effectiveness and execution of the derived grid user requirements, certification and testing procedures are developed by the FGW/ DKE with the involvement of the manufacturers and, if applicable, the TSO. They are then rendered into corresponding guidelines and regulations.

- Process coordinators: DKE (LV), FGW (EHV/ HV/MV)
- Time (expected): 2026 (start) to 2029–2030 (end)
- Cycle: one-off, revision as required
- Further stakeholders involved: manufacturers, TSO, DSO
- Processes directly affected: V4, V8
- Result: Certification and test procedures are in place.

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[11] Technical connection conditions (system operator-specific design of the Technical Connection Rules [TCR]).

R4. Assessment and, if necessary, derivation of procurement procedures

Procurement procedures will be developed for the derived grid user-specific requirements that have not been defined as minimum requirements (if need be; cf. V4). The BNetzA could be authorised to do this by the BMWK by an extension of section 12h EnWG. The concept is developed in cooperation with the stakeholders involved, possibly in the VDE FNN or by the TSO. The first step in the VDE FNN is a technical definition of a product if requirements that go beyond the minimum requirements have been identified in (R2). If a product and a procurement procedure are identified as a result of this process, the stakeholders involved (BNetzA, VDE FNN) shall define the further implementation steps and transfer them to a follow-up process. See also overarching process V4.

- Process coordinators: BNetzA
- Time (expected): 2026–2028 (start) to 2028–2030 (end)
- Cycle: one-off, needs-based adaptation
- Further stakeholders involved: TSO, BMWK
- Processes directly affected: V4
- Result: A procurement procedure for “resonance stability”, if required, is available.

R5. Coordinated “field tests” to gain experience with grid-forming inverters in the context of resonance stability

The targeted use of grid-forming inverters is an effective measure for ensuring system stability in scenarios with a high level of inverter penetration. However, there is still a lack of experience in the widespread operation of such inverters in the transmission and distribution grid. For this reason, the TSO and DSO carry out field tests in close co-operation with the manufacturers in order to test the grid-forming inverters. They take into account different technology-dependent limitations (e.g. rate of change of active power of wind turbines), at least in an illustrative way. Ultimately, the experience gained is incorporated into the development of models, specifications and requirements. In concrete terms, this could look as follows: The system operators are responsible for selecting, conceptualising and carrying out the field tests. The VDE FNN should be involved so as to maximise the efficient use of experience and thus the transfer of knowledge. The VDE FNN can play a coordinating role here. This is a sub-process of overarching process V2. Any regulatory questions are clarified there.

- Process coordinators: TSO, DSO
- Time (expected): immediately (start) until 2026–2028 (end)
- Cycle: when required
- Further stakeholders involved: TSO, DSO, manufacturers, research facilities, VDE FNN, BNetzA
- Processes directly affected: V2, F7, R2
- Result: Experience with grid-forming inverters in grid operation

5.2.4 Short-circuit current

K1. Developing and integrating an evaluation methodology for short-circuit current in inverter-dominated systems into existing processes

The existing standards and guidelines for deter-mining and evaluating the short-circuit current for a given grid connection do not, or only insufficiently, take into account the contributions from inverter-based grid users. There is a need for research involving DSO and TSO to develop a practical evaluation methodology for the short-circuit current in a inverter-dominated system. The results must then be incorporated into the relevant regulations. The aim of the process is to develop an evaluation methodology for short-circuit current in inverter-dominated systems.

- Process coordinators: DKE
- Time (expected): immediately (start) until 2024–2027 (end)
- Cycle: one-off integration, further development as required
- Further stakeholders involved: VDE FNN, TSO, DSO, research facilities
- Processes directly affected: V3, K4
- Result: An evaluation methodology for short-circuit current in the inverter-dominated system is available and is anchored in the regulations.

K2. Procurement procedure for short-circuit current that may be required, provided that preliminary investigations indicate corresponding demands

Firstly, the extent to which other measures, such as the procurement of inertia, have an influence on the short-circuit level should be examined. There is a need for research and analysis, particularly on the part of the TSO, to determine this (especially V3). Based on these results, suitable measures must be defined and implemented with the involvement of the BNetzA, the VDE FNN, the system operators and manufacturers to procure the necessary short-circuit contributions that are not covered by other measures (if there is a further need). See also overarching process V4.

- Process coordinators: BNetzA
- Time (expected): 2026–2027 (start) until 2027–2029 (end)
- Cycle: one-off, needs-based adaptation
- Further stakeholders involved: TSO, DSO, BMWK, VDE FNN, manufacturers
- Processes directly affected: V4, K3
- Result: A procurement procedure for short-circuit current is available in accordance with section 12h Energy Industry Act if demand has been identified.

K3. Evaluating demand and technical options from the distribution grid

Firstly, studies must be carried out by TSO to determine the demand for short-circuit current in the transmission grid resulting from the shutdown of conventional power plants. Furthermore, working together with DSO, system manufacturers and research facilities to clarify what potential exists to meet this demand through grid users in the distribution grid is important. The determination of system demands and the assessment of the technical possibilities can be addressed as part of the System Stability Report.

- Process coordinators: TSO
- Time (expected): immediately (start) until 2026–2027 (end)
- Cycle: one-off assessment, then updated cyclically as part of the procurement process
- Further stakeholders involved: DSO, research facilities, plant operators
- Processes directly affected: V3, V4, V8, V9, K2
- Result: The useful contribution of grid users in the distribution grid to cover the demand for short-circuit current is known.

K4. Guideline for DSO on risks from increasing short-circuit currents and suitable mitigation measures

Besides the short-circuit current from the transmission grid, decentralised grid users are also increasingly contributing to the level of short-circuit current. Depending on regional conditions, this can lead to a significant increase in the local short-circuit level. This must be taken into consideration when grid assets are being designed (especially protective devices). Both too high short-circuit current levels and too low short-circuit current levels are critical and must, therefore, be taken into account. Very high short-circuit currents may harm grid assets, very low currents may not trigger protective measures. For this reason, corresponding recommendations for action for DSO must be developed. The publisher might be the VDE FNN.

- Process coordinators: VDE FNN
- Time (expected): 2026 (start) until 2028 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: none
- Processes directly affected: V3, V4, V9, K1
- Result: Information or guidelines for DSO on risks due to increasing short-circuit currents and suitable remedial measures are available

K5. Forward-looking monitoring of the development of the short-circuit current level (especially at the TSO/DSO interconnection point)

New sources of short-circuit current such as decentralised, inverter-based renewable energy sources and storage units are only partially recorded in a systematic way. This makes it increasingly hard to determine the exact short-circuit current level. System operators must develop strategies and methods that can anticipate the determination of the level of short-circuit current. This involves forecasts along the usual planning horizons, e.g. as part of the grid expansion plans or the System Stability Report (V3).

- Process coordinators: TSO and DSO
- Time (expected): 2024 (start) until 2026 (end)
- Cycle: cyclical
- Further stakeholders involved: research facilities
- Processes directly affected: V3, V4, V6
- Result: Continuous monitoring and forecasting of the development of the short-circuit current level

K6. Investigations or studies on discharge voltage patterns in the target system, including the evaluation of any changing characteristics of the discharge voltage pattern

In the event of a short circuit, the voltage at the location of the fault will collapse and a so-called “discharge voltage pattern” will form in the grid due to the short-circuit current flowing radially into the fault. As the distance from the short-circuit location increases, the voltage rises again. However, sources of short-circuit current in the vicinity of the fault can reduce the expansion of the discharge voltage pattern. There is a need for research to determine, in the target grid scenario, how decentralised short-circuit current suppliers based on inverter technology influence the expansion of the discharge voltage pattern in the grid. If it turns out that the discharge voltage pattern is expanding too much, further measures must be developed. This can be done in the context of the System Stability Report.

- Process coordinators: TSO
- Time (expected): 2024 (start) until 2026 (end)
- Cycle: one-off implementation, further development or updating as required
- Further stakeholders involved: DSO, manufacturers, research facilities
- Processes directly affected: V3
- Result: The influence of decentralised short-circuit current suppliers based on inverter technology on the expansion of “discharge voltage pattern” in the grid is known.

5.2.5 Angular stability

W1. System studies to determine the demand for synchronising "phase angle power"

First of all, existing knowledge about inverter behaviour, measurement criteria for angular stability and the estimation of angular differences occurring during regular operation should be compiled in a meta-study. This serves to expand the methodology for assessing system stability as part of the network development plan or the System Stability Report (V3) in order to initiate the monitoring and evaluation of angular differences between grid groups and regions. This topic can be addressed as part of the System Stability Report.

- Process coordinators: TSO
- Time (expected): immediately (start) until 2024–2025 (end)
- Cycle: cyclical
- Further stakeholders involved: research facilities
- Processes directly affected: V3
- Result: The demand for synchronising "phase angle power" is known, in principle, and the network development plan methodology has been extended to ensure cyclical process execution.

W2. Cost-benefit analysis of technically viable options for meeting demand

When analysing technical options, e.g. as part of the System Stability Report (V3), various points must be taken into consideration: the technology readiness levels (TRL) for different time horizons, technology- and voltage-level-specific costs, the design of grid users at DSO level and the development of a pan-European coordinated solution. Interim results from W3 regarding the contributions of inverter-based grid users are also to be included here. The respective system operator is responsible for weighing up the various technologies and solutions as well as their investment requirements or operating costs. Finally, as part of a product definition, what must be clarified is whether a contribution to meeting demand is required from all grid users or whether demand should be met via market-based procurement with no restrictions on technology. These analyses can be addressed as part of the System Stability Report.

- Process coordinators: DSO, TSO
- Time (expected): 2024–2025 (start) until 2026–2027 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: manufacturers, research facilities
- Processes directly affected: V3, V4
- Result: Sensible technology options for meeting demand and defining products are known.

W3. Inclusion of inverter-based grid users in the coverage of demand for angular stability

The contribution of a grid user to angular stability must be described (e.g. differentiation according to operating points, inherent power/energy reserves or storage capacities). The inherent limitations of grid users and their systemic effects must be analysed, e.g. in the System Stability Report. This is a necessity if inverter-based grid users can be considered for maintaining angular stability according to the cost-benefit analysis from W2. This topic can be addressed as part of the System Stability Report.

- Process coordinators: TSO
- Time (expected): 2026–2027 (start) to 2027–2028 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: BNetzA
- Result: The necessary contribution of inverter-based grid users to angular stability is known.

5.2.6 System control

B1. Identification of critical factors and grid states to ensure the required system security

The increasing number of decentralised grid users and flexible loads is changing system behaviour and increasing the complexity of system control. Critical grid states must be identified for this changed system behaviour and suitable evaluation criteria and indicators derived. This can mean, for example, that a permissible distribution function of the frequency values occurring around the target value of 50 Hz is to be defined as the quality objective. The width of this distribution defines the tolerated deviations in the short-term range.

Potentially critical grid conditions must be recognisable at an early stage or already in the forecast so that appropriate countermeasures can be initiated.

- Process coordinators: TSO
- Time (expected): immediately (start) until 2024 (end)
- Cycle: ongoing
- Further stakeholders involved: DSO, BNetzA, research facilities
- Processes directly affected: V3, B2, V1
- Result: Critical factors and grid conditions are known.

B2. Review or further development (and where required standardisation) of the (n-1)-principle

One essential core of a secure energy supply is (n-1)-safety, which must be maintained at all times. It states that the grid must be able to cope with the failure of any grid asset (transformers, lines, etc.) at any time. Due to the ever-increasing utilisation of the system, such as weather-dependent overhead line operation, and the constant change in the generation landscape, system operation is already moving increasingly closer to the safety limits during normal operation. This represents an ever-increasing challenge. The existing (n-1)-principle is to be reviewed for possible improvements – particularly with regard to the integration of new types of grid assets – and further developed in order to be able to assure secure and interference-free energy transmission in the future. With the integration of new technologies, such as grid boosters, special protection schemes, etc., the existing (n-1)-principle must be revised and, if required, adapted with the aim of maintaining today's level of system security and expanding it in the future.

- Process coordinators: VDE FNN (distribution grid), TSO (transmission grid)
- Time (expected): immediately (start) until 2025–2027 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: BNetzA, research facilities, DSO
- Processes directly affected: V4, V7
- Result: The (n-1)-principle has been revised in line with requirements.

B3. Process and tool development for the visibility of the system status and real-time control (data exchange)

The ever-increasing complexity and growing number of market participants call for new tools and processes to be developed or the existing ones to be developed even further. Operators must also be able to assess the grid situation in the future by means of a suitable overview and the presentation of data and information.

- Process coordinators: VFE FNN, TSO, DSO
- Time (expected): immediately (start) until 2028 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: research facilities
- Processes directly affected: V6, V7
- Result: Processes and tools for monitoring the system status and control in real time have been further developed.

B4. Expansion/robustness of data exchange between system operators

In the field of system control, robust and standardised communication channels between system operators are an absolute must. The collection and exchange of data forms the basis for most processes, tools and IT systems that allow the system to be evaluated and contribute to decision-making. Expanding the existing communication channels between the system operators and further increase robustness is, thus, necessary. What is important here is that the focus should not be on a specific exchange protocol, but on a data format with standardised requirements and content. The starting point here could be the catalogue of measures for grid restoration, which is already being implemented.

- Process coordinators: VDE FNN, system operators amongst themselves
- Time (expected): immediately (start) until 2024–2028 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: -
- Processes directly affected: V6
- Result: Robust data exchange channels between system operators have been implemented or developed further.

B5. Accelerated standardisation process for smart metering systems, meters and sensors

As part of the standardisation partnership with the Federal Office for Information Security (BSI) referred to in section 27 MsbG (Metering Act), gaps in existing standards must be closed and missing standards created. The accelerated standardisation process aims to improve the basis for rolling out smart metering systems in such a way that logistics and installation, as well as IT and technical operation, can be carried out in a highly scalable manner and nationwide so that the mass rollout can take place on the required scale. The smart metering systems should also be able to be used for applications relevant to system stability (e.g. V5 and V6).

- Process coordinators: DKE
- Time (expected): ongoing (start) until 2024–2028 (end)
- Cycle: one-off
- Further stakeholders involved: BSI, VDE FNN
- Processes directly affected: V5, V6, S8
- Result: The standardisation for the rollout of smart metering systems has been completed.

B6. Establishing legal certainty for preventive and curative action by system operators to increase the degree of automation

One element in the increased utilisation of the grids is curative system control to ensure stability. At present, pilot projects are being developed and analysed in several places in order to provide the necessary framework conditions and prerequisites for the large-scale integration of these processes into the grid. For this to succeed, the legal conditions and securities must be established. Including not only the curative but also the preventive area and the interaction between them is important. To this end, the TSO and DSO must identify potential obstacles and possible solutions and submit them to the BMWK and the BNetzA.

- Process coordinators: TSO, DSO
- Time (expected): immediately (start) until 2025 (end)
- Cycle: one-off, needs-based update
- Further stakeholders involved: BMWK, BNetzA
- Processes directly affected: V2, V3
- Result: The BMWK and the BNetzA have an overview of the regulatory obstacles for system operators to carry out curative and preventive measures. This serves as the basis when any necessary legal and regulatory adjustments have to be made.

5.2.7 Grid and supply restoration

NVWA1. Determination of demand for secured generation capacity and energy for national grid and supply restoration per region for black-start-capable and partner units

In an energy system that relies 100% on renewables, it must be possible to restore the national grid and supply fast enough, even in phases when there is little sun and wind. To this end, the TSO must determine the demand for secured generation capacity and energy per region in the restoration process and assure their availability. This can be done as part of the System Stability Report. Besides black-start-capable units for restoring the grid, this also applies in particular to secured generation capacity and energy from partner units for replacement. Likewise, requirements regarding availability and volumes of such reserves must also be defined for supply restoration so as to adequately bridge the period until the TSO restore regular market activity. This process must be closely coordinated with the definition of the overarching robustness and resilience requirements (V1). For example, determining what level of re-supply can and should be achieved within a realistic period of time would also be necessary.

- Process coordinators: TSO, BNetzA
- Time (expected): ongoing (start) until 2025 (end)
- Frequency: regularly by TSO as required
- Further stakeholders involved: BMWK
- Processes directly affected: V1, V3
- Result: The demand for secured generation capacity and energy for the national restoration of the grid and supply per region for black-start and partner units is known.

NVWA2. New joint coordinating restoration platform (e.g. FNN expert network "Grid and Supply Restoration")

The change in the power plant portfolio and the load and generation structures in general will have a major impact on the grid and supply restoration of the future. This requires a network of experts in order to create a common understanding of the requirements. This includes the ongoing management of the mission statement, the understanding of the concepts, synchronisation of the methods for determining system demands, the processes and the requirements as well as the research activities.

- Process coordinators: VDE FNN
- Time (expected): immediately (start) until 2024 (end)
- Cycle: one-off set-up of the platform, regular exchange within the framework of the platform
- Further stakeholders involved: TSO, DSO, BNetzA, BMWK, scientists
- Processes directly affected: V1
- Result: A network of experts on the topic of restoring the grid and supply has been set up.

NVWA3. Conception and design of framework conditions for activities for extended testing of subsystems and the practising of processes

Testing and practising processes outside of regular operation is essential to ensure the successful restoration of the grid and supply if need be and to identify any necessary adjustments. The aim here is to identify how the testing of subsystems and the practising of (partially modified) processes can be carried out in the modified system and under increasingly difficult framework conditions. The aim of this platform is to identify any potential obstacles and highlight any necessary adjustments that need to be made to the framework conditions.

- Process coordinators: TSO and DSO
- Time (expected): 2024 (start) until 2025 (end)
- Cycle: one-off, needs-based adaptation
- Further stakeholders involved: BMWK, BNetzA
- Processes directly affected: V2
- Result: The requirements and potential obstacles for the extended testing of subsystems and practising processes are known. The potential need for legislative and regulatory adjustments has been identified.

NVWA4. Establishing a vision of "distribution grid islands" with regard to use cases accompanied by potential studies

Distribution grid islands formed by black starts or intercepts, e.g. at 110 kV level (medium voltage also possible), could supplement the TSO-led restoration process. What should be noted is that distribution grid islands can help to fulfil robustness and resilience requirements (V1). Potential studies and cost-benefit analyses must be carried out as a basis for the discussion on the political target definition. The potential studies and the definition of political objectives must be closely coordinated, since they are mutually dependent. The procedure must, therefore, be carried out in an iterative manner between NVWA4 and V1. Depending on the potential available locally or regionally, various supply tasks, which cannot be fulfilled per se in every distribution grid, are conceivable (key factors here include the synchronisation capability and the effort required to keep the island stable at 50 Hz). They range from securing the infrastructure of the grid (lowest requirements) to the full supply of customers by the DSO (highest requirements).

- Process coordinators: FNN, TSO, DSO
- Time (expected): immediately (start) until 2025–2026 (end)
- Cycle: iterative with V1, adaptation as required
- Further stakeholders involved: BNetzA
- Processes directly affected: V1, V8, K5
- Result: The active role that distribution grid islands can play in the grid and supply restoration concepts of the TSO is defined.

NVWA5. Incentivising the capabilities of new and existing grid users

It must be ensured that the system demands of the initially smaller subsystems (compared to the European connected grid) can be covered when the grid and supply are restored. These system demands and the corresponding technical requirements for grid users needed to meet them may go beyond the typical ancillary services. Incentives must, therefore, be set so that the necessary properties are available as and when required. To this end, the requisite technical properties must be defined and the demands for specific properties of the grid and supply restoration as well as for ancillary services and measures for system stability that go beyond the demands of normal operation must be determined. These demands (both for restoring the grid and the supply) must then be procured and covered in a structured manner (see V4).

- Process coordinators: BNetzA
- Time (expected): 2024 (start) until 2026 (end)
- Cycle: regularly, based on expected demand
- Further stakeholders involved: BMWK, TSO, DSO
- Processes directly affected: V4
- Result: The procurement system incentivises investment in new and existing grid users to actively contribute to grid and supply restoration.

5.3 Process dependencies

This section presents the process dependencies within the topics. Various information is summarised in the following figures. The focus here is on the interfaces and dependencies that exist between the various processes. It shows which processes (can) run sequentially or in parallel and where there are significant time dependencies and corresponding demands for coordination.

Time and responsibilities: In the following figures, the width of the process boxes is not an indication of the runtime of the processes. The process coordinators are named in the grey boxes. Further stakeholders involved are listed in the individual process descriptions. The process dependencies are depicted as follows.

Process dependencies: Setting up and executing the processes sometimes involves a considerable amount of effort. That is why resource planning must be carried out by the process coordinators or the managers of the processes and sub-processes at the start of the processes. The process dependencies, especially with regard to downstream processes, are of paramount importance here. Particularly for processes whose results form the basis of many other processes, it is vital that they are completed on schedule. The pressure to act is high in all processes. Sufficient resources must, thus, be allocated and it can be assumed that the current structures will not always be suitable and the human resources not always sufficient to address the new tasks. All process and sub-process coordinators must, therefore, provide additional staff as and when required whenever planning resources and adapt or expand their structures to the new tasks.

The process dependencies described in this section form the foundation for coordination between the various process coordinators. They also show elementary paths, so that any corresponding delays downstream must be checked in the event of any foreseeable delays in progress. Comprehensive monitoring of the execution of the System Stability Roadmap (see also Chapter 8) is thus necessary and provided for. This is less about control and more about the overarching management and subsequent adjustment of processes.

Form of visualisation: For arrows that enter a process (from the left), the processes are expected to be closely interlinked and (partial) results are key for the success of the subsequent process. Arrows with exclamation marks indicate a particularly close need for coordination, as some of the processes (should) run in parallel and there are also strong dependencies. Processes can be fully parallelised and do not significantly depend on each other, provided that the arrows enter a process from above or below.

At this point, it should be mentioned that the processes within the individual topics also have other dependencies. However, these are not critical for the roadmap from a process point of view, which is why they are not illustrated. Processes that need to be carried out and initiated on a recurring basis are also marked (circle with arrow). The runtime of the processes is shown in the blue-grey boxes in the border areas below. The start time identified by the experts as necessary is shown on the left, while the estimated end time is shown on the right.

The process coordinators are named in the grey boxes. SO stands for system operator and includes both TSO and DSO.

In addition, cross-topic dependencies may also arise; they must be checked by the process coordinators on a case-by-case basis and require additional coordination effort. The cross-topic analysis of the processes is presented in chapter 6.

The processes for each topic are divided into four groups: overarching framework, determination of system demands, rule-making and product definition and covering of system demands. It is also possible that individual groups in a topic are not represented. This pre-sorting serves to increase clarity within a topic. The grouping of the stability processes along relevant fields of action is presented in section 6.1.

5.3.1 Frequency

Figure 5.1 below illustrates the interplay and dependencies of the processes identified in the area of frequency stability. As already explained, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

There is a high degree of dependency between the processes in the area of frequency. The processes identified have the primary goal of substituting the decrease of the system-inherent inertia of rotating machines from conventional power plants and covering the increasing demand. In particular, grid-forming inverters are also to be developed as a source of supply. The starting points of the process sequence are the technical specification of inertia (F1) (What exactly must be provided?) and the definition of design-relevant system states (F4) (To what extent is inertia required?). Both processes are required input for the downstream processes and must, therefore, be completed at an early stage so as to avoid delays. In the future, a substantial proportion of the demand for inertia is to be covered by grid-forming inverters. Thus, the process for creating a test basis for the certification of grid-forming inverters (F6) is highly dependent on the aforementioned initial processes (F1, F4).

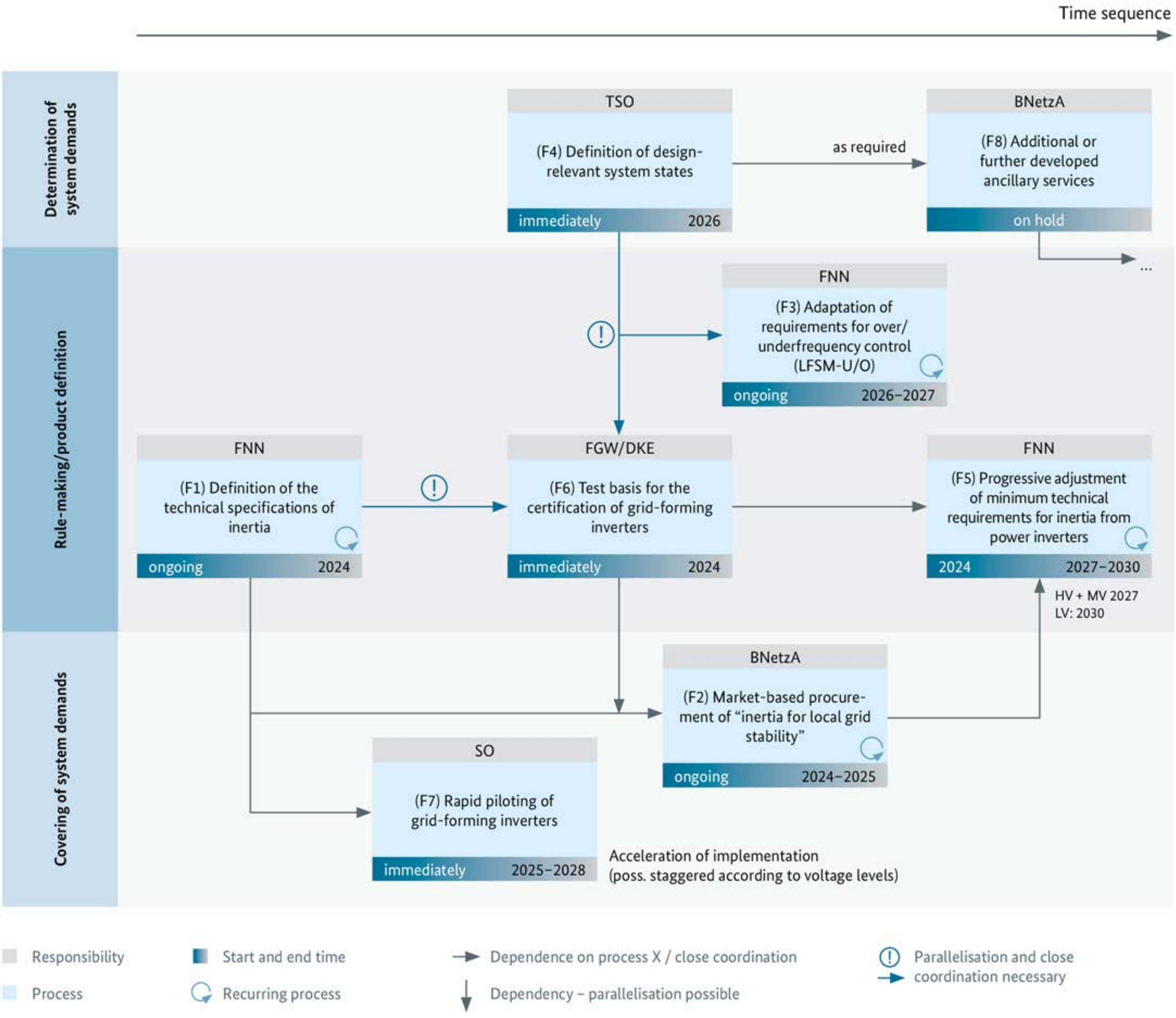

Figure 5.1: Dependencies: Stability processes relating to frequency

These processes must be closely coordinated and synchronised to ensure that grid-forming inverters can provide inertia to the desired specification and in the required quality. The design-relevant system states are also important input variables for adjusting the requirements for the LFSM-U and LFSM-O (F3), so that close coordination must also take place here. One accompanying strand is the coverage of the demand for inertia. A structured procurement concept (F2) must be introduced for this purpose. This procurement concept must define whether and to what extent inertia is to be procured via grid assets, minimum technical requirements or market elements. Together with the process for the test basis for certifying grid-forming inverters (F6), the process for the structured procurement of inertia (F2) forms the basis for deriving minimum technical requirements for inertia from inverters (F5). Early and close dialogue should be sought here.

5.3.2 Voltage

Figure 5.2 below illustrates the interplay and dependencies of the processes identified in the area of voltage stability. As already explained, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

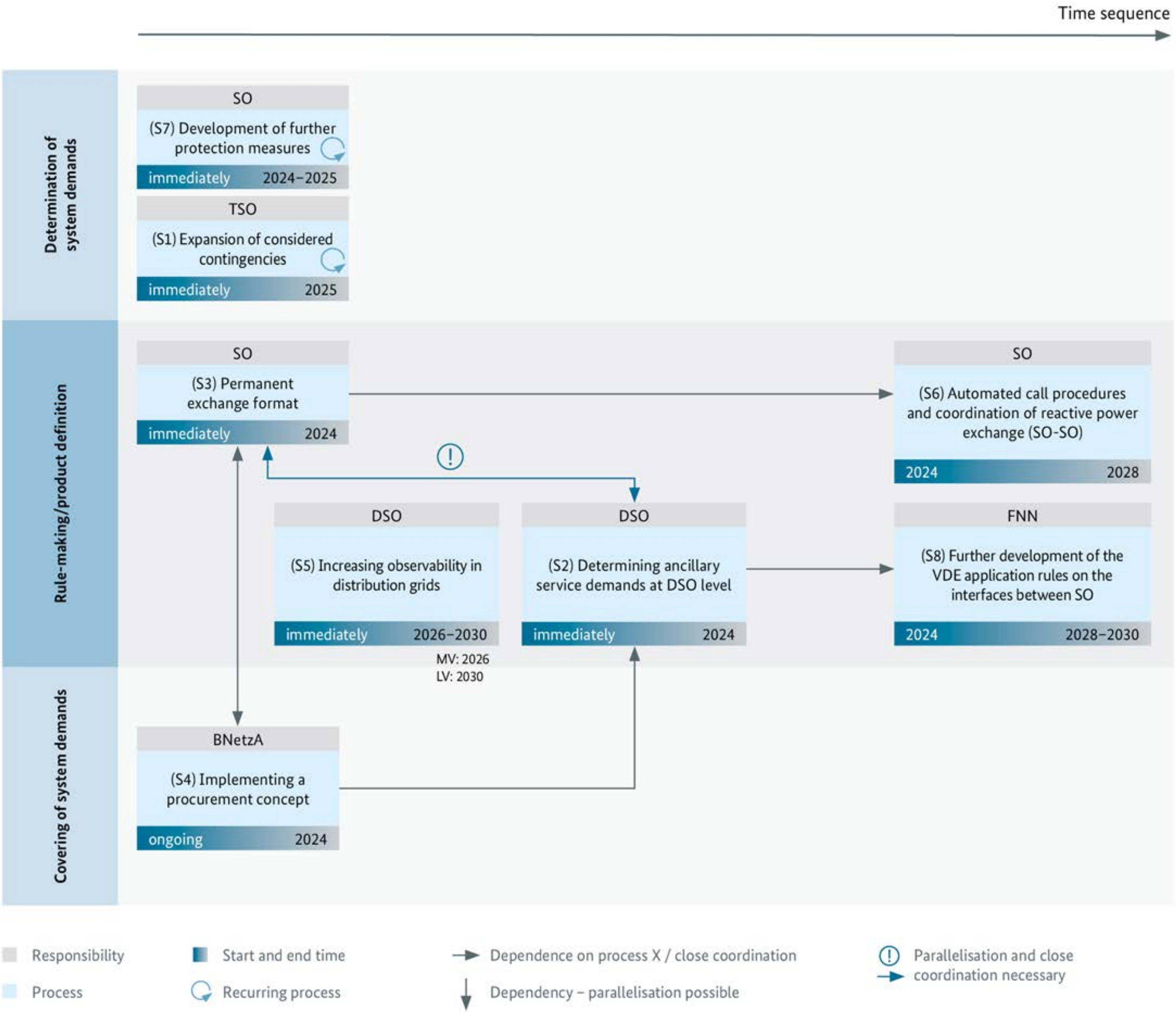

Figure 5.2: Dependencies: stability processes relating to voltage

There is also an increased dependency between the processes in the area of voltage stability. Dependency exists particularly in processes that increase coordination between system operators and enable the targeted and coordinated (vertical) exchange of reactive power between different grid levels. One key element might be the grid expansion plans in line with section 14d Energy Industry Act, which, among other things, also provide for the mandatory identification of the demand for reactive power (S2). This is intended, in particular, to strengthen coordination and the targeted exchange of reactive power between the grid levels. Consequently, there is a strong inter-dependence between S2 and the process of developing a permanent exchange format (S3). With the aid of the S3 process, a procedure is to be established for the exchange of planning and operational data on the provision of reactive power – both between grid users and the grid and between system operators. This includes information on planning system demands, operational call-offs and, if applicable, information on billing. Both processes must be parallelised or thought of together and coordinated. Based on the exchange format (S3), a process for the automated coordination and automated reactive power call-off of grid users and also between system operators should then be developed and initiated (S6). The establishment of the grid expansion plan process also results in the need to further develop the VDE application rules for the interfaces between system operators (S8). This may be necessary either to cover corresponding system demands and/or to define communication requirements for the exchange between system operators and between system operators and grid users. A further key connecting element is the introduction of market-based procurement of reactive power in accordance with section 12h EnWG (S4). The corresponding procurement concept is expected to be published in the first quarter of 2024. The aim here is to examine whether the concept is suitable for efficiently meeting the demands identified in the grid expansion plan. Otherwise, adjustments will have to be made. This may also have an impact on the Technical Connection Rules and the application rules for the interfaces between system operators (S8). Furthermore, the targeted and coordinated exchange of reactive power between system operators must be taken into account in the procurement concept. If this is not regulated directly as part of the concept for the market-based procurement of reactive power, an accompanying VDE-FNN regulation for the provision of reactive power between system operators must be drawn up. This order can also be derived from the procurement concept. Consequently, there is also a mutual dependency between S4 and the process for the permanent exchange format (S3), as this must also be harmonised with the procurement concept (S4). These two processes can be run in parallel and should be carried out in close coordination with each other.

These processes are accompanied by the expansion of the faults to be considered (S1) and the further development of protection measures to maintain voltage stability in disturbed grid operation (S7), which are to be carried out cyclically. Increasing observability in the distribution grid (S5) is also important. Although these three processes (S1, S5, S7) must be considered together with the other processes or serve as input for them, no critical dependency exists. They thus extend the other processes, but they are not a basic requirement for their execution.

5.3.3 Resonance stability

Figure 5.3 below illustrates the interplay and dependencies of the processes identified in the area of resonance stability. As already explained, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

The complexity of resonance stability increases significantly as the power system is increasingly penetrated by decentralised inverter-based grid users. The effects of possible oscillations caused by these new grid users are not yet known and might probably no longer be passively dampened by the inertia of the system in the future. On the way to a climate-neutral electricity system, active measures may be necessary here so as to prevent the unwanted and uncontrolled upswing of grid users and/or grid assets. They must be initiated at an early stage. As the challenges in the area of resonance stability are changing so much, the processes need to be largely re-established. As a result, there are high levels of dependency and a particularly high need for coordination between the various processes. Several iterations between the processes are expected to be necessary, too. This also means that the specified periods are subject to a high degree of uncertainty, since there are still some gaps in knowledge that need to be closed in this new process. As yet, it is not conclusively clear whether and to what extent there is a need at all.

First, standardised criteria and evaluation procedures for resonance stability (R1) must be developed. They serve as the basis for deriving both systemic and grid user-specific requirements (R2). The processes are, therefore, closely interlinked and may overlap in some cases. The definition of requirements at grid user-level (R2) will be realised in practice via minimum technical requirements, which, in turn, are to be considered together with certification and corresponding test procedures for the grid user properties (R3). These processes are thus directly dependent on each other, whereby the highest possible degree of parallelisation should be achieved. Practical experience in this comparatively new field of stability is necessary to define the systemic needs and to derive minimum technical requirements (R2). This experience is achieved on the one hand through accompanying research, but in particular through coordinated “field tests” to gain practical experience with grid-forming inverters (R5). The experience and findings gained from the field tests are, therefore, input for (almost) all identified resonance stability processes (R2, R3, R4) and must be closely harmonised with the minimum technical requirements (R2) in particular. Depending on the systemic requirements and corresponding demands, the structured procurement of products and measures to maintain resonance stability may be required (R4). This is a matter of a downstream process once the corresponding system demands are known. What must be taken into account is the fact that any procurement procedure may have repercussions on the minimum technical requirements (see also the overarching process of system stability (V4)).

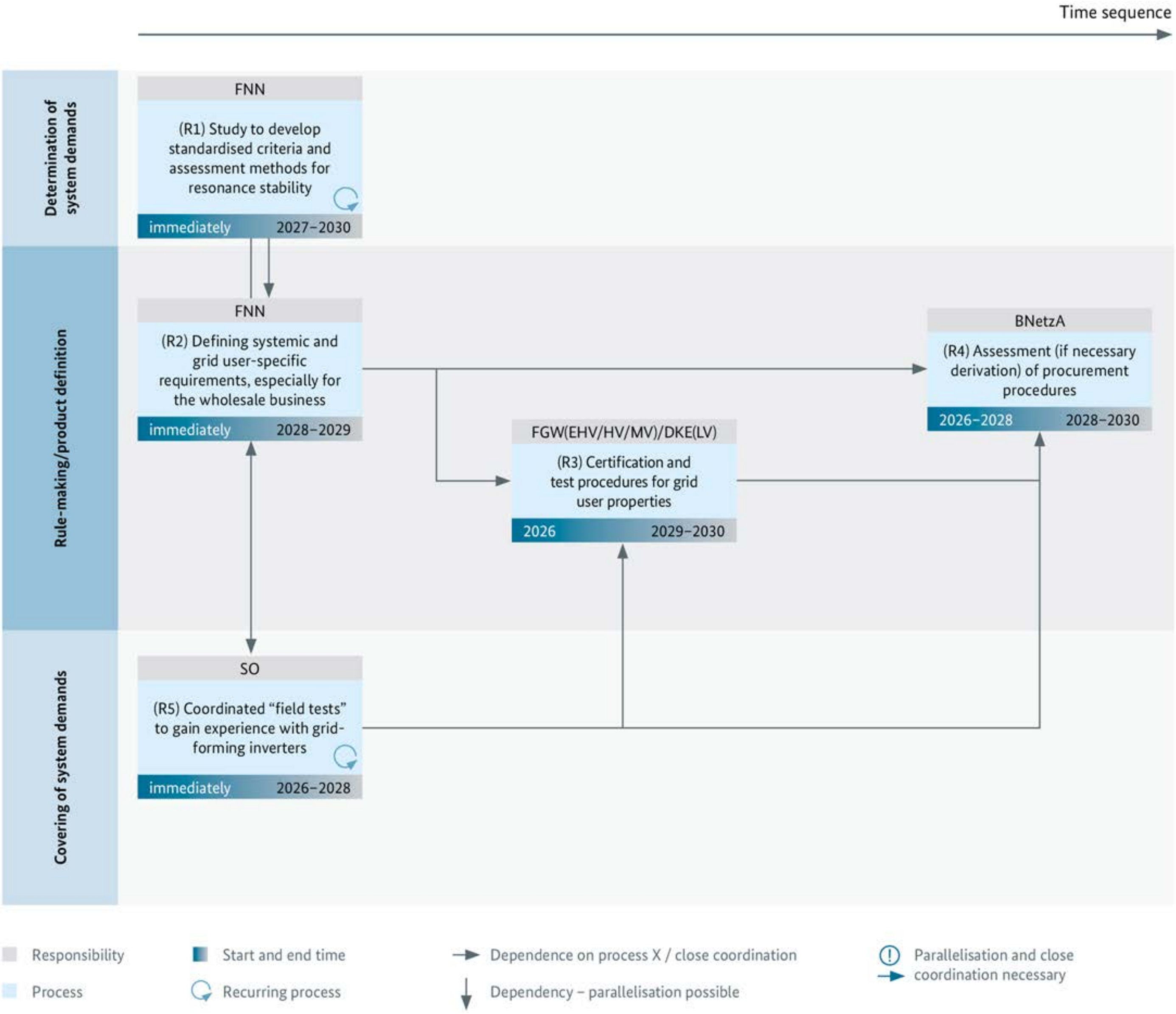

Figure 5.3: Dependencies: Stability processes relating to resonance stability

5.3.4 Short-circuit current

Figure 5.4 below illustrates the interaction and dependencies of the stability processes identified in the area of short-circuit current. As already explained, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

In the field of short-circuit current, the processes are sequential and the dependencies are relatively straightforward. This means that, in most cases, only partial parallelisation is possible and there is a need for close coordination. The starting point is the development and integration of an evaluation methodology for short-circuit currents in the inverter-dominated system (K1). The aim here is to examine existing approaches to see whether they are also appropriate in the inverter-dominated system or whether adaptations or alternatives should be used. This assessment methodology serves as input for creating a guideline for DSO on the risks of increasing short-circuit currents and suitable remedial measures (K4). This methodology is equally required to assess the demand for short-circuit current in the distribution grid and the technical options for supply from the distribution grid (K3). Building on the existing evaluation methodology (K1) and the demand and technical possibilities from the distribution grid (K3), establishing forward-looking monitoring of the development of the short-circuit current level is essential. The aim here is to forecast developments all along the planning perspective so that countermeasures can be taken sufficiently in advance if required. Parallel to the forecasting process, the issue of the spread of discharge voltage patterns in the grid (K6) must be analysed in a focused manner.

The process chain described is flanked by the structured procurement of – possibly additionally required – short-circuit current (K2). The process for market-based procurement already enshrined in section 12h EnWG serves this purpose, although it remains to be seen whether and to what extent the targeted procurement of inertia already covers the demand for the short-circuit current required. Depending on how the procurement concept has been designed, this may also necessitate the adaptation of the Technical Connection Rules and corresponding certification processes.

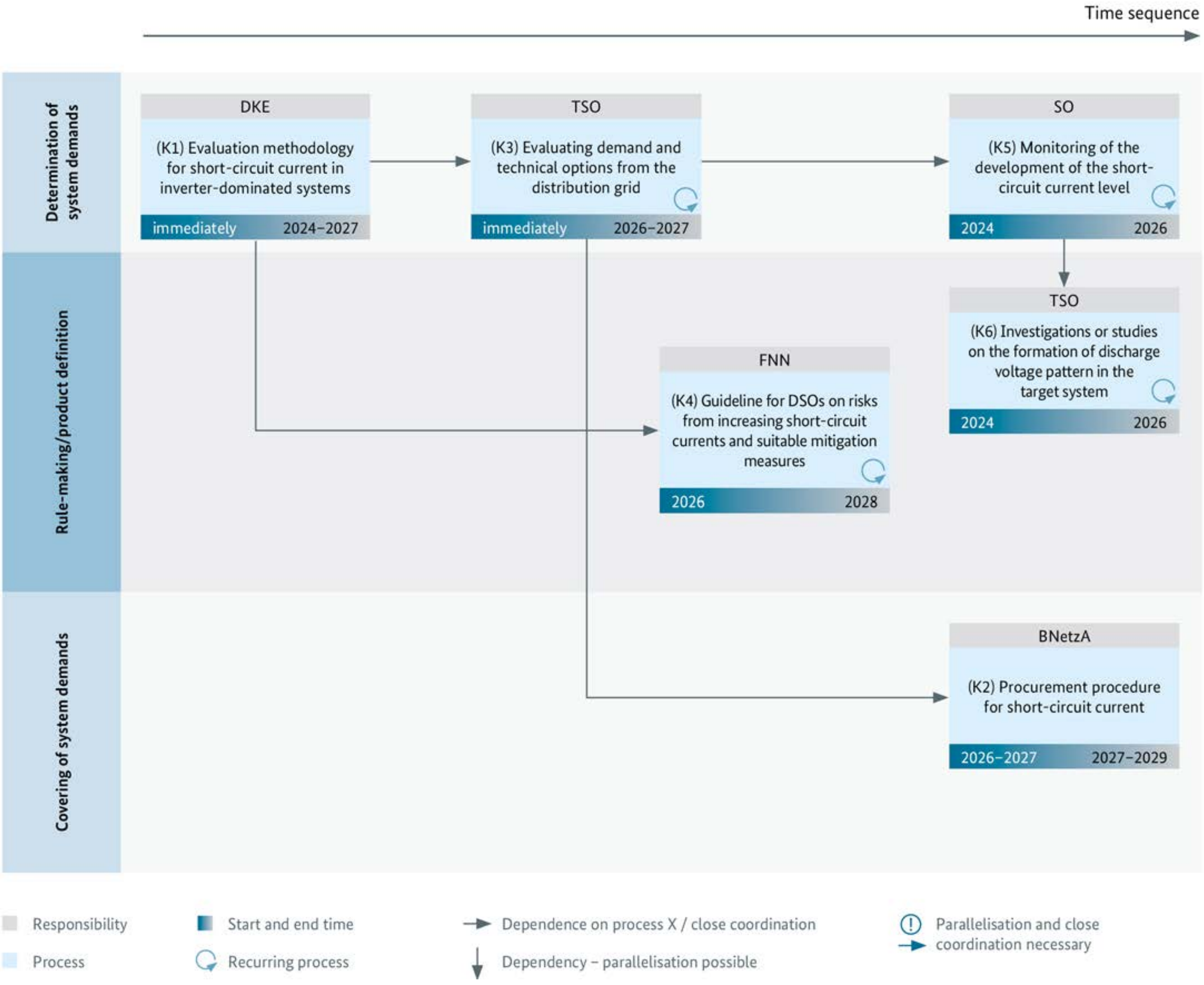

Figure 5.4: Dependencies: Stability processes relating to short-circuit current

5.3.5 Angular stability

Figure 5.5 below illustrates the interplay and dependencies of the processes identified in the area of angular stability. As already stated, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

In the area of angular stability, experts identified “only” three processes, which are to be regarded as a process chain. The first step is determining the demand for synchronising “phase angle power” (W1). If a demand is identified here, it will be necessary to assess which technical options can meet this demand sensibly and efficiently (W2). This should also enable the inclusion of inverter-based grid users to cover the demand for angular stability (W3). This process may overlap with the assessment of the supply options (W2) and there is a two-way interaction, as inverter-based grid users can be considered as a technically viable option for meeting demand.

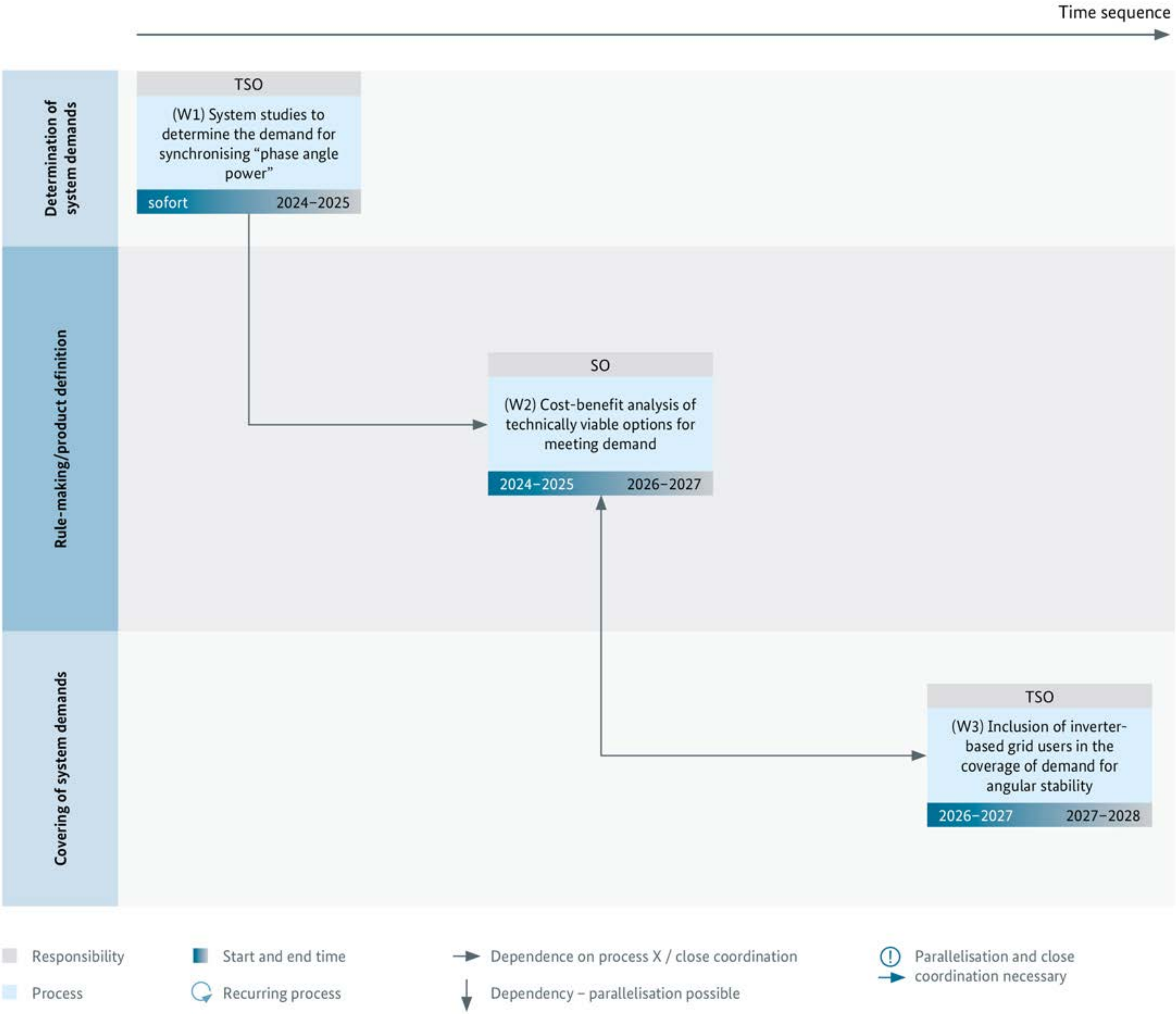

Figure 5.5: Dependencies: Stability processes relating to angular stability

5.3.6 System control

Figure 5.6 below illustrates the interplay and dependencies of the stability processes identified in the area of system control. As already explained, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

In the area of system control, the processes identified are largely independent and can be fully run in parallel. The only dependency is between the identification of critical factors and grid states to ensure the necessary system security (B1) and the testing or further development of the (n-1)-principle (B2). The issue of (n-1)-security represents an essential core of secure energy supply, which means that this would have to be adapted with regard to newly identified critical grid states.

Figure 5.6: Dependencies: Stability processes relating to system control

5.3.7 Grid and supply restoration

Figure 5.7 below illustrates the interaction and dependencies of the stability processes identified in the area of grid and supply restoration. As already explained, these are adaptations and further developments of existing processes or the need to review existing processes, or new processes to be set up.

There are various interdependencies between the processes in the area of grid and supply restoration. However, they are designed in such a way that the processes can be run in parallel. The results and findings of the individual processes are to be utilised profitably in further processes, so that the implementation of the processes should be closely coordinated.

The core element is the initiation of a network of experts on the topic of grid and supply restoration (NVWA2). The aim is to discuss relevant issues and develop recommendations for action and proposed solutions. They can serve as input to the TSO, who continue to coordinate and control the grid and supply restoration. Consequently, these results also serve as input for the process of defining the role of distribution grid islands in the restoration of the grid and supply (NVWA4) and for the process of conceptualising and designing framework conditions for extended testing of subsystems (NVWA3). Moreover, the network of experts should provide advice on the process of incentivising the capability of new and existing grid users (NVWA5).

The conception and design of framework conditions for activities for the extended testing of subsystems and exercising of processes (NVWA3) also depend on the role of the distribution grids and the technology available. There is, therefore, an increased need for coordination, especially with the process for defining the role of distribution grids (NVWA4), but also with the incentivisation process (NVWA5).

The determination of the demand for secured generation capacity and energy for national restoration per region for black-start units and partner units (NVWA1), on the other hand, can be carried out without any increased coordination effort with the other processes.

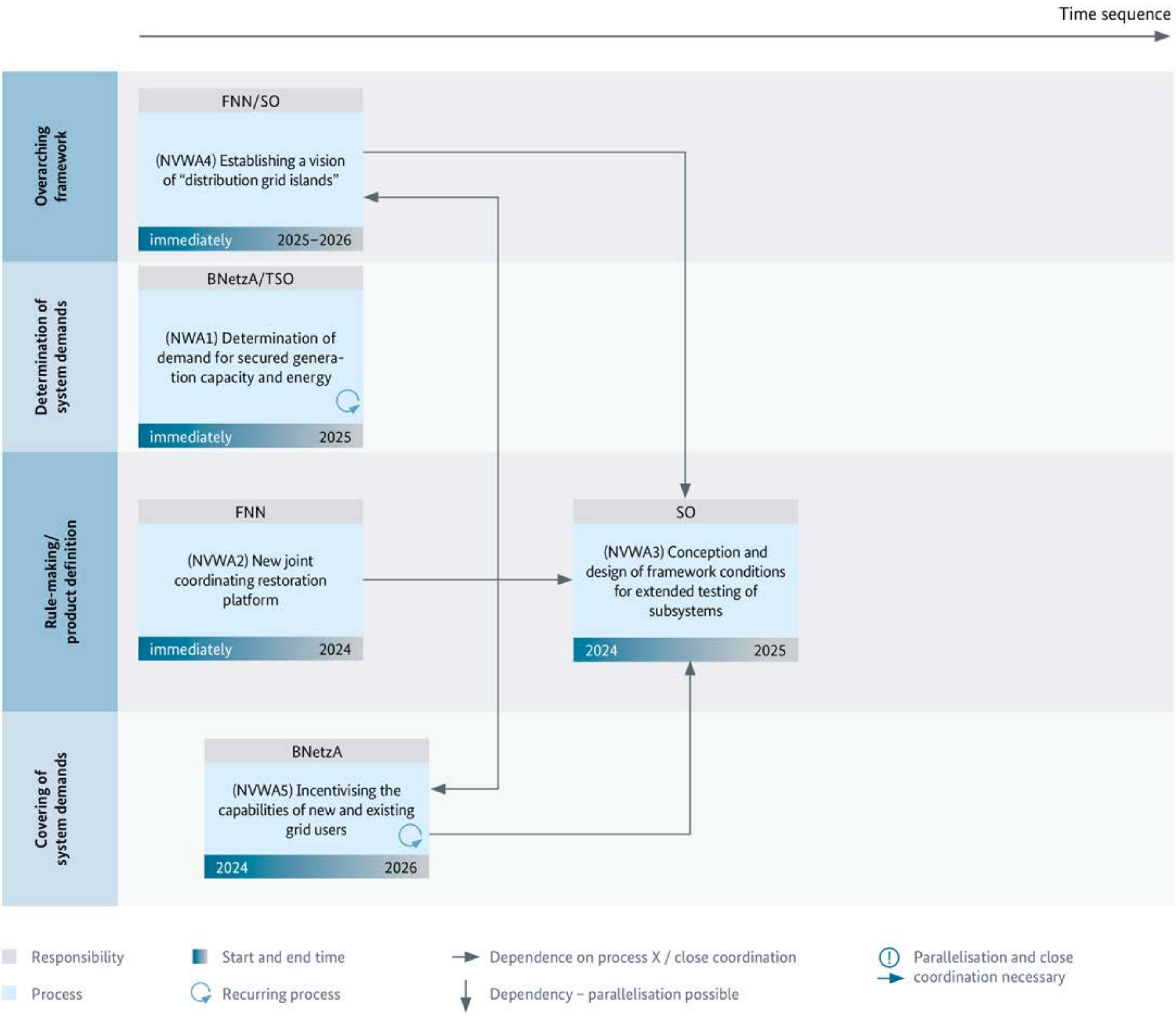

Figure 5.7: Dependencies: Stability processes relating to grid and supply restoration

6 Roadmap perspectives

Chapter 5 presented the stability processes developed for each topic and showed their interdependencies within the respective topic. Overarching processes were also identified and presented. In chapter 6, the processes identified in chapter 5 will now be considered and categorised from a higher-level or implementation-oriented perspective. In doing so, the perspectives of fields of action, responsibilities and sub-goals are considered. Figure 6.1 shows the different perspectives of the roadmap.

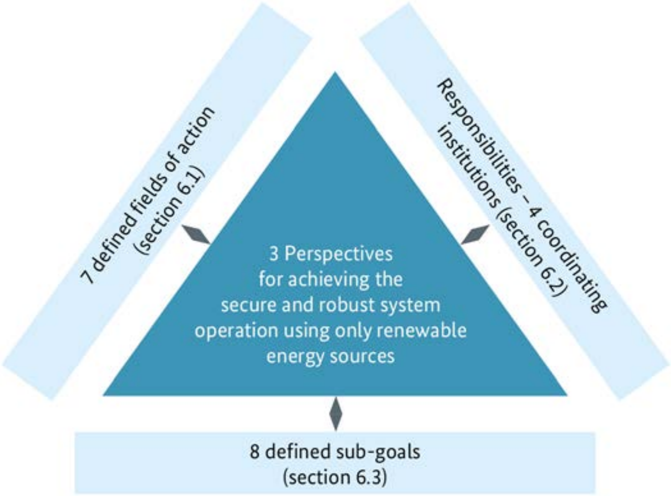

Figure 6.1: Roadmap perspectives

Both the overarching processes of system stability and the stability processes for each topic pursue the goal of achieving the secure and robust system operation, even when relying only on renewable energy sources. To this end, each of the processes contributes to one or more specific sub-goals, which are described in section 6.3. The processes are also assigned to different categories, which are based on relevant fields of action. The corresponding visualisation of the roadmap along the fields of action ("what") is presented in section 6.1.

In sections 6.2 and 6.3, the processes are grouped according to the coordinating institutions ("who") and sub-goals. Looking at the processes from different perspectives reveals inter-relationships and interdependencies across topics, which can facilitate the complex execution of the processes. The resulting roadmap milestones are described in chapter 7.

6.1 Processes according to the fields of action

Considering the processes according to topics individually (see chapter 5) is not sufficient, since the fields of action of determining and satisfying system demands, for example, are relevant in all topics. That is why grouping the processes along the fields of action is expedient. To this end, the processes identified by the experts were categorised into seven relevant fields of action. Each of these fields of action is a key component for the secure and robust system operation using only renewable energy sources. Such categorisation according to fields of action permits the topic-specific stability processes to be combined, since, for example, the derivation of design-relevant cases for determining demand in the area of voltage (process S1) and frequency (process F4) must be considered together. This supports the enactment of the roadmap. What should be explicitly pointed out is that, together with the experts from the industry, only the processes with the greatest need for action or new processes to be established were focussed on for the analysis according to fields of action. Individual processes may be relevant for several fields of action.

How should the visualisation of the processes be read? The overarching processes of system stability are shown in blue, and the topic-specific processes in grey. Any vertical arrows indicate dependencies between the processes. Grey arrows mean that a close exchange between the processes is necessary or that they partly overlap with each other. The responsible process coordinators are shown to the left of the processes. SO stands for system operator and includes both TSO and DSO. The basic harmonisation and coordination of the processes takes place as part of the implementation of the roadmap, see chapter 8.

6.1.1 Overarching system requirements and framework

This field of action includes political objectives as well as descriptions for the target system and the defined system security. Processes in this field of action, therefore, predominantly include centralised definitions, fundamental decisions and processes for setting the framework. These processes are designed to address risk at an early stage and ensure certainty of action. In concrete terms, target figures must also be developed for the various topics so that further processes can be aligned with them and corresponding quantification of demands is also possible. This might be, for example, a time interval that specifies the time by which full supply should be restored after a blackout. Due to the orientation of the processes in this field of action, they are often the sovereign responsibility of the BMWK or the regulatory authority BNetzA or are used for coordination within the industry and are then coordinated by the VDE FNN or the system operators. Figure 6.2 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *"How should the visualisation of the processes be read?"*

The field of action comprises six processes. The key element is the development of resilience requirements for the system so that design-relevant system states can be derived and system demands quantified. Industry processes relating to specific topics, such as the role and coordination of distribution grids with regard to grid and supply restoration, are also provided for. One key component of this field of action is the enabling of broad field tests for extended capabilities to maintain system stability. Since they serve the overarching goal of system security, it is vital that uncertainties and regulatory obstacles that may hinder implementation are successively identified and then eliminated.

Due to their high steering effect, all processes in the area of action should start at once and be carried out within the next one to three years.

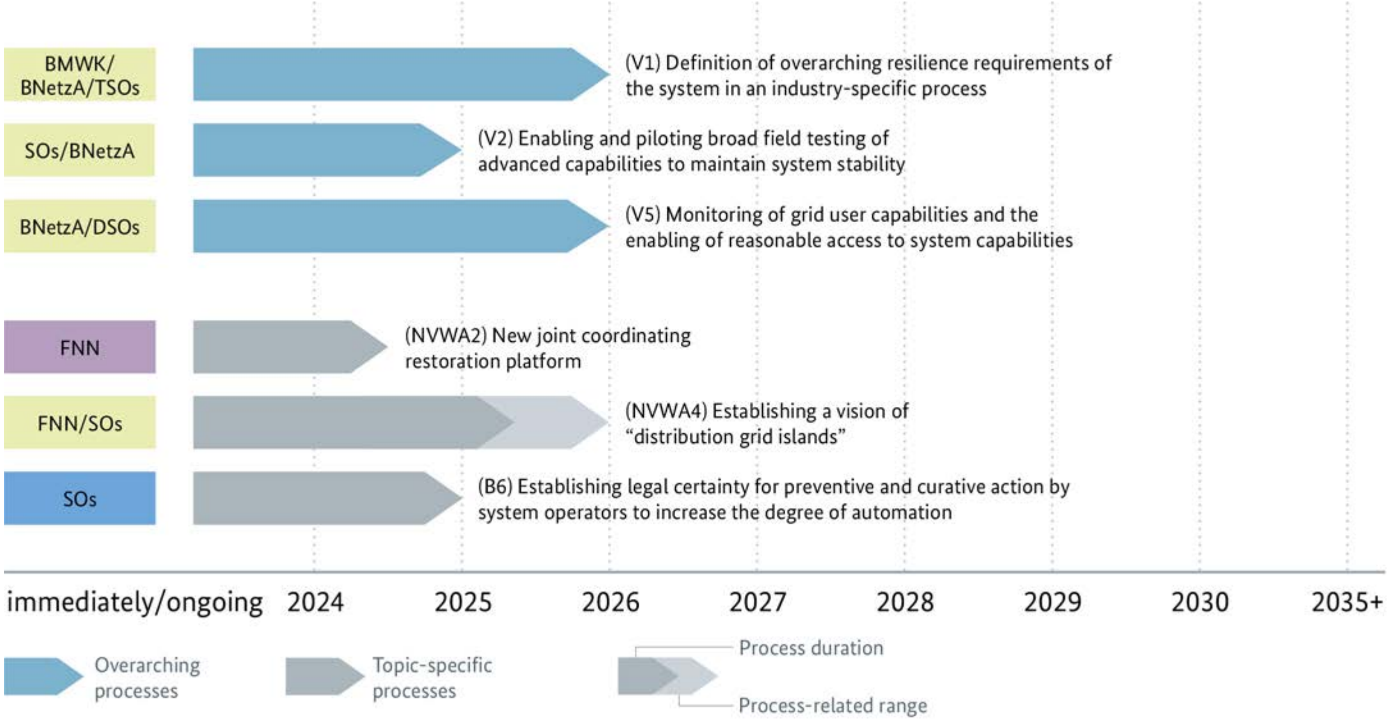

Figure 6.2: Processes in the field of action: overarching system requirements and framework

6.1.2 Determining the system demands

System operators utilise ancillary services and system stability measures that ensure the secure and robust system operation at all times. To this end, it is essential that the extent to which the corresponding measures are required is known at all times. This field of action encompasses all the stability processes that address the issue of determining system demands. In Germany, overall system responsibility lies with the transmission system operators, which is why a large proportion of the processes for determining system demands are the responsibility of the TSO. Since many of the potential future supply options are connected to the distribution grid, the distribution system operators also have an important role to play. Figure 6.3 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *"How should the visualisation of the processes be read?"*

The field of action comprises 14 processes. The core task is to translate the overarching system requirements into concrete demands for ancillary services and measures for system stability and to quantify them. This is to be ensured using process V3. The first step is to expand the design-relevant system states and the failure cases that are being considered with regard to new future requirements. Should there still be gaps in the methods available for determining system demands (e.g. for the short-circuit current in the inverter-dominated system), they must be closed.

The identified system demands must be reported in a transparent manner so that any potential gaps in provision can be identified and addressed at an early stage. In particular, this also calls for forecasts of future demand, as is already the case today in the accompanying documents of the network development plans of the TSO and the DSO. In the future, part of the demand analyses will be determined in a structured form in the regular System Stability Report.

The determination of the system demands must be carried out promptly. The corresponding processes are almost all due to start immediately and are largely expected to be completed in the coming years.

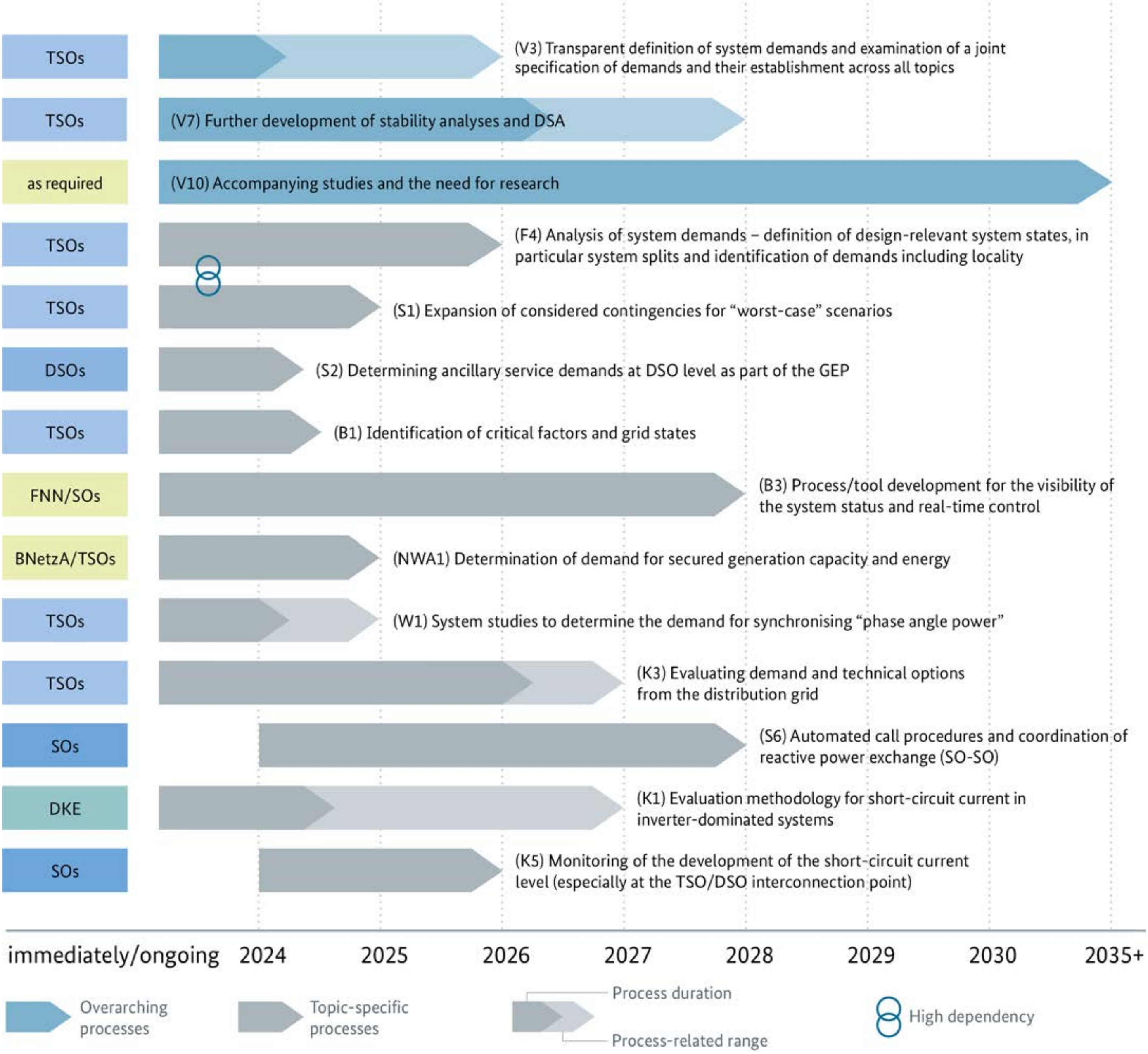

Figure 6.3: Processes in the field of action: Determining the system demands

6.1.3 Covering the system demands

The demand for the ancillary services and system stability measures identified must be able to be satisfied at all times so that the system can be operated safely and robustly. Possible changes in demand over time must be taken into account. All the processes that address the coverage of the demand for ancillary services and measures for system stability are brought together in this field of action. In terms of covering system demands, this can mean both that countermeasures are taken to reduce the demand for ancillary services (e.g. the targeted reduction of power ramps) and that sources of supply are tapped. Figure 6.4 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *"How should the visualisation of the processes be read?"*

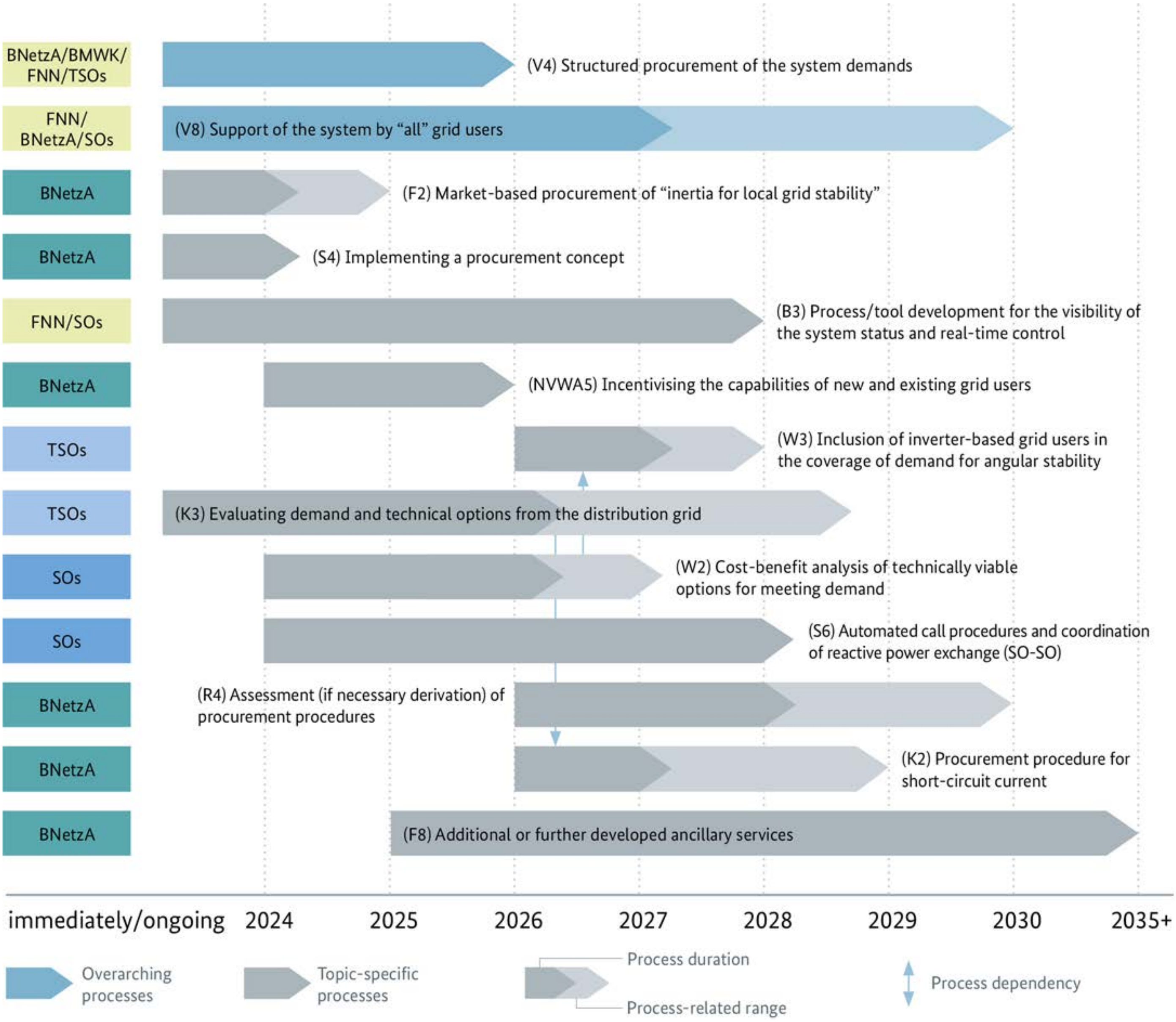

Figure 6.4: Processes in the field of action: Covering the system demands

The field of action comprises 13 processes. The demands can be covered in various ways. One option is to oblige grid users to provide certain features via minimum technical requirements. This makes particular sense if the provision is either associated with little effort or is required to such an extent that (almost) all grid users must participate. This option is also useful if properties are fundamentally and permanently required for secure and robust system operation. Minimum technical requirements are decreed by the VDE FNN. As the System Stability Roadmap aims to highlight the requisite adaptation processes and does not address the specific design of these regulations, technical rules, regulations and instructions are summarised in a separate field of action (cf. section 6.1.4). Alternatively, or additionally, system demands can also be procured market-based. Different market designs are possible and the expected supply and demand should be considered. On the one hand, market-based processes are useful if supply exceeds demand and the market can, therefore, allocate the available options efficiently. On the other, market-based procurement processes can incentivise investment, which is particularly useful when demand exceeds supply or will do so in the future. This way, for example, grid users can be incentivised to retrofit certain system-supporting features. This is also known as increasing static efficiency. Responsibility for organising the processes for the market-based procurement of ancillary services lies primarily with the BNetzA. System demands can also be covered by the system operators' assets and, in some cases, by means of the coordinated exchange across grid levels.

During implementation, it is important to ensure that the most efficient option or combination of options can be selected. This depends largely on the level of demand and available supply over time, meaning that the efficiency of various provision options may also shift by 2045.

The processes in this field of action, therefore, address extensions and additions in terms of:

- the structured and, where applicable, market-based procurement,
- the incentivisation of additional options for covering the demand,
- any potentially additionally required or further developed ancillary service products.

System demands must be covered at all times, which is why many processes are going to start immediately or have already started. With regard to stability measures whose demands cannot yet be reliably anticipated, the processes must be synchronised in line with the determination of demands.

6.1.4 Technical rules, regulations and instructions

To ensure safe and robust system operation, all grid users must follow rules and regulations. The connection rules of the VDE FNN, which regulate grid access, are of particular relevance here. The regulations are already revised on a cyclical basis, in line with changing system requirements. However, the fundamental transformation to an inverter-based electricity system that relies on renewable energies is increasing the pressure to act even further and this will necessitate a large number of adjustments and further developments to the regulations. This field of action encompasses all processes that either involve the adaptation or further development of regulations or the creation of technical instructions. Certification also falls under this field of action. Figure 6.5 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *"How should the visualisation of the processes be read?"*

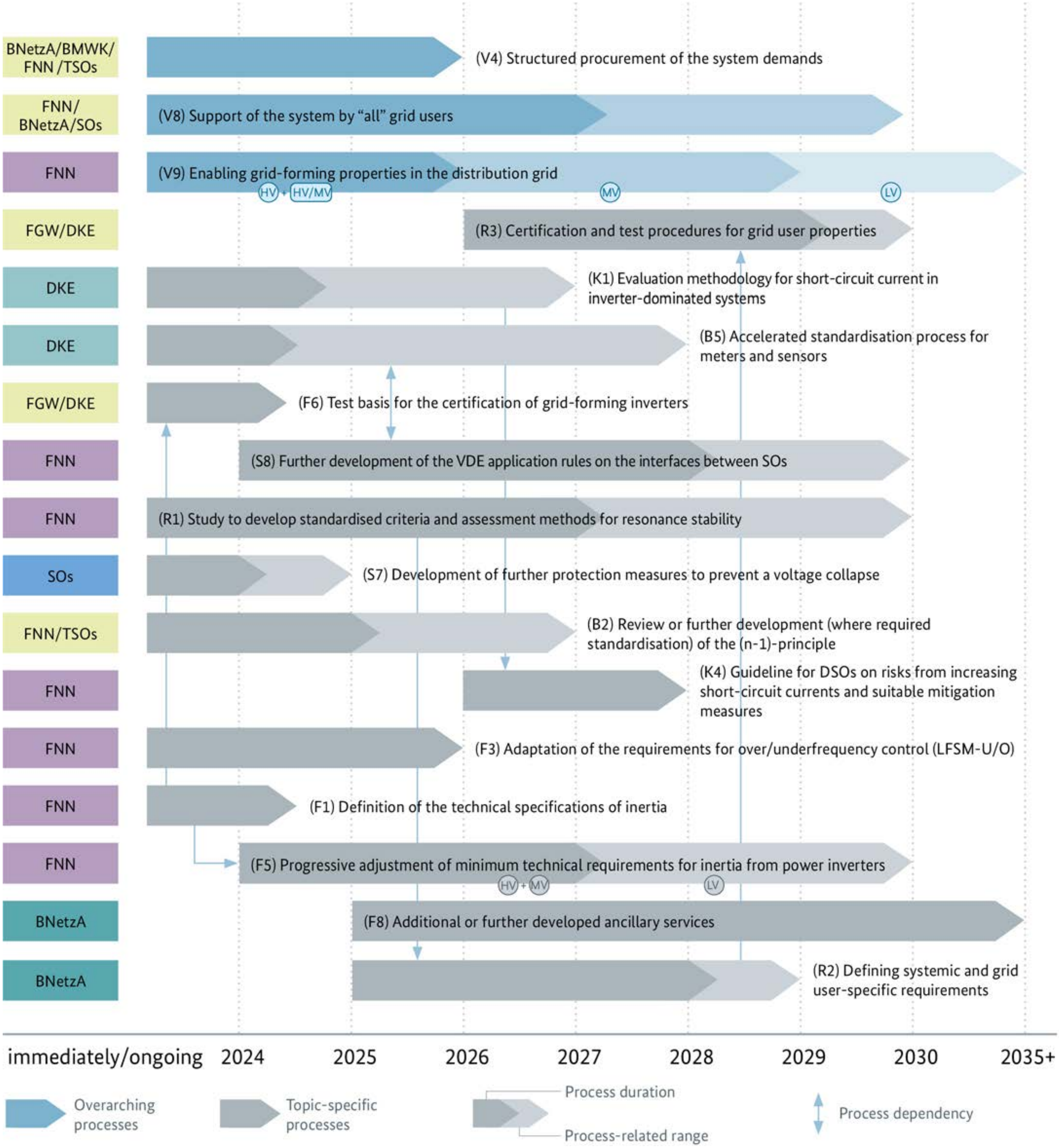

Figure 6.5: Processes in the field of action: Technical rules, regulations and instructions

The field of action comprises 17 processes. The key component is the further development of the Technical Connection Rules for an inverter-dominated system. This also includes the development and harmonisation of evaluation methods for newer stability phenomena such as resonance stability or the evaluation of short-circuit currents in inverter-dominated systems. A further component is the introduction of additional system stability measures, such as the primary control based on network security as part of the LFSM-U and LFSM-O. The aim of these further developments is to enable the increased integration of grid-forming inverters into the system. These will play a key role in maintaining secure and robust system operation using only renewable energy sources, which is why they have been identified as a separate field of action (cf. section 6.1.6).

In accordance with section 19 of the Energy Industry Act (EnWG), the VDE is the body authorised to adopt the general minimum technical requirements. The VDE FNN is the executive body of the VDE, which is why responsibility for the processes in this field of action lies primarily with the VDE FNN.

The area of responsibility is supplemented by the German Commission for Electrical, Electronic & Information Technologies (DKE) and the Federation of Wind and other Decentralised Energies (FGW), particularly in the areas of testing and certification as well as short-circuit current assessment. The regulations must be adapted as soon as possible so that as many grid users as possible are equipped with the corresponding properties early on. This is why the processes must basically always be initiated at the earliest possible stage. However, any revision must be synchronised with the knowledge gained, which means that it will not always be possible to complete the process in the short term. Nevertheless, due to their importance, the processes should start at an early stage. Some of them have already started. Potential inefficiencies in the process itself can be knowingly accepted here. All processes in this area of action should be completed by 2035 at the latest.

6.1.5 System resilience

The electricity grids are the “backbone” of the energy transition and must be developed further in line with the energy transformation. Besides the requisite grid expansion, making even better use of the existing grid infrastructure and ensuring that grid operations remain robust are also important. For this to happen, the system must be resilient. Resilience encompasses the system’s robustness, adaptability and ability to recover from internal and external influences. This field of action encompasses all the processes that increase the resilience of the system. Figure 6.6 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *“How should the visualisation of the processes be read?”*

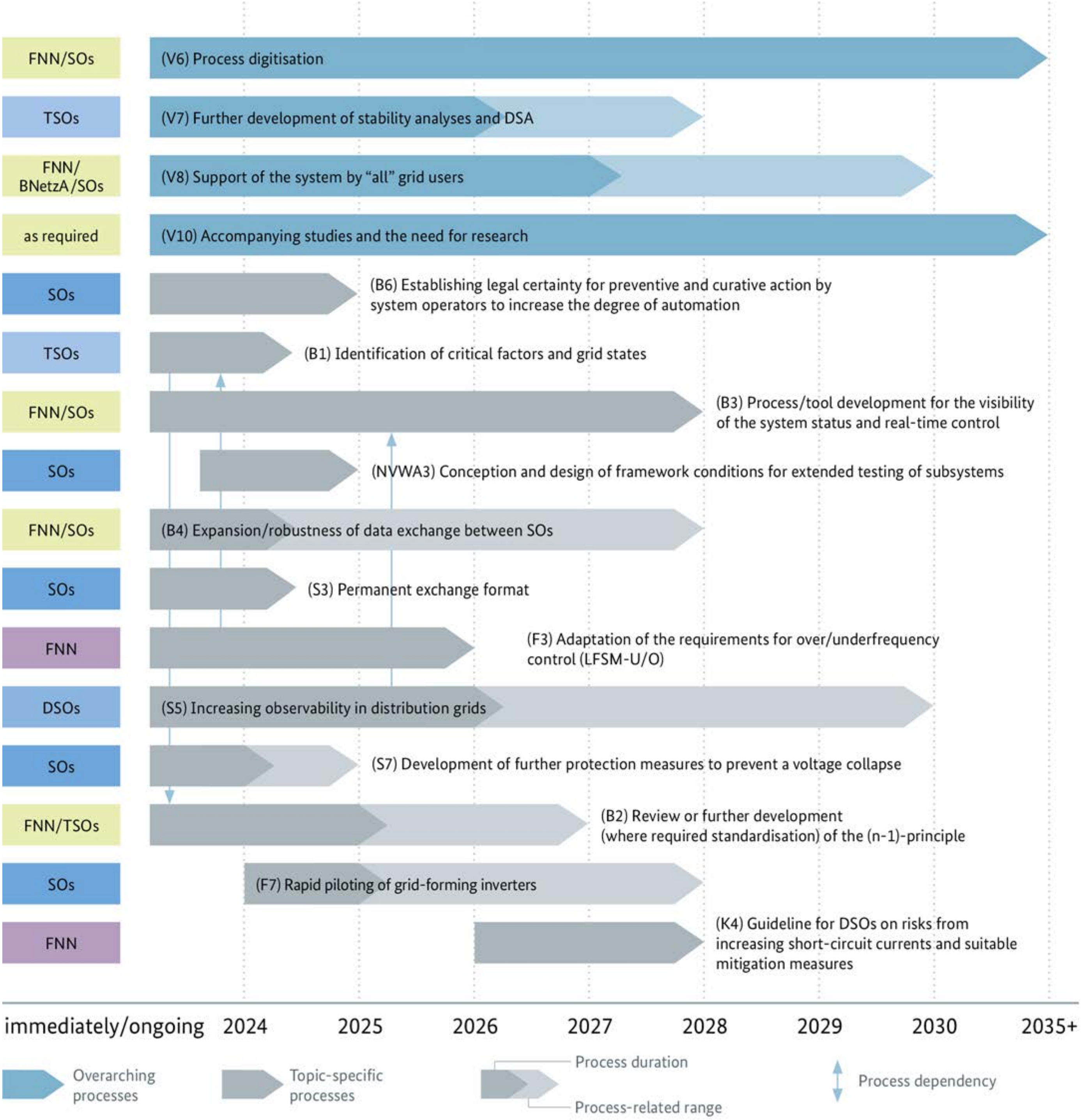

Figure 6.6: Processes in the field of action: System resilience

The field of action comprises 16 processes. The focus of the processes is on grid operation. The processes are intended to increase observability in the grids and enable potentially critical grid situations to be recognised and rectified at an early stage. To this purpose, the horizontal and vertical exchange between the system operators is to be strengthened further. The transformation to an inverter-based system that relies on renewables may also make it necessary to further develop the (n-1)-principle, since there will be more periods with significant surplus generation, for example. Moreover, operational experience must be gained with grid-forming inverters, which are regarded as a key technology. Integration must succeed, without jeopardising system resilience.

Coordinating the tasks for the individual processes is primarily the responsibility of the transmission and distribution system operators and the VDE FNN. Since system resilience is an overarching goal, the BNetzA and the BMWK are also directly involved in some of the stability processes.

The processes are to be started immediately and largely carried out over the next five years.

6.1.6 Grid-forming inverters

Grid-forming inverters will play a key role in maintaining safe and robust system operation using only renewable energy sources. Almost all future grid users (PV, wind turbines, battery storage units, heat pumps, charging infrastructure for electric mobility including bidirectional charging, etc.) are connected to the grid via inverters. There is, therefore, huge potential for implementing them in a grid-forming way. With the right design, grid-forming inverters can substitute the system-supporting properties of large power plants and provide almost all of the requisite ancillary services and measures for system stability. However, a high penetration of grid-forming inverters can also be a burden on the system and has not yet been conclusively researched (see V10). For example, it must be ensured that the inverters do not resonate and vibrate against each other, since this would jeopardise system stability. There is a lack of practical experience and specifications in this area. Grid-forming inverters can support grid and supply restoration, but can also lead to unwanted and hard-to-identify grid islands, which may even pose a risk to life. This field of action, therefore, brings together all the processes that should enable grid-forming inverters to be a key technology in maintaining stability in our system. Figure 6.7 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *“How should the visualisation of the processes be read?”*

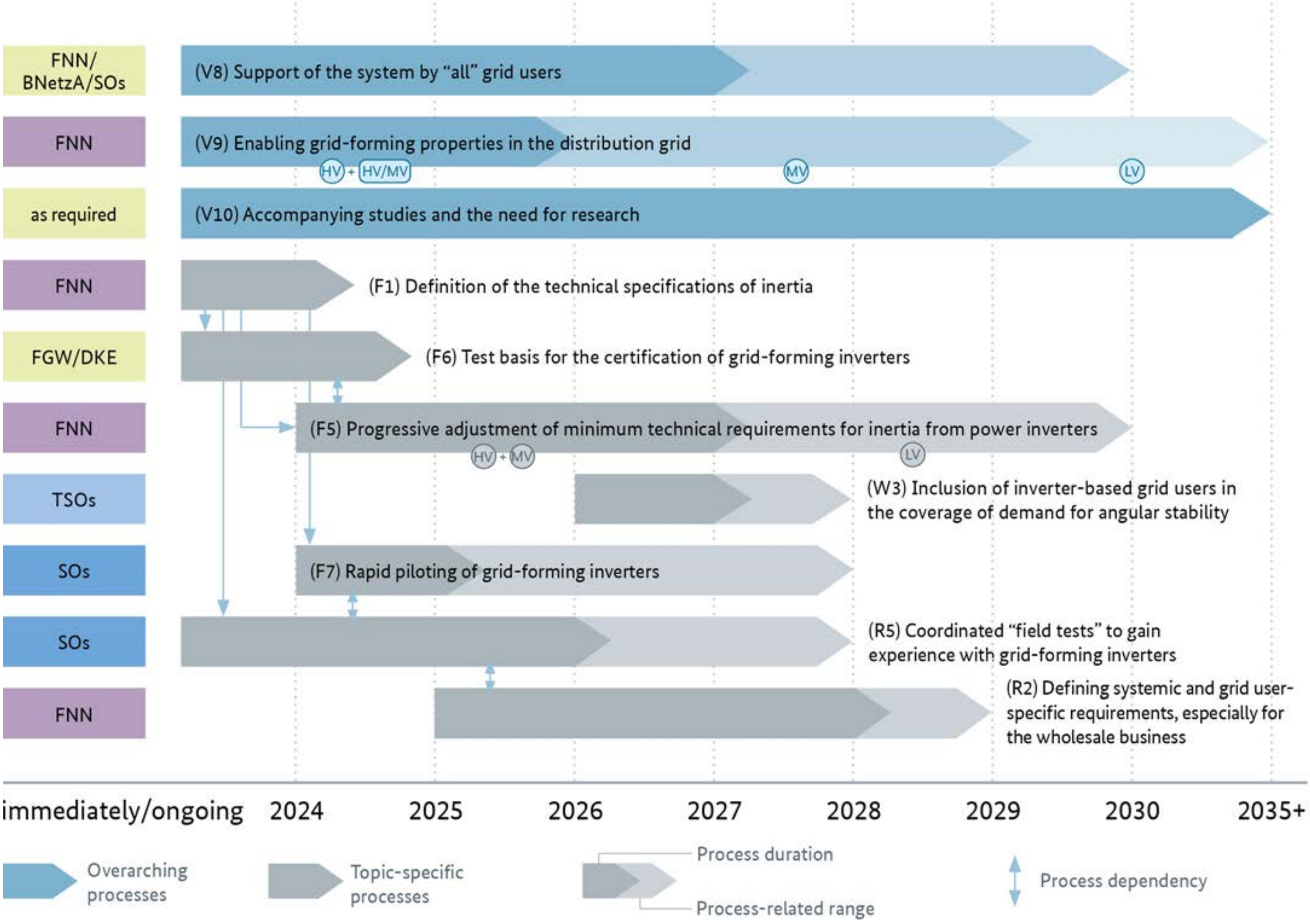

Figure 6.7: Processes in the field of action: Grid-forming inverters

The field of action comprises ten processes. Grid-forming inverters are not a proven technology on the mass market. In principle, this offers huge potential, but various aspects still need to be clarified. This is where the processes in the field of action come in. On the one hand, experience needs to be gathered and, on the other, corresponding technical requirements need to be specified. These activities need to be carried out hand in hand and require appropriate accompanying research. Grid-forming properties are not intended in principle and for all grid users. Rather, it is important to clarify where this is sensible and manageable.

The overall aim is to enable grid-forming properties in the system so as to benefit from the stabilising advantages. However, there is still a great need for action here, which is why the associated processes will take five or more years. The aim is to tap any potential that can be utilised in the short term at an early stage and so gain insights for expansion into other areas.

Process coordination in this field of action is broadly diversified. What is to be expected is that accompanying research will be necessary to a greater extent.

6.1.7 Research, field testing and piloting.

The transformation to a climate-neutral system based on renewables involves making significant changes. Unlike the current system, it is not possible to draw on several decades of operating experience. New technologies such as grid-forming inverters and their interactions in the electricity grid have not been fully researched, for example. The grid and supply restoration in a large inverter-dominated inter-connected system has also not yet been tested. This field of action addresses these and similar issues and brings together all the processes for piloting, research and conducting field tests. The additional activities should be based on findings from ongoing research projects. For the field tests, it is important that they can be on a large scale – up to the GW range – in order to gain truly fundamental experience within a European framework. This may also require some adjustment to the existing regulatory framework. Experience from other countries where grid users on this scale are already being installed should be taken into account. The primary goal here is to gain experience and knowledge. The findings can then be used in further processes, e.g. to derive technical connection rules or to revise the grid restoration plans. Figure 6.8 below shows the processes assigned to the field of action. Information on the visualisation can be found in the introduction to section 6.1 *“How should the visualisation of the processes be read?”*

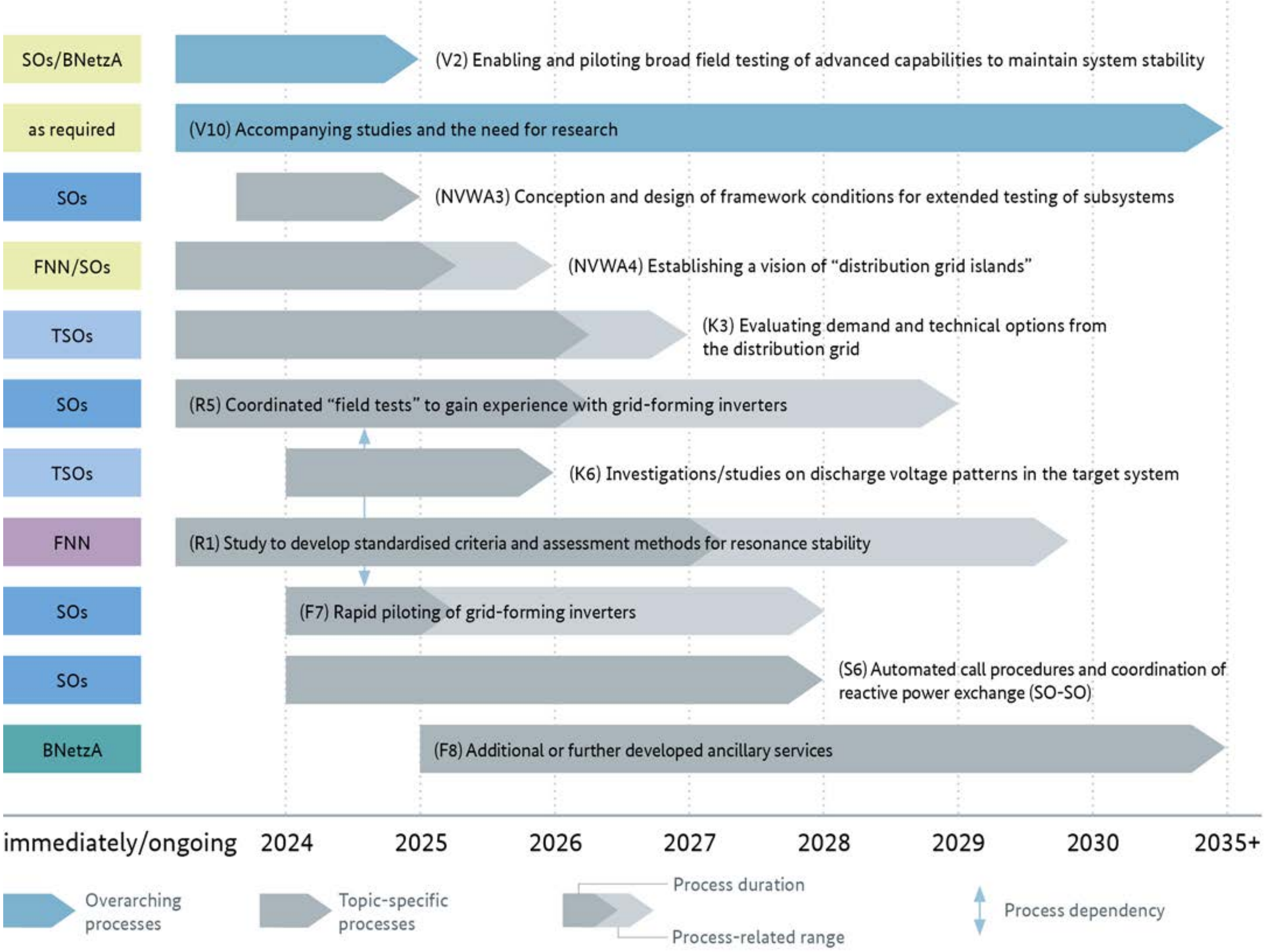

Figure 6.8: Processes in the field of action: Research, field testing and piloting.

The field of action comprises eleven processes. One key element for the safe and robust system operation using only renewable energy sources is testing and gaining experience during the transition period. This makes it possible to gather experience at an early stage, to make adjustments and take well-founded decisions. Important topics will be the restoration of the grid and supply in the system with a large number of decentralised fluctuating renewables, the integration of grid-forming inverters into the system, and general stability issues in the decentralised inverter-dominated system, particularly as regards resonance stability.

The processes must all be started promptly so that findings and partial results can be fed into further processes at an early stage. The duration of the process is based on the ramp-up to achieving 100% renewable energy sources in Germany, so that, on the one hand, experience can be gained gradually and, on the other, this experience can still be incorporated. The coordination of the processes and the tasks in the processes are more broadly diversified. This means, for example, that it must be ensured that target figures are clearly defined and that pilot trials and field tests can be carried out quickly. As part of their system responsibility, system operators must ensure that demands are met and that cooperation between system operators is strengthened further. Various technical coordination processes and the (further) development of methods and calculation procedures may become necessary, and this should be supported by the VDE FNN. The central component will be research facilities that are to develop the relevant findings. Thus, structured research funding in Germany is a central instrument in this field of action and – if not already in place – must be aligned accordingly. Due to the urgency of the “Easter Package” objectives, short-term findings will also have to be obtained, in parallel, using other formats. Rapid and independent piloting by system operators and the pooling of experience are, therefore, essential. The motto here is “work in parallel wherever possible”. In the process, use should be made of any findings from ongoing research projects.

6.2 Processes according to coordinating institutions

In this section, the processes are grouped according to the process-coordinating institutions. The focus is on the process coordinators who are responsible for a larger number of processes. A detailed description of the processes and their dependencies is not repeated here, since this has already been done in detail in chapter 5 and section 6.1.

It is important to emphasise that, besides the process-coordinating institution, i.e. the initiator, other stakeholders may also be involved in the respective process. Key work packages can and will also be allocated to these other stakeholders. The content design and structuring of the actual processes are not the subject of this roadmap, but are the responsibility of the respective institutions.

Process-coordinating institutions have different characters in the process design. Processes in the area of responsibility of the BMWK and the BNetzA, for example, are often characterised by the fact that they initiate processes and create a framework. The BNetzA, for example, may commission the transmission system operators to develop a procurement concept for new ancillary services, or the BMWK may initiate a platform in which experts define systemic resilience requirements based on the results of the individual stability processes. In these examples, the specific design of the process would then be organised by the TSO or the experts. Thus, the responsibility here primarily relates to the start of the process as well as the monitoring and ensuring that the required result is achieved. Processes in the area of responsibility of the system operators, the VDE FNN, the DKE or FGW, for example, are often of a clearly operational nature, so that (major) parts of the content-related work are also carried out by these institutions. The VDE FNN, for example, is responsible for adapting and designing the Technical Connection Rules, while the DKE and FGW are responsible for standardisation and creating test specifications. The TSO are responsible for maintaining stability in system operation, which means that many of the processes in their area of responsibility must inherently be handled by them.

This, however, explicitly does not mean that no other stakeholders can or must play an active role in these processes. One example of this is the process for assessing the demand and technical options from the distribution grid in the topic of short-circuit current (K3). This is the task of the TSO responsible for the system, although the process can only be designed together with the DSO. Processes in the field of research, field tests and piloting are also often carried out, or at least actively supported, by research facilities.

The following subsections do not provide a separate overview of the processes that are coordinated by DKE or FGW. The reason for this is the small number of processes in the respective area of responsibility. However, the coordinating institutions DKE and FGW and the corresponding processes obviously have the same importance as all stability processes of the roadmap.

6.2.1 Federal Network Agency

Figure 6.9 below shows the processes for which the Federal Network Agency (BNetzA) as the national regulatory authority is in charge. As mentioned at the beginning, the BNetzA’s process coordination primarily consists of initiating and controlling processes and setting the corresponding framework conditions, rather than the operational implementation of the processes as such. Besides the chronological order of the processes, the relevant fields of action are also highlighted.

As expected, the processes in the BNetzA’s sphere of responsibility address the fields of action of overarching system requirements and framework as well as covering system demands. Here, the BNetzA is responsible, in particular, for setting incentives and introducing structured procurement systems. The field of action overarching system requirements and framework must be prioritised. In terms of processes, this includes enabling broad field tests for extended capabilities to maintain system stability.

In parallel, and building on this, there are processes in the field of action covering system demands, such as the process already launched for the market-based procurement of the inertia for local grid stability, but also potential procurement systems for short-circuit current and resonance stability (cf. also V4). The need for the latter does not yet exist, meaning that the initiation of these processes is dependent on the results of upstream processes. The dependencies can be found in detail in section 5.3.

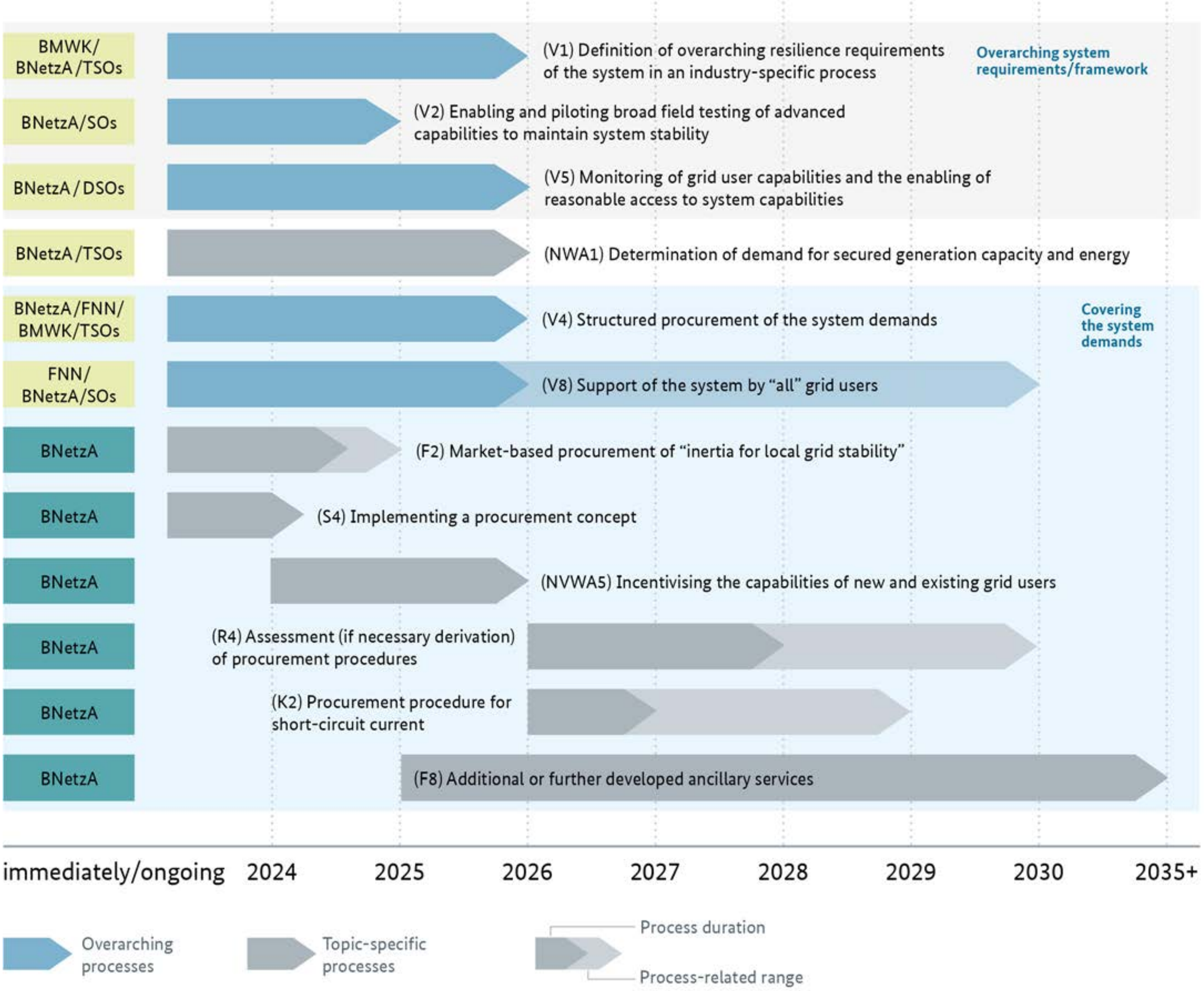

Figure 6.9: Processes in the area of responsibility of the Federal Network Agency

6.2.2 Federal Ministry for Economic Affairs and Climate Action

Figure 6.10 below shows the processes in the area of responsibility of the Federal Ministry of Economic Affairs and Climate Protection (BMWK). As mentioned at the beginning, the BMWK's coordination of the process primarily consists of initiating and controlling processes, setting appropriate framework conditions and legal requirements, and bundling process results into resilience requirements for the system. Due to its natural role, the BMWK is also involved in a large number of stability processes, but does not, however, coordinate these processes. Besides the duration of the processes, the relevant fields of action are highlighted. The central process of the BMWK is the overarching process V1, in which many sub-processes are brought together and the system's overarching resilience requirements are derived.

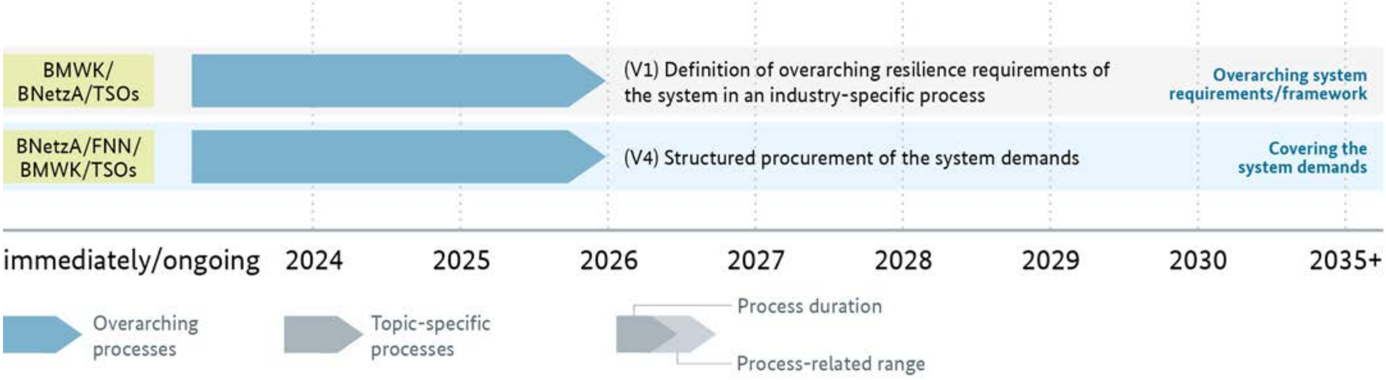

Figure 6.10: Processes in the area of responsibility of the Federal Ministry for Economic Affairs and Climate Protection

6.2.3 Forum Network Technology/network operation of the VDE

Figure 6.11 below shows the processes in area of responsibility of the VDE FNN. As mentioned at the beginning, the process coordination of the VDE FNN consists of the operational implementation of the tasks and, specifically, the creation of application rules and technical instructions. Besides the chronological order of the processes, the relevant fields of action are highlighted. In accordance with section 19 of the Energy Industry Act (EnWG), the VDE is the authorised body for adopting the general minimum technical requirements. The processes in the VDE FNN's area of responsibility, therefore, primarily address the field of action technical rules, regulations and instructions. In addition, some processes are assigned to the fields of action *system resilience* and *overarching system requirements/framework*.

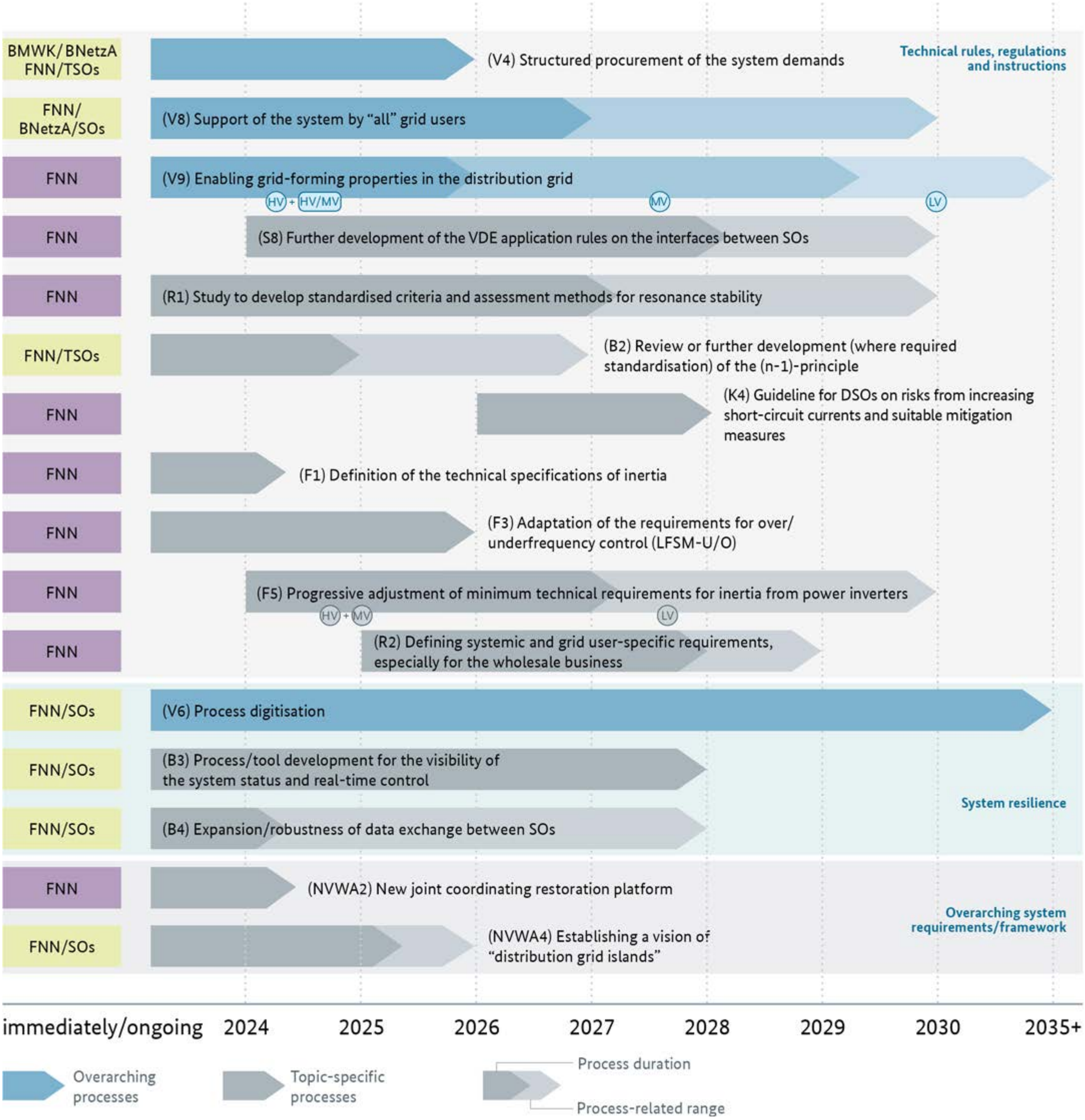

Figure 6.11: Processes in the area of responsibility of VDE FNN

6.2.4 Transmission and distribution system operators

Figure 6.12 below shows the processes in the area of responsibility of the transmission and distribution system operators (TSO and DSO). SO stands for system operator and includes both transmission and distribution system operators.

As mentioned at the beginning, process coordination consists of the operational implementation of tasks. Besides the chronological order of the processes, the relevant fields of action are highlighted. Due to their responsibility for the system, a large number of processes from almost all fields of action are the responsibility of the system operators. One focus is on the fields of action determining the system demands, covering the system demands and system resilience. The system operators also have an essential role to play in the area of technical regulations and instructions, although the coordination of the process here lies with VDE FNN.

Excursus on grid expansion: The expansion of the transmission and distribution grids is also essential in order to ensure the secure and robust operation of the system using 100% renewables. Grid expansion and modification, especially in a preventive, anticipatory manner and using innovative grid assets, can help to avoid stability problems. Besides active implementation by the system operators, it is, therefore, necessary to examine whether and which further adjustments could also be required at regulatory level.

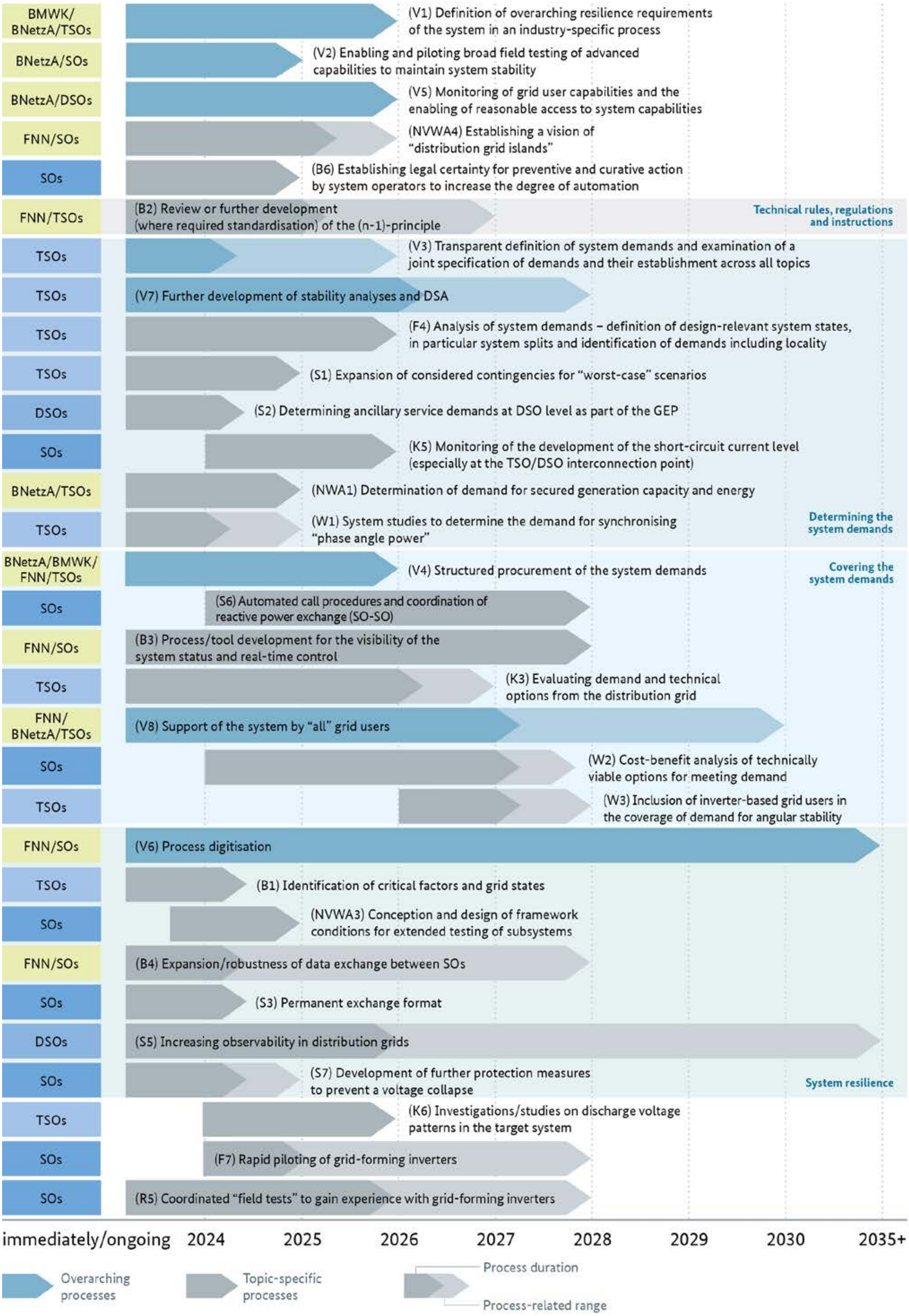

Figure 6.12: Processes for which the transmission and distribution system operators are responsible

6.3 Processes according to the sub-goals

Besides categorisation according to fields of action, eight sub-goals can be derived from the vision (cf. Figure 6.13). These sub-goals break down the overarching goal into concrete, realisable guidelines. This way, it is possible to check, while the respective processes are being implemented, whether they actually contribute to the corresponding sub-goals or whether they need to be readjusted. A monitoring process carried out by the BMWK and the BNetzA is also provided for this purpose (see also Chapter 8). While the categorisation into fields of action is problem-oriented and can be used to communicate the challenges for the electricity system, categorisation according to sub-goals is solution-oriented and can provide important guidance for the downstream monitoring process. Parts of the fields of action and sub-goals correspond directly with each other. However, the urgency and scope of the need for action are heterogeneous, which is why some of the sub-goals start at different levels and thus contribute to focussing. The objective *“System demands are known at all times, both in operation as well as in short and long-term planning”* (1) includes all ancillary services and measures for system stability. However, the system developments are particularly relevant with regard to the available inertia, the short-circuit current, the short-circuit power and the restoration of the grid and supply, which is why they are emphasised as separate sub-goals (3 and 4).

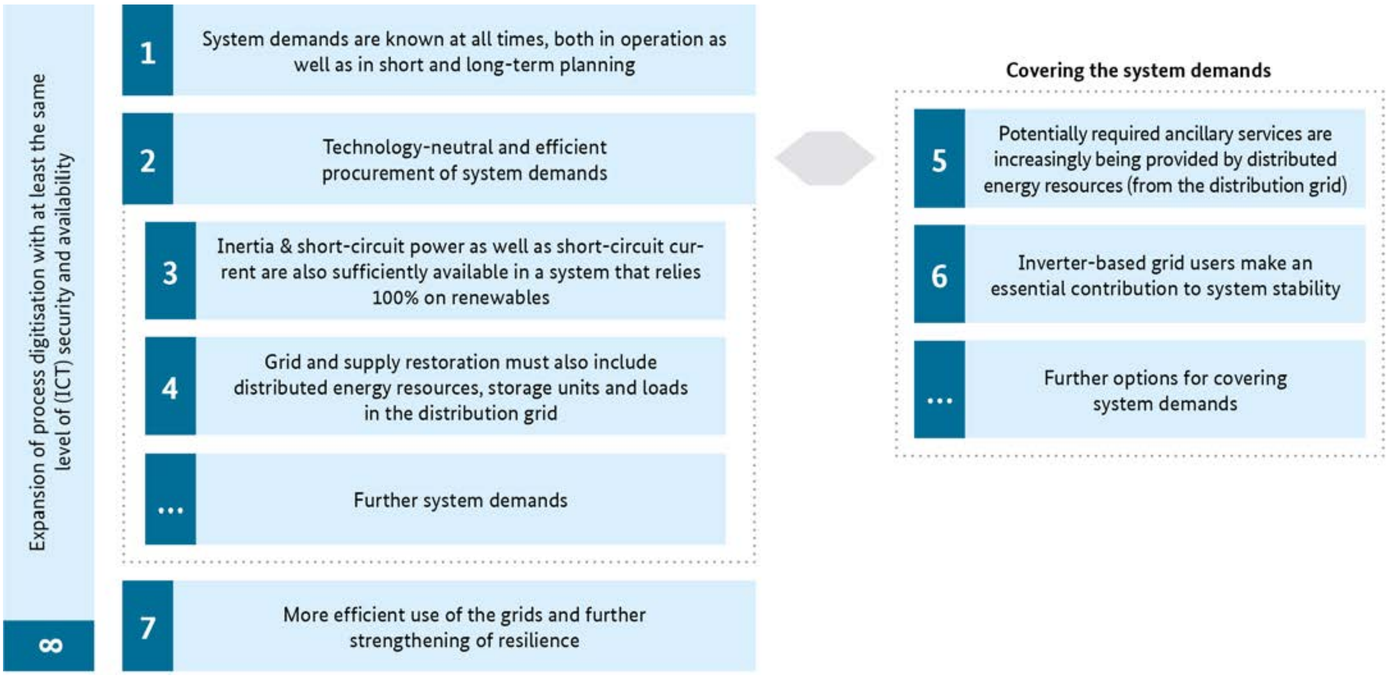

Figure 6.13: Sub-goals of the stability processes

This does not mean that topics such as voltage stability are less relevant, but that the expected need for action and adaptation is lower or that implementation is already more advanced and/or clearer. Individual processes can also contribute to several sub-goals. The sub-goal of *"Technology-neutral and efficient procurement of system demands"* (2) also relates to all ancillary services and measures for system stability. Particularly important components are the fact that inverter-based grid users from the distribution grids take on even more tasks and make an essential contribution to system stability (5 and 6). That is why corresponding subgoals were formulated. Furthermore, process digitisation is seen as another key component for maintaining system stability, which is why it is also included as a sub-goal (8). The efficient utilisation of the grids and the strengthening of their resilience (7) round off the derived sub-goals. The subgoals were derived from the vision (see chapter 4) and formulated by the roadmap stakeholders. The working groups and the advisory board agreed on the vision. The sub-goals, therefore, describe the endeavours of the Federal Government and the experts involved in drawing up the roadmap.

How should the visualisation of the processes be read? The overarching processes of system stability are shown in blue, and the topic-specific stability processes in grey. The responsible process coordinators are shown to the left of the processes. SO stands for system operator and includes both TSO and DSO.

6.3.1 System demands are known at all times, both in operation and in short and long-term planning (sub-goal 1)

In order to operate the electricity system safely, various requirements must be met on a sustained basis. For example, the system must be able to react to outages and be able to manage any imbalances between load and generation. To this end, ancillary services and system stability measures are used to continuously ensure the secure and robust operation of the system. To do this efficiently, these requirements must be known at all times to ensure system stability.

That is why system demands must be known at all times, both in operation as well as in short and long-term planning

Figure 6.14 below shows all the processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

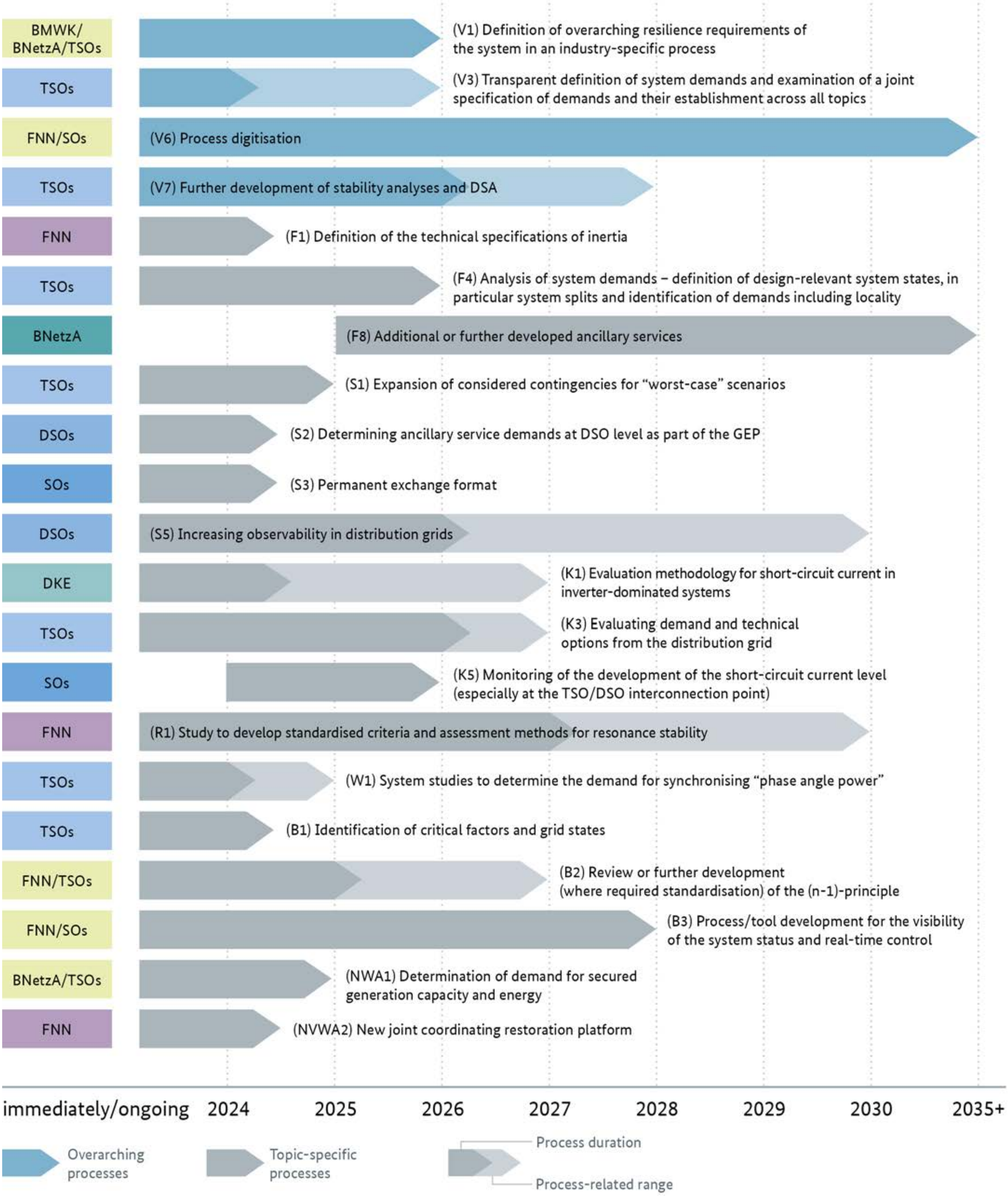

Figure 6.14: Processes relating to the sub-goal *System demands are known at all times, both in operation as well as in short and long-term planning*

6.3.2 Technology-neutral and efficient procurement of system demands (sub-goal 2)

Transparency and technological openness are important framework conditions for meeting the demand for ancillary services and system stability measures. This creates planning security, on the one hand, and enables innovation on the other. Demand should also be met efficiently, i.e. from the most suitable source in each case.

To this end, technical minimum requirements for grid users, markets such as the balancing power market and fully integrated network components (FINCs) are to be utilised as needed.

Figure 6.15 below shows all processes that contribute to the sub-goal. A detailed visualisation of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

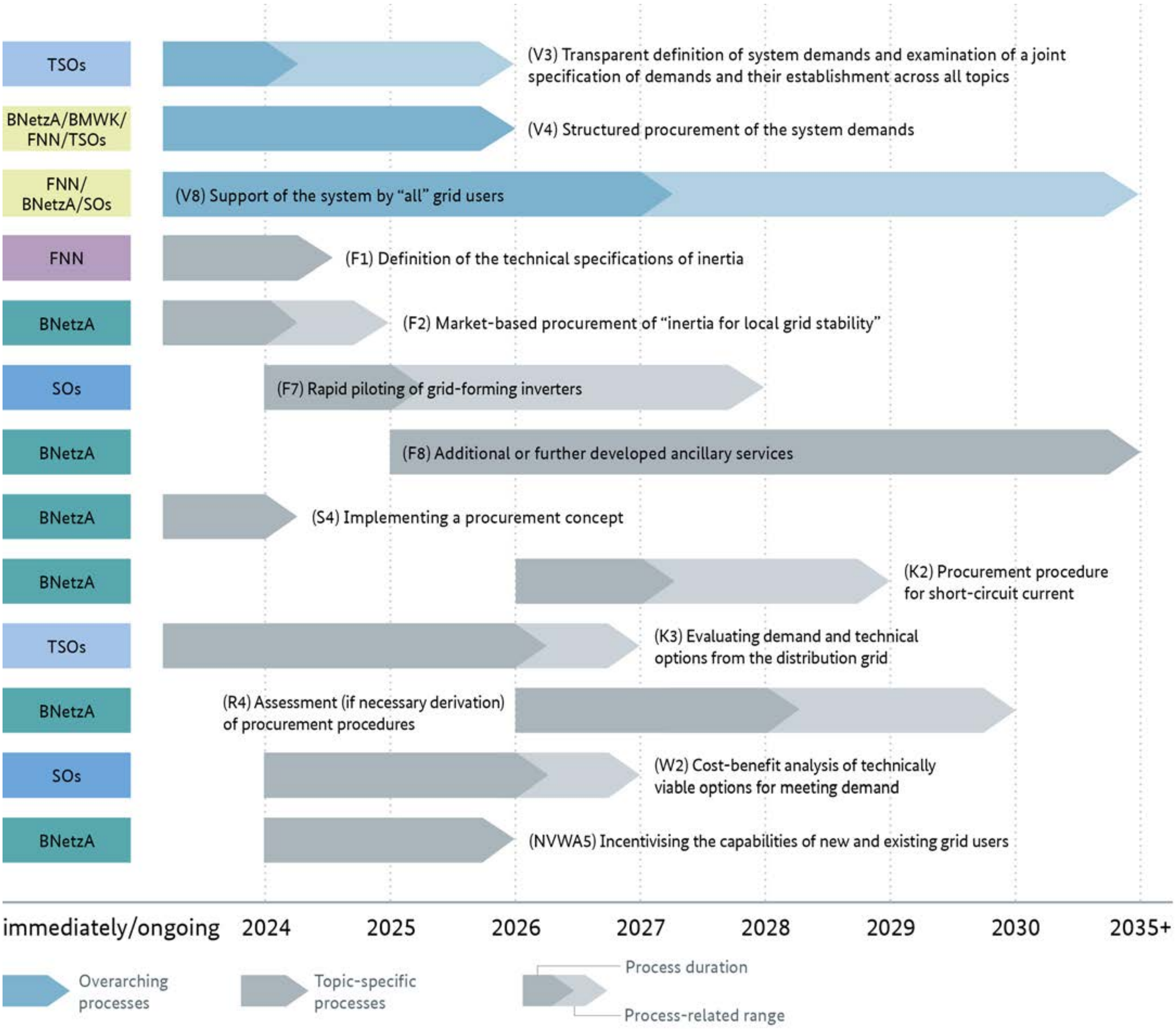

Figure 6.15: Processes for the sub-goal *Technology-neutral and efficient procurement of system demands*

6.3.3 Inertia and short-circuit power as well as short-circuit current are also sufficiently available in a system that relies 100% on renewables (sub-goal 3)

These days, inertia and short-circuit power as well as short-circuit current are mainly provided by large power plants. In the future, however, they will also have to be provided by inverter-based grid users as an alternative.

The aim is to ensure the availability of the necessary inertia, the short-circuit power and the requisite short-circuit current at all times, even in a system that relies 100% on renewables, without exceeding the permissible current limits.

Figure 6.16 below shows all the processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

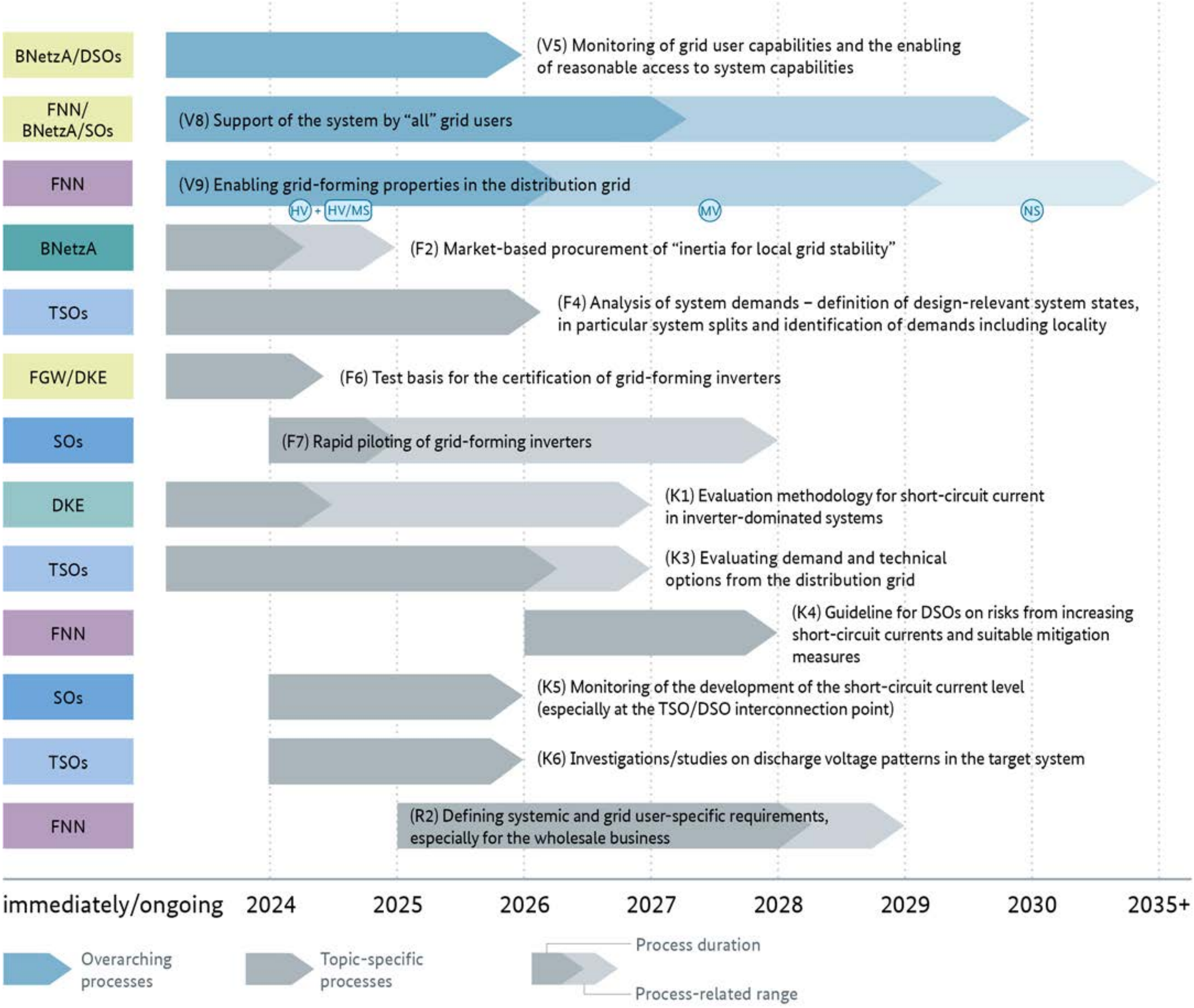

Figure 6.16: Processes relating to the sub-goal *Inertia and short-circuit power as well as short-circuit current are also sufficiently available in a system that fully relies on renewables*

6.3.4 The restoration of the grid and supply must also include distributed energy resources, storage units and loads in the distribution grid (sub-goal 4)

The German electricity grid is one of the most stable and robust energy supply systems in the world. The very rare power outages that do occur are brief and usually limited to small areas. However, the unfortunate concatenation of errors, material failure, natural disasters or targeted attacks can, in extremely rare and exceptional cases, lead to large parts of the power grid going black, i.e. the power supply can no longer be maintained. Such events are also called blackouts.

The aim is to ensure that, in the event of a blackout, the grid and supply are restored in a robust, fast and reliable manner.

In particular, the inclusion of fluctuating distributed energy resources, storage units and loads from the distribution grid must be enabled. The increasing complexity of system control and an increased need for coordination between the system operators must be taken into account here.

Figure 6.17 below shows all the processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

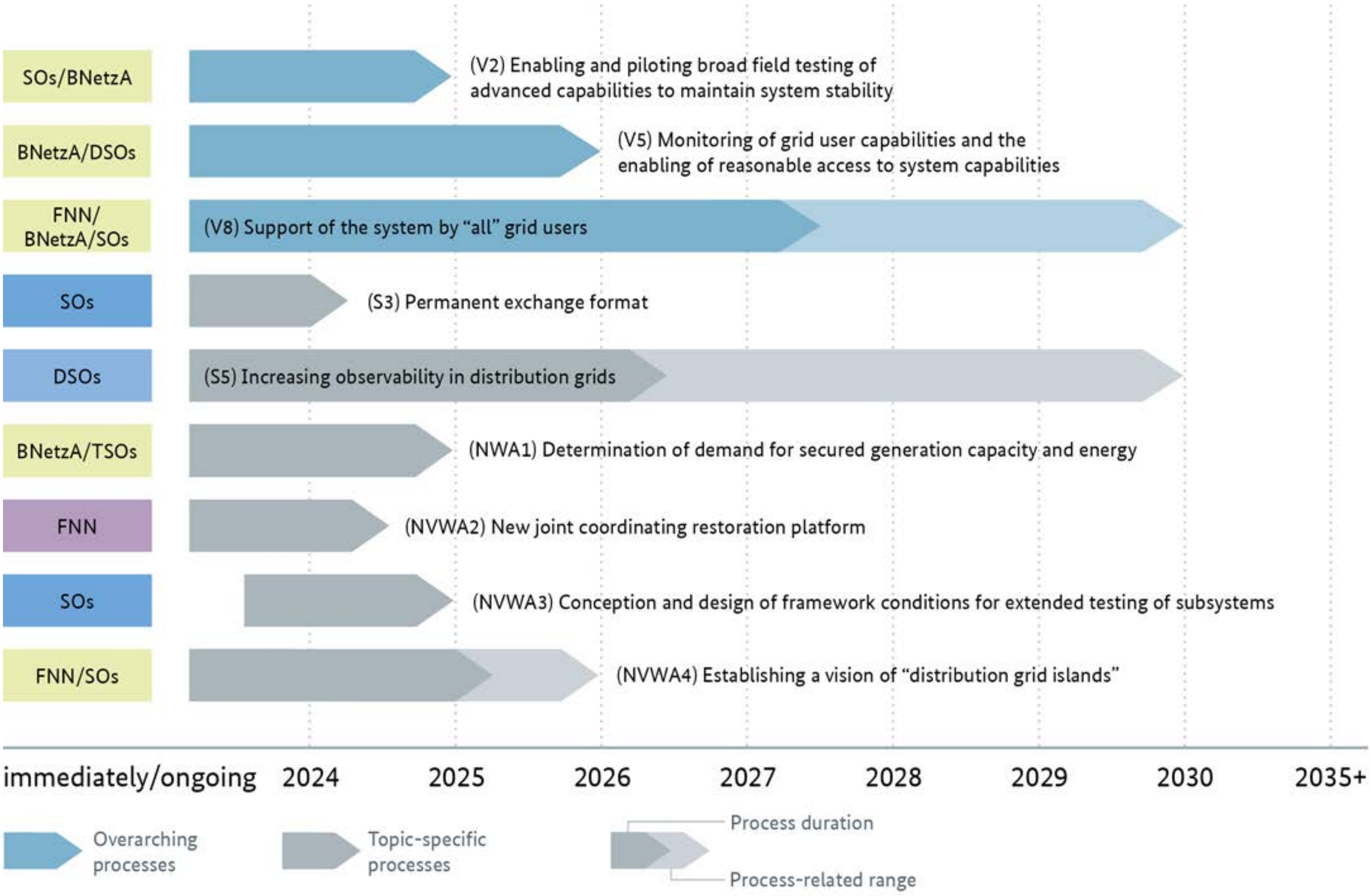

Figure 6.17: Processes relating to the sub-goal *The restoration of the grid and supply must also include distributed energy resources, storage units and loads in the distribution grid*

6.3.5 Potentially required ancillary services are increasingly being provided by distributed energy resources (from the distribution grid) (subgoal 5)

By 2045, electricity demand is to be permanently met by decentralised renewable energy sources. Most of them will be connected to the distribution grid. Ancillary services and measures for system stability must, therefore, increasingly be provided by these sources in the future. The potential for this is huge. However, in order to realise this potential, the necessary technical and regulatory framework conditions must be created.

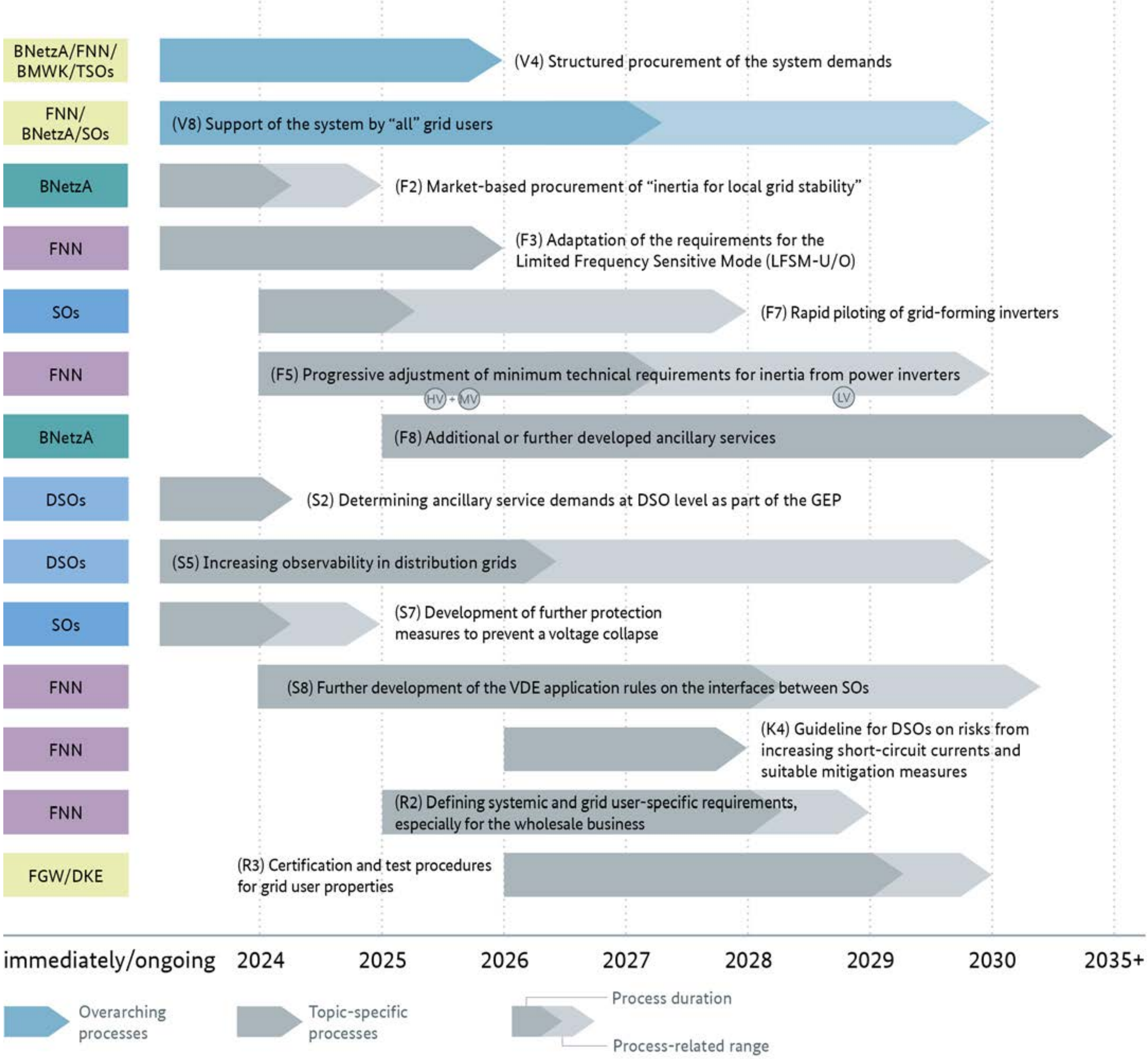

Figure 6.18: Processes relating to the sub-goal *Potentially required ancillary services are increasingly provided by decentralised energy resources (from the distribution grid)*

The potential for ancillary services and measures for system stability to also be provided by distributed energy resources from the distribution grid is to be exploited.

Figure 6.18 shows all the processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

6.3.6 Inverter-based grid users make an essential contribution to system stability (sub-goal 6)

Wind and solar energy are the main pillars of our climate-neutral energy supply. Unlike large power plants, they are connected to the grid via inverters, just like charging points for electric vehicles or heat pumps. With the right design and coordination, inverters can provide ancillary services and system stability measures that enable the system to be operated safely even when using only renewable energy sources.

The potential for inverter-based grid users to make an essential contribution to system stability is to be exploited.

Figure 6.19 below shows all the processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

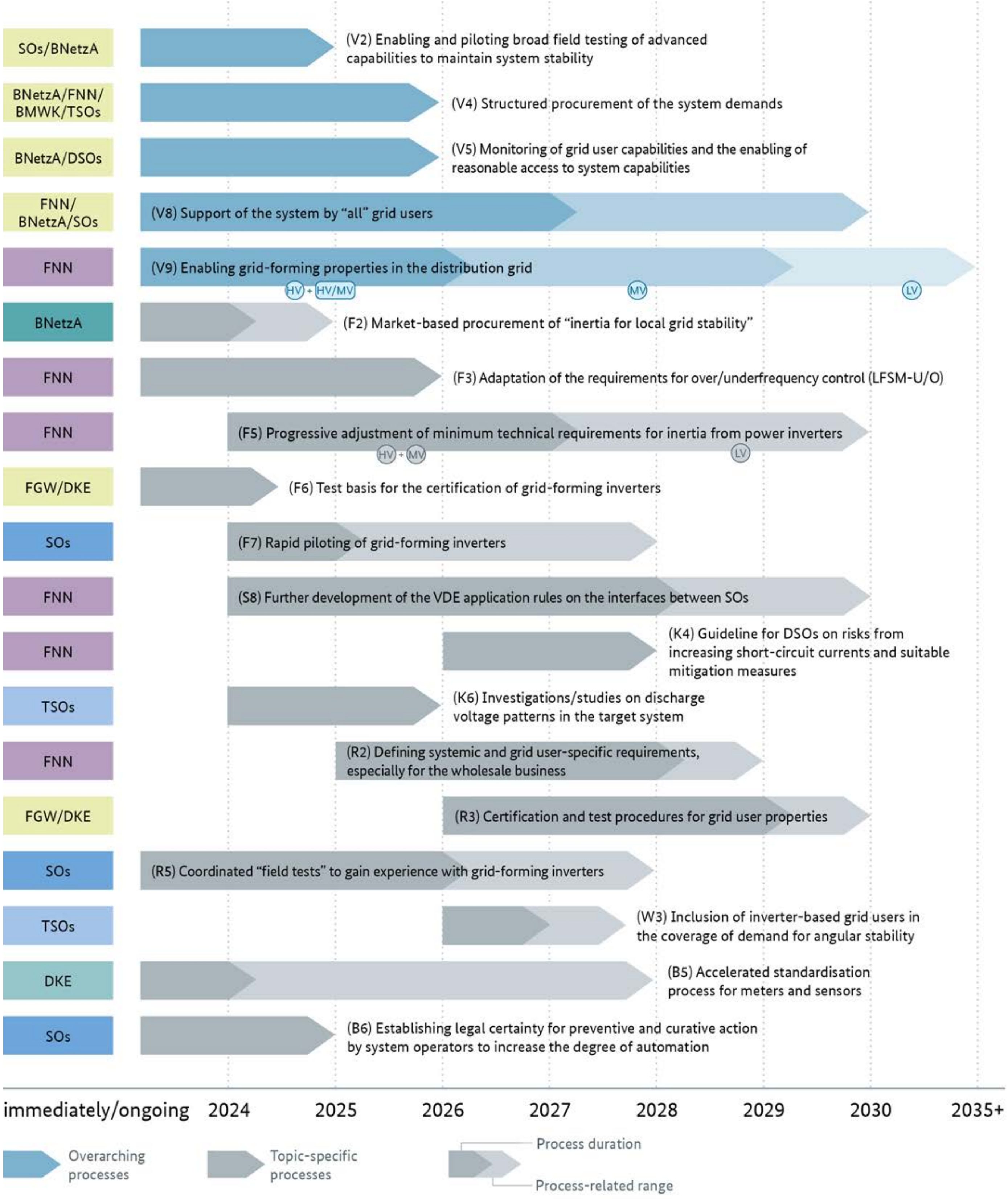

Figure 6.19: Processes relating to the sub-goal *Inverter-based grid users make an essential contribution to system stability*

6.3.7 More efficient use of the grids and further strengthening of resilience (sub-goal 7)

The electricity grids are the “backbone” of the energy transition. Robust electricity grids are necessary, to absorb the electrical energy generated, e.g. by wind and solar, transport it to the load centres and distribute it there. This also necessitates the expansion of our grid. Besides expansion, however, making particularly efficient use of the grid is important. This reduces the required expansion of the grid and increases the efficiency of the system. In Germany, the optimised use of the electricity grid has been enshrined in law.

The more efficient utilisation of the grids is to be further strengthened and new potential tapped.

Figure 6.20 below shows all processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

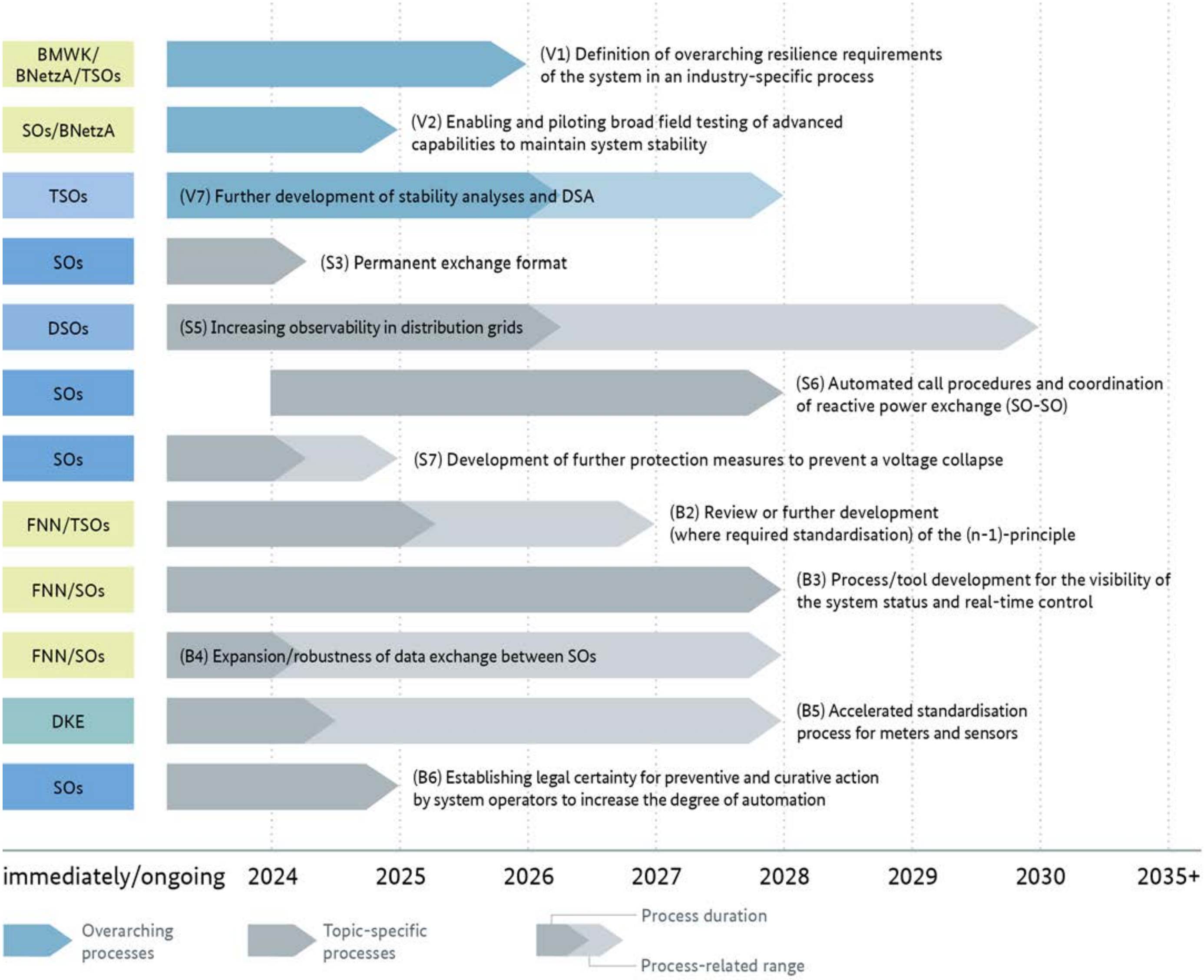

Figure 6.20: Processes relating to the sub-goal *More efficient use of grids and further strengthening of resilience*

6.3.8 Expansion of process digitisation with at least the same level of (ICT) security and availability (sub-goal 8)

The number of producers and consumers in the grid will continue to rise significantly until 2045. Millions of distributed energy resources, charging points for electric vehicles (including bidirectional charging) and heat pumps will shape the electricity system. This means that the system will not be spread across a few broad shoulders, but across many narrow ones. This will also lead to greater harmonisation and coordination efforts.

This is to be achieved, among other things, by expanding process digitisation, while ensuring that the current (ICT) security and availability are at least maintained.

Figure 6.21 below shows all processes that contribute to the sub-goal. A detailed description of the processes and their dependencies is not repeated here, as this has already been done in detail in chapter 5 and section 6.1.

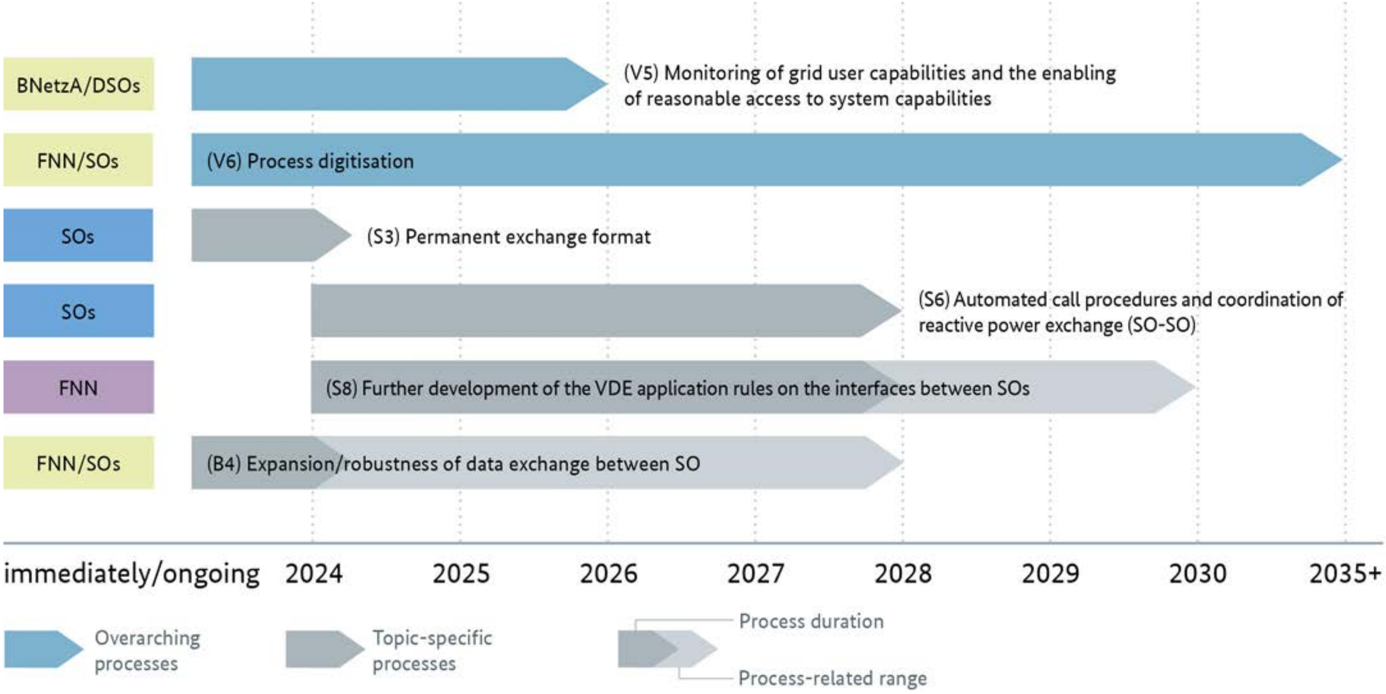

Figure 6.21: Processes relating to the sub-goal *Expansion of process digitisation with at least the same level of (ICT) security and availability*

7 System Stability Roadmap

The System Stability Roadmap identifies 41 topic-specific stability processes and ten overarching stability processes that are necessary to ensure the safe and robust operation using only renewable energy sources. This includes the description of the processes and the visualisation of process dependencies (chapter 5) as well as the categorisation of the processes from various perspectives (chapter 6). This chapter presents a milestone plan (Figure 7.1) for achieving the secure and robust operation of a system which wholly relies on renewable energy sources. A tabular overview of all identified processes (section 7.2) is provided below.

7.1 Milestone plan

In order to ensure the secure and robust operation of the system using only renewable energy sources at all times, overarching processes relating to system stability and topic-specific stability processes have been identified. They are new processes as well as process adjustments and extensions. The processes were derived from relevant issues and the corresponding needs for action in the individual topics. They were developed by experts belonging to topic-specific working groups and can be found in the accompanying papers (see section 2.3).

As described in the previous sections, the processes address various sub-goals and fields of action. Across the processes, there are milestones that need to be achieved to ensure the safe and robust system operation using only renewables. These milestones are key points on the way to achieving the target and serve as a guide to the progress made in implementing the roadmap. Figure 7.1 shows key milestones in the System Stability Roadmap. The times specified were based, on the one hand, on the known duration of established or comparable processes and, on the other, on the time at which the result of the process is required. This results in a natural uncertainty, which – as with all forecasts – increases in line with the distance of the forecast horizon. Individual milestones are currently subject to a particularly high degree of uncertainty or will be reached in stages, differentiated by grid level. This staggering is indicated by a horizontal line for the Technical Connection Rules for grid-forming inverters. Uncertainties may result, for example, from the fact that partial results are expected at different times. The position of the milestones within a single year does not indicate when the milestone will be achieved in the course of that year. All the milestones of a corresponding year are to be achieved in the course of this year.

Across all milestones, three paths are particularly key to the successful implementation of the System Stability Roadmap:

First path – defining the level of security and determining the system demand: Where it is not yet clear, the target level of security for the power supply system must be defined. Based on this, so-called design-relevant system states can then be defined. Design-relevant system states describe predictable and unpredictable events which may confront the system and which must be managed. They are required because it is neither technically possible nor economically viable to cover all conceivable events. The design-relevant system states defined make it possible to quantify the demand for ancillary services and other measures for system stability and thus to identify them transparently. In some cases, assessment procedures need to be further developed in order to identify system demand (e.g. for the required short-circuit current contribution from inverter-based grid users). In part, completely new evaluation criteria will also have to be derived and established (e.g. for resonance stability). The identification of requirements should include both known ancillary services and additional ancillary services that will be required in the future as well as further measures for system stability.

Second path – covering the system demands: The second central path is the coverage and structured procurement of system demands. To this end, suitable procurement procedures must be introduced and technical connection rules and regulations supplemented and adopted. Grid assets and HVDC converter stations can and should also contribute to meeting demand. An additional building block is the further expansion of information and data exchange between system operators (SOs) and renewable energy sources and loads as well as between the system operators themselves. Among other things, this should also enable the targeted vertical exchange of reactive power. Comprehensive process digitisation and standardised data spaces are prerequisites for this increased coordination.

Third path – establishing grid-forming inverters: The third central path concerns the penetration of grid-forming inverters in the transmission and distribution grids. Grid-forming inverters are a key technology for maintaining system stability in the future system. What, however, is lacking is experience with their widespread use. This must be gained in pilot tests and the technical requirements have to be defined. Furthermore, technical connection rules (differentiated according to voltage levels or power classes) have to be drawn up for grid-forming inverters. This will ensure that the potential of grid-forming inverters (e.g. for providing inertia) can be utilised safely and appropriately in order to make a significant contribution to system stability.

The high pressure to act makes it necessary to carry out the processes in parallel: Safe, but also fast action is required. It is important to reach the milestones on time so as not to delay the subsequent processes, some of which build on each other. Preliminary results are often sufficient for starting the follow-up processes, which can be refined or readjusted as required in the further implementation process of the roadmap.

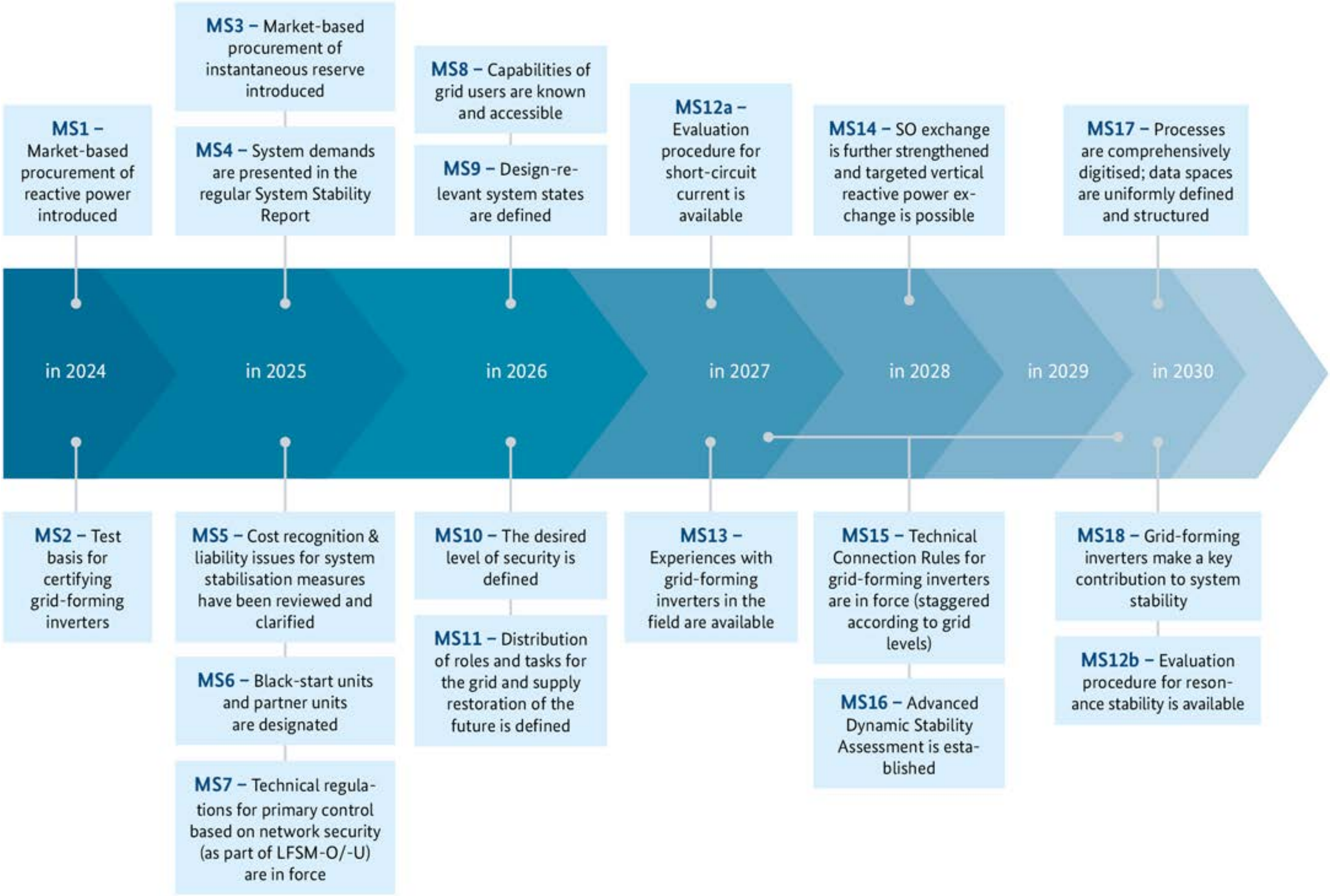

Figure 7.1: Key milestones of the System Stability Roadmap (The introduction of the Technical Connection Rules for grid-forming inverters is to be staggered according to grid levels, which is why a time period is shown here as a horizontal line).

MS1 – Market-based procurement of reactive power is introduced

The procedure to determine the market-based procurement of reactive power is currently underway. The corresponding procurement concept is expected to be published in the first quarter of 2024. This will then be implemented by the system operators. This milestone defines the procurement procedure and introduces the market-based procurement of reactive power. In the future, this should also enable the targeted exchange of reactive power across grid levels (to be achieved in 2024).

MS2 – Test basis for certifying grid-forming inverters

Grid-forming inverters can and should play a key role in maintaining the safe and robust operation of a system that fully relies on renewables. Appropriate verification procedures and test processes must, therefore, also be developed for newly introduced requirements, such as grid-forming properties, with which the accredited certification bodies can check how well the grid users conform with the grid connection rules. This milestone provides a (first) test basis for the certification of grid-forming inverters. This may be differentiated (e.g. according to power class and/or grid level) and must be regularly expanded in the future (to be achieved in 2024).

MS3 – Market-based procurement of inertia is introduced

According to section 12h Energy Industry Act (EnWG), the efficiency of the market-based procurement of non-frequency ancillary services must be reviewed again by 31 December 2023. As the TSO have already identified a demand for inertia in the network development plan and this has been confirmed by the BNetzA, the justification that led to the exemption from market-based procurement in 2020 (no need in the considered design-relevant system states at that time) is obsolete. The BNetzA has already started to draw up a procurement concept and will, therefore, not decide on a new exemption from the market-based procurement of the “inertia for local grid stability” (inertia). With this milestone, a procurement concept for inertia will be defined and introduced (to be achieved in 2025).

MS4 – System demands are presented in the regular System Stability Report

The demand for ancillary services and system stability measures must be identified transparently and sufficiently in advance. This is done in a regular System Stability Report. Preference is given to demands that still need to be procured in a structured way. On the one hand, demand is identified in as aggregated a manner as possible, since a larger field of suppliers can be expected. On the other hand, demand may only be aggregated to the extent that makes sense to cover demand. Potential demand for new ancillary services or system stability measures is also identified and reported, if identified. When identifying potential solutions for covering demand in the System Stability Report, synergies in covering of various ancillary services and system stability measures are also taken into account (to be published for the first time in 2025).

MS5 – Cost recognition and liability issues for system stabilisation measures have been reviewed and clarified

Identified liability issues for system-stabilising measures and their cost recognition have been clarified in order to have legal and planning certainty. This applies in particular – but not exclusively – to pilot tests of grid-forming inverters in the distribution grid or extended functions and tests in the context of grid and supply restoration.

This does not mean that all costs should in principle be categorised as “permanently uncontrollable costs”. Nor does it mean that requirements at grid user level are always remunerated[12] (to be achieved in 2025).

MS6 – Black-start units and partner units are designated

Even with fluctuating resources, it must be possible to restore the grid and supply during periods of low sunshine and wind. With this milestone, the demand for secured generation capacity and energy per region in the restoration has been determined and concepts for securing availability developed. Besides black-start units for grid restoration, this also applies, in particular, to secured generation capacity and energy from partner units for grid and supply restoration, but also for subsequent load-following operation (to be achieved in 2025).

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[12] According to the ruling of the European Court of Justice of 2 September 2021 in infringement proceedings C-718/18, the BNetzA alone and independently decides “whether” and “how” to recognise costs in this area.

MS7 – Technical regulations for primary control based on network security (as part of LFSM-O/-U) are in force

Primary control based on network security is to be incorporated into the Technical Connection Rules at national level as early as 2024. With this milestone, the primary control based on network security is transferred to the Technical Connection Rules and synchronised with the revised NC-RFG (2025) (to be achieved in 2025).

MS8 – Capabilities of grid users are known and accessible

Stability-relevant capabilities and master data of relevant grid users are comprehensively documented and are available in a standardised data format. Moreover, reasonable access to the grid user capabilities and stored parameters as well as, in some cases, demand-orientated parameter changes by the system operators are possible (to be achieved in 2026).

MS9 – Design-relevant system states are defined

Based on the determination of the desired level of security (MS10), design-relevant system states are defined. Both milestones are developed in parallel “hand in hand”. These cases define states in undisturbed and disturbed system operation that have to be mastered. These design-relevant system states cover all possible events that need to be managed so as to maintain the targeted level of security and enable the clear quantification of the demand for ancillary services and measures for system stability (to be achieved in 2026).

MS10 – The desired level of security is defined

The targeted level of security was defined in sufficiently precise terms so that the qualitative and quantitative demands for ancillary services and system stability measures can be derived from it. This concerns the completion of all topics such as dealing with system split events as well as target time ranges and intervals for restoration after a blackout. This is done iteratively with the quantification of demands (to be achieved in 2026).

MS11 – Distribution of roles and tasks for the grid and supply restoration of the future is defined

This milestone defines the active role that distribution grids should play in the grid and supply restoration concepts of the TSO. Potential adjustments arise especially in the restoration of the supply, as the control of the decentralised feed-in and possibly controllable loads lies within the area of the DSO. Adjustments might also result from these new tasks in grid restoration. The concepts have been adapted accordingly (to be achieved in 2026).

MS12 – Evaluation procedure for short-circuit current and resonance stability is available

The existing standards and guidelines for determining the maximum and minimum short-circuit current for a given grid connection do not or only insufficiently take into consideration the contributions from inverter-based grid users. With this milestone, the assessment procedures have been adapted so that the corresponding regulations can be adapted (to be achieved in 2027 short-circuit current – M12a).

The second element of this milestone is the existence of standardised criteria and evaluation procedures for resonance stability. Here, in particular, the identification of critical grid areas and frequency ranges and the handling of high modelling uncertainties must be taken into account. The criteria and procedures are published in a suitable form, e.g. as a concept paper or guideline (to be achieved in 2030 resonance stability – M12b).

MS13 – Experiences with grid-forming inverters in the field are available

Extensive experiences have already been gained with the use of grid-forming inverters in grid operation (large and small grid users). They are analysed and can be used as input to develop the Technical Connection Rules, among other things. Moreover, potential obstacles were identified and the corresponding need for action and research derived (to be achieved in 2027).

MS14 – System operator exchange is further strengthened and targeted vertical reactive power exchange is possible

Horizontal and vertical exchange between system operators is even more pronounced. This is achieved, among other things, through the coordinated grid expansion plan processes and the exchange between TSO and DSO on the one hand and DSO and DSO on the other. With this milestone, the exchange processes are also so advanced and automated that targeted vertical reactive power exchange is possible. This will enable, in practice, the more targeted and efficient utilisation of the existing reactive power potential (to be achieved in 2028).

MS15 – Technical Connection Rules for grid-forming inverters are in force (staggered according to grid levels)

So that grid-forming inverters can be connected to the grid to ensure the safe and robust operation of the system with only renewable energy sources, the relevant Technical Connection Rules must be defined. This milestone represents a technical connection guideline for grid-forming inverters. This may be differentiated (e.g. according to power class and/or grid level) and, as with all minimum requirements, can be expanded in the future. The achievement of the milestone is based on the adoption of the revised RfG (Network Code Requirements for Generators) in 2025 and the planned 2.5-year transition period for implementation in national regulations. It is to be expected that, at least for the higher grid levels, corresponding regulations will be adopted before 2028. Due to the special features of the low voltage level, only reduced or later specifications may be made in the RfG, so that any national implementations for low voltage may not be available until after 2028. The horizontal line illustrates this in Figure 7.1 (to be achieved in 2027–2030).

MS16 – Advanced Dynamic Stability Assessment is established

This milestone defines the further development of the Dynamic Stability Assessment. The grid status is evaluated in real time and suitable countermeasures can be taken in the event of any predicted critical stability phenomena. To this end, the decision support systems for the operators have also been further developed so that the initiation of countermeasures could be (partially) automated (to be achieved in 2028).

MS17 – Processes are comprehensively digitised; data spaces are uniformly defined and structured

This milestone arks the comprehensive digitisation of processes that are relevant to system stability (in particular grid status and grid control). Exchange formats that enable the exchange of necessary data and operating states have been established. Data silos are broken down and information is made accessible through data spaces (to be achieved in 2030).

MS18 – Grid-forming inverters make a significant contribution to system stability

A differentiation has been made as to which characteristics are to be provided by grid users for each grid level or performance class. Grid-forming properties are also widespread in grid users in the distribution grid and can be expanded further in the future. This way, the grid users (generators, loads, storage units) make a significant contribution to system stability and provide ancillary services. Grid-forming inverters should already contribute towards system stability before 2030, and this should be significant from 2030 onwards at the latest (to be achieved in 2030).

Epilogue: The System Stability Roadmap provides a structured list of the requisite adjustments and further development of existing processes as well as the new processes required to maintain system stability. Implementation must be coordinated and calls for a high level of commitment from all stakeholders. The tasks are varied and demanding and the pressure to act is huge. When designing and implementing the processes, detailed questions and obstacles will also arise that need to be answered and resolved. It is to be expected that this will, in part, require the adaptation and expansion of existing structures of process and sub-process coordinators and an increase in personnel. Prioritisation across processes may also be required if sufficient resources cannot be allocated in good time. However, the industry is well positioned to carry out these processes and to guarantee the secure and robust system operation in the long term, even when using only renewable energy sources.

7.2 Process overview

With the assistance of experts from the various areas, 41 topic-specific stability processes and ten overarching processes for system stability were identified in the roadmap. Each of them describes either a new process to be established or the further development or adaptation of an existing process. The roadmap does not set out the content of the processes, but, rather, it shows in a structured manner which fields of action need to be addressed. This involves clearly communicating who the process coordinator is, i.e. the initiator of the process, when the process is to be started as well as the expected duration of the process. Figure 7.2 below shows all the processes identified grouped by topics with the respective process coordinators and the start and end times. The chart is presented as a GANTT chart (bar chart). The process coordinators are responsible for the actual design of the processes, the definition of sub-goals and the assignment of sub-responsibilities.

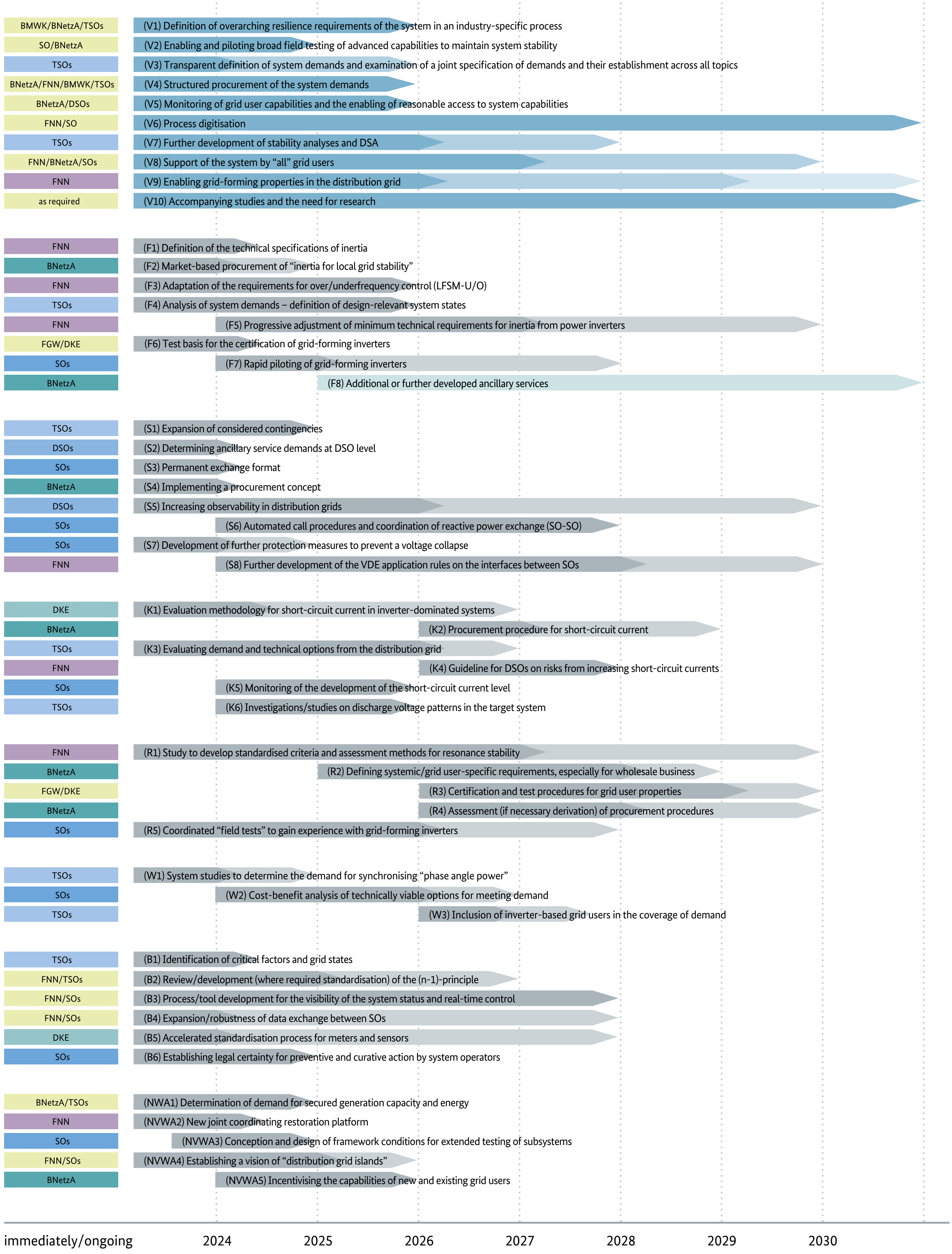

Figure 7.2: GANTT chart of the identified stability processes and overarching processes for system stability

8 Outlook: implementation of the roadmap

A total of 41 topic-specific stability processes and ten overarching processes were identified as part of the System Stability Roadmap. Most of them must be initiated, adapted or implemented by five different players. In almost all processes, several players are involved and have to take on sub-process responsibilities. There are also dependencies between the processes. To implement the processes, the institutions may, therefore, need additional staff and resources to solve the tasks that have been identified. A finer prioritisation of processes across the topics may also be necessary if sufficient resources cannot be allocated at an early stage. This is particularly relevant since a large number of processes in the area of coordination of individual institutions are to start in parallel and at once.

Exchange platform

For the successful implementation, which is challenging in terms of coordination, an exchange platform will continue to be necessary. Although the results of the roadmap were developed with the involvement of all stakeholders, new ambiguities, uncertainties and conflict situations may arise during implementation. This applies, in particular, to the specific design of the individual processes, since this step has yet to be taken. Any delays caused by this must be avoided at all costs so as not to block the already challenging path to achieving a climate-neutral energy system. This calls for solution-orientated action and mutual support.

With the Forum for System Stability, the BMWK will create a regular exchange platform in which the urgency of certain processes can be highlighted and processes can be prioritised if resources cannot be allocated on time and in sufficient quantities. The Forum for System Stability is intended to provide intensive support for carrying out the roadmap. It is meant to serve as an exchange platform for the stakeholders responsible for carrying out the various roadmap processes. Any potential problems and conflict situations should also be communicated to the BMWK and BNetzA by the forum as early as possible so that they can be resolved in a targeted manner.

Monitoring

The need for action is great and urgent, and many processes must be initiated immediately. Some processes have relatively long implementation periods in relation to the goal of a climate-neutral energy system. Due to the dynamic developments in the energy system and the inherent uncertainty of long planning horizons, opportunities must also be created so that this roadmap can be adapted and added to.

The System Stability Report is already an instrument that the BNetzA can use to monitor the status of the implementation of measures in the area of system stability. Alongside the Forum for System Stability, the System Stability Report is thus an integral part of the monitoring concept.

All the processes identified in the System Stability Roadmap will be supported as part of this concept. The aim of monitoring is to enable the players to communicate the progress of the processes within the above-mentioned exchange platform and to make such information transparently accessible. Monitoring is also intended to ensure that any hurdles can be anticipated and measures introduced to prevent delays. The BMWK will actively create communication channels to the respective process coordinators and support them in successfully implementing the processes.

Coordination with other federal government programmes

The triad of generation adequacy, grid adequacy and system stability is of great importance for the success of the energy transition. In order for the transformation into a climate-neutral energy system to succeed, the federal government is pursuing a variety of approaches. Dividing the task into several modules is both sensible and necessary. The Climate-neutral Electricity System Platform and the System Development Strategy are particularly important components that interface with the System Stability Roadmap.

With regard to the Climate-neutral Electricity System Platform, the focus is on developing an adjusted electricity market design. As part of the System Development Strategy, the BMWK is developing a cross-sectoral vision for the future energy infrastructure. This should ensure the coherence of the various follow-up processes, such as the network development plan for electricity, gas and hydrogen, as well as the other sector- and energy carrier-specific strategies and programmes.

The German government's energy research funding programme can also make an important contribution. In the research projects funded, questions on future electricity grid operation based on renewable energies are being developed, in which system stability plays a central role.

Consideration of the interfaces between these building blocks is another essential aspect in the implementation of the System Stability Roadmap.

Together

The implementation of the System Stability Roadmap must be supported by all stakeholders involved in a committed and constructive manner, as was the case when it was drawn up. The overarching goal of a climate-neutral electricity system can only be achieved through good cooperation.

List of figures

Figures

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