Engineering Roadmap to 100% Renewables

December 2022

An Engineering Framework report on the steps required to operate the National Electricity Market at 100% instantaneous penetrations of renewables

Important notice

Purpose

This publication provides stakeholders with an overview of engineering challenges and associated actions that will need to be undertaken to operate the National Electricity Market (NEM) for the first period of 100% instantaneous penetration of renewables, and an indication of actions required to satisfy more regular operation at 100% renewable penetration.

Responsibility for undertaking these actions and meeting the technical requirements identified in this report will ultimately be shared across many parties, including AEMO, network service providers, market bodies, market participants, and governments. This report does not seek to allocate new responsibilities. Instead, it seeks to provide AEMO's perspective of the actions needed and promote discussion on the priority and relevance of these actions, to facilitate their efficient implementation over an appropriate timeframe in the long-term interests of consumers.

This document has been prepared by AEMO using information available at 21 November 2022. Information made available after this date may have been included in this publication where practical.

This document uses many terms that have meanings defined in the National Electricity Rules (NER). The NER meanings are adopted unless otherwise specified.

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Version control

Version	Release date	Changes
1	1/12/2022	Initial publication

Contents

1 Introduction from the CEO

Preparing Australia's power system for tomorrow

Australia's energy transition is underway and gathering pace due to a combination of technological innovation, government policies, market forces and consumer preferences. As Australia's independent system and market operator and system planner, AEMO's role is to ensure safe, reliable, and affordable energy today, and enable the energy transition for the benefit of all Australians.

The Australian Government has legislated a target of net-zero emissions by 2050 and, by 2030, a 43% reduction in 2005-level emissions, aiming to have 82% of energy in the NEM from renewable sources by then. This target complements individual state and territory government energy policies and renewable energy zones and targets.

As Australia moves rapidly away from its traditional dependency on coal generation, our energy future will be built on four pillars:

1. Low-cost renewable energy, taking advantage of the abundant wind, solar and hydro resources that Australia has to offer.
2. Firming technology like pumped hydro, batteries, and gas generation, to smooth out the peaks and fill in the gaps from that variable renewable energy.
3. New transmission and modernised distribution networks to connect these new and diverse low-cost sources of generation to our towns and cities.
4. Power systems capable of running, at times, entirely on renewable energy.

This *Engineering Roadmap to 100% Renewables* report focuses primarily on the fourth point. That is, to tackle the question of what needs to be done, from an engineering perspective, to enable Australia's main interconnected power system to run reliably and securely at times without fossil fuels. In answering this, the report touches on aspects of the other three pillars of this power system transformation, due to their interdependency.

This report delves into the preconditions that must be met in order to operate the National Electricity Market (NEM) power system at up to 100% instantaneous penetration of renewable generation.

In this report, "instantaneous" means a half-hour period. Naturally, these half-hour periods will become more frequent, as the duration operating entirely on renewables extends to hours or days at a time.

The reason AEMO is seeking to define the necessary engineering changes is that our forecasts indicate that by 2025 there will start to be sufficient renewable resource potential in the NEM to, at times, meet 100% of demand.

This report should be read in conjunction with AEMO's long-range development plan for the NEM, the *Integrated System Plan* (ISP) and other major publications, such as the electricity and gas statements of opportunities, system security reports, and *Quarterly Energy Dynamics* reports.

While this Roadmap is focused on the east coast NEM, learnings are being applied to Western Australia's South West Interconnected System (SWIS) and Wholesale Electricity Market (WEM).

Preparing for high instantaneous penetrations of renewables – and the first period of 100% instantaneous operation – is a critical part of enabling future power system operability at net-zero emissions.

Operating at intervals of 100% renewable power means the NEM, catering to the energy demands of 23 million people, will need to be able to operate securely and reliably without coal or gas.

At these times, coal generators will be offline; either intentionally decommitted, unexpectedly offline for maintenance or failures, mothballed, or retired. Coal plants take many hours, or even days, to restart operation, so once taken offline, they can't be relied on to meet immediate intraday energy demands, or provide system restart services.

Operating regularly with 100% renewable power also means reducing the need for regular reliance on gas-fired generators to firm the electricity supply.

Measuring instantaneous penetration of renewables

- AEMO measures the instantaneous penetration of renewables by determining the percentage of total generation produced from renewable sources over a 30-minute period, using meter data sent to AEMO by larger generators and estimated data for smaller generators such as rooftop photovoltaics (PV).
- Renewable sources include grid-scale wind and solar, hydro generation, biomass, storage, and rooftop PV.

Operating a gigawatt-scale power system at 100% instantaneous renewable generation is a feat unparalleled worldwide.

Relying on variable power generation from the sun and the wind is a technical challenge on two major fronts – the quantum of generation and the attributes of the electricity flow:

- First, the output of solar and wind generation is as changeable as the weather itself. Complementary engineering solutions in the form of firming technologies, such as battery storage or pumped hydro, are needed to smooth out the ups and downs of variable renewable generation.
- Second, energy from the sun and wind is converted to electricity via inverters, which don't inherently deliver all of the same stabilising attributes that traditional synchronous generators provide to the power system.

The power system will require additional engineering solutions to provide essential system services to maintain a stable electrical voltage and frequency and ensure a secure state of operation. Proven technologies such as synchronous condensers will play a role, alongside newer technologies such as grid-forming inverters.

The human dimensions of this transition are as important as the technical requirements.

The power system exists to serve energy consumers, and therefore, the interests of consumers must be at the centre of planned engineering solutions.

This position is recognised in the National Electricity Objective, which requires that investment in the power system must be in the long-term interests of consumers.

AEMO is working with other market bodies, including the Australian Energy Regulator, the Australian Energy Market Commission and the Energy Security Board, to ensure this is the case, given the cost of energy is fundamental to the cost of living.

AEMO wants to help signal to the energy industry and policy makers the efforts needed to ensure AEMO and network service providers (NSPs) are ready and able to run the grid with a high level of renewable power. It is, after all, the cheapest form of energy, which will help keep downward pressure on energy prices for consumers and help meet Australia’s emission reduction commitments.

Daniel Westerman

Chief Executive Officer, AEMO

2 Key messages

Purpose of this *Engineering Roadmap to 100% Renewables*

The increasing proportion of renewable energy generation in the NEM, alongside the decommissioning of fossil fuel generation, is leading to a once in a lifetime change in the way the energy system is designed and operated. However, new renewable generators are seldom installed at the same network locations as retiring fossil fuel generators, and the power system support capabilities between these generation classes differ. As such, the transition is not a 'straight swap' of generation assets, with changes required to the supporting infrastructure and management of the energy system to maintain a secure energy supply in an evolving landscape.

The *Engineering Roadmap to 100% Renewables* provides an overview of the engineering challenges and associated actions that will need to be undertaken to operate the NEM for the first period of 100% instantaneous penetration of renewables, and the actions required to satisfy more regular operation at 100% renewable penetration. Responsibility for undertaking these actions and meeting the technical requirements identified in this report will ultimately be shared across many parties, including AEMO, NSPs, market bodies, market participants, and governments. This report does not seek to allocate new responsibilities. Instead, it seeks to provide AEMO's best current perspective of the actions needed and promote discussion on the priority and relevance of these actions, to facilitate their efficient implementation over an appropriate timeframe in the long-term interests of consumers.

The first period of operation at 100% instantaneous penetration of renewables

- Operating the NEM power system is a real-time task, with control rooms and support functions at AEMO, NSPs and market participants working together to maintain a secure and reliable system 24 hours a day. It is critical to prepare for the first instance of any new operational condition in advance of that condition arising, and preparing for that first instance often also enables the system to operate under that condition on a regular basis.
- The NEM will reach the point where it can operate at 100% instantaneous penetration of renewables many years in advance of the time where it can operate at 100% renewables on an extended basis (over many weeks or months). Therefore, the average penetration of renewables will lag the maximum instantaneous penetration of renewables as the generation and firming resources in the NEM evolve.
- This Roadmap focuses on the actions needed to prepare for the first period of operation at 100% instantaneous penetration of renewables, because these actions are also critical for more regular operation at 100% renewables.
- The term '100% renewables' is used throughout this report to refer to the first instance of operation at 100% instantaneous penetration of renewables.

Key actions required to achieve operation at 100% renewables

This Roadmap has been divided into three broad themes, all of which are pivotal to operating the power system at 100% renewables:

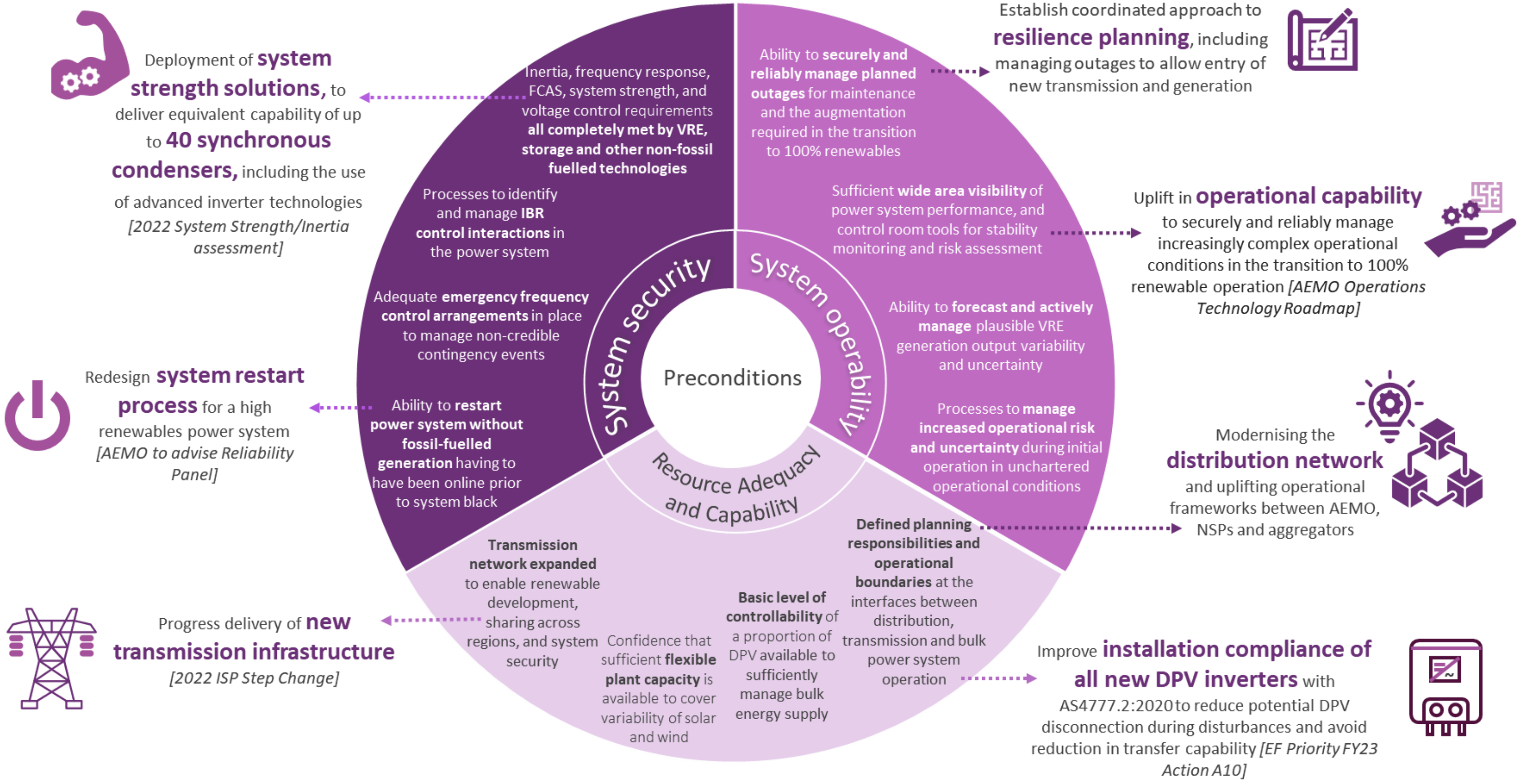
- **Power system security** – maintaining the secure technical operating envelope of the power system under increasing renewable penetrations.
- **System operability** – the ability to securely and reliably operate the power system and transition through increasingly complex operating conditions.
- **Resource adequacy and capability** – building the energy resources and network capability to unlock the renewable potential and the flexible capacity to balance variability over different timeframes.

Within each of these themes, the Roadmap unpacks the engineering and operational readiness steps required to operate at 100% renewables for the first time, by:

1. Identifying the **preconditions** that need to be satisfied to transition to and operate at 100% renewables. These can be considered 'target end-state objectives' that Roadmap actions are designed to meet.
2. For each precondition, assessing **current and emerging challenges** associated with achieving the end state objective. This highlights both 'present forward' issues relevant today and in the near term, and also 'future back' issues anticipated to emerge at very high renewable penetrations.
3. On this basis, identifying **actions necessary** to achieve the precondition, starting from today's current state to the end state objective.

Figure 1 presents a summary view of the preconditions that need to be met before the NEM power system can operate at 100% renewables, and a small selection of key actions to achieve these preconditions. The full Roadmap (in Section 4 and Appendix A1) provides greater breadth and depth of detail for these preconditions and actions.

Figure 1 Select actions and technical preconditions required to operate the NEM at up to 100% instantaneous penetration of renewables



Deployment of **system strength solutions,** to deliver equivalent capability of up to **40 synchronous condensers,** including the use of advanced inverter technologies *[2022 System Strength/Inertia assessment]*

Redesign **system restart process** for a high renewables power system *[AEMO to advise Reliability Panel]*

Progress delivery of **new transmission infrastructure** *[2022 ISP Step Change]*

System security

Inertia, frequency response, FCAS, system strength, and voltage control requirements **all completely met by VRE, storage and other non-fossil fuelled technologies**

Processes to identify and manage **IBR control interactions** in the power system

Adequate **emergency frequency control arrangements** in place to manage non-credible contingency events

Ability to **restart power system without fossil-fuelled generation** having to have been online prior to system black

Preconditions

System operability

Ability to **securely and reliably manage planned outages** for maintenance and the augmentation required in the transition to 100% renewables

Sufficient **wide area visibility** of power system performance, and control room tools for stability monitoring and risk assessment

Ability to **forecast and actively manage** plausible VRE generation output variability and uncertainty

Processes to **manage increased operational risk and uncertainty** during initial operation in unchartered operational conditions

Resource Adequacy and Capability

Transmission network expanded to enable renewable development, sharing across regions, and system security

Confidence that sufficient **flexible plant capacity** is available to cover variability of solar and wind

Basic level of controllability of a proportion of DPV available to sufficiently manage bulk energy supply

Defined planning responsibilities and operational boundaries at the interfaces between distribution, transmission and bulk power system operation

Establish coordinated approach to **resilience planning**, including managing outages to allow entry of new transmission and generation

Uplift in **operational capability** to securely and reliably manage increasingly complex operational conditions in the transition to 100% renewable operation *[AEMO Operations Technology Roadmap]*

Modernising the **distribution network** and uplifting operational frameworks between AEMO, NSPs and aggregators

Improve **installation compliance of all new DPV inverters** with AS4777.2:2020 to reduce potential DPV disconnection during disturbances and avoid reduction in transfer capability *[EF Priority FY23 Action A10]*

Relevant acronyms

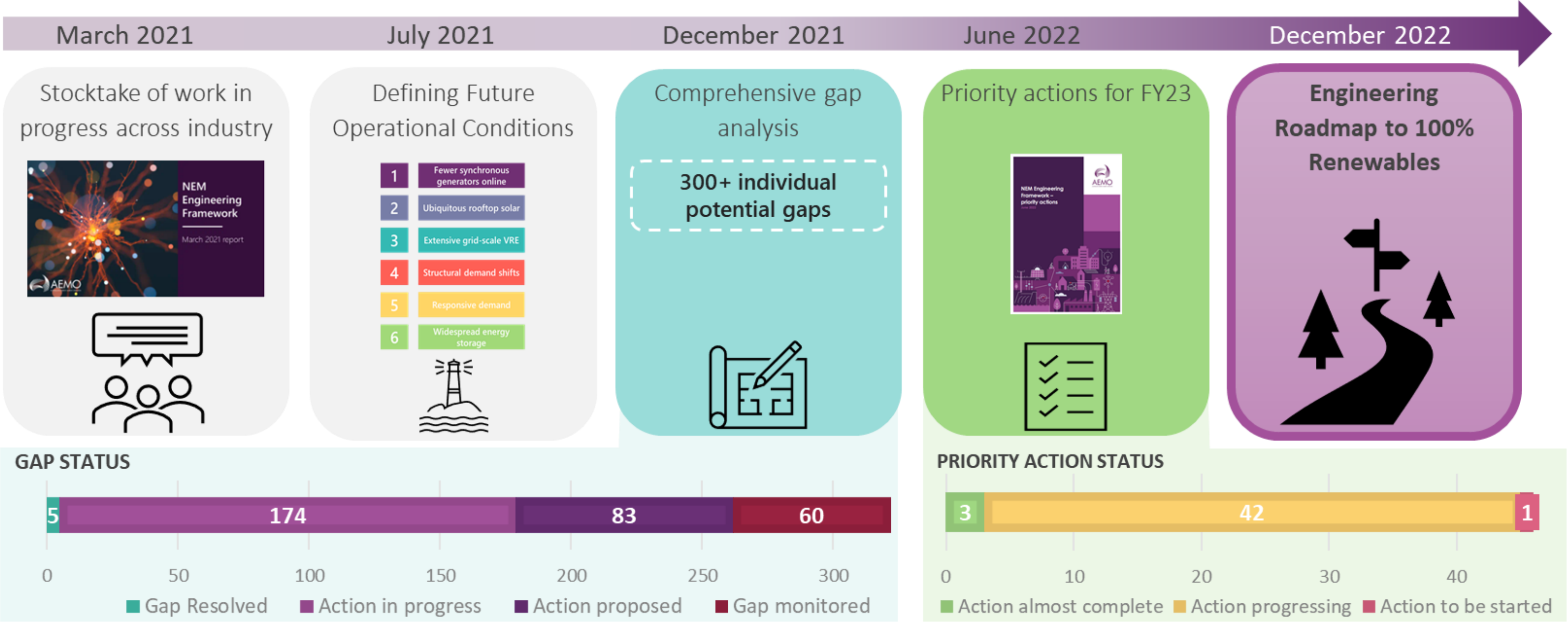
DPV: Distributed photovoltaics; **EF:** Engineering Framework; **FCAS:** Frequency control ancillary service; **VRE:** Variable Renewable Energy

3 Context

3.1 The journey to date

This Roadmap represents AEMO's current best view of engineering and operational readiness requirements for operation with 100% instantaneous renewables, building on the gaps and actions developed with stakeholders in previous Engineering Framework publications[1]. Figure 2 summarises the Engineering Framework's evolution to date along with the current statuses of the gaps and actions published in previous reports.

Figure 2 Evolution of Engineering Framework to date



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[1] Engineering Framework reports are available at https://aemo.com.au/initiatives/major-programs/engineering-framework/reports-and-resources.

3.2 What 100% renewable operation might look like

Projections in the 2022 ISP *Step Change* scenario[2] indicate that by 2025 there will start to be sufficient renewable resource potential[3] in the NEM to at times meet 100% of demand. However, this does not necessarily mean that these periods will result in an instantaneous renewable penetration of 100%. Many factors can contribute to actual penetration outcomes being lower than the overall renewable resource potential, including:

- Market behaviour, such as some renewable generators choosing not to generate at their full available resource potential when the wholesale price of energy is negative, or non-renewable generators bidding themselves into the market for commercial reasons.
- Network constraints, such as limits on transmission line capacity, that mean not all this resource potential can be dispatched in the market and carried by the network to consumers.
- System requirements, such as the need to maintain sufficient essential system services, that may currently result in fossil fuel generators being dispatched to provide essential system services in the absence of capabilities being available from non-fossil fuel alternatives.
- Limitations on the level of distributed photovoltaic (DPV) generation to manage power system security and distribution network conditions leading to curtailment[4] of this renewable resource.

This roadmap focuses on the steps needed to prepare the NEM for the first period of operation at 100% instantaneous penetration of renewables. To reach this objective, consideration of factors other than the instantaneous penetration is also required, including the adequacy of energy supply during periods either side of the first 100% period. Reliability requirements may mean that the first period of 100% renewable operation could need renewable resource potential well above the level required to meet customer load at that time. This is to ensure there is sufficient capacity to meet demand at other times of the day when renewable resource potential may be lower. Similarly, the first period where renewable resource potential is sufficient to satisfy 100% of demand may not lead to an instantaneous penetration of 100%, if that would risk reserve margins becoming too low to meet future demand in that day.

The need to maintain a secure power system may also influence when the first period of 100% renewable penetration arises. In some cases, coal- or gas-fired generation might need to remain online to provide essential system services, resulting in curtailment of renewables to keep these non-renewable generators online.

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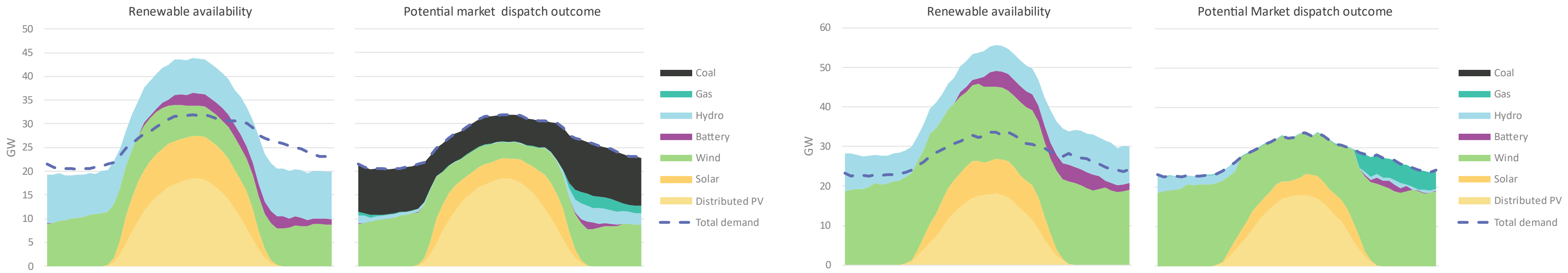
[2] See https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2022-integrated-system-plan-isp.

[3] Resource potential refers to the total available energy from renewable generators at an instant in time given the weather conditions at that time.

[4] Curtailment of DPV can occur through several mechanisms, including inverters automatically reducing their output in response to high network voltage, consumers responding to price or congestion signals through behavioural or market-based mechanisms, or through emergency DPV curtailment schemes as directed by NSPs and/or AEMO.

Figure 3 shows two hypothetical future days with different levels of renewable resource availability across the day, leading to different renewable resource potential profiles. The day shown on the left has 100% renewable resource potential during the middle of the day but does not result in 100% dispatch. The hypothetical day shown on the right includes additional renewable resource potential and assumes sufficient essential system services are available from renewable generation and network assets to operate without coal generators online for the full day. In this case, the system can securely operate at 100% renewable penetration during the middle of the day, with gas fired generation coming online later in the day to cover afternoon demand.

Figure 3 Hypothetical future resource mix at times of high renewable resource availability



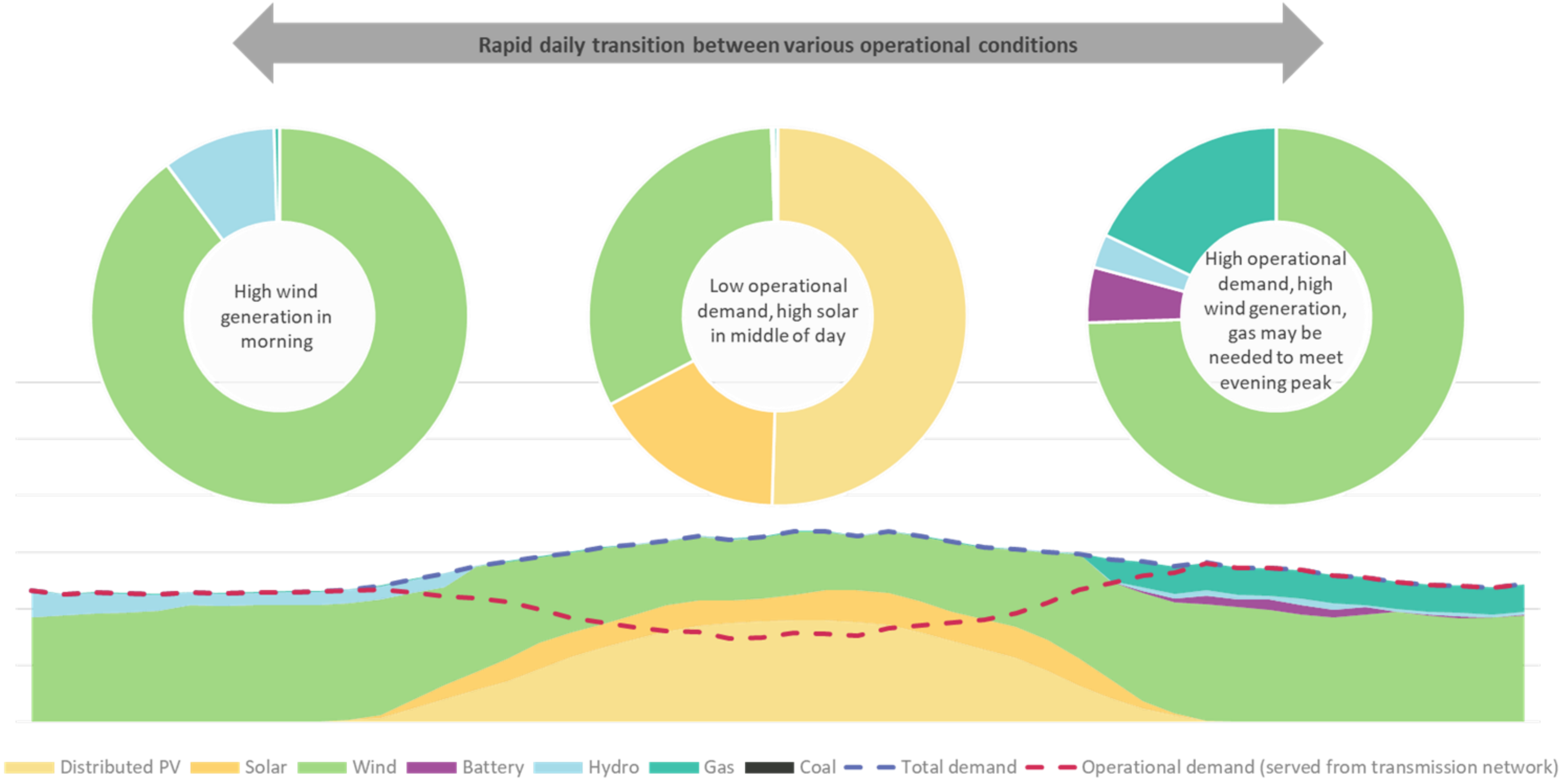
Day where full renewable resource potential cannot be utilised

Day with viable 100% renewable penetration

Periods of 100% instantaneous penetration of renewables could be reached through a diverse range of operational conditions, and it is not yet clear which conditions and resource mixes are likely to produce market outcomes that lead to the first period of 100% operation.

Figure 4 shows how, over the course of a hypothetical day, a broad range of resource mixes could lead to prolonged periods of 100% renewable penetration. Notably, the resource mix around midday is driven by strong DPV generation leading to low operational demand, while in the evening the comparatively high operational demand is predominantly met by grid-scale wind generation. These resource mixes, and the transition between them, will require distinct actions to manage the system securely in real time.

Figure 4 Daily resource mixes that could lead to 100% instantaneous penetration of renewables



3.3 The first instance of 100% renewable operation

The NEM evolved from the historical integration of smaller regional power systems. The resultant layout of the NEM, coupled with evolving jurisdictional policies on energy and carbon abatement, means that the transition to 100% instantaneous renewable penetration is occurring in some market regions ahead of others. Preparation for 100% renewable operation needs to consider how individual regions will operate securely at high penetrations of renewables, because this will influence how the interconnected NEM needs to operate throughout this complex transition.

The transition to the first instances of 100% renewable operation will involve an incremental decrease in the minimum number of synchronous fossil fuel units generating into the NEM at any given time as these units adapt their operating practices to reflect market and system conditions. Some of these generators have the capability to come online and offline throughout the day, while other less flexible generators may start to decommit their capacity from the market for longer periods of days, months, or seasons. This roadmap aims to ensure the NEM is prepared for when 100% renewables could occur as an outcome of market dispatch, without any synchronous fossil fuel units producing energy. This report seeks to position the NEM in readiness to operate under a 100% renewable condition.

Transition of fossil fuel generating unit operating practices

Operation at 100% instantaneous penetration of renewables does not mean that all fossil fuel generators have exited the market permanently. There are many reasons why fossil fuel generators may not be online or available to generate into the system in a given half-hour, including:

- **Economic dispatch** – generators may be available, but not dispatched if there is more economic generation available.
- **Forced outage** – generators may unexpectedly disconnect from the system due to fault conditions arising on the network or within the plant itself, leading to units tripping offline.
- **Decommitment** – generators may choose to decommit from the market temporarily in response to factors such as maintenance requirements, or fuel availability.
- **Mothballing** – economic conditions or extended maintenance periods could lead to generators withdrawing from the market for an extended period, perhaps on a seasonal basis or even for years at a time.

Preparation for the first instance of 100% renewable operation needs to occur ahead of the ‘last’ fossil fuel generating unit going offline for any of the above reasons. The transition of fossil fuel generating unit operating practices means this could happen well in advance of the eventual retirement of all these units.

Preparation requires:

- Proactive planning for plausible changes to availability of essential system services currently tied to generator availability. This could be enabled and provided by other technologies through markets, network planning processes, or system security frameworks (including system strength, frequency control, inertia, and system restoration).
- Resource adequacy planning and jurisdictional and commercial decisions around fossil fuel generator operating practices will need to consider how the energy and dispatchable capacity requirements of the NEM can be met by other means.
- Preparedness of control rooms to operate the system in new conditions

Planning and enabling the investment required to efficiently, securely, and reliably operate at up to 100% renewable penetration NEM-wide will require an extensive effort across AEMO, NSPs, market participants, and governments ahead of time.

Assessment of each of the above points ahead of the first period with no fossil fuel units online will provide the basis for ensuring the NEM remains secure, reliable, and resilient in the absence of these generators. It is therefore critical that the NEM's planning and operational processes pre-emptively prepare for changes in the operating patterns of fossil fuel generators, well ahead of announced closure dates[5,6].

3.4 Planning for an operational transition

Planning processes in the NEM seek to ensure that the necessary asset development and investments are made to efficiently maintain sufficient network and generation capacity and essential system services over the planning time horizon, usually up to 10 years in advance, or longer in the case of activities such as the ISP. It is important to note that there are limitations to what can be assessed and actioned in the planning timeframe, due to uncertainties in the design and performance of assets that have not yet been developed. These uncertainties mean that planning decisions are always a best estimate, leaving detailed analysis of power system operability closer to operational timeframes where there is greater certainty of system parameters.

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[5] See AEMO, Generation Information, at https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-planning-data/generation-information.

[6] See AEMC, Generator three year notice of closure, at https://www.aemc.gov.au/rule-changes/generator-three-year-notice-closure#:~:text=The%20rule%20is%20based%20on,to%20the%20market%20before%20closing.

As the system transitions to higher levels of inverter-based resources (IBR) generation, the behaviour of the power system is less well understood, meaning the assessment of operability is becoming more detailed and complex, requiring increased time and effort to establish operational confidence. However, in addition to performing complex power system simulations, additional actions are likely to be required to build operational confidence in uncharted territory:

- Trialling the operation of the power system and monitoring performance in real time, with appropriate fail safe/roll back measures in place.
- Reviewing the performance of the power system following trials or system disturbances to assess the cause of instabilities. These can then be used to tune the models used for assessing future performance
- Using engineering margin in both planning and operational decisions for phenomena that can't be accurately modelled ahead of time.

Ireland's independent system operator EirGrid developed an approach to actively plan and prepare Ireland's power system for increasing renewable dispatch through a sequence of 'operational trials,' successively expanding the power system's defined limits at each iteration[7]. AEMO has translated this concept for the NEM in terms of a transition through a series of operational 'hold points', the successful relaxation of which can be considered operational milestones.

Figure 5 illustrates the general sequence of steps needed for AEMO to prudently transition to new operating regimes associated with major hold points on the way to 100% renewables operation NEM-wide. The process recognises that:

- While planning solutions might be in place, the planning process may not be able to identify and address all relevant technical issues and phenomena that can occur in operating a gigawatt-scale power system in real time.
- Each new operational milestone will correspond to a completely new, materially different, technical operating envelope for individual regions and eventually the NEM.

Precisely identifying the future sequence of hold points in the transition to 100% renewables is difficult ahead of time but can be considered iteratively, on an ongoing basis in the planning process to signal the most critical and onerous to manage. It is also important to note that not all hold points may be related to minimum synchronous generating unit combinations – others may involve factors such as number of IBR online, aggregate VRE output from new renewable energy zone (REZ) developments or the level of uncontrollable distributed energy resources (DER). With the progression through these hold points, it is anticipated that a greater penetration of renewable generation can be accommodated on the system.

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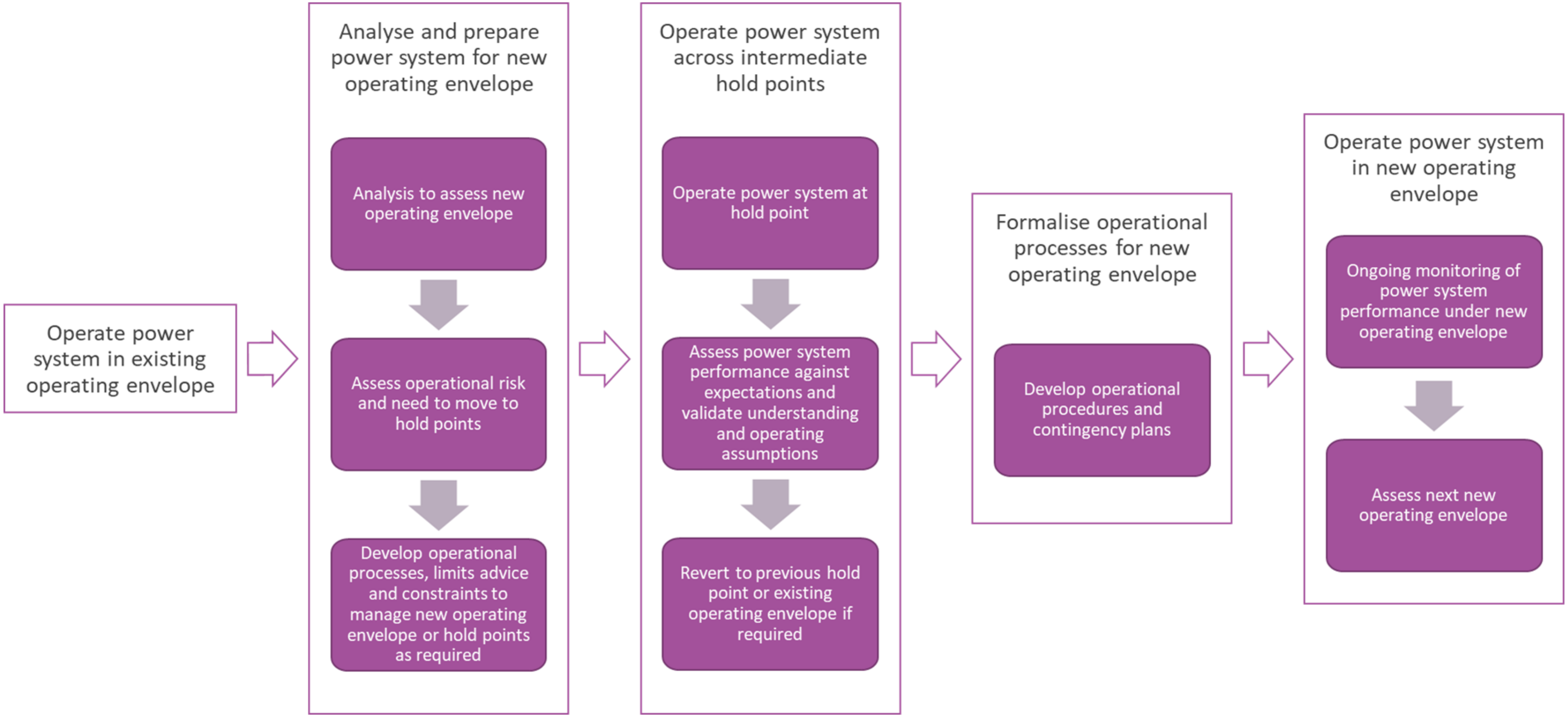
[7] See AEMO, *Maintaining Power System Security with High Penetrations of Wind and Solar Generation – International insights for Australia*, October 2019, Section 3.8, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf and EirGrid, *Shaping our electricity future*, 2021, Section 6.3, at https://www.eirgridgroup.com/site-files/library/EirGrid/Shaping_Our_Electricity_Future_Roadmap.pdf.

Figure 5 General process to be operationally prepared to 'relax' a hold point and move on to the next one



Operate power system in existing operating envelope

Analyse and prepare power system for new operating envelope

- Analysis to assess new operating envelope
- Assess operational risk and need to move to hold points
- Develop operational processes, limits advice and constraints to manage new operating envelope or hold points as required

Operate power system across intermediate hold points

- Operate power system at hold point
- Assess power system performance against expectations and validate understanding and operating assumptions
- Revert to previous hold point or existing operating envelope if required

Formalise operational processes for new operating envelope

- Develop operational procedures and contingency plans

Operate power system in new operating envelope

- Ongoing monitoring of power system performance under new operating envelope
- Assess next new operating envelope

A transparent, structured approach is required to manage this process within AEMO's operational risk tolerance and not compromise consumer expectations for secure and reliable supply.

The process has been informed by AEMO and ElectraNet's ongoing work to assess the potential for relaxing the current two synchronous generator requirement for the South Australian region[8]. The experience in South Australia has highlighted the step change in AEMO and NSP operational capability required to enable the transition to the first 100% renewable periods.

Subsequent iterations of this process in the transition to 100% will be increasingly complex, with system dynamics determined by IBR (large and small) controls and stabilising plant such as synchronous condensers, fewer synchronous fossil fuel generating units, and increasing aggregate impact of weather on the supply demand balance. This underscores the importance of several activities for securely and reliably enabling the operational transition, including:

- NSP engineering studies to develop limit advice, necessary to define the secure technical envelope of the power system, which AEMO requires to operationalise through constraints in the dispatch process.
- Staged implementation of new limits to successively commission the system to new operating points, with reversion to previous defined technical envelopes if issues are identified.
- Collaboration between NSPs and AEMO to continuously monitor, assess and manage high-impact, low probability (non-credible contingency) risks in an increasingly complex operating environment.
- Establishing fit-for-purpose operational visibility of the dynamic behaviour of the power system through NSP development of high-speed monitoring and necessary communications infrastructure for integration with AEMO wide area monitoring systems (WAMS).
- Developing real-time and look-ahead stability assessment capability to validate constraints defining the technical envelope and provide operators the decision support tools they need to proactively manage operational risks.

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[8] See https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/congestion-information-resource/related-resources/operation-of-davenport-and-robertstown-synchronous-condensers.

3.5 Interacting roadmaps and processes

As a foundation to preparing for 100% instantaneous renewables, significant work and investment will be needed across industry and government to build the generation and transmission outlined in the ISP, meet the requirements identified in AEMO's annual system security reports, and design and implement new regulatory and market frameworks. Some foundational technical enablers are already well-advanced, including actions to uplift and streamline the connection process for utility-scale generation (via the Connections Reform Initiative[9]), and actions to uplift AEMO's operational tools and processes (via the Operations Technology Roadmap[10]).

The Engineering Roadmap complements these foundational efforts by providing AEMO's integrated view of the engineering and operational readiness steps needed to prepare the NEM for the first periods of 100% instantaneous renewable penetration, with a focus on steps that are additional to those captured in AEMO's other publications.

The Roadmap assessment of preconditions, and actions necessary to achieve these, directly supports AEMO's implementation of the Operations Technology Roadmap, focusing on the uplift in operational capability (control room and supporting functions) to facilitate secure and reliable system operations as the power system transforms. This includes implementation of projects underway and planned to uplift operational capabilities and efforts to prioritise initiatives to address emerging capability gaps as operational conditions change.

In addition to these engineering activities, a large volume of regulatory reform work is underway to refine the frameworks and markets required for the future NEM. Given the engineering focus of the Roadmap, references to regulatory reform in Section 4 have been limited to denoting where an action is dependent on an in-flight reform. Where such a reference is made, further detail on the relevant reform is noted in the associated section of the Appendix.

The solutions to many of the identified technical challenges throughout the Roadmap may ultimately be resolved most efficiently through regulatory and market reforms. However, emphasis in this Roadmap has been placed on technical requirements, without presuming specific pathways for regulatory solutions. Further work will need to be undertaken among the market bodies and with stakeholders in 2023 to explore how the Engineering Roadmap can guide future reform priorities.

Figure 6 summarises how these different engineering and reform processes are collectively contributing to building readiness for operation of the NEM at 100% renewables.

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[9] See https://aemo.com.au/consultations/industry-forums-and-working-groups/list-of-industry-forums-and-working-groups/connections-reform-initiative.

[10] See https://aemo.com.au/initiatives/major-programs/operations-technology-roadmap.

Figure 6 Roadmaps and processes helping to prepare the NEM for instantaneous operation at 100% renewables

Plan, design, and build an operable system

Build network and generation resources
e.g. delivery of actionable Integrated System Plan projects

Improve and streamline processes
e.g. Connections Reform Initiative

Design and implement regulatory and market reform to support effective and efficient planning and operations
e.g. NEM 2025 Reform Program

Define technical requirements
e.g. System Strength and Inertia Reports

Uplift operational tools and processes
e.g. Operations Technology Roadmap

Identify engineering and operational needs for operation at 100% renewables
e.g. **Engineering Roadmap to 100% Renewables**

Completion of actions identified by engineering and reform processes

Capability established to operate NEM with periods of 100% renewables

3.6 Next steps and engagement

AEMO welcomes feedback on this Roadmap. Given the breadth of technical content covered, combined with the dynamic nature of the energy transition, the Roadmap is positioned as a living document. AEMO will leverage stakeholder input and monitor the progression of actions over time to help inform and periodically shape its strategic approach.

A public webinar has been scheduled for 3 February 2023 to provide stakeholders with an overview of the Roadmap and an opportunity to ask questions of the Roadmap's authors. To register for this webinar, please complete the form here. Please note that this meeting will be recorded by AEMO and may be accessed and used by AEMO for dissemination to those that cannot attend. By attending the meeting, you consent to AEMO recording the meeting and using the record for this purpose. No other recording of the meeting is permitted.

For stakeholders wishing to provide written feedback on the Roadmap, please contact AEMO at FutureEnergy@aemo.com.au.

In addition to the stakeholder webinar, AEMO envisages the next steps following publication of this Roadmap will include:

- Continued delivery of 46 FY23 Engineering Framework priority actions[11].
- Consideration by the market bodies to explore the implications of the Roadmap on future regulatory and market reform priorities.
- Additional priority actions for AEMO that arise from the Roadmap, if not already underway, will be assessed as part of AEMO's FY24 budget planning process.
- An update report in mid-2023 summarising the progress made on FY23 Engineering Framework priorities, and any additional engineering or operational readiness commitments AEMO is making for FY24.

In addition to these steps in the NEM, work is underway in Western Australia to leverage the insights from this roadmap, as outlined in Section 3.7.

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[11] Documented in https://aemo.com.au/-/media/files/initiatives/engineering-framework/2022/nem-engineering-framework-priority-actions.pdf.

3.7 Considerations for Western Australia's Wholesale Electricity Market (WEM)/South West Interconnected System (SWIS)

AEMO operates the Western Australian electricity system (SWIS) and market (WEM). The Western Australian energy transition is progressing at pace as government, industry and consumers seek to decarbonise the energy sector. The themes presented in this report for operation of the NEM at 100% instantaneous penetration of renewables are aligned with AEMO's needs to achieve the same goals in Western Australia.

Like the NEM, the capability to operate the SWIS at 100% instantaneous penetration of renewables is contingent on:

- AEMO's ability to access sufficient services and capabilities to maintain power system security and reliability while operating without synchronous generation, and
- Achieving safe transition between operational conditions in real time.

This report identifies critical underpinning capabilities AEMO would require to achieve these goals in Western Australia. These must be assessed in the specific context of the market frameworks through which AEMO operates the WEM, and the required fleet capability and electrical characteristics of the SWIS.

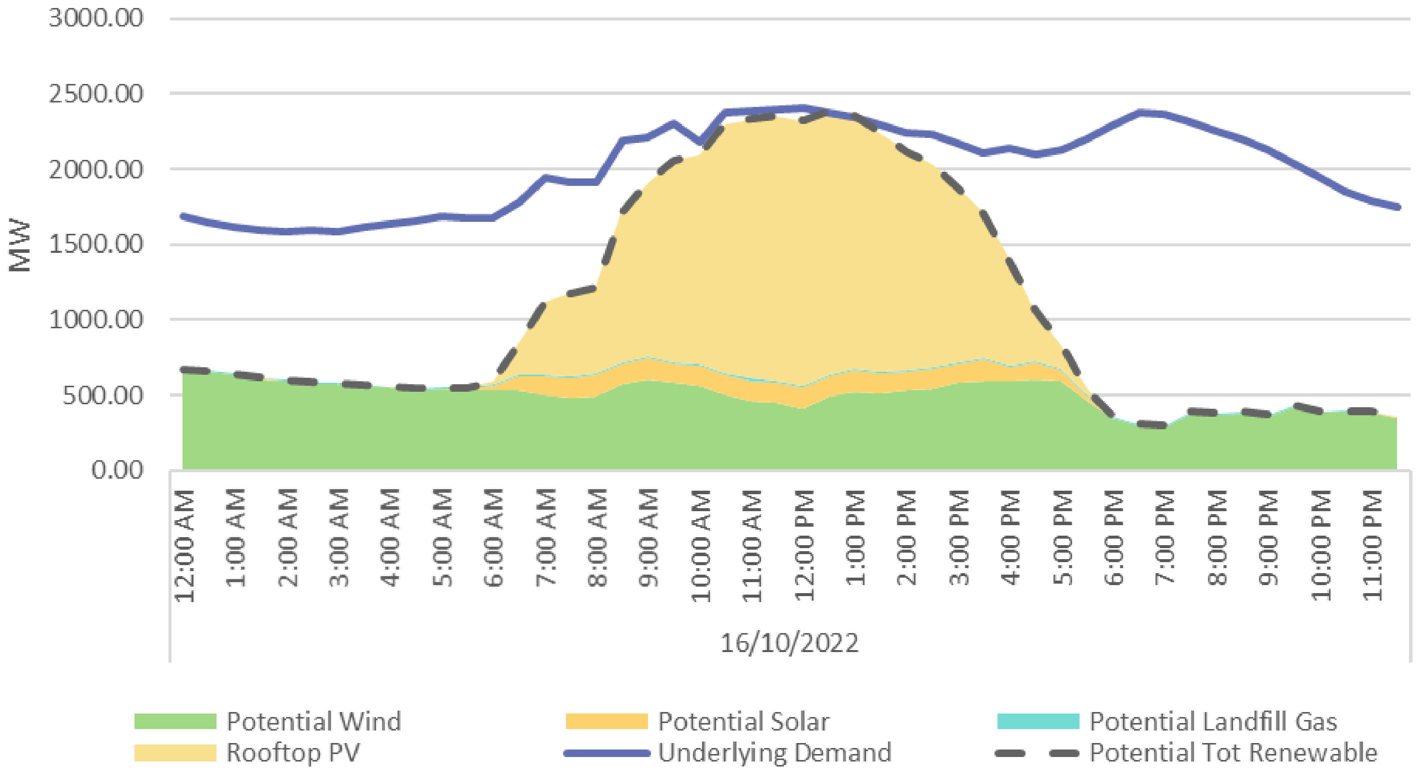
The WEM is undergoing significant reform under the WA Government's Energy Transformation Strategy, with new market arrangements developed as part of Stage 1 of the strategy to commence by 1 October 2023. The new market will see the WEM operated though Security Constrained Economic Dispatch alongside a range of foundational reforms, not least the introduction of a range of new Frequency Co-Optimised Essential System Services (FCESS), including a rate of change of frequency (RoCoF) Control Service for the procurement of inertia. Stage 2 of the Energy Transformation Strategy will continue to evolve elements of the WEM to enable the energy transition and enhance participation in the WEM.

These initiatives are significant in mapping the pathway to 100% instantaneous penetration of renewables and the Western Australian Government's announced targets for decarbonisation.

Significant milestones have been reached in the WEM in achieving resource sufficiency from renewables, with recent records in penetration of renewables (81% in November 2022) and penetration of DPV (74% in October 2022). Critically, both these records were achieved while utility-scale renewables were economically curtailed in response to energy market prices. AEMO estimates renewable availability exceeded 100% of total demand during the October event, as shown below in Figure 7.

AEMO is continuing to characterise the needs of the system which must be met by renewables and renewable-enabling technologies, alongside a pathway to real-time transition to 100% instantaneous penetration of renewables. AEMO intends to release a roadmap of actions associated with the energy transition in WA in 2023.

Figure 7 WEM renewable resource potential vs underlying demand on 16 October 2022



4 Action roadmap

The Roadmap is divided into three broad themes, all of which are pivotal to operating the power system at 100% renewables. These three themes are: **Power system security**, **System operability**, and **Resource adequacy and capability**. Content across the three broad themes is further separated into 14 distinct sections, as listed in Table 1.

Table 1 Roadmap themes and grouping

Theme	Roadmap sections
Power system security: maintaining the secure technical operating envelope of the power system under increasing renewable penetrations.	• Frequency and inertia • Transient and oscillatory stability • System strength and converter driven stability • Voltage control • System restoration
System operability: the ability to securely and reliably operate the power system and transition through increasingly complex operating conditions.	• Monitoring and situational awareness • Operational processes • Power system modelling
Resource adequacy and capability: building and integrating the energy resources and network capability to enable the renewable potential and the flexible capacity to balance variability over different time frames.	• Utility-scale variable renewable energy (VRE) • Distributed energy resources (DER) • Structural demand shifts • Transmission • Distribution • Firming

How to read the roadmap

The steps required to enable the operation of the NEM at 100% instantaneous penetration of renewables are summarised in Roadmap graphics throughout Section 4. These Roadmap graphics sort the actions required by their associated technical precondition[12]. The Roadmap graphics also provide an indication on the current status of

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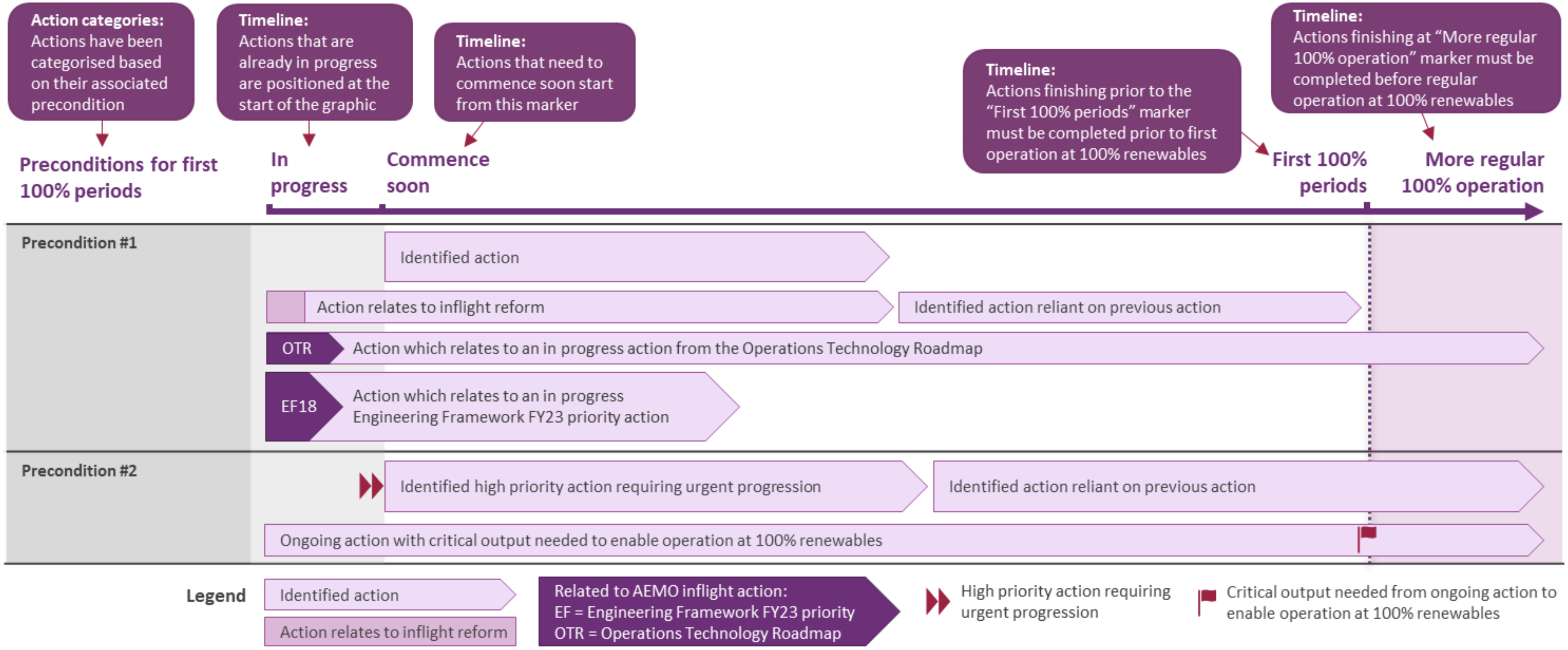
[12] 'Preconditions' have been used to describe the categories of system requirements that must be met to operate the NEM at up to 100% instantaneous penetration of renewables.

the actions, and whether they are required to be completed to meet a precondition for the first instances of operating at 100% renewables, or are more relevant for enabling regular operation at 100% renewables. Some actions placed earlier in the timeline are intended to address current or emerging near-term issues, which are required to effectively manage today's power system. These actions will be critical in securely and reliably enabling the increase of renewable penetrations from today's levels, providing a foundation for subsequent actions in the transition to 100% renewable operation. Appendix A1 provides further detail on the required actions, while Figure 8 below provides a reading guide to support the interpretation of the Roadmap graphics.

Figure 8 Roadmap to operation at 100% instantaneous penetration of renewables – reading guide



4.1 Power system security

Maintaining the secure technical operating envelope of the power system under increasing renewable penetrations.

The transition to 100% renewable operation will require the progressive expansion of the technical envelope of the power system to be able to accommodate this dispatch outcome – with new approaches required to maintain many essential power system requirements. This is a major transition challenge given most of these requirements are provided for by fossil fuel generation today, but technology transition is underway.

Power system security relates to the ability of the power system to manage ongoing variability, as well as sudden, large and unexpected disturbances. AEMO's power system security responsibilities are set out in the NER[13] and system standards[14], and operationalised through guidelines and procedures[15]. This section of the Roadmap lists the preconditions that need to be satisfied across AEMO's key system security responsibilities in the transition to 100% renewables, and actions necessary to meet these preconditions.

A major technical challenge for maintaining power system security in the renewable transition is the changing stability and dynamics of the power system in the evolution from a largely synchronous fossil fuel generation-based power system to one characterised by many (small and large) inverter-based technologies.

Effectively integrating this level of IBR entry within the power system presents both challenges and opportunities. Stability in the context of traditional power systems is well understood, informed by an extensive power engineering knowledge base and operational experience globally over many decades. Increasing penetrations of IBR generation have led to the emergence of new forms of instability and the need for re-examination of previously well-understood forms[16]. The capability and flexibility of modern IBR controls also mean there are opportunities for these technologies to assist with addressing many renewable integration challenges[17].

The key design choice for a high IBR future is compatibility between IBR and the power system, comprising both:

- How IBR plant should operate in the power system, specified in grid codes and performance requirements, and

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[13] See AEMC, *National Electricity Rules*, November 2022, Clause 4.3.1 Responsibility of AEMO for power system security, at https://energy-rules.aemc.gov.au/ner/429/187180#4.3.1.

[14] Standards for the performance of the power system as set out in NER Schedule 5.1a, and power system security standards determined by the Reliability Panel, defined in NER cl. 8.8.1(a)(2).

[15] See https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/power-system-operation.

[16] Hatziargyriou, Nikos, et al., *Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies*, April 2020, IEEE PES Technical Report PES-TR77.

[17] See AEMO, *Application of Advanced Grid-scale Inverters in the NEM*, August 2021, at https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf.

- The extent to which the synchronous AC power system itself should evolve to accommodate the IBR, in terms of fundamental control philosophy, system standards and system-level management strategies.

The Roadmap has taken a pragmatic approach in this regard, by assuming that (for at least the next decade) the power system will continue to be a synchronous AC power system operating with relatively narrow permitted ranges for frequency and voltage deviations, as it is today. This then focuses attention on technically feasible and plausible paths, and sets parameters for new technology innovation and entry sooner in the transition. While there are various ways the power system might evolve, some appear to be less plausible in the foreseeable future and will require further research to determine if the changes bring sufficient benefit to overcome the cost[18].

In this context, the Roadmap assumes that general principles for maintaining power system security today (as listed in NER cl 4.2.6) will continue to hold:

- The power system should be operated such that it is and will remain in a secure operating state, to the extent practicable.
- Following a contingency event or a significant change in power system conditions, AEMO should take all reasonable actions to return the power system to a secure operating state within 30 minutes.
- Emergency frequency control schemes are available and in service to restore the power system to a satisfactory operating state following protected events and significantly reduce the risk of cascading outages and major supply disruptions following significant multiple contingency events.
- Sufficient system restart ancillary services (SRAS) are available, in accordance with the system restart standard, to allow the restoration of power system security and any necessary restarting of generating units following a major supply disruption.
- Sufficient inertia should be available in each inertia sub-network to meet the applicable inertia requirements.
- Sufficient three phase fault level should be maintained at each fault level node to meet the applicable system strength requirements.

Roadmap actions associated with power system security largely fall into two categories:

1. Actions to better understand power system limits and expand the technical envelope (some of which are captured in Section 4.2.3 on power system modelling).
2. Actions to ensure capabilities are available to allow the system to be operationally maintained within the expanded technical envelope.

This section is divided into the key system management tasks AEMO must undertake to maintain power system security – managing frequency and inertia, transient stability and oscillations, system strength and converter driven stability, voltage control, and system restoration.

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[18] G-PST, *System Needs and Services for Systems with High IBR Penetration*, October 2021, at https://globalpst.org/wp-content/uploads/GPST-IBR-Research-Team-System-Services-and-Needs-for-High-IBR-Networks.pdf.

Unbundling power system requirements in operational timeframes

There has been much discussion by industry stakeholders in recent years regarding the aspiration to unbundle NEM system requirements in operational timeframes to enable their provision in an efficient way that is independent of specific asset configurations*. The extent to which this unbundling will be practicable is still unknown, and clarity on this is not expected without extensive modelling and operational experience through progressive hold points to understand physical properties of future system assets. Like other grid operators around the word, AEMO's understanding of the power system's technical envelope continues to evolve as the generation mix becomes increasingly dominated by IBR. This understanding is informed by AEMO's experience operating parts of the NEM and SWIS at high levels of penetration, learning from actual system events, and transitioning to higher-fidelity modelling tools that better capture the behaviour of fast-acting IBR control systems.

Power system stability, the underlying physical dynamic capability and response of the power system to disturbances, is the key determinant of the technical envelope at any given time. It is an outcome of the interaction of many electrical and mechanical elements within a complex, non-linear, dynamic system. The strength and resilience of a system to recover from a disturbance relates to all network components, including synchronous and IBR generation, as well as network and generator protection systems. As a result:

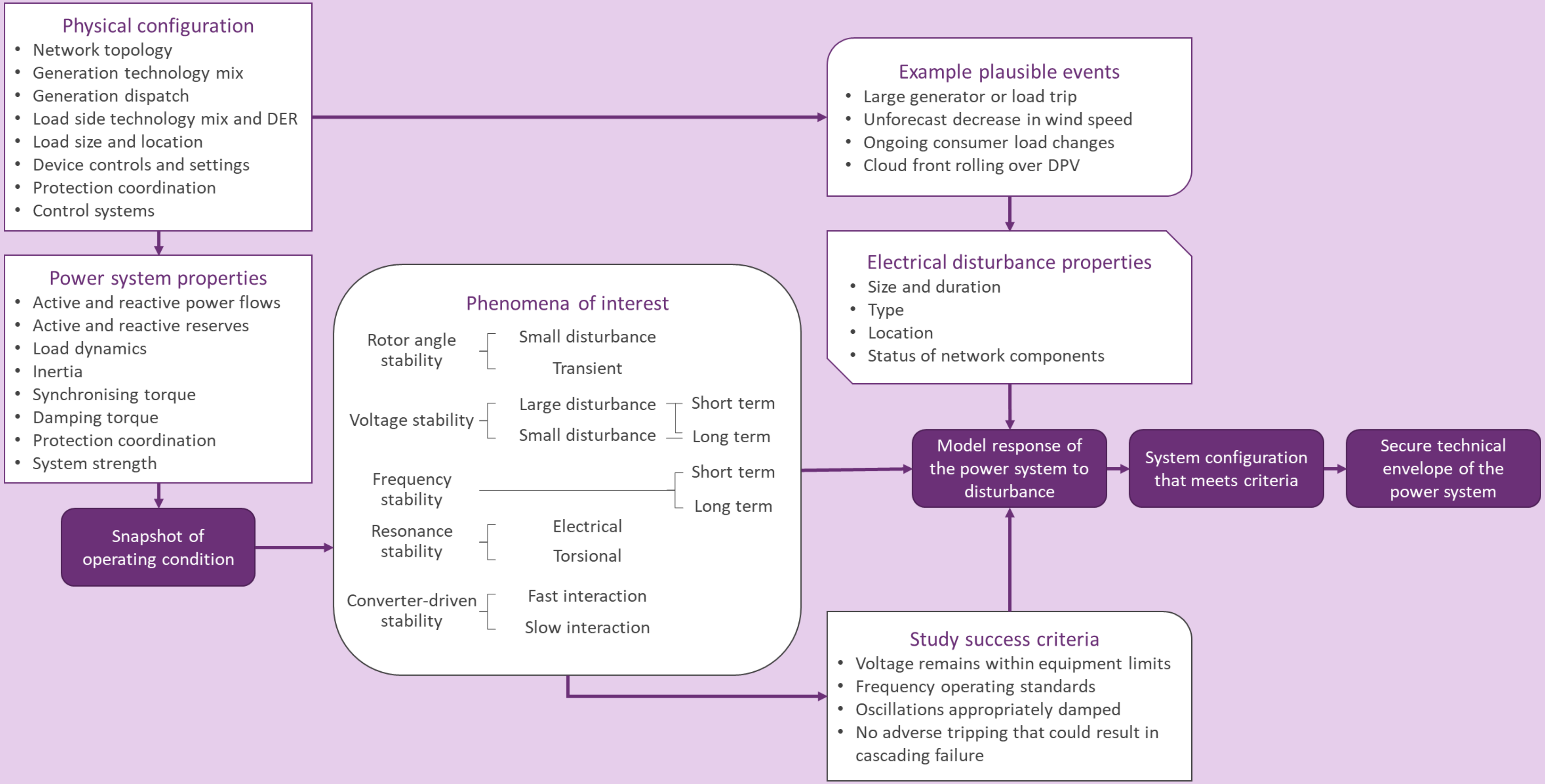
- System needs and technical scarcities are inter-dependent: different stability mechanisms interact simultaneously to determine the dynamic behaviour of the power system following a disturbance, which means it is never entirely possible to isolate one single mechanism for study from the others.
- Services to address these needs are coupled with each other: different local, autonomous and signalled device responses and other control actions, calibrated to assist with returning the power system to stable equilibrium, can address multiple technical scarcities and imbalances at the time.

The technical envelope of the power system is currently assessed in terms of physical configurations of assets – including network topology, generating plant online and their power output, and other factors – and implemented operationally through constraints in the dispatch process and unit commitment. AEMO expects this same process will be required at times of 100% renewables, noting that defining secure configurations of assets will be required even with no fossil-fuelled generation online. Further work by market bodies and industry over the coming years will be needed to evaluate the extent to which unbundling of power system requirements in operational timeframes is technically feasible, and in what circumstances it results in improved outcomes for consumers over the long term.

Power system security is generally assessed using power system studies on a snapshot representation of the system's physical configuration. These snapshots can represent actual instances in time or boundary conditions depending on the phenomena of interest. It is, however, never entirely possible to isolate a single phenomenon for study without making assumptions about the remaining behaviour of the power system. For example, to assess frequency stability, one must assume that voltage remains within acceptable bounds and any associated response will not affect frequency outcomes.

Figure 9 shows how power system security is assessed and how the outcomes of studies help define the technical envelope.

Figure 9 How the technical envelope of the power system is determined



* See Page 14 of EF Priority Actions Report, at https://aemo.com.au/-/media/files/initiatives/engineering-framework/2022/nem-engineering-framework-priority-actions.pdf.

4.1.1 Frequency and inertia

In a synchronous AC power system, frequency reflects the balance between active power generated and consumed. AEMO is responsible for managing power system frequency and time error in accordance with the Frequency Operating Standard (FOS)[19].

Actions in this section assume that the current tiered, hierarchy of frequency control services will persist by the first 100% renewable periods. This structure is characterised by two foundational premises: frequency will continue to act as an indicator of supply-demand balance in the power system; and that it will continue to be necessary to maintain frequency within relatively narrow bounds around a nominal value for equipment to operate safely. Actions related to inertia are included under this section to acknowledge the critical role mechanical inertia plays on managing the rate of change of frequency (RoCoF). However, it also acknowledged that inertia is an inherent physical property of the power system that impacts the overall system dynamic performance, and all forms of stability more generally, both local and global, which will require consideration as frequency response is increasingly provided by IBR.

As the power system evolves, with increasing DC applications, and continued proliferation of IBR and other modern power-electronic devices within AC power systems, these premises may change, and will require new control strategies and methods to capitalise on the wider frequency ranges that may be tolerable.

Table 2 Identified preconditions for first 100% renewable periods and associated challenges – frequency management

Preconditions for first 100% periods	Current and emerging challenges
Ability to keep system frequency within defined limits following credible and non-credible events, including RoCoF containment and effective emergency frequency control arrangements	• Reducing inertial response due to ongoing displacement or retirement of synchronous generation, replaced with IBR. – Increasing potential for high RoCoF conditions following credible and non-credible contingency events, leading to excessive emergency frequency control scheme (EFCS) action. • Reducing load available for shedding in the daytime due to increasing DPV uptake which is reducing effectiveness of UFLS schemes to arrest frequency decline during a non-credible contingency. – With continued DPV growth, existing UFLS schemes will trip net-generating, reverse flowing the feeders, exacerbating the initiating MW imbalance
Frequency response and frequency control ancillary services (FCAS) reserve requirements completely met by VRE, storage, demand response and other non-fossil fuel technologies	• Changing contingency FCAS reserve requirements – Contingencies to be considered and associated risk profiles are changing with evolving generation and load mixes – Increasing secondary risks such as DPV disconnection during disturbances and run-back schemes. • Increasing regulation FCAS volumes required due to increasing variability in the supply-demand balance and forecast uncertainty with ongoing growth in DPV and VRE. • Reduction in available frequency response due to VRE and DPV displacing synchronous fossil fuel generation online.

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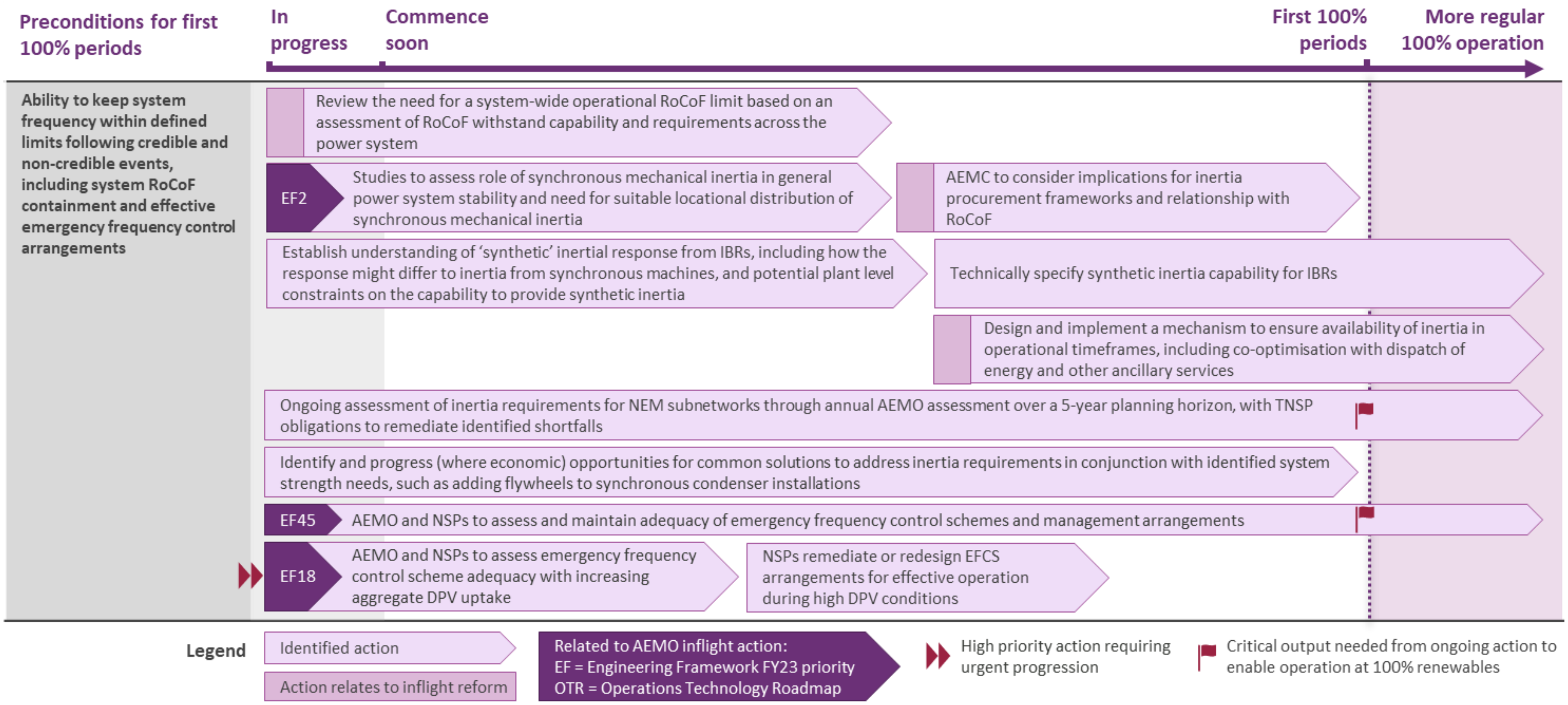
[19] AEMO, *Power System Security Guidelines*, May 2022, Section 16, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power_System_Ops/Procedures/SO_OP_3715%20Power-System-Security-Guidelines.pdf.

Preconditions for first 100% periods	Current and emerging challenges
	– Could result in challenges in maintaining sufficient narrowband primary frequency response (PFR), regulation and contingency frequency control in the power system, since DPV does not currently supply these services • Reduction in reserve availability for frequency control. – Low availability of raise FCAS in periods with high VRE online operating without headroom. • Low availability of lower FCAS service when synchronous generators are at minimum load.
Adequate system inertia monitoring and accurate inertia forecast capability (supply and demand side) required as an input to constraints	• Inertia estimation currently based on synchronous generation unit commitment and does not consider load side inertia contributions. – As inertia reduces, will be become increasingly difficult to determine when low inertia thresholds have been crossed and accurate inertia calculation will be increasingly critical for inertia-dependent constraints and coordination of FCAS requirements.

Figure 10 Actions to achieve identified preconditions for first 100% renewable periods – frequency and inertia

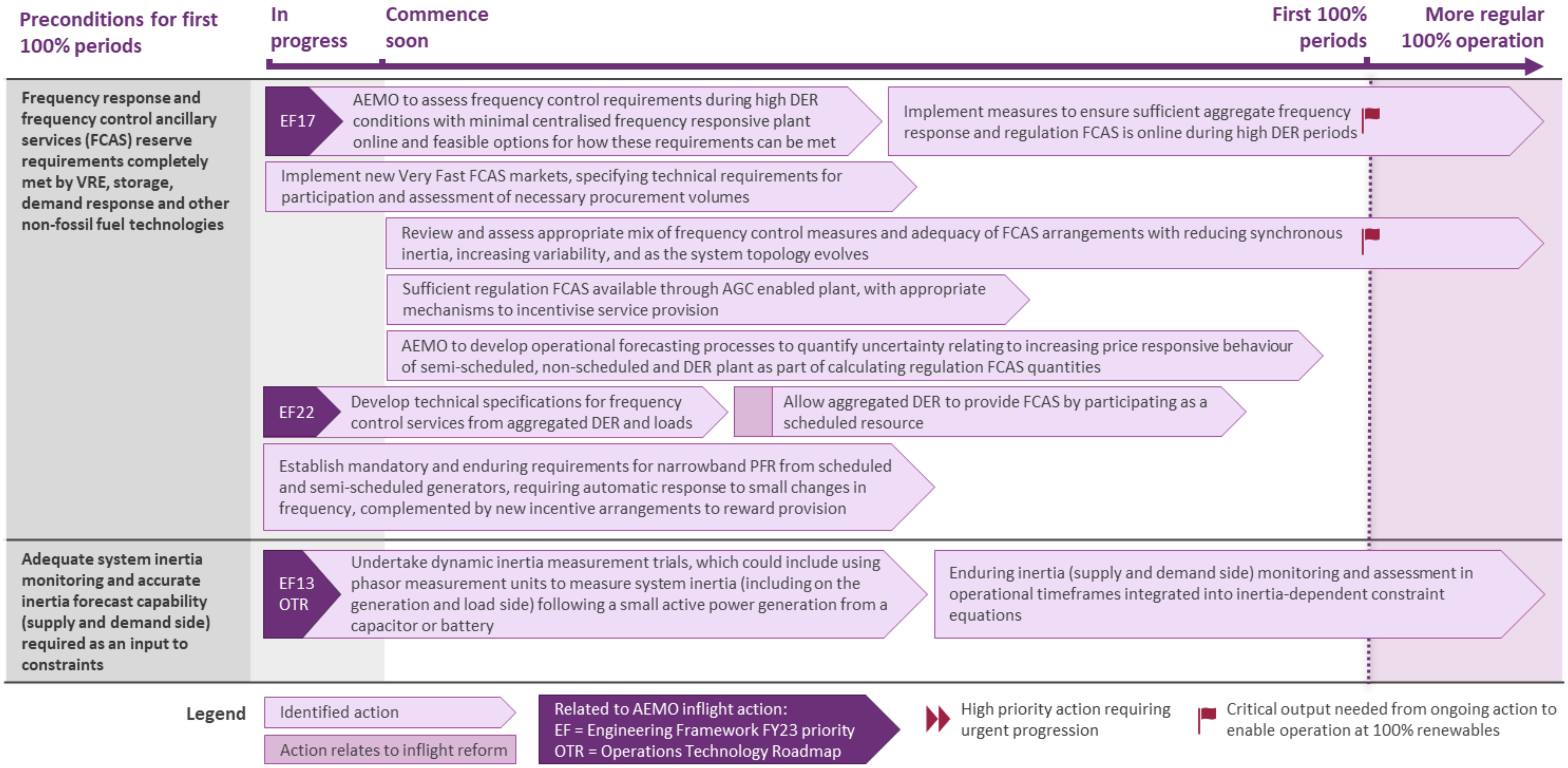


Ability to keep system frequency within defined limits following credible and non-credible events, including system RoCoF containment and effective emergency frequency control arrangements

- Review the need for a system-wide operational RoCoF limit based on an assessment of RoCoF withstand capability and requirements across the power system
- EF2 Studies to assess role of synchronous mechanical inertia in general power system stability and need for suitable locational distribution of synchronous mechanical inertia
- AEMC to consider implications for inertia procurement frameworks and relationship with RoCoF
- Establish understanding of 'synthetic' inertial response from IBRs, including how the response might differ to inertia from synchronous machines, and potential plant level constraints on the capability to provide synthetic inertia
- Technically specify synthetic inertia capability for IBRs
- Design and implement a mechanism to ensure availability of inertia in operational timeframes, including co-optimisation with dispatch of energy and other ancillary services
- Ongoing assessment of inertia requirements for NEM subnetworks through annual AEMO assessment over a 5-year planning horizon, with TNSP obligations to remediate identified shortfalls ⚑
- Identify and progress (where economic) opportunities for common solutions to address inertia requirements in conjunction with identified system strength needs, such as adding flywheels to synchronous condenser installations
- EF45 AEMO and NSPs to assess and maintain adequacy of emergency frequency control schemes and management arrangements ⚑
- ⏩ EF18 AEMO and NSPs to assess emergency frequency control scheme adequacy with increasing aggregate DPV uptake
- NSPs remediate or redesign EFCS arrangements for effective operation during high DPV conditions

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority OTR = Operations Technology Roadmap
- ⏩ High priority action requiring urgent progression
- ⚑ Critical output needed from ongoing action to enable operation at 100% renewables



Preconditions for first 100% periods | **In progress** | **Commence soon** | **First 100% periods** | **More regular 100% operation**

Frequency response and frequency control ancillary services (FCAS) reserve requirements completely met by VRE, storage, demand response and other non-fossil fuel technologies

- EF17 – AEMO to assess frequency control requirements during high DER conditions with minimal centralised frequency responsive plant online and feasible options for how these requirements can be met
- Implement measures to ensure sufficient aggregate frequency response and regulation FCAS is online during high DER periods ⚑
- Implement new Very Fast FCAS markets, specifying technical requirements for participation and assessment of necessary procurement volumes
- Review and assess appropriate mix of frequency control measures and adequacy of FCAS arrangements with reducing synchronous inertia, increasing variability, and as the system topology evolves ⚑
- Sufficient regulation FCAS available through AGC enabled plant, with appropriate mechanisms to incentivise service provision
- AEMO to develop operational forecasting processes to quantify uncertainty relating to increasing price responsive behaviour of semi-scheduled, non-scheduled and DER plant as part of calculating regulation FCAS quantities
- EF22 – Develop technical specifications for frequency control services from aggregated DER and loads
- Allow aggregated DER to provide FCAS by participating as a scheduled resource
- Establish mandatory and enduring requirements for narrowband PFR from scheduled and semi-scheduled generators, requiring automatic response to small changes in frequency, complemented by new incentive arrangements to reward provision

Adequate system inertia monitoring and accurate inertia forecast capability (supply and demand side) required as an input to constraints

- EF13 OTR – Undertake dynamic inertia measurement trials, which could include using phasor measurement units to measure system inertia (including on the generation and load side) following a small active power generation from a capacitor or battery
- Enduring inertia (supply and demand side) monitoring and assessment in operational timeframes integrated into inertia-dependent constraint equations

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority; OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- ⚑ Critical output needed from ongoing action to enable operation at 100% renewables

See Table 16 in Appendix Section A1.1.1 for details of actions related to frequency and inertia.

4.1.2 Transient and oscillatory stability

This section covers actions related to the ability of the power system to remain stable and in synchronism when subject to small (oscillatory stability) and large disturbances (transient stability)[20]. This requires the presence of synchronising torque and damping torque, historically provided by synchronous machines.

Additionally, for a high renewables system, this requires sufficient system strength to ensure new oscillation modes associated with the stability of grid-following inverter-based plant are managed. Actions associated with this can be found in Section 4.1.3.

Table 3 Identified preconditions for first 100% renewable periods and associated challenges – transient and oscillatory stability

Preconditions for first 100% periods	Current and emerging challenges
Appropriate stability limits in place for projected reductions in operation of synchronous machines	• Reducing synchronising torque and inertia with reduced operation of synchronous fossil fuel generators. – Uncertain impact of reducing inertia on transient stability limits. – Unknown transfer limits at 100% renewables
Appropriately damped local and inter-area oscillations	• Reducing damping torque with less synchronous fossil fuel generation online, and changing network topology with VRE development. – Small signal oscillation modes will change as the system topology, inertia and control systems evolve. – Ongoing oscillations following a large contingency event could be inadequately damped • Root cause of emerging oscillatory modes not well understood

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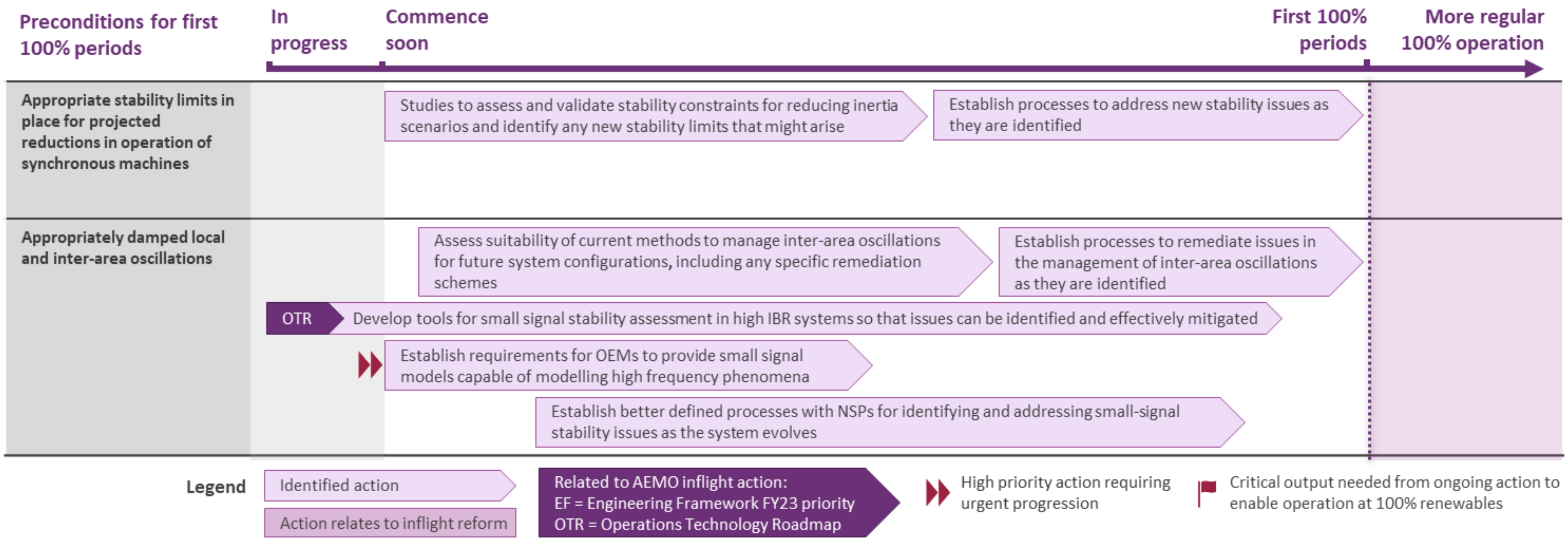
[20] See https://www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/2016/power-system-stability-guidelines.pdf.

Figure 11 Actions to achieve identified preconditions for first 100% renewable periods – transient and oscillatory stability



Preconditions for first 100% periods	Actions
Appropriate stability limits in place for projected reductions in operation of synchronous machines	Studies to assess and validate stability constraints for reducing inertia scenarios and identify any new stability limits that might arise Establish processes to address new stability issues as they are identified
Appropriately damped local and inter-area oscillations	Assess suitability of current methods to manage inter-area oscillations for future system configurations, including any specific remediation schemes Establish processes to remediate issues in the management of inter-area oscillations as they are identified OTR Develop tools for small signal stability assessment in high IBR systems so that issues can be identified and effectively mitigated ⏩ Establish requirements for OEMs to provide small signal models capable of modelling high frequency phenomena Establish better defined processes with NSPs for identifying and addressing small-signal stability issues as the system evolves

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority; OTR = Operations Technology Roadmap
- ⏩ High priority action requiring urgent progression
- ⚑ Critical output needed from ongoing action to enable operation at 100% renewables

See Table 17 in Appendix Section A1.1.2 for details of actions related to transient and oscillatory stability.

4.1.3 System strength and converter driven stability

System strength is an essential power system security service which ensures the ability of the power system to maintain a minimum amount of fault level, and a stable voltage waveform at any given location, both during steady state operation and following a disturbance[21]. The NEM's system strength standard[22] comprises:

- A minimum three phase fault level for power system security (to meet existing system limits including protection system operation, stable voltage control and overall system stability).
- A requirement for stable voltage waveforms at connection points (also known as the efficient level of system strength) for future grid connected IBR.

In 2020, the IEEE Power system Dynamic Performance Committee added two new stability classes ("Converter driven stability" and "Resonance stability") to account for the faster, more complex dynamics arising from IBR[23]. The technical report also recognises the need to model these stability classes in electro-magnetic transient (EMT) domain. Because having a stable voltage waveform is critical for the operation of grid-following inverters whose control systems require a frequency reference to "latch" onto to generate power that is in synchronism with the rest of the system, the delivery of system strength is anticipated to be a critical factor in managing these new forms of stability.

Table 4 Identified preconditions for first 100% renewable periods and associated challenges – system strength and converter driven stability

Preconditions for first 100% periods	Current and emerging challenges
System strength requirements met by alternatives to system configurations that require minimum loading on synchronous fossil fuel generators.	• Reduction in system strength due to reduced operation of synchronous fossil fuel generation and connection of inverter-based VRE and DER, impacting: – Stability of the voltage waveform in response to small changes, as well as during or after a fault – Protection system maloperation or failure to operate – Adverse interactions between several IBR or between IBR and the network – Recovery from non-credible events – Power quality and voltage unbalance – Stability of traditional, thyristor-controlled HVDC links – Potential impact on connection and synchronisation of DER

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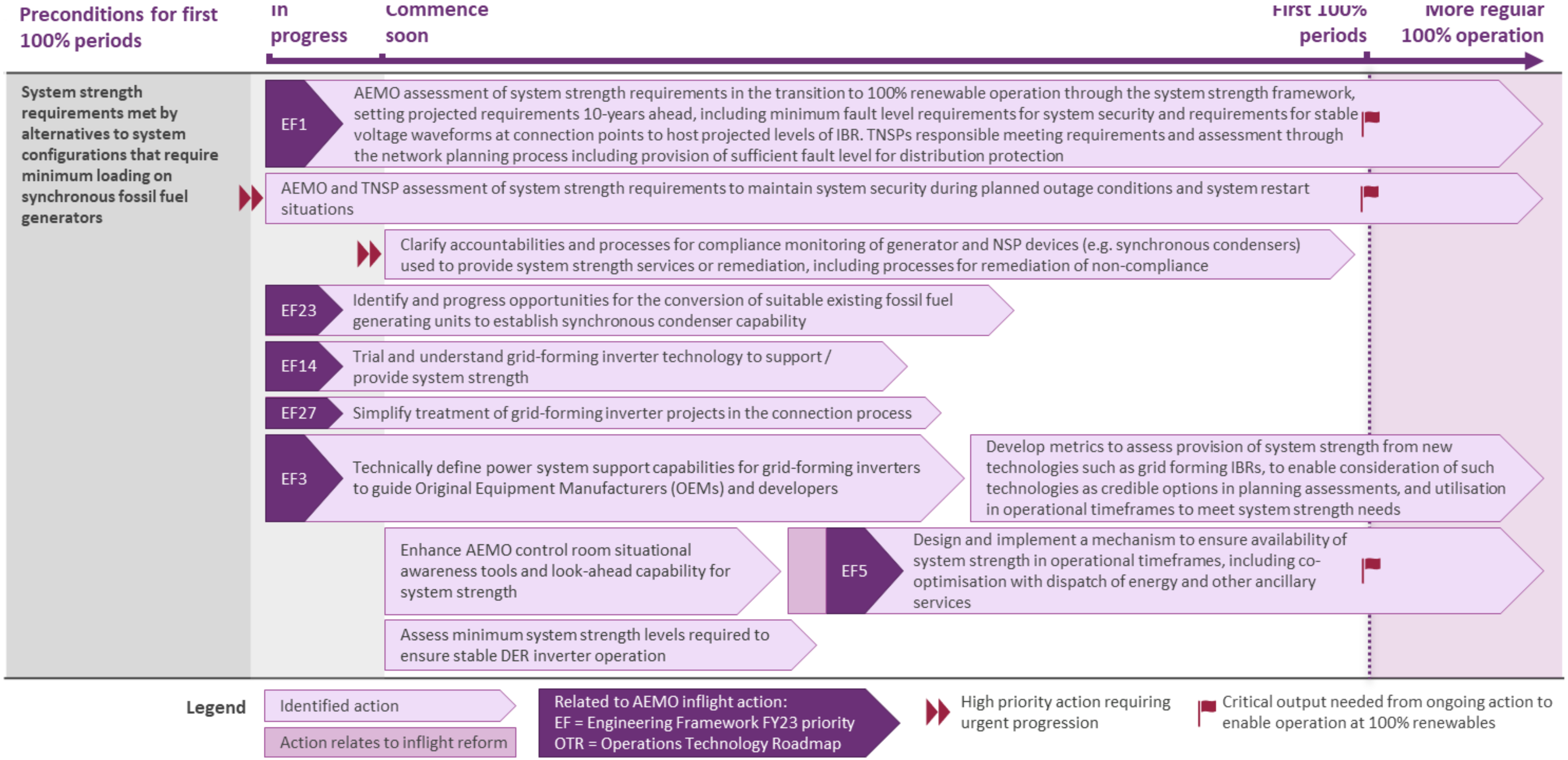
[21] For definitions and descriptions of system strength and power system security, please refer to AEMO's Power System Requirements, updated in July 2020 and accessible via https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

[22] Further information on these requirements can be found in AEMO's System strength requirements methodology, at https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-strength-requirements/system-strength-requirements-methodology.pdf?la=en.

[23] Hatziargyriou, Nikos, et al., *Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies*, April 2020, IEEE PES Technical Report PES-TR77.

Preconditions for first 100% periods	Current and emerging challenges
Ability to identify and manage fast and slow converter interaction driven oscillations.	• Scale and location of IBR, small and large scale. – Increasing potential for instabilities due to coupling between IBR controls and grid components, and the performance of these controls in weak grid conditions. – Limited visibility and monitoring of new oscillatory modes, and limited ability to identify root cause of oscillations.

Figure 12 Actions to achieve identified preconditions for first 100% renewable periods – system strength and converter driven stability



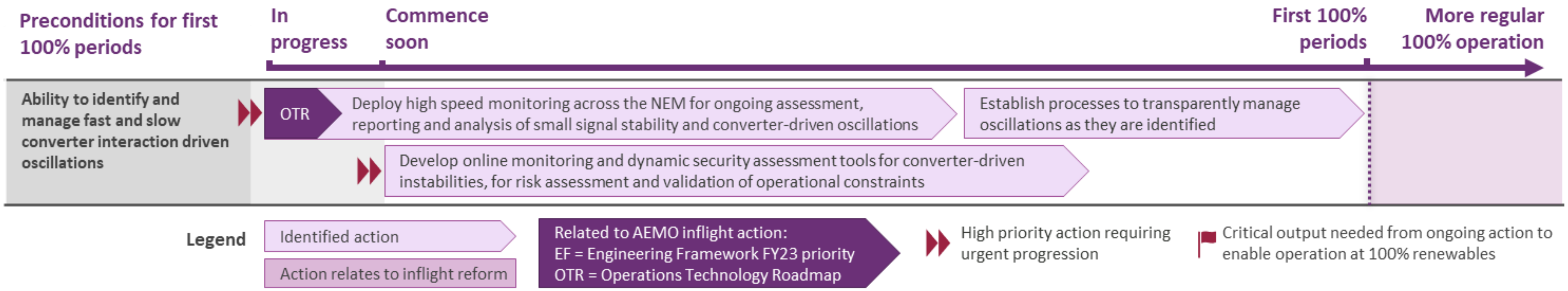
Preconditions for first 100% periods | **In progress** | **Commence soon** | **First 100% periods** | **More regular 100% operation**

System strength requirements met by alternatives to system configurations that require minimum loading on synchronous fossil fuel generators ▶▶

- EF1 – AEMO assessment of system strength requirements in the transition to 100% renewable operation through the system strength framework, setting projected requirements 10-years ahead, including minimum fault level requirements for system security and requirements for stable voltage waveforms at connection points to host projected levels of IBR. TNSPs responsible meeting requirements and assessment through the network planning process including provision of sufficient fault level for distribution protection 🚩
- AEMO and TNSP assessment of system strength requirements to maintain system security during planned outage conditions and system restart situations 🚩
- ▶▶ Clarify accountabilities and processes for compliance monitoring of generator and NSP devices (e.g. synchronous condensers) used to provide system strength services or remediation, including processes for remediation of non-compliance
- EF23 – Identify and progress opportunities for the conversion of suitable existing fossil fuel generating units to establish synchronous condenser capability
- EF14 – Trial and understand grid-forming inverter technology to support / provide system strength
- EF27 – Simplify treatment of grid-forming inverter projects in the connection process
- EF3 – Technically define power system support capabilities for grid-forming inverters to guide Original Equipment Manufacturers (OEMs) and developers
- Develop metrics to assess provision of system strength from new technologies such as grid forming IBRs, to enable consideration of such technologies as credible options in planning assessments, and utilisation in operational timeframes to meet system strength needs
- Enhance AEMO control room situational awareness tools and look-ahead capability for system strength
- EF5 – Design and implement a mechanism to ensure availability of system strength in operational timeframes, including co-optimisation with dispatch of energy and other ancillary services 🚩
- Assess minimum system strength levels required to ensure stable DER inverter operation

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority; OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- 🚩 Critical output needed from ongoing action to enable operation at 100% renewables



Preconditions for first 100% periods

In progress

Commence soon

First 100% periods

More regular 100% operation

Ability to identify and manage fast and slow converter interaction driven oscillations

⏩ OTR – Deploy high speed monitoring across the NEM for ongoing assessment, reporting and analysis of small signal stability and converter-driven oscillations

Establish processes to transparently manage oscillations as they are identified

⏩ Develop online monitoring and dynamic security assessment tools for converter-driven instabilities, for risk assessment and validation of operational constraints

Legend

Identified action

Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

⏩ High priority action requiring urgent progression

🚩 Critical output needed from ongoing action to enable operation at 100% renewables

See Table 18 in Appendix Section A1.1.3 for details of actions related to system strength and converter driven stability.

4.1.4 Voltage control

Voltage control is the ability to manage reactive power in an AC power system to ensure network voltage levels meet a target voltage range within the relevant limits set by NSPs while enabling active power transfer from generation to load. This reflects the capability of generation and the network to serve the power demanded by loads and is constrained by maximum power transfer capability and voltage drop associated with power flow through inductive reactances in the network.

Adequate dynamic reactive reserves are maintained to ensure acceptable voltage outcomes across the system in the event of a contingency. Reserve requirements are sized based on prevailing system conditions and the severity of the critical contingency. Voltage instability can lead to cascading outage situations with loss of load or tripping of transmission lines and other network components through protection action, potentially triggering generator loss of synchronism and frequency instability.

In real time, AEMO primarily utilises the automated VAr Dispatch Scheduler (VDS) system to dispatch transmission network service provider (TNSP) and generator reactive power devices in the NEM to meet specified voltage control objectives.[24]

Minimum fault levels are also required for voltage control to limit the step change in voltage following the switching of reactive plant. This is covered under the minimum fault level requirement under system strength and converter driven stability in Section 4.1.3.

Table 5 Identified preconditions for first 100% renewable periods and associated challenges – voltage control

Preconditions for first 100% periods	Current and emerging challenges
Sufficient steady state and dynamic reactive support to maintain reactive margins and voltage disturbances within limits, completely provided by non-fossil fuel technologies	• Reduced synchronous fossil fuel generation operation. • Reducing dynamic reactive capability and system strength impacting voltage stability margins. • Reducing steady state voltage control.
Coordinated voltage control at transmission-distribution interface for times of high DER	• Increasing DPV generation in the daytime. – Increasing need for reactive support for steady state voltage control as DPV reduces transmission network loading. – TNSPs increasingly adjusting voltage set points to support distribution network voltage profile with increasing DPV in the daytime, impacting reactive power management in transmission network. – Increasing manual interactions between control rooms to adjust reactive power interchange at the transmission-distribution interface.

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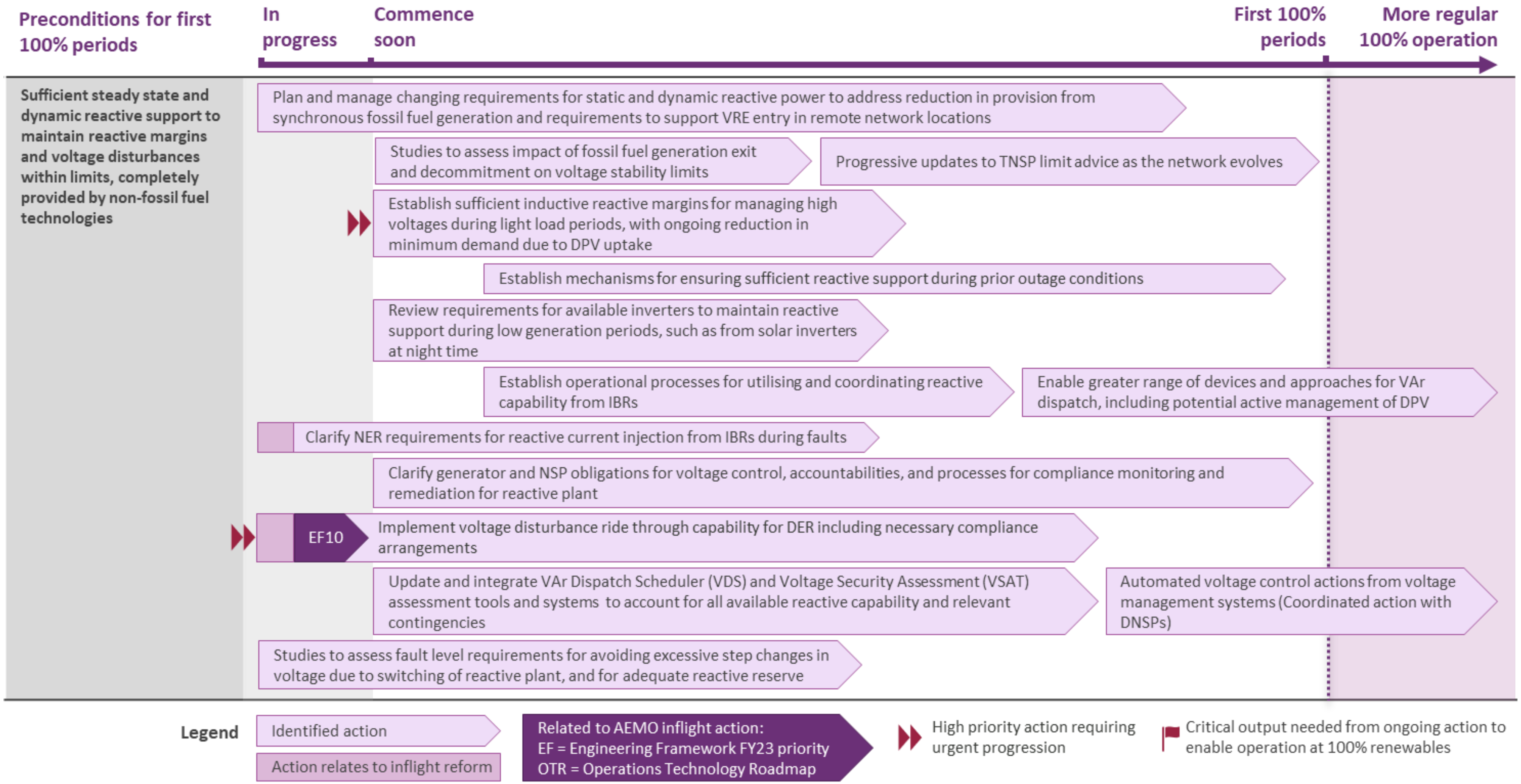
[24] Refer to Section 14 of AEMO Power System Security Guideline for further information – https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/power_system_ops/procedures/so_op_3715-power-system-security-guidelines.pdf?la=en.

Preconditions for first 100% periods	Current and emerging challenges
Reactive support and voltage control arrangements for highly variable, long distance VRE power flows to load centres, and more variable daily demand profiles across transmission and distribution networks	• VRE and REZ development. – Reactive support requirements for increasing power transfers over long distances from VRE to load centres. – Larger, more variable intraday changes in the voltage profile due to changes VRE power flows, including changes in rooftop PV output due to cloud cover. With increasing renewables, the voltage profile will vary as a function of more frequent, less predictable weather changes (wind speed and solar irradiance), not just the typical daily load profile.
Sufficient reactive power absorption capability to securely supply load	• Changing power factor of demand. – Declining reactive power demand observed in some parts of the NEM as loads shift from traditionally inductive to capacitive. This is potentially driven by replacement of synchronous and induction motors with inverter-based equipment and other technology changes. Impacts both day and night-time demand. – Potential voltage swings from new load behaviour could impact local voltage attributes and overall load profile.

Figure 13 Actions to achieve identified preconditions for first 100% renewable periods – voltage control



Preconditions for first 100% periods

In progress

Commence soon

First 100% periods

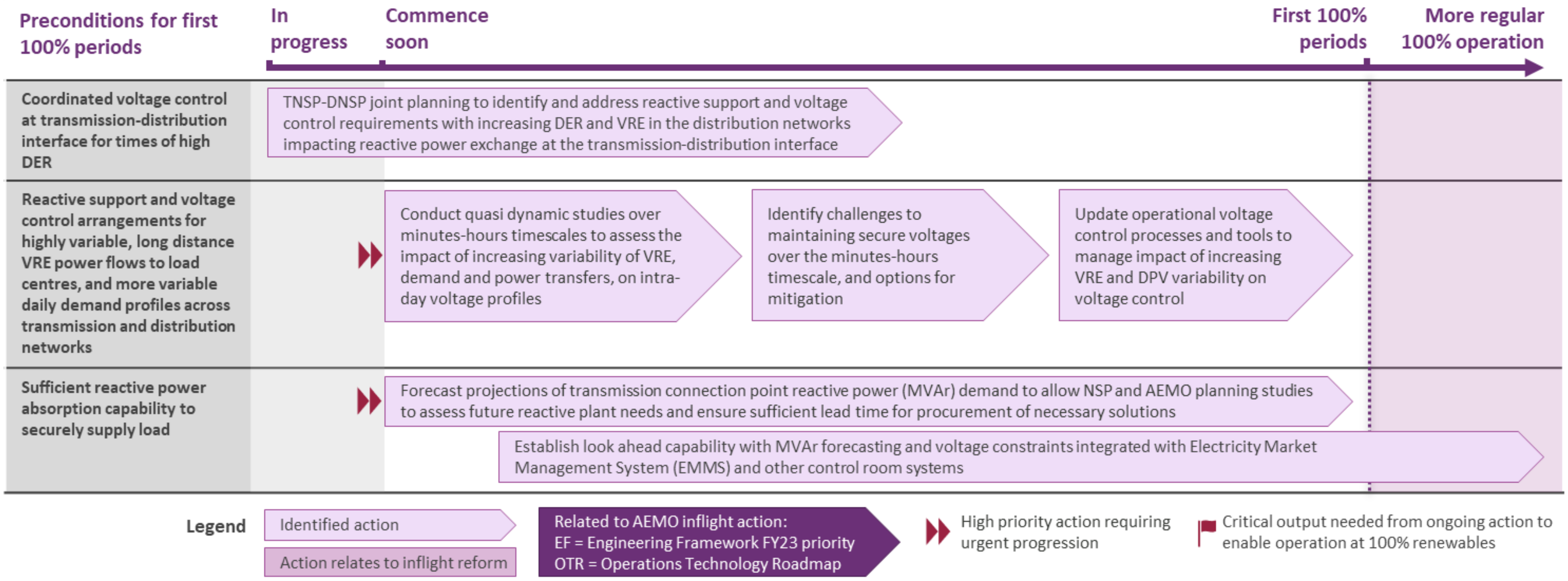
More regular 100% operation

Sufficient steady state and dynamic reactive support to maintain reactive margins and voltage disturbances within limits, completely provided by non-fossil fuel technologies

- Plan and manage changing requirements for static and dynamic reactive power to address reduction in provision from synchronous fossil fuel generation and requirements to support VRE entry in remote network locations
- Studies to assess impact of fossil fuel generation exit and decommitment on voltage stability limits
- Progressive updates to TNSP limit advice as the network evolves
- ▶▶ Establish sufficient inductive reactive margins for managing high voltages during light load periods, with ongoing reduction in minimum demand due to DPV uptake
- Establish mechanisms for ensuring sufficient reactive support during prior outage conditions
- Review requirements for available inverters to maintain reactive support during low generation periods, such as from solar inverters at night time
- Establish operational processes for utilising and coordinating reactive capability from IBRs
- Enable greater range of devices and approaches for VAr dispatch, including potential active management of DPV
- Clarify NER requirements for reactive current injection from IBRs during faults
- Clarify generator and NSP obligations for voltage control, accountabilities, and processes for compliance monitoring and remediation for reactive plant
- ▶▶ EF10 Implement voltage disturbance ride through capability for DER including necessary compliance arrangements
- Update and integrate VAr Dispatch Scheduler (VDS) and Voltage Security Assessment (VSAT) assessment tools and systems to account for all available reactive capability and relevant contingencies
- Automated voltage control actions from voltage management systems (Coordinated action with DNSPs)
- Studies to assess fault level requirements for avoiding excessive step changes in voltage due to switching of reactive plant, and for adequate reactive reserve

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- 🚩 Critical output needed from ongoing action to enable operation at 100% renewables



Preconditions for first 100% periods | **In progress** | **Commence soon** | **First 100% periods** | **More regular 100% operation**

Coordinated voltage control at transmission-distribution interface for times of high DER

- TNSP-DNSP joint planning to identify and address reactive support and voltage control requirements with increasing DER and VRE in the distribution networks impacting reactive power exchange at the transmission-distribution interface

Reactive support and voltage control arrangements for highly variable, long distance VRE power flows to load centres, and more variable daily demand profiles across transmission and distribution networks

- ⏩ Conduct quasi dynamic studies over minutes-hours timescales to assess the impact of increasing variability of VRE, demand and power transfers, on intra-day voltage profiles
- Identify challenges to maintaining secure voltages over the minutes-hours timescale, and options for mitigation
- Update operational voltage control processes and tools to manage impact of increasing VRE and DPV variability on voltage control

Sufficient reactive power absorption capability to securely supply load

- ⏩ Forecast projections of transmission connection point reactive power (MVAr) demand to allow NSP and AEMO planning studies to assess future reactive plant needs and ensure sufficient lead time for procurement of necessary solutions
- Establish look ahead capability with MVAr forecasting and voltage constraints integrated with Electricity Market Management System (EMMS) and other control room systems

Legend

Identified action

Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

⏩ High priority action requiring urgent progression

⚑ Critical output needed from ongoing action to enable operation at 100% renewables

See Table 19 in Appendix Section A1.1.4 for details of actions related to voltage control.

4.1.5 System restoration

Despite best endeavours, the power system can, on rare occasions, experience cascading failures resulting in loss of supply to large portions of the power system. Following this, control room operators in the NEM require the ability to restore the power system through system restart ancillary services (SRAS)[25]. Under AEMO's SRAS Guidelines[26], there are two types of SRAS:

- Black start services required to reenergise its surrounding network to allow load and other generation to connect. This requires distinct technical capabilities from generating units that may not be included in default plant designs.
- Restoration support services to assist in stable and ongoing energisation of the network. One such example may be provision of load blocks to maintain minimum loading on units providing black start services.

In addition, system restoration requires the careful planning of re-energisation pathways that enable a stable sequential restoration of supply across the network. Under a 100% renewable scenario, system restoration is complicated by changes to network and generation topology, meaning effective planning is required in advance of many existing SRAS capable fossil fuelled units becoming unavailable.

While it is possible that the first instances of 100% instantaneous penetration of renewables could have fossil fuelled generation on standby (for example gas units running warm) to provide black start services, increasingly regular operation of the power system at 100% renewables will require significant revision to existing system restoration frameworks and technological uplift to identify alternative system restoration technologies.

Table 6 Identified preconditions for first 100% renewable periods and associated challenges – system restoration

Preconditions for first 100% periods	Current and emerging challenges
Effective restart arrangements, plans, procedures in place for first 100% renewables period, including adequate SRAS capable plant built in suitable locations	• Reduced availability of SRAS-capable units as synchronous fossil fuel plant exit. – Coal fleet will be offline during first 100% renewables periods and unlikely to be available for black start at short notice. – Limited selection of black start pathways following the decline of available black start resources – Insufficient new SRAS capable plant being built. • New approaches will be needed to energise VRE centres in remote locations – Increasing VRE connection in remote locations far from existing SRAS pathways. • Large transformers in future REZs will require high inrush current for energisation

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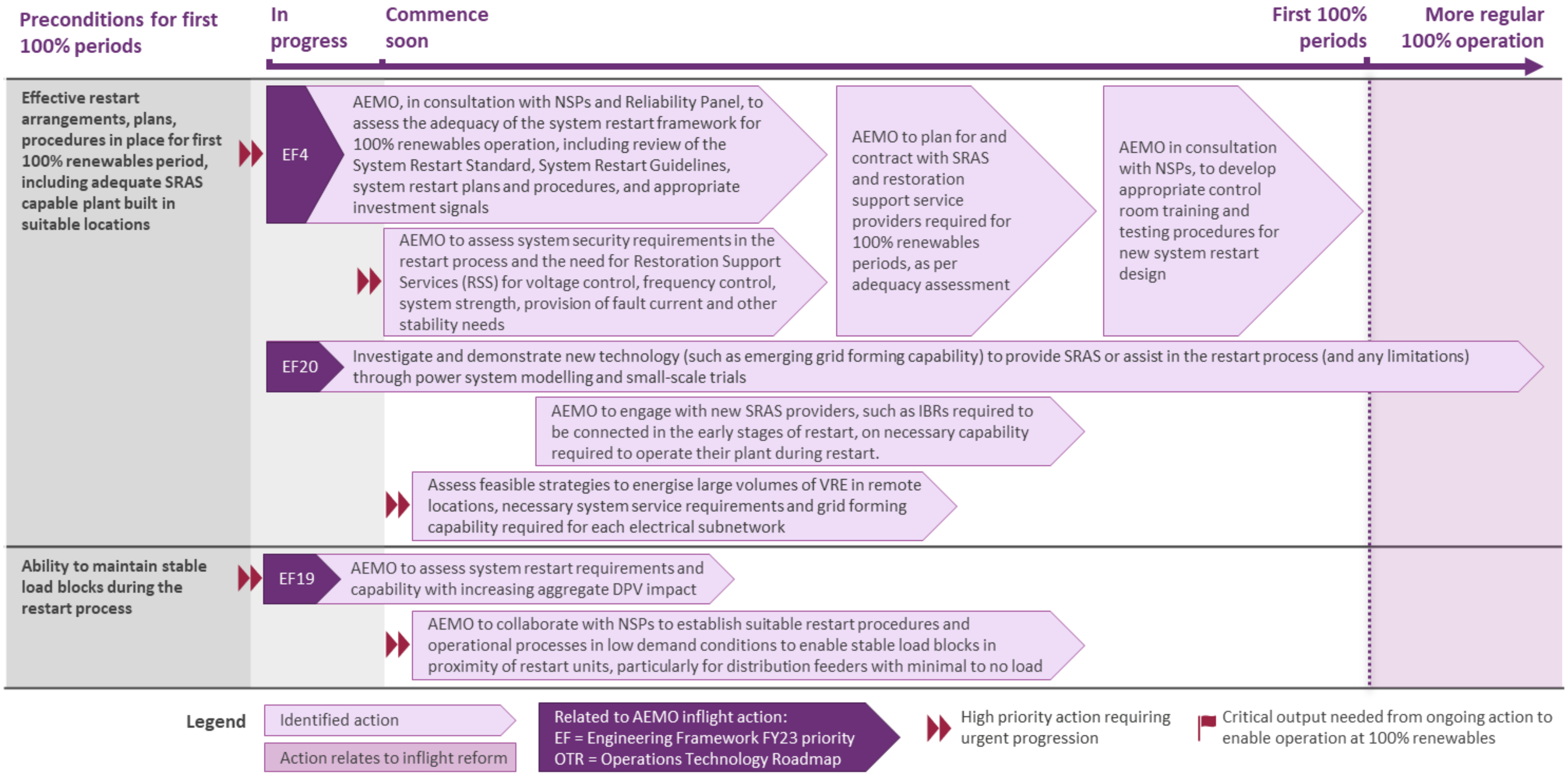
[25] For more information, see Section 3.4 of AEMO's Power System Requirements document, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

[26] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/sras/sras-guideline-2021.pdf?la=en.

Preconditions for first 100% periods	Current and emerging challenges
Ability to manage uncontrolled DPV generation during the restart process	• Ongoing growth in DPV generation reducing the daytime availability of stable load blocks required for the system restoration process.

Figure 14 Actions to achieve identified preconditions for first 100% renewable periods – system restoration



Effective restart arrangements, plans, procedures in place for first 100% renewables period, including adequate SRAS capable plant built in suitable locations

EF4 AEMO, in consultation with NSPs and Reliability Panel, to assess the adequacy of the system restart framework for 100% renewables operation, including review of the System Restart Standard, System Restart Guidelines, system restart plans and procedures, and appropriate investment signals

AEMO to assess system security requirements in the restart process and the need for Restoration Support Services (RSS) for voltage control, frequency control, system strength, provision of fault current and other stability needs

AEMO to plan for and contract with SRAS and restoration support service providers required for 100% renewables periods, as per adequacy assessment

AEMO in consultation with NSPs, to develop appropriate control room training and testing procedures for new system restart design

EF20 Investigate and demonstrate new technology (such as emerging grid forming capability) to provide SRAS or assist in the restart process (and any limitations) through power system modelling and small-scale trials

AEMO to engage with new SRAS providers, such as IBRs required to be connected in the early stages of restart, on necessary capability required to operate their plant during restart.

Assess feasible strategies to energise large volumes of VRE in remote locations, necessary system service requirements and grid forming capability required for each electrical subnetwork

Ability to maintain stable load blocks during the restart process

EF19 AEMO to assess system restart requirements and capability with increasing aggregate DPV impact

AEMO to collaborate with NSPs to establish suitable restart procedures and operational processes in low demand conditions to enable stable load blocks in proximity of restart units, particularly for distribution feeders with minimal to no load

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- Critical output needed from ongoing action to enable operation at 100% renewables

See Table 20 in Appendix Section A1.1.5 for details of actions related to system restoration.

4.2 System operability

The ability to securely and reliably operate the power system and transition through increasingly complex operating conditions.

The renewable transition will involve increasingly complex operational conditions characterised by:

- Faster, more complex system dynamics with reducing inertia and stability outcomes are increasingly determined by fast-acting IBR controls as synchronous fossil fuel generation operates less and less.
- Increasing impact of weather on the supply-demand balance and energy adequacy with increasing volumes of VRE and DPV.
- Increasingly decentralised operation through the ongoing uptake of DPV and other DER in the distribution network
- Changing system risk profile and underlying resilience of the system as the system topology and resource mix evolve.

Managing this increasing complexity in the transition to 100% renewables will a step change in operational capability. Progressing this uplift, while simultaneously operating a real, gigawatt-scale power system is akin to "rebuilding a plane while flying it." Section 3.4 sets out the steps required for NSPs and AEMO to navigate previously untested and unchartered operating territory on the way to the first periods of 100% renewable operation, keeping within operational risk tolerances and aligning with societal expectations for secure and reliable supply.

This process will be increasingly difficult as renewable penetrations increase. The Operability section of the Roadmap identifies the uplift required in AEMO and NSP operational capability required to achieve these steps. It covers system

Operations Technology Roadmap

AEMO's Operational Technology Roadmap, completed in June 2022, sets a strategic vision for the uplift in tools and capability required to manage and enable the transformative change anticipated in the NEM and WEM over the next decade. It is focussed on AEMO core real-time control room operational responsibilities, supporting operational functions (planning, forecasting, monitoring, reporting and analytics) and foundational enablers (software, hardware, data and automation).

The OTR includes detailed roadmaps across 10 operational technology areas to 2030, each compromising of a future vision, drivers for change, risk assessment, high-level cost benefit, data requirements and tool requirements. The roadmaps establish architectural foundations for bridging the gap between:

- Current capability – baselined through the application of a business capability model developed through AEMO's Future State Architecture project.
- Required capability – considering capability gaps using reference architectures developed through the Electric Power Research Institute (EPRI) Control Room of the Future framework informed by best practices across system operators internationally.

The focus is on the development of secure, flexible, adaptable operational technology environment in which systems are integrated, interoperable and automated – able to be evolve and adjust as needed over time.

and weather monitoring requirements for control room awareness of system state and operational risks; operational processes required to schedule and dispatch the power system and manage the technical envelope; and foundational power system modelling and analysis capability.

Most actions in this section of the Engineering Roadmap will progress through AEMO's Operational Technology Roadmap (OTR). Engineering Roadmap actions will flow directly into next stages of the OTR program as it moves into implementation phase. The Engineering Roadmap:

- Identifies relevant AEMO operational uplift actions underway
- Highlights urgent actions for consideration in the prioritisation and scoping of near team OTR initiatives over the next two years, with detail gathered in developing the Engineering Roadmap to inform OTR implementation.
- Utilises the OTR vision to 2030 to inform sequencing and next steps for longer term actions.
- Identifies key external dependencies, in particular between AEMO operational process and NSP capability, and the need for uplifting action across these dependencies for the preconditions to be satisfied.

4.2.1 Monitoring and situational awareness

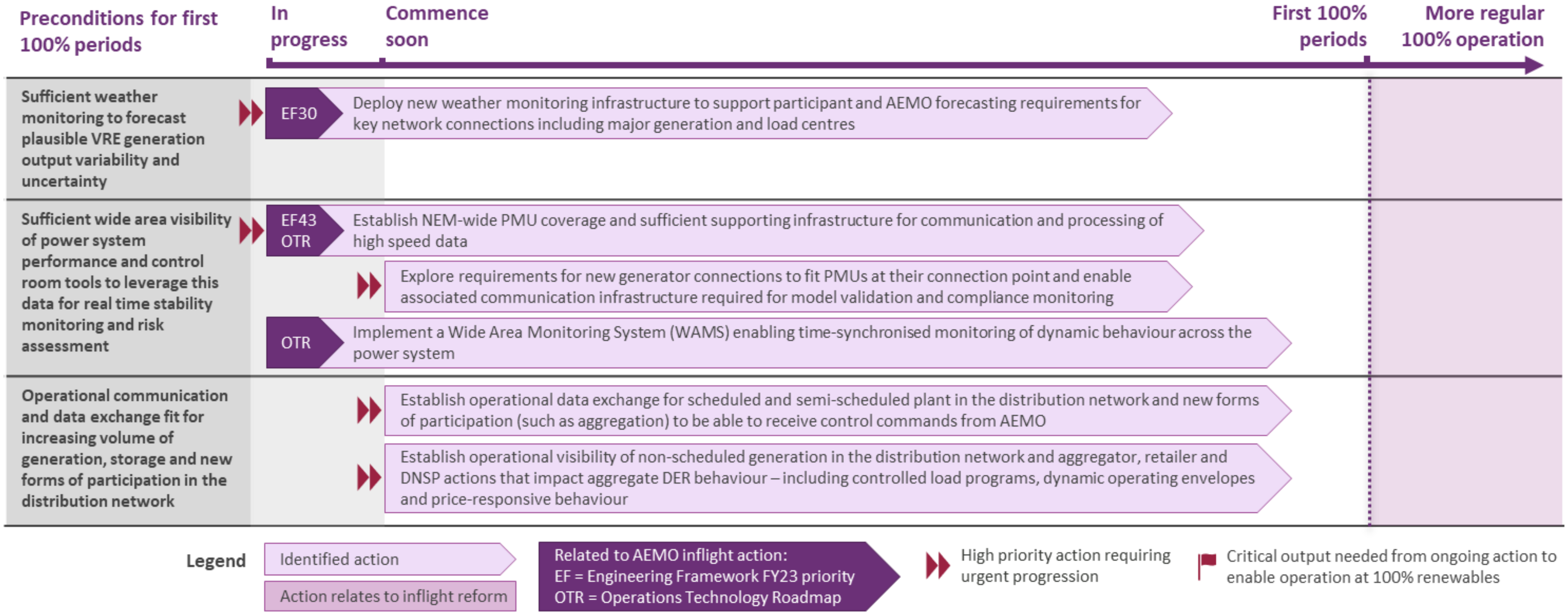
As part of its power system security responsibilities, AEMO is required to monitor the operating status of the power system. This section covers the uplift required for appropriate control room awareness of system state and operational risk in the renewable transition. It covers actions that serve as prerequisites for several other Roadmap preconditions, as follows:

- High-speed monitoring to understand system stress and identify interactions and transient behaviour that cannot be easily detected through traditional SCADA, required for real time and look-ahead dynamic security assessment, online risk monitoring, power system model validation and post event root cause analysis.
- Fit-for-purpose weather monitoring required operational forecasting
- Operational coordination to establish visibility of increasing decentralised participation, required for state estimation, scheduling and dispatch

Table 7 Identified preconditions for first 100% renewable periods and associated challenges – monitoring and situational awareness

Preconditions for first 100% periods	Current and emerging challenges
Sufficient weather monitoring to forecast plausible VRE generation output variability and uncertainty	• Location of weather monitoring not aligned with location of weather-dependent generation.
Sufficient wide area visibility of power system performance and control room tools to leverage this data for real time stability monitoring and risk assessment	• Insufficient high-speed power system monitoring. • Limited ability to identify oscillations and other emerging forms of instability expected to emerge as the power system evolves.
Operational communications and data exchange fit for increasing volume of generation, storage and new forms of participation in the distribution network	• Participants with stand-alone or aggregated assets within or across distribution networks have no pathway to provide telemetry to or receive control signals from AEMO. – Impacts scheduled and semi-scheduled plant in the distribution network and new forms of aggregated participation (including demand response service providers greater than 5 MW). – Will become increasingly material as decentralised participation scales, and limit AEMO's ability to operate the power system securely.

Figure 15 Actions to achieve identified preconditions for first 100% renewable periods – monitoring and situational awareness



Sufficient weather monitoring to forecast plausible VRE generation output variability and uncertainty

- EF30 – Deploy new weather monitoring infrastructure to support participant and AEMO forecasting requirements for key network connections including major generation and load centres

Sufficient wide area visibility of power system performance and control room tools to leverage this data for real time stability monitoring and risk assessment

- EF43 OTR – Establish NEM-wide PMU coverage and sufficient supporting infrastructure for communication and processing of high speed data
- Explore requirements for new generator connections to fit PMUs at their connection point and enable associated communication infrastructure required for model validation and compliance monitoring
- OTR – Implement a Wide Area Monitoring System (WAMS) enabling time-synchronised monitoring of dynamic behaviour across the power system

Operational communication and data exchange fit for increasing volume of generation, storage and new forms of participation in the distribution network

- Establish operational data exchange for scheduled and semi-scheduled plant in the distribution network and new forms of participation (such as aggregation) to be able to receive control commands from AEMO
- Establish operational visibility of non-scheduled generation in the distribution network and aggregator, retailer and DNSP actions that impact aggregate DER behaviour – including controlled load programs, dynamic operating envelopes and price-responsive behaviour

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action:
  EF = Engineering Framework FY23 priority
  OTR = Operations Technology Roadmap
- High priority action requiring urgent progression
- Critical output needed from ongoing action to enable operation at 100% renewables

See Table 21 in Appendix Section A1.2.1 for details of actions related to monitoring and situational awareness.

4.2.2 Operational processes

This section of the Roadmap covers uplift required across key operational processes for securely and reliably operate the power system and manage new operating conditions as they emerge in the renewable transition. It sets out preconditions relating to operational processes required for scheduling and dispatching the power system, and to manage the secure technical envelope, including operational forecasting, outage coordination, constraints and dynamic security assessment, reserve management and operator training. Detailed information about these operational processes is provided in AEMO's power system operating procedures[27].

The ongoing effectiveness of these processes is critically dependent on fit-for-purpose locational and wide area monitoring (Section 4.2.1) and foundational power system modelling capability (Section 4.2.3).

Table 8 Identified preconditions for first 100% renewable periods and associated challenges – operational processes

Preconditions for first 100% periods	Current and emerging challenges
Ability to operationally forecast energy adequacy and quantify VRE variability and uncertainty over different timeframes	• Current deterministic approach to operational forecasting focused mainly on capacity adequacy will not be adequate in a high renewable power system. – There is a limit to the accuracy of deterministic forecasts of weather-driven variability in the supply-demand balance, even using current best practice approaches • Increasing operational forecasting workload and pace of development required.
Ability to securely and reliably manage planned outages for maintenance and the augmentation required in the transition to 100% renewables	• Limited opportunities to schedule maintenance of key system elements due to their criticality for system security as margins reduce. • Increasingly complex studies and coordination required within and across regions in the outage planning process. • No framework in place to ensure required plant is online for system security during planned outages. Largely managed in an ad hoc manner.
Dynamic security assessment and contingency analysis capability across the range of stability phenomena – real-time and look-ahead	• Limited ability to identify and monitor stability issues in real time, and diagnose root cause in order to mitigate issues. • Transient, voltage and small signal stability assessment tools in place. No frequency security tool in place. • Limited 'look ahead' capability for dynamic security assessment.
Reserve assessment and management processes in place to balance VRE variability and uncertainty and account for the availability of stored energy	• Current 30-minute ahead STPASA assessment period may no longer be appropriate to manage price and weather-driven variability in supply and demand • Increasing volatility in power system conditions even under shorter-term timeframes driven by highly unpredictable market prices and responses. • Limited visibility and largely manual process to manage energy limitations during scarcity periods.
Significant uplift in industry training standards to ensure operator capability and sufficient training for new tools, procedures and processes	• Any new operational tools and procedures required in the transition to 100% renewables operation will also require significant training to be undertaken

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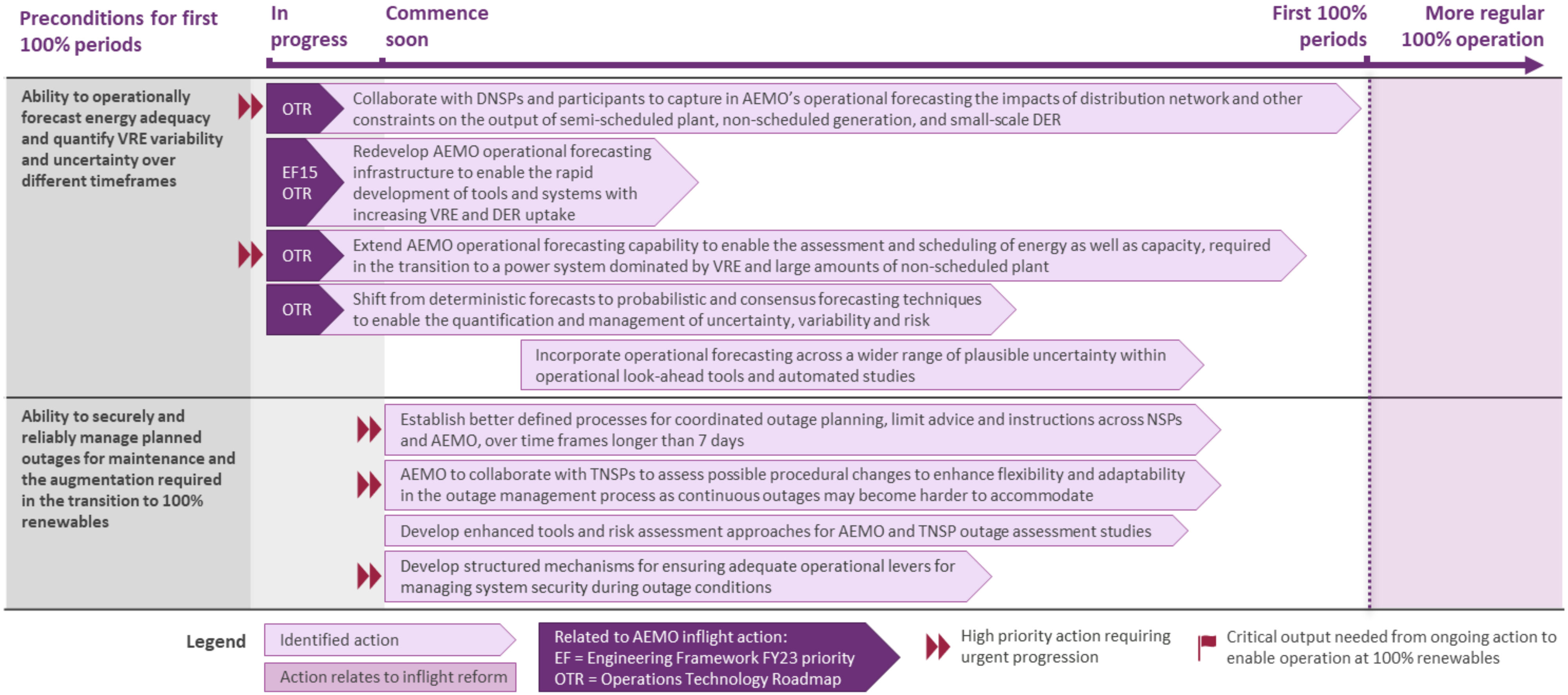
[27] See https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/power-system-operation/power-system-operating-procedures

Figure 16 Actions to achieve identified preconditions for first 100% renewable periods – operational processes



Ability to operationally forecast energy adequacy and quantify VRE variability and uncertainty over different timeframes

- ▶▶ OTR – Collaborate with DNSPs and participants to capture in AEMO's operational forecasting the impacts of distribution network and other constraints on the output of semi-scheduled plant, non-scheduled generation, and small-scale DER
- EF15 OTR – Redevelop AEMO operational forecasting infrastructure to enable the rapid development of tools and systems with increasing VRE and DER uptake
- ▶▶ OTR – Extend AEMO operational forecasting capability to enable the assessment and scheduling of energy as well as capacity, required in the transition to a power system dominated by VRE and large amounts of non-scheduled plant
- OTR – Shift from deterministic forecasts to probabilistic and consensus forecasting techniques to enable the quantification and management of uncertainty, variability and risk
- Incorporate operational forecasting across a wider range of plausible uncertainty within operational look-ahead tools and automated studies

Ability to securely and reliably manage planned outages for maintenance and the augmentation required in the transition to 100% renewables

- ▶▶ Establish better defined processes for coordinated outage planning, limit advice and instructions across NSPs and AEMO, over time frames longer than 7 days
- ▶▶ AEMO to collaborate with TNSPs to assess possible procedural changes to enhance flexibility and adaptability in the outage management process as continuous outages may become harder to accommodate
- Develop enhanced tools and risk assessment approaches for AEMO and TNSP outage assessment studies
- ▶▶ Develop structured mechanisms for ensuring adequate operational levers for managing system security during outage conditions

Legend

Identified action

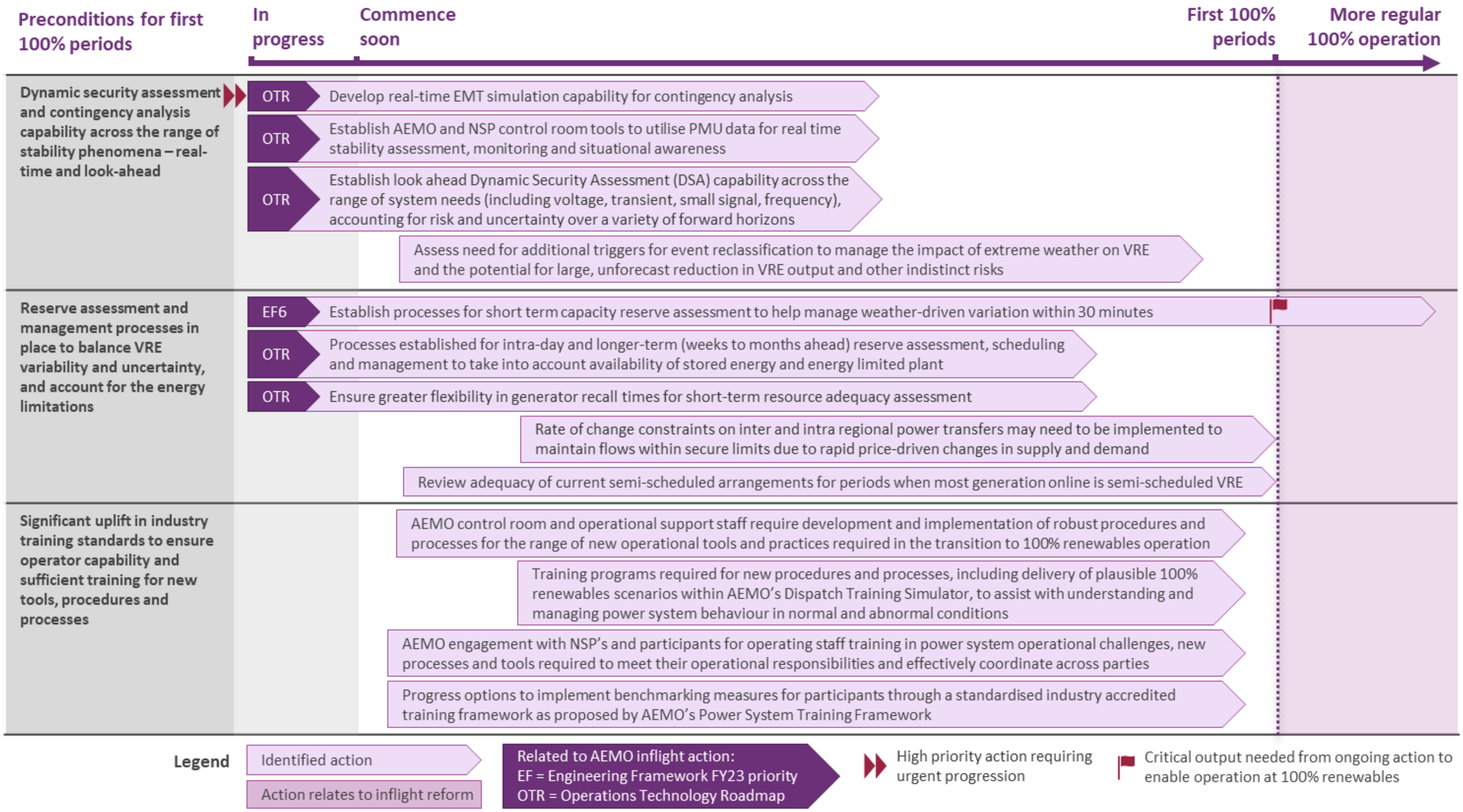
Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

▶▶ High priority action requiring urgent progression

⚑ Critical output needed from ongoing action to enable operation at 100% renewables

Action roadmap – system operability



Preconditions for first 100% periods | **In progress** | **Commence soon** | **First 100% periods** | **More regular 100% operation**

Dynamic security assessment and contingency analysis capability across the range of stability phenomena – real-time and look-ahead ▶▶

- OTR – Develop real-time EMT simulation capability for contingency analysis
- OTR – Establish AEMO and NSP control room tools to utilise PMU data for real time stability assessment, monitoring and situational awareness
- OTR – Establish look ahead Dynamic Security Assessment (DSA) capability across the range of system needs (including voltage, transient, small signal, frequency), accounting for risk and uncertainty over a variety of forward horizons
- Assess need for additional triggers for event reclassification to manage the impact of extreme weather on VRE and the potential for large, unforecast reduction in VRE output and other indistinct risks

Reserve assessment and management processes in place to balance VRE variability and uncertainty, and account for the energy limitations

- EF6 – Establish processes for short term capacity reserve assessment to help manage weather-driven variation within 30 minutes
- OTR – Processes established for intra-day and longer-term (weeks to months ahead) reserve assessment, scheduling and management to take into account availability of stored energy and energy limited plant
- OTR – Ensure greater flexibility in generator recall times for short-term resource adequacy assessment
- Rate of change constraints on inter and intra regional power transfers may need to be implemented to maintain flows within secure limits due to rapid price-driven changes in supply and demand
- Review adequacy of current semi-scheduled arrangements for periods when most generation online is semi-scheduled VRE

Significant uplift in industry training standards to ensure operator capability and sufficient training for new tools, procedures and processes

- AEMO control room and operational support staff require development and implementation of robust procedures and processes for the range of new operational tools and practices required in the transition to 100% renewables operation
- Training programs required for new procedures and processes, including delivery of plausible 100% renewables scenarios within AEMO's Dispatch Training Simulator, to assist with understanding and managing power system behaviour in normal and abnormal conditions
- AEMO engagement with NSP's and participants for operating staff training in power system operational challenges, new processes and tools required to meet their operational responsibilities and effectively coordinate across parties
- Progress options to implement benchmarking measures for participants through a standardised industry accredited training framework as proposed by AEMO's Power System Training Framework

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action:
  EF = Engineering Framework FY23 priority
  OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- 🚩 Critical output needed from ongoing action to enable operation at 100% renewables

See Table 22 in Appendix Section A1.2.2 for details of actions related to operational processes.

4.2.3 Power system modelling

Power system modelling is a foundational pre-requisite across the range of AEMO, NSP, and participant activities required in the transition to 100% renewable operation, including connecting and integrating new generation, planning the actions necessary to securely, reliably and affordably transition, and operationally navigating a series of increasingly complex operating conditions.

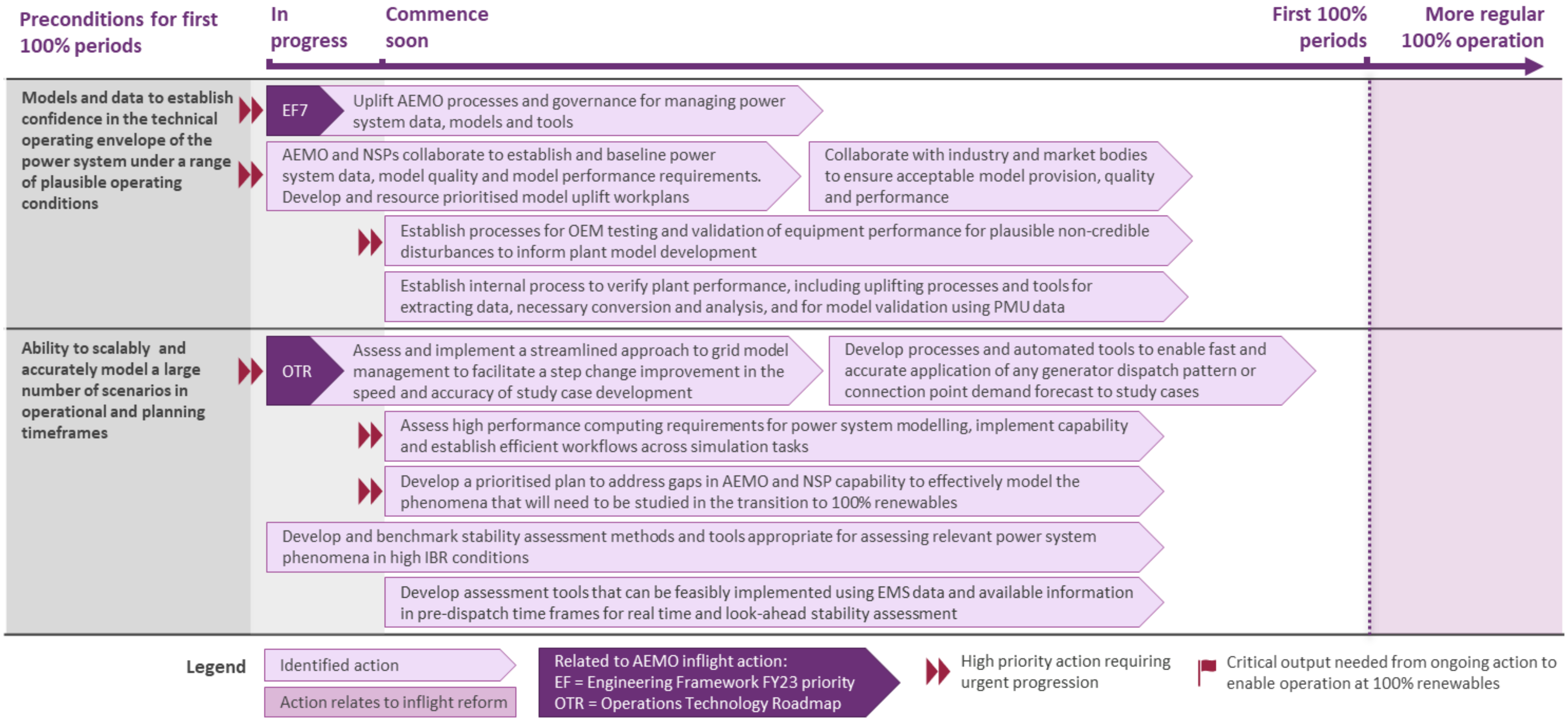
Current tools and capability will not be sufficient for AEMO and TNSPs to effectively model, with sufficient speed and accuracy, the range of phenomena and scenarios that will need be studied on the way to 100% renewable operation, or to support effective operation of real-time tools that rely on accurate power system models.

Without action, lack of confidence in the technical operating envelope of the power system will be a significant bottleneck in the transition to, and operation at, 100%. Concerted industry effort and targeted investment across key processes, systems and tools is underway to help enable the step change in modelling capability required to make this possible, however efforts need to be significantly increased.

Table 9 Identified preconditions for first 100% renewable periods and associated challenges – power system modelling

Preconditions for first 100% periods	Current and emerging challenges
Models and data to establish confidence in the technical operating envelope of the power system under a range of plausible operating conditions	• Decline in model quality, while system operation becomes increasingly complex. • Greater uncertainty margins necessary to account for limited adequacy of available models.
Ability to scalably and accurately model a large number of scenarios in operational and planning timeframes	• Increasing reliance on complex dynamic models requiring greater ongoing efforts in model maintenance. • Largely manual study case development process for future system studies. Can take months to include augmentations and connections, and represent dispatch and demand conditions for different study snapshots. • Increasingly computationally-intensive studies. Limited high performance computing capability.
Future system studies to assess the secure technical envelope of the power system with reducing, and eventually no, synchronous fossil fuel generation online	• Limited understanding of likely system behaviour and performance under higher IBR penetration. • Existing approaches or knowledge no longer valid under significantly different future system conditions. • Increasing uncertainty and complexity in future system conditions that could lead to a broad range of system configurations.
Studies to develop limit advice and assess system adequacy in operational transition to first 100%	• Manual, resource intensive Electromagnetic transient (EMT) studies required in advance of real time operations. • Limits advice generally reviewed only when changes to network are made e.g. during generator connections. • Emerging critical hold points in transition to 100% renewables will require significant, concerted effort across TNSPs and AEMO to enable operational transition.

Figure 17 Actions to achieve identified preconditions for first 100% renewable periods – power system modelling



Models and data to establish confidence in the technical operating envelope of the power system under a range of plausible operating conditions

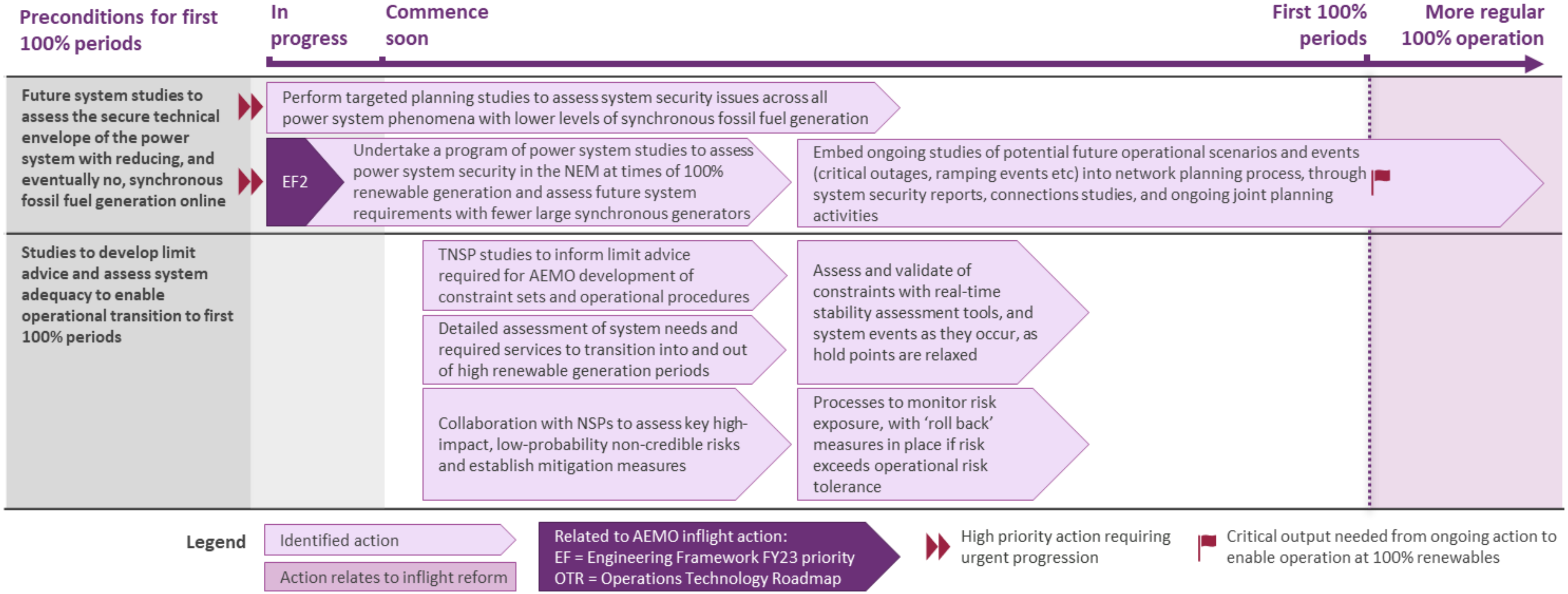
- EF7 – Uplift AEMO processes and governance for managing power system data, models and tools
- AEMO and NSPs collaborate to establish and baseline power system data, model quality and model performance requirements. Develop and resource prioritised model uplift workplans → Collaborate with industry and market bodies to ensure acceptable model provision, quality and performance
- Establish processes for OEM testing and validation of equipment performance for plausible non-credible disturbances to inform plant model development
- Establish internal process to verify plant performance, including uplifting processes and tools for extracting data, necessary conversion and analysis, and for model validation using PMU data

Ability to scalably and accurately model a large number of scenarios in operational and planning timeframes

- OTR – Assess and implement a streamlined approach to grid model management to facilitate a step change improvement in the speed and accuracy of study case development → Develop processes and automated tools to enable fast and accurate application of any generator dispatch pattern or connection point demand forecast to study cases
- Assess high performance computing requirements for power system modelling, implement capability and establish efficient workflows across simulation tasks
- Develop a prioritised plan to address gaps in AEMO and NSP capability to effectively model the phenomena that will need to be studied in the transition to 100% renewables
- Develop and benchmark stability assessment methods and tools appropriate for assessing relevant power system phenomena in high IBR conditions
- Develop assessment tools that can be feasibly implemented using EMS data and available information in pre-dispatch time frames for real time and look-ahead stability assessment

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority; OTR = Operations Technology Roadmap
- ⏩ High priority action requiring urgent progression
- ⚑ Critical output needed from ongoing action to enable operation at 100% renewables



Preconditions for first 100% periods

In progress

Commence soon

First 100% periods

More regular 100% operation

Future system studies to assess the secure technical envelope of the power system with reducing, and eventually no, synchronous fossil fuel generation online ▶▶

- Perform targeted planning studies to assess system security issues across all power system phenomena with lower levels of synchronous fossil fuel generation ▶▶
- EF2 – Undertake a program of power system studies to assess power system security in the NEM at times of 100% renewable generation and assess future system requirements with fewer large synchronous generators
- Embed ongoing studies of potential future operational scenarios and events (critical outages, ramping events etc) into network planning process, through system security reports, connections studies, and ongoing joint planning activities 🚩

Studies to develop limit advice and assess system adequacy to enable operational transition to first 100% periods

- TNSP studies to inform limit advice required for AEMO development of constraint sets and operational procedures
- Detailed assessment of system needs and required services to transition into and out of high renewable generation periods
- Collaboration with NSPs to assess key high-impact, low-probability non-credible risks and establish mitigation measures
- Assess and validate of constraints with real-time stability assessment tools, and system events as they occur, as hold points are relaxed
- Processes to monitor risk exposure, with 'roll back' measures in place if risk exceeds operational risk tolerance

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action:
  EF = Engineering Framework FY23 priority
  OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- 🚩 Critical output needed from ongoing action to enable operation at 100% renewables

See Table 23 in Appendix Section A1.2.3 for details of actions related to power system modelling.

4.3 Resource adequacy and capability

Having a sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of supply and demand.

The first 100% renewable periods will require sufficient renewable generation online to meet demand at that period, energy adequacy before and after that period so as not to require fossil fuel generation to be online to meet reserve requirements, and available dispatchable capacity to be able to transition in and out of high renewable periods.

This section of the Roadmap covers actions necessary to establish the bulk renewable energy, network capability, and resource flexibility necessary to enable this outcome, including:

- Building, connecting and integrating the renewable energy required to reach 100% renewable resource potential, including utility-scale VRE and DER.
- Planning for structural demand shifts that could materially influence overall capacity and energy requirements, depending on the pace of end use electrification.
- Building and modernising network infrastructure, including transmission network capacity to transfer power from renewable generation centres to load centres, and distribution network capability to accommodate increasing DPV and other DER uptake.
- Dispatchable capacity to firm renewable generation variability and uncertainty over different timescales (minutes, hours, and days).

AEMO's ISP and NSP planning work highlight the scale of investment required across these areas by the time of the first projected periods of 100% renewable resource potential in 2025, and more regular occurrence in 2030, under AEMO's ISP *Step Change* scenario. In addition to this development, this section of the Roadmap also highlights integration actions require to ensure system security and operability as the system evolves.

4.3.1 Utility-scale variable renewable energy (VRE)

Utility-scale VRE encompasses utility scale solar and wind generation for installations larger than 5 megawatts (MW). Generating systems with intermittent output are generally classed as semi-scheduled. Under this category AEMO forecasts the wind and solar generation output and includes it as part of its central dispatch process. During operation AEMO can constrain down the generation of these units to manage system security.

Under the ISP *Step Change* scenario, approximately 27 gigawatts (GW) of utility-scale VRE is projected by 2025. This would require a year-on-year increase of approximately 4 GW per year in the coming decade. A key point of consideration in this report is specifically the connection of these installations into the NEM, both the volume of connections that will be needed in the short to medium term and how the connection process itself can be updated to meet this demand in a timely manner.

Some of this work has been progressed with the Connections Reform Initiative[28] which is currently underway and is working to streamline the connections process for these installations.

Table 10 Identified preconditions for first 100% renewable periods and associated challenges – utility-scale VRE

Preconditions for first 100% periods	Current and emerging challenges
Connect and securely integrate increasing volumes of VRE	• 16 GW of VRE in the NEM today. ISP projects approximately 27 GW of VRE installed when first 100% renewable resource potential begin to emerge in 2025.
Confidence in VRE plant performance under during different plausible disturbances and operating conditions	• Several current issues will become increasingly significant with expected growth in VRE generation: – Quality and performance of models provided by participants in the connection process. – Solar and wind farm non-compliance with performance standards – relating to firmware updates, compliance with capability curves. – Operator technical knowledge of plant if they have been designed and commissioned by third parties. – Increasing level of solar and wind farm non-conformance with dispatch instructions.

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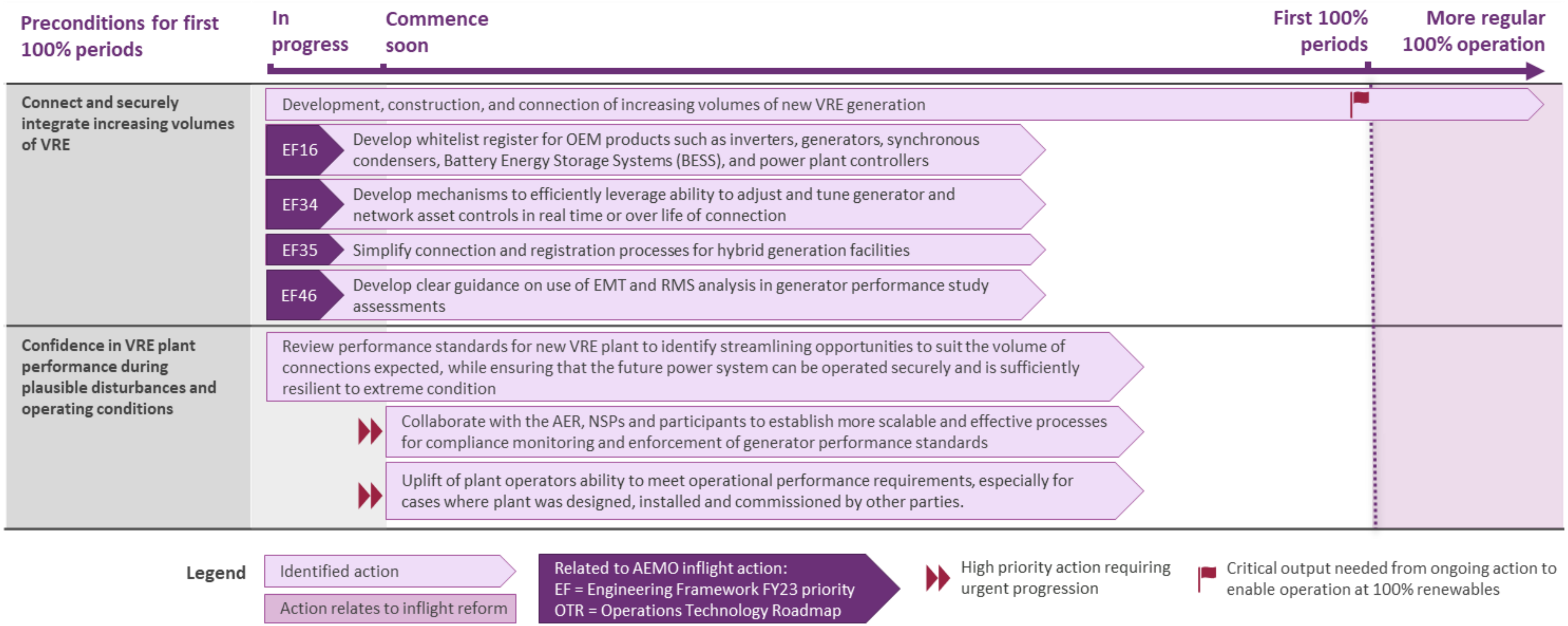
[28] AEMO. Connections Reform Initiative seeking to address concerns with delays and increasing complexity in the NEM. For further details, see https://aemo.com.au/consultations/industry-forums-and-working-groups/list-of-industry-forums-and-working-groups/connections-reform-initiative.

Figure 18 Actions to achieve identified preconditions for first 100% renewable periods – utility-scale VRE



Connect and securely integrate increasing volumes of VRE

- Development, construction, and connection of increasing volumes of new VRE generation
- EF16 Develop whitelist register for OEM products such as inverters, generators, synchronous condensers, Battery Energy Storage Systems (BESS), and power plant controllers
- EF34 Develop mechanisms to efficiently leverage ability to adjust and tune generator and network asset controls in real time or over life of connection
- EF35 Simplify connection and registration processes for hybrid generation facilities
- EF46 Develop clear guidance on use of EMT and RMS analysis in generator performance study assessments

Confidence in VRE plant performance during plausible disturbances and operating conditions

- Review performance standards for new VRE plant to identify streamlining opportunities to suit the volume of connections expected, while ensuring that the future power system can be operated securely and is sufficiently resilient to extreme condition
- ⏩ Collaborate with the AER, NSPs and participants to establish more scalable and effective processes for compliance monitoring and enforcement of generator performance standards
- ⏩ Uplift of plant operators ability to meet operational performance requirements, especially for cases where plant was designed, installed and commissioned by other parties.

Legend

Identified action

Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

⏩ High priority action requiring urgent progression

⚑ Critical output needed from ongoing action to enable operation at 100% renewables

See Table 24 in Appendix Section A1.3.1 for details of actions related to utility-scale VRE.

4.3.2 Distributed energy resources (DER)

DER comprise devices and capability behind the meter that offset or shift individual customer demand (sometimes referred to as customer energy resources [CER]), and larger commercial and industrial facilities (less than 5 MW) embedded within the distribution network not part of central dispatch.

The predominant form of DER in the NEM today is DPV generation[29]. Australia has experienced strong growth in DPV generation over the last decade, from fewer than 100,000 systems in 2010 to over 3 million by early 2022. AEMO expects this growth to continue, from about 16 GW of DPV installed in the NEM today, projected to increase to 29 GW by 2027 under the 2022 ISP *Step Change* scenario. Other forms of DER are also expected to emerge over this period, including behind-the-meter storage and electric vehicles (EVs), both passive as well as DER with coordination on-site and aggregated management.

The majority of the DPV fleet today cannot be actively managed, is invisible to AEMO or the NSPs, and does not have the same level of oversight and enforcement of compliance as utility-scale generation. The size of this fleet has begun to materially impact system operation in South Australia in recent years and is expected to similarly impact other regions and eventually NEM-wide, well before the first 100% renewable periods.

This section of the Roadmap is focussed on preconditions necessary to securely and reliably operate the system with high levels of DER, highlighting the need for DER performance and controllability commensurate with the aggregate size and contribution of this fleet.

Table 11 Identified preconditions for first 100% renewable periods and associated challenges – DER

Pre-conditions for first 100% periods	Current and emerging challenges
Clearly defined operational roles and processes for managing system security and coordination across parties at times of high DER penetration	• Increasing need for coordination across parties to manage system security during high DPV periods. • Operational challenges expected to emerge with increasing aggregation and coordination of DER and flexible demand in the distribution network.
Basic level of controllability for a sufficient proportion of the DPV fleet	• DPV is an increasingly large source of generation that cannot be curtailed, risking insecure operating conditions. • Requirement for some form of last-resort DPV control has arisen in South Australia and Queensland, expected to emerge NEM-wide by 2024 to maintain system security during extreme abnormal conditions (such as regional islanding or separation, or prior outage conditions).

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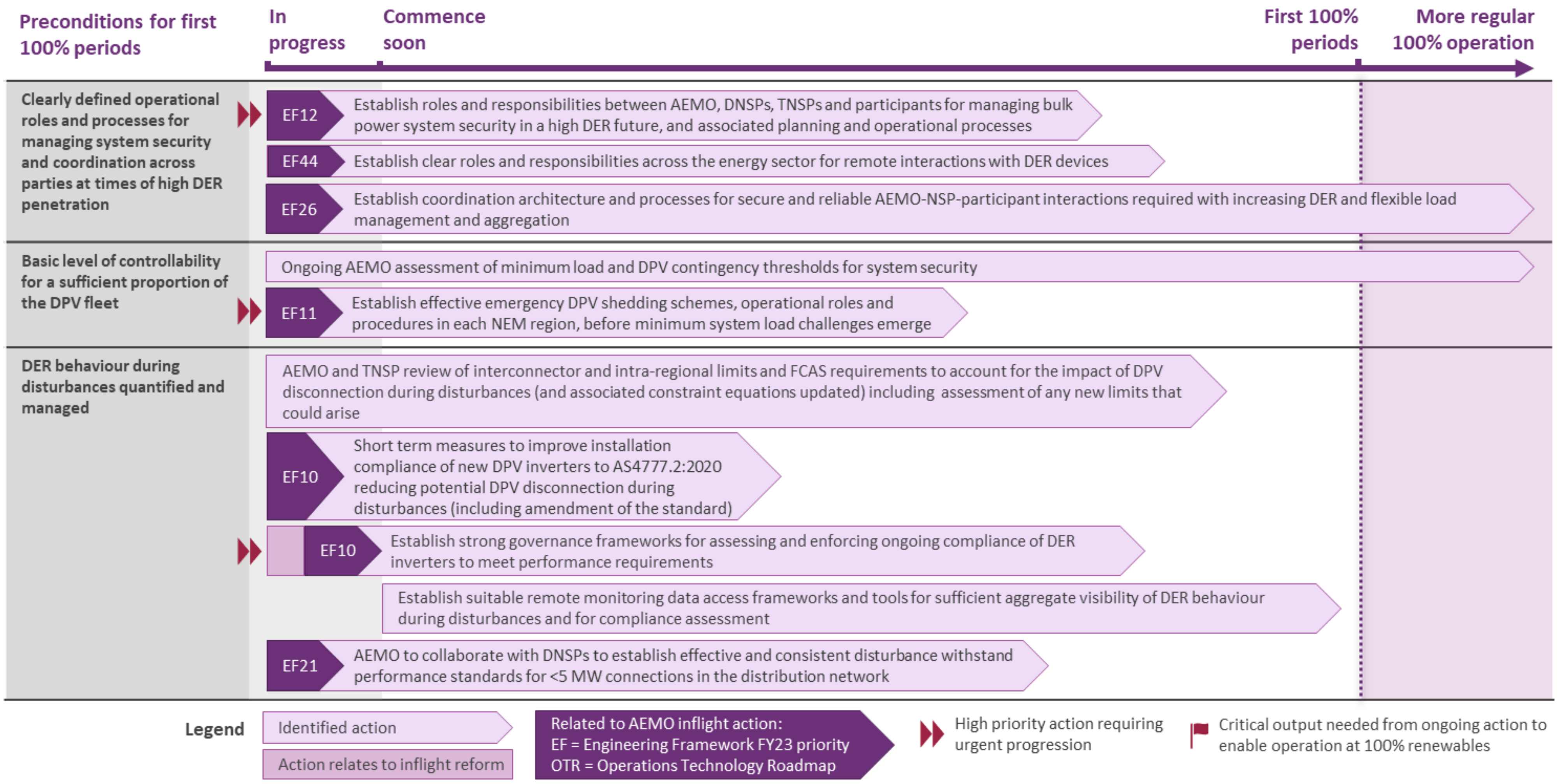
[29] DPV includes all grid-connected solar installations that are not part of central dispatch. AEMO classifies these devices under the following groupings: Rooftop PV captures systems up to 100 kilowatts (kW) in size, with systems up to 10 kW labelled residential and systems from 10 kW to 100 kW labelled commercial. PV non-scheduled generation (PVNSG) refers to systems larger than 100 kW and smaller than 30 MW (the current threshold for semi-scheduled status).

Pre-conditions for first 100% periods	Current and emerging challenges
DER behaviour during disturbances quantified and managed	• Increasing DPV disconnection during disturbances is driving up contingency sizes. • New AS4777.2:2020 requirements for disturbance ride-through in place, but with high levels of non-compliance – there is a lack of oversight and enforcement of compliance. • Insufficient visibility of DER behaviour during disturbances, and during short-duration timeframes (eg. oscillations) • Models do not represent the changing technology and growth in DPV.
Sufficient visibility and predictability of DER behaviour	• Insufficient aggregate DER monitoring and visibility of residential DER behaviour accessible to distribution network service providers (DNSPs) and AEMO. • Insufficient AEMO operational visibility of larger commercial and industrial embedded DER in the distribution network. • Minimal AEMO visibility and understanding or price-responsive DER, orchestrated or coordinated by different parties and management systems. While this is currently < 200MW, volumes are projected to grow to 1 GW by 2025 and > 4GW by 2030, under ISP Step Change scenario.
Enabling consumer participation and provision of demand-side flexibility	• Consumer DER adoption and usage decisions not always aligned with system needs. • Low uptake of demand response despite volume of flexible loads. • Limited participation pathways for DER to provide network and system services.

Figure 19 Actions to achieve identified preconditions for first 100% renewable periods – DER



Clearly defined operational roles and processes for managing system security and coordination across parties at times of high DER penetration ▶▶

EF12 Establish roles and responsibilities between AEMO, DNSPs, TNSPs and participants for managing bulk power system security in a high DER future, and associated planning and operational processes

EF44 Establish clear roles and responsibilities across the energy sector for remote interactions with DER devices

EF26 Establish coordination architecture and processes for secure and reliable AEMO-NSP-participant interactions required with increasing DER and flexible load management and aggregation

Basic level of controllability for a sufficient proportion of the DPV fleet ▶▶

Ongoing AEMO assessment of minimum load and DPV contingency thresholds for system security

EF11 Establish effective emergency DPV shedding schemes, operational roles and procedures in each NEM region, before minimum system load challenges emerge

DER behaviour during disturbances quantified and managed ▶▶

AEMO and TNSP review of interconnector and intra-regional limits and FCAS requirements to account for the impact of DPV disconnection during disturbances (and associated constraint equations updated) including assessment of any new limits that could arise

EF10 Short term measures to improve installation compliance of new DPV inverters to AS4777.2:2020 reducing potential DPV disconnection during disturbances (including amendment of the standard)

EF10 Establish strong governance frameworks for assessing and enforcing ongoing compliance of DER inverters to meet performance requirements

Establish suitable remote monitoring data access frameworks and tools for sufficient aggregate visibility of DER behaviour during disturbances and for compliance assessment

EF21 AEMO to collaborate with DNSPs to establish effective and consistent disturbance withstand performance standards for <5 MW connections in the distribution network

Legend

Identified action

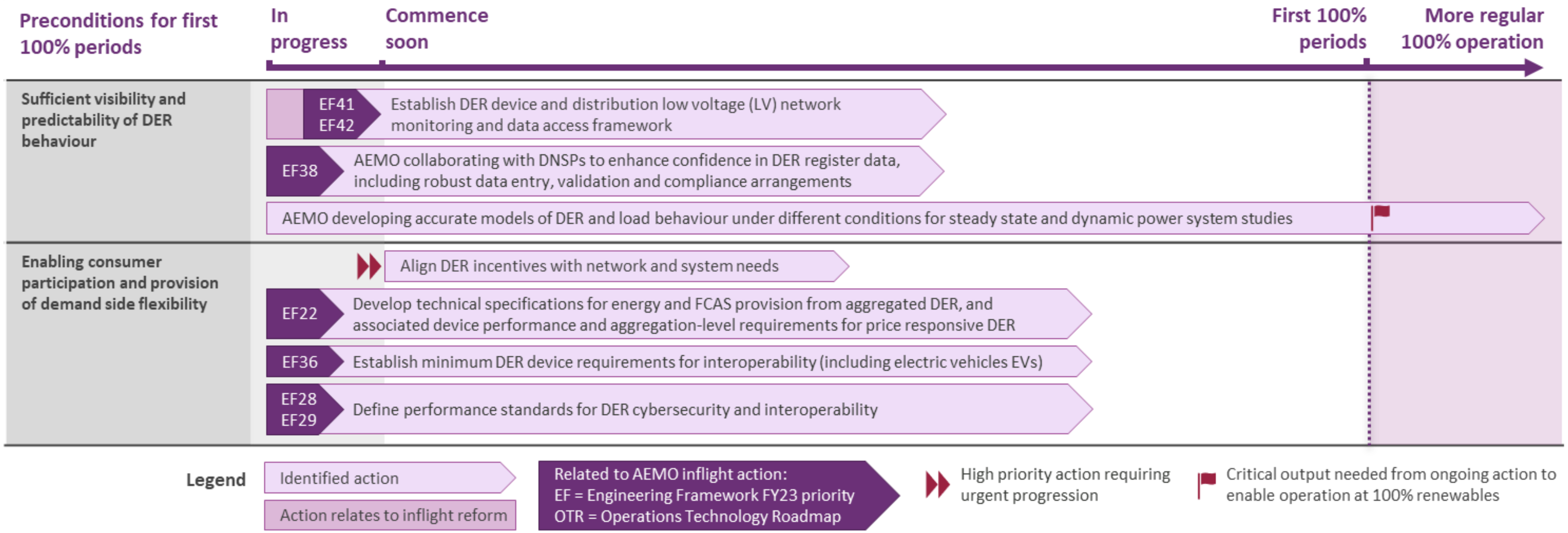
Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

▶▶ High priority action requiring urgent progression

⚑ Critical output needed from ongoing action to enable operation at 100% renewables

Action roadmap – resource adequacy and capability



Preconditions for first 100% periods | **In progress** | **Commence soon** | **First 100% periods** | **More regular 100% operation**

Sufficient visibility and predictability of DER behaviour

- EF41 EF42 Establish DER device and distribution low voltage (LV) network monitoring and data access framework
- EF38 AEMO collaborating with DNSPs to enhance confidence in DER register data, including robust data entry, validation and compliance arrangements
- AEMO developing accurate models of DER and load behaviour under different conditions for steady state and dynamic power system studies 🚩

Enabling consumer participation and provision of demand side flexibility

- ⏩ Align DER incentives with network and system needs
- EF22 Develop technical specifications for energy and FCAS provision from aggregated DER, and associated device performance and aggregation-level requirements for price responsive DER
- EF36 Establish minimum DER device requirements for interoperability (including electric vehicles EVs)
- EF28 EF29 Define performance standards for DER cybersecurity and interoperability

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action:
  EF = Engineering Framework FY23 priority
  OTR = Operations Technology Roadmap
- ⏩ High priority action requiring urgent progression
- 🚩 Critical output needed from ongoing action to enable operation at 100% renewables

See Table 25 in Appendix Section A1.3.2 for details of actions related to DER.

4.3.3 Structural demand shifts

Structural demand shifts refers to changes to the types of load on the system, that have the potential to have major impacts on power system behaviour, due to their significant size of demand and/or unique performance behaviour. While not directly impacting the displacement of fossil fuel generation, many structural demand shifts are being driven by the same underlying desire to decarbonise, with electrification seen as a key contributor. Structural demand shifts can include new sources of loads owing to the electrification of various sectors – such as transportation, industry (through the replacement of fuels including petrol and diesel) and residential (from gas heating, water heating and cooking) – as well as the introduction of new technologies such as from sector coupling (hydrogen electrolysers) and load blocks (such as data centres).

The 2022 ISP projects in its *Step Change* scenario that by 2050:

- EVs would make-up 99% of road transport.
- An additional 67 terawatt hours (TWh) will be required to address new industrial and residential electrification.
- An extra 58 TWh will be required for hydrogen consumption.

It is important that the performance standards of these new load connections keep up with their anticipated growth to ensure that they do no-harm, maintaining power system security as it transitions to higher penetrations of renewables. Simultaneously an opportunity is presented by these loads, where if integrated appropriately, they could provide support to renewables.

Table 12 Identified preconditions for first 100% renewable periods and associated challenges – structural demand shifts

Preconditions for first 100% periods	Current and emerging challenges
Fit for purpose performance requirements and connection processes for new loads, confidence in their operation during all operating conditions	• Managing significant volume of large load connections expected with end-use electrification. – Large volume of connection applications and proposals, many of which are inverter-based – including data centres and hydrogen electrolysers. • Performance of this plant could adversely impact power system stability, power quality and resilience: – Risk of increasing contingency sizes associated with unexpected disconnection of new large loads. – Stability impact of large load developments connecting in weak grid areas, far from generation centres. – Possible adverse interaction of large inverter-based loads with other IBR leading to power system instability. – New large IBR loads may increase requirements for local system strength.
Planning for energy adequacy and flexibility requirements to consider possible structural demand shifts	• Increasing local and aggregated energy balance and power quality impacts from the sudden switching of larger domestic loads and DER devices. • Limited visibility of new load connections and understanding of their daily and seasonal profiles, including potential drivers in their behaviour. • Challenges in planning for structural reductions in load, from large industrial load closures or consumer grid defection.

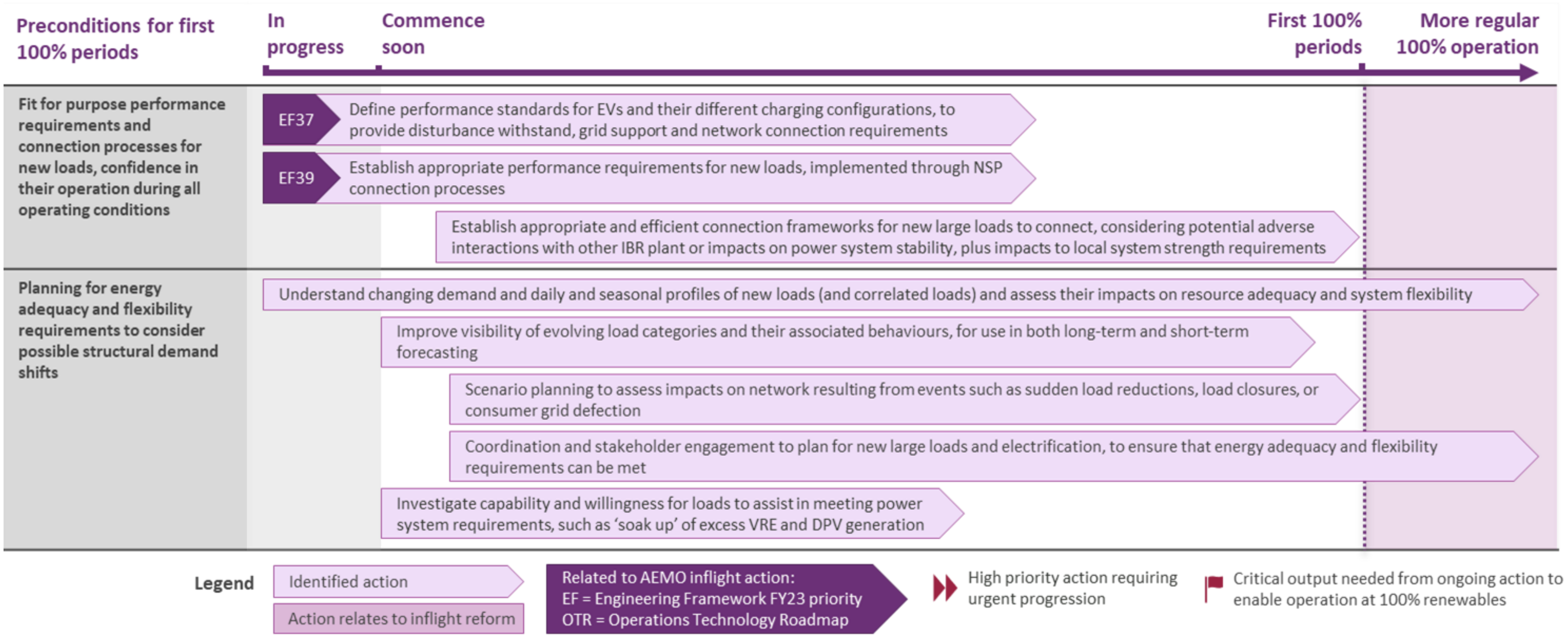


Figure 20 Actions to achieve identified preconditions for first 100% renewable periods – structural demand shifts

Fit for purpose performance requirements and connection processes for new loads, confidence in their operation during all operating conditions

- EF37 Define performance standards for EVs and their different charging configurations, to provide disturbance withstand, grid support and network connection requirements
- EF39 Establish appropriate performance requirements for new loads, implemented through NSP connection processes
- Establish appropriate and efficient connection frameworks for new large loads to connect, considering potential adverse interactions with other IBR plant or impacts on power system stability, plus impacts to local system strength requirements

Planning for energy adequacy and flexibility requirements to consider possible structural demand shifts

- Understand changing demand and daily and seasonal profiles of new loads (and correlated loads) and assess their impacts on resource adequacy and system flexibility
- Improve visibility of evolving load categories and their associated behaviours, for use in both long-term and short-term forecasting
- Scenario planning to assess impacts on network resulting from events such as sudden load reductions, load closures, or consumer grid defection
- Coordination and stakeholder engagement to plan for new large loads and electrification, to ensure that energy adequacy and flexibility requirements can be met
- Investigate capability and willingness for loads to assist in meeting power system requirements, such as 'soak up' of excess VRE and DPV generation

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action:
  EF = Engineering Framework FY23 priority
  OTR = Operations Technology Roadmap
- ▶▶ High priority action requiring urgent progression
- ⚑ Critical output needed from ongoing action to enable operation at 100% renewables

See Table 26 in Appendix Section A1.3.3 for details of actions related to structural demand shifts.

4.3.4 Transmission

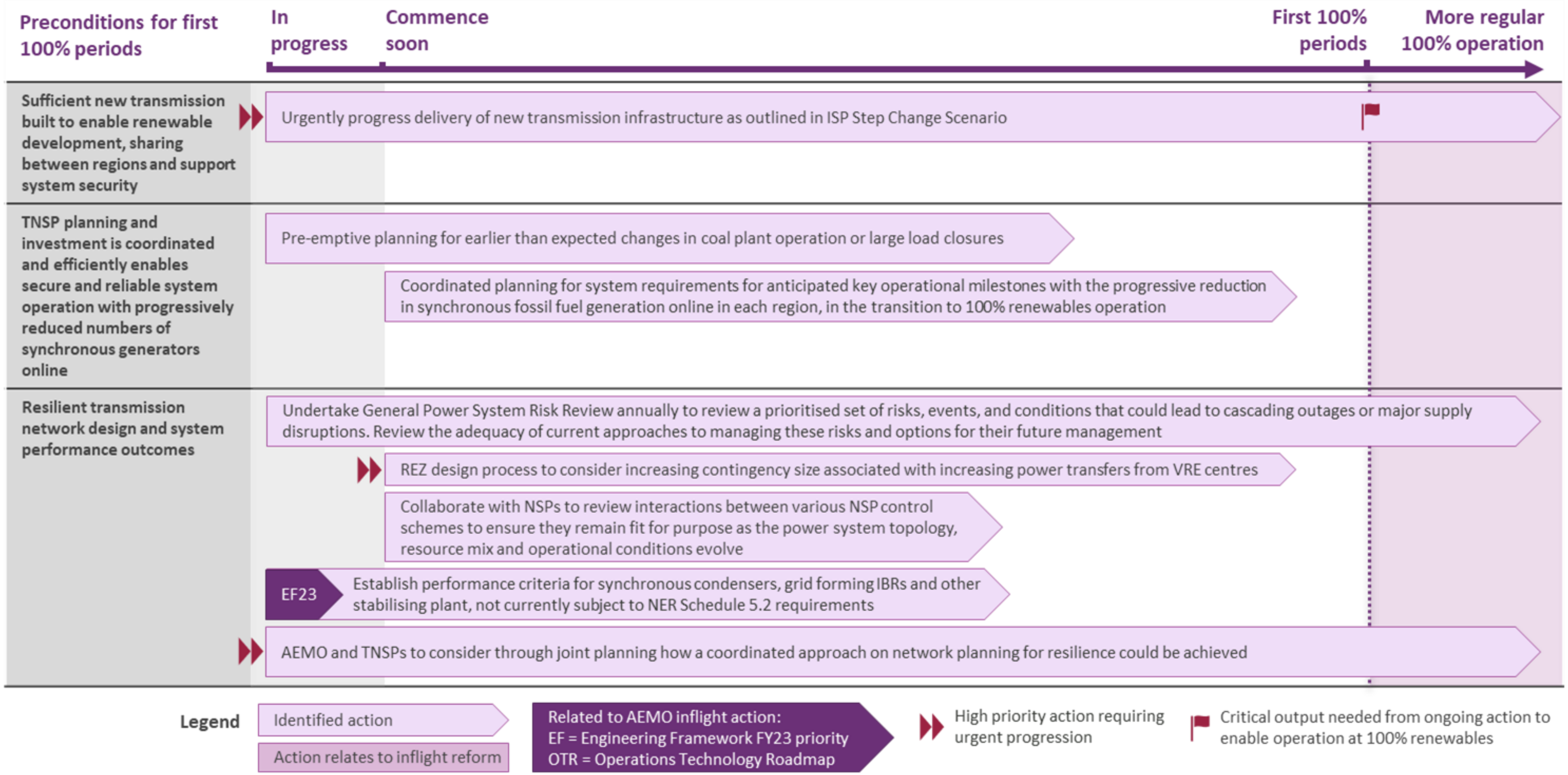
Transmission infrastructure is critical as the NEM progresses to the first periods of 100% renewable penetration. It will support the integration of dispersed VRE across the power system, facilitate the sharing and storage of renewable energy, and provide the firming needed, especially during times of localised 'dunkelflautes' (when weather conditions mean wind and solar generation can produce little to no energy). TNSPs, and particularly their planning and investment decision-making frameworks, are crucial to achieving energy security by expanding the technical operating envelope so 100% renewable penetration can be achieved.

Transmission line development enables the use of the renewable energy potential by reducing thermal constraints and in turn improving system security in areas of high renewable connections, often in weak areas of the network. The ISP anticipates that by 2050 approximately 10,000 km of new transmission infrastructure is needed to integrate the capacity of renewables required to reach extended periods of 100% renewables. Progress is needed on committed, anticipated, and actionable ISP projects to support the first 100% renewable periods.

Table 13 Identified preconditions for first 100% renewable periods and associated challenges – transmission

Preconditions for first 100% periods	Current and emerging challenges
Sufficient new transmission built to enable renewable development, sharing between regions and support system security	• Protracted timeframes for planning assessment and project approval. • Deployment and project delivery risks due to supply chain issues and skills shortages. • Challenges in gaining social licence from local communities for new transmission.
TNSP planning and investment is coordinated and efficiently enables secure and reliable system operation with progressively reduced numbers of synchronous generators online	• Risk of reduced coal operation sooner than anticipated in planning studies or closure of major loads. • Need for coordination as transmission networks are developed and as generation and storage connect to the power system, to ensure sufficient transmission network to enable connection and dispatch of necessary resources.
Resilient transmission network design and system performance outcomes	• As power-system conditions change (such as changing generation mix), the possible events that may occur on the transmission system will change, without consideration these may cause significant risks, that could lead to cascading outages or major supply disruptions. • Enhancing protection schemes needs to keep up with the potential performance capabilities of new transmission infrastructure (such as grid forming IBR), otherwise there is a risk of sub-optimal affordability outcomes. • Limited ability to pre-emptively manage non-credible event risk in operational timeframes resulting in increasing reliance on special protection schemes. • Potential for increased continency sizes due to growing power transfers from VRE centres.

Figure 21 Actions to achieve identified preconditions for first 100% renewable periods – transmission



Preconditions for first 100% periods	Actions
Sufficient new transmission built to enable renewable development, sharing between regions and support system security	⏩ Urgently progress delivery of new transmission infrastructure as outlined in ISP Step Change Scenario 🚩
TNSP planning and investment is coordinated and efficiently enables secure and reliable system operation with progressively reduced numbers of synchronous generators online	Pre-emptive planning for earlier than expected changes in coal plant operation or large load closures Coordinated planning for system requirements for anticipated key operational milestones with the progressive reduction in synchronous fossil fuel generation online in each region, in the transition to 100% renewables operation
Resilient transmission network design and system performance outcomes	Undertake General Power System Risk Review annually to review a prioritised set of risks, events, and conditions that could lead to cascading outages or major supply disruptions. Review the adequacy of current approaches to managing these risks and options for their future management ⏩ REZ design process to consider increasing contingency size associated with increasing power transfers from VRE centres Collaborate with NSPs to review interactions between various NSP control schemes to ensure they remain fit for purpose as the power system topology, resource mix and operational conditions evolve EF23 Establish performance criteria for synchronous condensers, grid forming IBRs and other stabilising plant, not currently subject to NER Schedule 5.2 requirements ⏩ AEMO and TNSPs to consider through joint planning how a coordinated approach on network planning for resilience could be achieved

Legend

- Identified action
- Action relates to inflight reform
- Related to AEMO inflight action: EF = Engineering Framework FY23 priority; OTR = Operations Technology Roadmap
- ⏩ High priority action requiring urgent progression
- 🚩 Critical output needed from ongoing action to enable operation at 100% renewables

See Table 27 in Appendix Section A1.3.4 for details of actions related to transmission.

4.3.5 Distribution

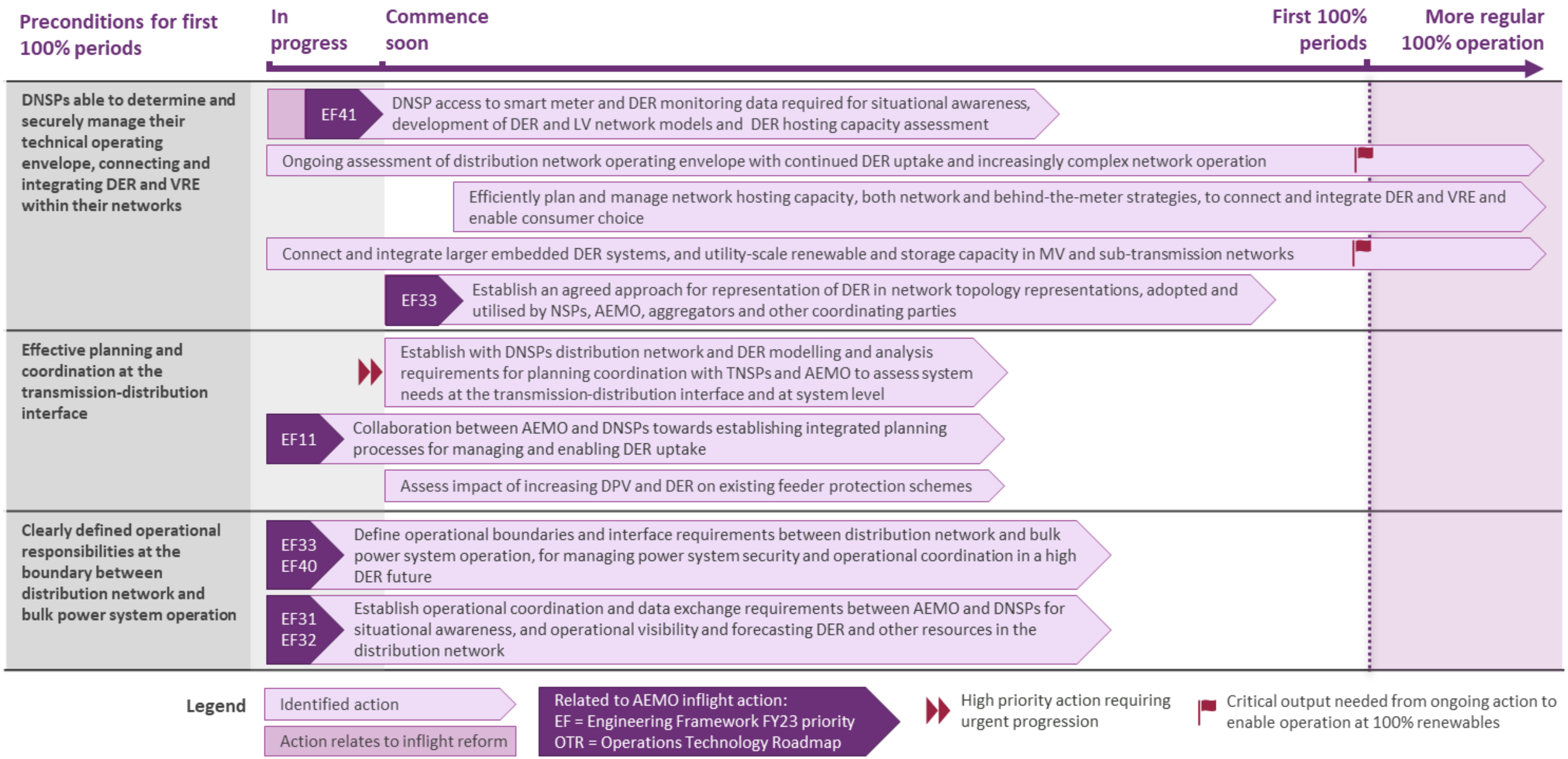
Distribution networks will play a crucial role enabling role in the renewable transition by facilitating the entry and the integration of residential DPV and other small-scale DER in the low voltage (LV) networks, commercial and industrial generation and storage embedded in the LV/medium voltage (MV) network, and utility-scale plant in the sub-transmission network.

This section of the Roadmap is focussed on steps required to empower and enable the step change required in distribution network capability to allow distribution network service providers (DNSPs) to manage increasingly complex interactions within their networks, operational coordination with TNSPs and AEMO, and to eventually serve as a platform for system-level flexibility. It comprises foundational elements for a highly decentralised power system such as data and visibility, system security responsibilities, definition of operating zones and responsibilities across distribution-transmission-bulk power system interfaces.

Table 14 Identified preconditions for first 100% renewable periods and associated challenges – distribution

Preconditions for first 100% periods	Current and emerging challenges
DNSPs able to determine and securely manage their technical operating envelope, connecting and integrating DER and VRE within their networks	• Increasingly wide and complex range of operating conditions to consider in planning and operations. – DPV impact on LV network voltage profile, power flows and protection coordination. – Congestion in DNSP MV, HV sub-transmission networks due to larger, embedded DER and utility VRE connections. • Limited data and monitoring of LV network assets and customer DER behaviour (for most DNSPs outside Victoria). – Impacting ability to study and define operating envelopes and consider efficiently improve DER hosting capacity.
Effective planning and coordination at the transmission-distribution interface	• Increasing planning and coordination requirements between DNSPs and TNSPs for voltage control. • Reducing system-wide fault level impacting distribution network protection coordination.
Clearly defined operational responsibilities at the boundary between distribution network and bulk power system operation	• Increasing need to coordinate with other parties to securely maintain safe and reliable distribution network operation and bulk power system security. • Defining and implementing distribution network limits for aggregated DER participation.

Figure 22 Actions to achieve identified preconditions for first 100% renewable periods – distribution



DNSPs able to determine and securely manage their technical operating envelope, connecting and integrating DER and VRE within their networks	EF41	DNSP access to smart meter and DER monitoring data required for situational awareness, development of DER and LV network models and DER hosting capacity assessment
		Ongoing assessment of distribution network operating envelope with continued DER uptake and increasingly complex network operation 🚩
		Efficiently plan and manage network hosting capacity, both network and behind-the-meter strategies, to connect and integrate DER and VRE and enable consumer choice
		Connect and integrate larger embedded DER systems, and utility-scale renewable and storage capacity in MV and sub-transmission networks 🚩
	EF33	Establish an agreed approach for representation of DER in network topology representations, adopted and utilised by NSPs, AEMO, aggregators and other coordinating parties
Effective planning and coordination at the transmission-distribution interface	▶▶	Establish with DNSPs distribution network and DER modelling and analysis requirements for planning coordination with TNSPs and AEMO to assess system needs at the transmission-distribution interface and at system level
	EF11	Collaboration between AEMO and DNSPs towards establishing integrated planning processes for managing and enabling DER uptake
		Assess impact of increasing DPV and DER on existing feeder protection schemes
Clearly defined operational responsibilities at the boundary between distribution network and bulk power system operation	EF33 EF40	Define operational boundaries and interface requirements between distribution network and bulk power system operation, for managing power system security and operational coordination in a high DER future
	EF31 EF32	Establish operational coordination and data exchange requirements between AEMO and DNSPs for situational awareness, and operational visibility and forecasting DER and other resources in the distribution network

Legend

Identified action

Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

▶▶ High priority action requiring urgent progression

🚩 Critical output needed from ongoing action to enable operation at 100% renewables

See Table 28 in Appendix Section A1.3.5 for details of actions related to distribution.

4.3.6 Firming

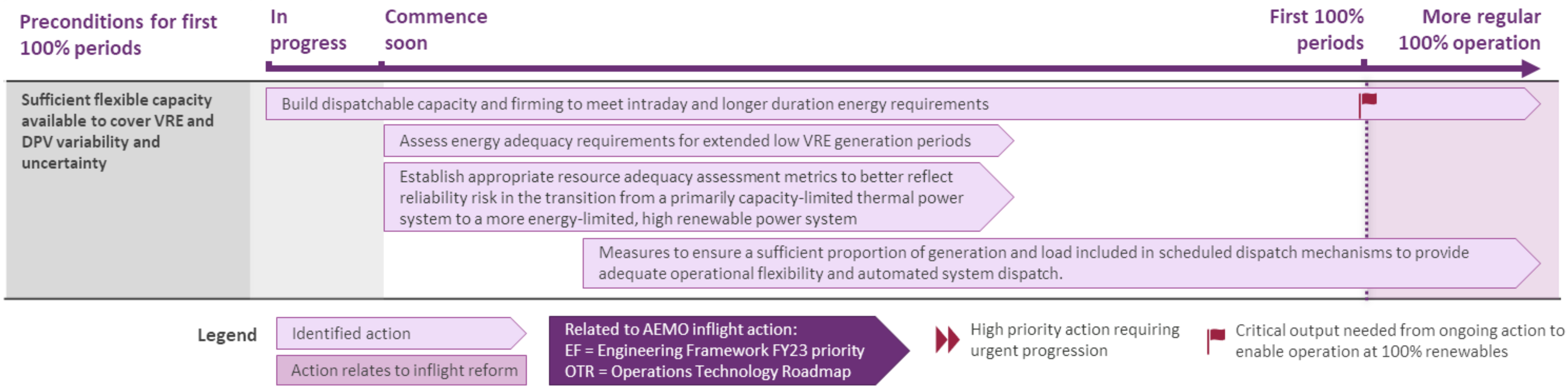
As the NEM progresses towards periods of 100% renewables, sufficient resource flexibility is required to manage the variability of the generation from VRE and DER over different timescales due to changing weather conditions (such as sudden cloud cover over solar, or extended solar or wind droughts). This can include ensuring sufficient resource adequacy and ramping needs within the five-minute dispatch interval, intra-day, seasonal, and long duration periods.

The need for firming capacity will be exacerbated as coal-fired generation withdraws. The 2022 ISP indicates that the firming capacity from dispatchable storage and generation will need to treble to sufficiently firm renewables by 2050, and will be achieved through technologies such as batteries, pumped hydro, and gas-fired generation. While less important for enabling the first periods of 100% renewable operation, it is acknowledged that adequate energy to meet demand during extended low VRE periods will be critical in the transition to more regular 100% operation.

Table 15 Identified preconditions for first 100% renewable periods and associated challenges – firming

Preconditions for first 100% periods	Current and emerging challenges
Sufficient flexible capacity available to cover VRE and DPV variability and uncertainty	• Increasing magnitude and frequency of large weather-driven ramps. This is becoming increasingly challenging to manage for several reasons: – Increasing VRE leads to decommitment of ramping resources due to low energy prices or plant operating limits. – Increasing ramps associated with daily diurnal solar profile and faster, less predictable ramps from significant DPV clusters due to cloud movements. – As large fossil-fuelled generating units operate less often, the availability of ramping resources is reduced. • Increasing uncertainty of operational demand and availability of VRE. Not possible to accurately model and precisely identify ramps in deterministic forecasts ahead of time. – Makes short-term operational planning more challenging, including demand forecasting and outage planning. • Extended periods of low wind and solar generation can deplete available firming sources (for example southern NEM states have historically experienced extended periods of low wind and solar generation in winter months). – AEMO projections have identified increasing seasonal gas supply risks in these states from 2023 onwards.

Figure 23 Actions to achieve identified preconditions for first 100% renewable periods – firming



Sufficient flexible capacity available to cover VRE and DPV variability and uncertainty

- Build dispatchable capacity and firming to meet intraday and longer duration energy requirements
- Assess energy adequacy requirements for extended low VRE generation periods
- Establish appropriate resource adequacy assessment metrics to better reflect reliability risk in the transition from a primarily capacity-limited thermal power system to a more energy-limited, high renewable power system
- Measures to ensure a sufficient proportion of generation and load included in scheduled dispatch mechanisms to provide adequate operational flexibility and automated system dispatch.

Legend

Identified action

Action relates to inflight reform

Related to AEMO inflight action:
EF = Engineering Framework FY23 priority
OTR = Operations Technology Roadmap

High priority action requiring urgent progression

Critical output needed from ongoing action to enable operation at 100% renewables

See Table 29 in Appendix Section A1.3.6 for details of actions related to firming.

A1. Detailed actions

This appendix provides a detailed view of the actions summarised in Section 4, divided across the same 14 individual roadmaps.

A1.1 Power system security

A1.1.1 Frequency and inertia

This table relates to Section 4.1.1 in the main report.

Table 16 Actions needed for operating at 100% instantaneous penetration of renewables – frequency and inertia

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Ability to keep system frequency within defined limits following credible and non-credible events, including RoCoF containment and effective emergency frequency control arrangements	• Review the need for a system-wide operational RoCoF limit based on an assessment of RoCoF withstand capability and requirements across the power system. – Being considered in Reliability Panel’s 2022 Frequency Operating Standard review. • Studies to assess role of synchronous mechanical inertia in general power system stability and need for suitable locational distribution of synchronous mechanical inertia. – Dependency: 100% studies work considering impact of inertia on system strength, transient and small-signal oscillation modes – discussed further in [Power system modelling] – *EF FY23 Action A2: Initiate a program of power system studies to assess power system security in the NEM at times of 100% renewable generation.* – Further work required to assess impact of reducing inertia on protection adequacy. • AEMC to consider implications for inertia procurement frameworks and relationship with RoCoF. • Establish understanding of ‘synthetic’ inertial response from IBRs, including how the response might differ to inertia from synchronous machines, and potential plant level constraints on the capability to provide synthetic inertia. – IBR synthetic inertia contribution is related to its operating condition. – IBR have limited or no ability to provide synthetic inertial responses when operating at or near full MW output. This is in contrast to synchronous inertia which is a function of unit commitment. – This may require consideration of a headroom management to operationalise ‘synthetic’ inertial response from IBRs, similar to present frequency control markets. • Technically specify synthetic inertia capability for IBR. – Required to standardise this capability for inclusion as an ‘inertia support service’ utilised by TNSPs in meeting their inertia obligations and for effectively modelling and accounting for the contribution of this plant in frequency response across the NEM.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Related to *EF FY23 action A3: Collaborate with industry on a voluntary specification for grid-forming inverters.* • Design and implement a mechanism to ensure availability of inertia in operational timeframes, including co-optimisation with dispatch of energy and other ancillary services. – The Operational Security Mechanism could be implemented as a transitional tool for valuing, scheduling and procuring security services such as inertia in operational time frames, without the ongoing use of Directions by AEMO. – A rule change for evolving the existing inertia framework, such as introducing a potential Inertia Spot Market, has been lodged with the AEMC, which could provide a value to the dispatch of inertia in the NEM. • Ongoing assessment of inertia requirements for NEM subnetworks through annual AEMO assessment over a 5-year planning horizon, with TNSP obligations to remediate identified shortfalls. – Opportunity to consider enduring inertia mechanisms. – Assessment of future needs will increasingly need to account for availability of other frequency responses. • Identify and progress opportunities (where economic) for common solutions to address inertia requirements in conjunction with identified system strength needs, such as adding flywheels to synchronous condenser installations. • AEMO and NSPs to assess and maintain adequacy of emergency frequency control schemes and management arrangements. – AEMO's 2022 Power System Frequency Risk Review identified the potential for excessive OFGS and UFLS action, with higher RoCoF events expected with the projected reduction in system inertia. AEMO will continue to monitor this in future general power system risk reviews and review OFGS/UFLS, if required. – Dependency: Effective emergency frequency control capability with increasing aggregate DPV impact – discussed in this section [Frequency and inertia]. – Establish appropriate measures for effective management of over-frequency events in the NEM including coordination of overfrequency trip settings of new generator connections. – *EF FY23 Action A45: Evaluate the coordination of over-frequency management settings in all NEM regions including any recommended mitigations.* • AEMO and NSPs to assess emergency frequency control scheme adequacy with increasing aggregate DPV uptake. – *EF FY23 Action A18: Review NEM-wide UFLS scheme adequacy, identify need for corrective action and progress resolution.* – Determine most onerous, plausible non-credible contingency events. – Develop models suitable for assessing behaviour of UFLS in high DPV periods, capturing relevant factors such as DPV disconnection, load shake-disconnection, and dynamic arming of UFLS relays. – Determine emergency underfrequency response requirements and collaborate with NSPs to identify pathways for delivering this response in high DPV, low demand periods. – Dependency: Compliance with AS4777.2:2020 for all new DPV being installed, as DPV tripping on underfrequency exacerbates MW imbalance during underfrequency events [Distributed energy resources]. • NSPs remediate or redesign EFCS arrangements for effective operation during high DPV conditions. – NSP responsibility to maintain EFCS effectiveness and to resolve any adequacy issues identified by AEMO through the Power System Frequency Risk Review (PSFRR) / General Power System Risk Review (GPSRR) process.
Frequency response and frequency control ancillary services (FCAS) reserve requirements completely met by VRE,	• AEMO to assess frequency control requirements during high DER conditions with minimal centralised frequency responsive plant online and feasible options for how these requirements can be met.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
storage, demand response and other non-fossil fuel technologies	– *EF FY23 Action A17: Assess narrowband frequency control during projected operational conditions with very high DPV. Investigate options to achieve sufficient aggregate response.* – Dependency: Impact of DPV uptake on narrowband PFR requirements discussed further in [Distributed energy resources]. • Implement measures to ensure sufficient aggregate frequency response and regulation FCAS is online during high DER periods. – May require mechanisms to manage headroom from large scale VRE and storage and narrowband PFR from DER devices. • Implement new Very Fast FCAS markets, specifying technical requirements for participation and assessment of necessary procurement volumes. – AEMO's published its final Market Ancillary Services Specification (MASS) for the new Very Fast FCAS services in October 2022, to come into effect in October 2023 to coincide with the commencement of the new markets. This sets out technical performance and measurement requirements for participants to register as Very Fast FCAS providers. • Review and assess appropriate mix of frequency control measures and adequacy of FCAS arrangements with reducing synchronous inertia, increasing variability, and as the system topology evolves. – Planning studies and service procurement decisions co-optimising between FCAS procurement and inertia levels. – New very fast contingency FCAS procurement will be 'inertia aware'. New constraints being formulated for this. – Review regional FCAS and frequency response requirements in the transition to 100% renewable operation. Required to manage system security risks associated with significant proportions of FCAS provided by relatively few plant with little geographic diversity. – Potential increased dependency on key interconnectors to transfer frequency services may impact resilience of the power system. – Regulation FCAS volumes may need to increase due to increased aggregate MW variability within the 5 minute time frame. – Ongoing monitoring of Regulation FCAS utilisation and performance is required. • Sufficient regulation FCAS available through AGC enabled plant, with appropriate mechanisms to incentivise service provision. – Requires AGC enablement with suitable aggregation of systems required for AGC, with control logic to enable transition between generating with and without an energy cap and providing regulation. – Mechanisms required to incentivise plants to provide headroom. • AEMO to develop operational forecasting processes to quantify uncertainty relating to increasing price responsive behaviour of semi-scheduled, non-scheduled and DER plant as part of calculating regulation FCAS quantities. – Dependency: Discussed further in [Operational processes]. • Develop technical specifications for frequency control services from aggregated DER and loads. – Aggregated DER can today provide contingency FCAS. – *EF FY23 action A22: Consider the requirements for energy and FCAS provision from aggregated DER within the delivery of reform initiatives.* • Allow aggregated DER to provide FCAS by participating as a scheduled resource. – This could be achieved through the proposed Scheduled Lite dispatch model. • Establish mandatory and enduring requirements for narrowband PFR from scheduled and semi-scheduled generators, requiring automatic response to small changes in frequency, complemented by new incentive arrangements to reward provision. – AEMO continues to work with OEMs to enable updates to their controls. – Enduring PFR arrangements establishing through AEMC PFR incentive arrangements Rule change completed in September 2022, coming into effect in 2025. Includes double-sided frequency performance payments to incentivise plant behaviour to encourage better primary frequency outcomes.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Dependency: Assess narrowband primary frequency response needs as increasing DPV displaces frequency responsive plant online in the daytime.
Adequate system inertia monitoring and accurate inertia forecast capability (supply and demand side) required as an input to constraints	• Undertake dynamic inertia measurement trials, which could include using phasor measurement units to measure system inertia (including on the generation and load side) following a small active power generation from a capacitor or battery. – *EF FY23 Action A13: Provide regularly updated information on NEM inertia. Support dynamic inertia measurement trial.* • Enduring inertia (supply and demand side) monitoring and assessment in operational timeframes integrated into inertia-dependent constraint equations.

A1.1.2 Transient and oscillatory stability

This table relates to Section 4.1.2 in the main report.

Table 17 Actions needed for operating at 100% instantaneous penetration of renewables – transient and oscillatory stability

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Appropriate stability limits in place for projected reductions in operation of synchronous machines	• Studies to validate stability constraints for reducing inertia scenarios as synchronous fossil fuel units decommit/exit and identify any new stability limits that might arise. – Impacts on transfer limits are not well understood. Studies will be required to investigate how transfer limits will change to inform development of constraint equations for planning studies. • Establish processes to address new stability issues as they are identified.
Appropriately damped local and inter-area oscillations	• Assess suitability of current methods to manage inter-area oscillations for future system configurations, including any specific remediation schemes. • Establish processes to remediate issues in the management of inter-area oscillations as they are identified. • Develop tools for small signal stability assessment in high IBR systems so that issues can be identified and effectively mitigated. • Establish requirements for OEMs to provide small signal models capable of modelling high frequency phenomena. • Establish better defined processes with NSPs for identifying and addressing small-signal stability issues as the system evolves.

A1.1.3 System strength and converter driven stability

This table relates to Section 4.1.3 in the main report.

Table 18 Actions needed for operating at 100% instantaneous penetration of renewables – system strength and converter driven stability

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables

System strength requirements met by alternatives to system configurations that require minimum loading on synchronous fossil fuel generators	• AEMO assessment of system strength requirements in the transition to 100% renewable operation through the system strength framework, setting projected requirements 10-years ahead, including minimum fault level requirements for system security and requirements for stable voltage waveforms at connection points to host projected levels of IBR. TNSPs responsible meeting requirements and assessment through the network planning process, including provision of sufficient fault level for distribution protection.
	– *EF FY23 action A1: Implement new system strength Rules, including formal consultation on changes to the System Strength Requirements Methodology and Impact Assessment Guidelines*. Publish new system strength standards for the coming decade, requiring services to ensure fault levels needed for a secure system as well as services to facilitate future renewable generation connections.
	– Ensure any new forms of instability (e.g. oscillatory modes) that may be introduced through wide spread deployment of new assets to meet system strength requirements of synchronous condensers are adequately considered in detailed design of system strength solutions.
	– Dependency: AEMO 2022 system security studies investigating system strength requirements for a plausible future 100% renewables period. Discussed further in [Power system modelling].
	  – Critical factor likely to be 11kV and 22kV protection due to the costs involved and large number of such schemes. A fault at the remote end of an 11/22kV feeder will need to be cleared whilst still complying with the requirement to cater for circuit breaker fail protection at the zone substation. Fault level needs to be adequate to operate any local backup overcurrent elements at the zone substation (e.g. transformer protection).
	  – Additionally, the fault current requirement will need to exist for at least 1 second, possibly up to 3 seconds, depending on the design of the protection systems and the presence of distribution fuses.
	• AEMO and TNSP assessment of system strength requirements to maintain system security during planned outage conditions and system restart situations.
	– Dependency: System strength under planned outage situations can be considered under the new system strength framework. Discussed further in [Operational processes].
	– Dependency: Restoration support services for system strength will be required for effective system restart during 100% renewables periods. Discussed further in [System restoration].
	• Clarify accountabilities and processes for compliance monitoring of generator and NSP devices (e.g. synchronous condensers) used to provide system strength services or remediation, including processes for remediation of non-compliance.
	– Assessment and validation of stabilising devices installed as part of new generator connections.
	– Dependency: Performance standards for NSP operated stabilising plant discussed further in [Transmission].
	• Identify and progress opportunities for the conversion of suitable existing fossil fuel generating units to establish synchronous condenser capability.
	– *EF FY23 Action A23: Promote the addition of synchronous condenser capability in new and existing synchronous generator investment and retirement decisions.*
	– Establish participation pathways and technical requirements for grid forming services.
	• Trial and understand grid-forming inverter technology to support / provide system strength.
	– *EF FY 23 Action A14: Support ARENA advanced inverter funding round.*

Preconditions for first 100% periods	**Action needed for operating at 100% instantaneous penetration of renewables**
	– Enable advanced inverter capabilities on new grid-scale batteries. • Simplify treatment of grid-forming inverter projects in the connections process. – *EF FY23 Action A27: Publish a fact sheet to clarify the pathway for grid-forming inverters through the existing connections process.* • Technically define power system support capabilities for grid-forming inverters to guide Original Equipment Manufacturers (OEMs) and developers. – *EF FY23 action A3: Collaborate with industry on a voluntary specification for grid-forming inverters.* • Develop metrics to assess provision of system strength from new technologies such as grid forming IBRs, to enable consideration of such technologies as credible options in planning assessments, and utilisation in operational timeframes to meet system strength needs. • Enhance AEMO control room situational awareness tools and look-ahead capability for system strength. – Dependency: Discussed further in [Operational processes]. • Design and implement a mechanism to ensure availability of system strength in operational timeframes, including co-optimisation with dispatch of energy and other ancillary services. – The Operational Security Mechanism could be implemented as a transitional tool for valuing, scheduling and procuring security services such as system strength in operational time frames, without the ongoing use of Direction by AEMO. – May include new arrangements for managing commitment of synchronous generators, synchronous compensators, or availability of advanced IBR such as BESS with grid forming controls. – *EF FY23 Action A5: Advocate for market-based approach to dispatch resources for system security, which will support the operation of the system, remunerate and signal value for system security contributions, and reduce current requirement for directions while helping build understanding of the power system over time.* • Assess potential system strength requirements to ensure stable DER inverter operation.
Ability to identify and manage fast and slow converter interaction driven oscillations	• Deploy high speed monitoring across the NEM for ongoing assessment, reporting and analysis of small signal stability and converter driven oscillations. – Dependency: High speed monitoring requirements discussed further in [Monitoring and situational awareness]. • Establish processes to transparently manage oscillations as they are identified. • Develop online monitoring and dynamic security assessment tools for converter driven instabilities, for risk assessment and validation of operational constraints. – Dependency: Requires control room tools for real-time and forward-looking stability assessment, discussed further in [Operational processes].

A1.1.4 Voltage control

This table relates to Section 4.1.4 in the main report.

Table 19 Actions needed for operating at 100% instantaneous penetration of renewables – voltage control

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Sufficient steady state and dynamic reactive support to maintain reactive margins and voltage disturbances within limits, completely provided by non-fossil fuel technologies	• Plan and manage changing requirements for static and dynamic reactive power to address reduction in provision from synchronous fossil fuel generation and requirements to support VRE entry in remote network locations. – Dependency: AEMO 2022 system security studies investigating steady state voltage control during a plausible, low demand, future 100% renewables period. Discussed further in [Power system modelling]. • Studies to assess impact of fossil fuel generation exit and decommitment on voltage stability limits. • Progressive updates to TNSP limit advice as the network evolves. • Establish sufficient inductive reactive margins for managing high voltages during light load periods, with ongoing reduction in minimum demand due to DPV uptake. – Reactive margins specified for capacitive reactive support (required during high demand times) in the NEM but not for reactors. • Establish mechanisms for ensuring sufficient reactive support during prior outage conditions. – Dependency: Discussed further in [Operational processes]. • Review requirements for available inverters to maintain reactive support during low generation periods such as from solar inverters at night time. • Establish operational processes for utilising and coordinating reactive capability from IBRs. – Capability is required in generator performance standards however manual process to manage operationally and not considered within VDS. • Enable greater range of devices and approaches for VAr dispatch. • Clarify NER requirements for reactive current injection from IBRs during faults. – Ongoing rule change: “Efficient reactive current access standards for inverter-based resources”. • Clarify generator and NSP obligations for voltage control, including accountabilities, and processes for remediation and compliance monitoring of installed reactive plant. • Implement voltage disturbance ride through capability for DER including necessary compliance arrangements. – *EF FY 23 Action A10: Collaborate with industry on identified non-compliance risks for small-scale inverters’ performance during disturbances. Collaborate with market bodies on enduring frameworks, roles and responsibilities for DER installation and performance compliance.* – Dependency: Covered in [Distributed energy resources]. • Update and integrate VAr Dispatch Scheduler (VDS) and Voltage Security Assessment (VSAT) assessment tools and systems to account for all available reactive capability and relevant contingencies. – Update models to include all resources and assets with reactive capability, and controls. – tools need to consider all contingencies, reactive power margins and available resources at a regional level. • Automated voltage control actions from voltage management systems (Coordinated action with DNSPs).

	• Studies to assess fault level requirements for avoiding excessive step changes in voltage due to switching of reactive plant, and for adequate reactive reserve. – Dependency: Discussed further in [System strength and converter driven stability]
Coordinated voltage control at transmission-distribution interface for times of high DER	• TNSP-DNSP joint planning to identify and address reactive support and voltage control requirements with increasing DER and VRE in the distribution networks impacting reactive power exchange at the transmission-distribution interface.
Reactive support and voltage control arrangements for highly variable, long distance VRE power flows to load centres, and more variable daily demand profiles across transmission and distribution networks	• Conduct quasi dynamic studies over minutes-hours timescales to assess the impact of increasing variability of VRE, demand and power transfers, on intra-day voltage profiles. – This analysis is required for transmission, sub-transmission and distribution networks. • Identify challenges to maintaining secure voltages over the minutes-hours timescale, and options for mitigation. – This will require review of limitations to transmission and distribution voltage controlling plant operation (e.g. if transformer tap changers or switched shunts have maximum operation per hour/day limits that could be exceeded) and distribution network voltage control strategies with a more rapidly changing transmission voltage profile. • Update operational voltage control processes and tools to manage impact of increasing VRE and DPV variability on voltage control. – This will require development of new procedures and operator training. – Operational tools will need to capture and track key risk factors, e.g. if shunt lock out from excessive switching is a risk, control rooms may need visibility of the number of shunt switching events over some period.
Sufficient reactive power absorption capability to securely supply load	• Forecast projections of transmission connection point reactive power (MVAr) demand to allow for NSP and AEMO planning studies to assess future reactive plant needs and ensure sufficient lead time for procurement of necessary solutions. – If this is not possible, conservative power factor assumptions for planning studies will need to be agreed between NSPs and regulatory bodies. • Establish look ahead capability with MVAr forecasting and voltage constraints integrated with Electricity Market Management System (EMMS) and other control room systems.

A1.1.5 System restoration

This table relates to Section 4.1.5 in the main report.

Table 20 Actions needed for operating at 100% instantaneous penetration of renewables – system restoration

Preconditions for first 100% periods	Actions needed for operating at 100% instantaneous penetration of renewables
Effective restart arrangements, plans, procedures in place for first 100% renewables period, including adequate SRAS capable plant built in suitable locations	• AEMO, in consultation with NSPs and Reliability Panel, to assess the adequacy of the system restart framework for 100% renewables operation, including review of the System Restart Standard, System Restart Guidelines, system restart plans and procedures, and appropriate investment signals. – *EF FY23 action A4: Review current system restart framework, documenting potential areas to improve incentives for new service providers. Provide advice to Reliability Panel ahead of upcoming System Restart Standard review.* – Determine and assess need for new restart pathways, and new synchronising points. As coal fleet will be offline during 100% renewables operation and require 16-24 hours time to start, restart pathways will need to start with gas or diesel plant, hydro generation initially and then IBRs. – Dependency: Test new restart design using Dispatch Training Simulator during 100% renewables scenarios [Operational processes].

Preconditions for first 100% periods	Actions needed for operating at 100% instantaneous penetration of renewables
	– Review adequacy of investment signals for new SRAS sources given their capability and location. • AEMO to assess system security requirements in the restart process and the need for Restoration Support Services (RSS) for voltage control, frequency control, system strength, provision of fault current and other stability needs. – System security requirements of some of these restart paths will require RSSs to manage voltage and fault levels, especially to connect the IBRs that are required in the early stages. – Synchronous condensers may be required strategic locations, without the coal fired generation fleet available to provide system strength and fault current. – Sufficient voltage control required to counteract Ferranti effect on lightly loaded lines and energise transformers. – SRAS guideline recognises the need for RSS but currently none contracted. • AEMO to plan for and contract with SRAS and restoration support service providers required for 100% renewables periods, as per adequacy assessment. • AEMO in consultation with NSPs to develop appropriate control room training and testing procedures for new system restart design. • Investigate and demonstrate new technology (such as emerging grid forming capability) to provide SRAS or assist in the restart process (and any limitations) through power system modelling and small-scale trials. – Trial sub-section/region of the NEM at 100% IBR operation if feasible. – *EF FY23 Action A20: Advocate for demonstrating capability of new technology to provide SRAS*. • AEMO to engage with new SRAS providers, such as IBRs required to be connected in the early stages of restart, on necessary capability required to operate their plant during restart. • Assess feasible strategies to energise large volumes of VRE in remote locations, necessary system service requirements and grid forming capability required for each electrical subnetwork. – VRE will required to be connected much earlier than in current restart plans. Additional system strength services will be required to enable this. – Will require a significant number of network elements to be energised to reach VRE centres. Likely to be significant transformer inrush currents on energisation that will need to be managed. – Dependency: Investigate and demonstrate new technology (such as emerging grid forming capability) to provide SRAS or assist in the restart process (and any limitations) through power system modelling and small-scale trials. – Dependency: AEMO to engage with new SRAS providers, such as IBRs required to be connected in the early stages of restart, on necessary capability required to operate their plant during restart.
Ability to maintain stable load blocks during the restart process	• AEMO to assess system restart requirements and capability with increasing aggregate DPV impact. – *EF FY23 Action A19: Review system restart adequacy across the NEM, identify need for corrective action and progress resolution.* – Develop PSCAD models for DPV behaviour suitable for system restart studies. – Determine suitable restart pathways in low demand conditions. • AEMO to collaborate with NSPs to establish suitable restart procedures and operational processes in low demand conditions to enable stable load blocks in proximity of restart units, particularly for distribution feeders with minimal to no load. – Implement suitable active control of a sufficient proportion of DPV systems for the restoration process which can be effectively enacted during black start conditions. – Likely that internet or customer Wi-Fi based DPV control mechanisms will not be suitable under restricted communication scenarios.

A1.2 System operability

A1.2.1 Monitoring and situational awareness

This table relates to Section 4.2.1 in the main report.

Table 21 Actions needed for operating at 100% instantaneous penetration of renewables – monitoring and situational awareness

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Sufficient weather monitoring to forecast plausible VRE generation output variability and uncertainty	• Deploy weather monitoring infrastructure to support participant and AEMO forecasting requirements for renewable energy zones (REZs), DPV generation within load centres and other key network locations. – Plan and enable construction of new weather monitoring infrastructure through the REZ design process. – Commissioning of new weather monitoring data streams and provision to AEMO and the meteorological industry so it can improve the base weather models. – Dependency: Required for operational forecasting of VRE [Operational processes]. – *EF FY23 Action A30: Advocate for new weather monitoring infrastructure requirements to support REZs.*
Sufficient wide area visibility of power system performance and control room tools to leverage this data for real time stability monitoring and risk assessment	• Establish NEM-wide PMU coverage and sufficient supporting infrastructure for communication and processing of high speed data. – AEMO has been collaborating with NEM TNSPs to establish priority locations for PMUs, with coverage over 140 high voltage substations (corresponding to about 1000 3-phase channels) expected by December 2025. – Key priority is for NSPs to upgrade communication links and prepare PMUs to begin streaming the data. – *EF FY23 Action A43: Promote widespread phasor measurement unit (PMU) roll-out and high-speed data ingestion/automation.* • Explore requirements for new generator connections to fit PMUs at their connection point and enable associated communication infrastructure required for model validation and compliance monitoring. – Currently no requirements to install a PMU when registering and connecting new plant in the NEM. Some NSPs require installation of power quality meters however this data is not time synchronised, which is a key requirement for cause-effect analysis. – Will require communication pathways and integration within WAMs. Transmission-connected plant can utilise TNSP communication infrastructure. – Distribution-connected plant will need to establish feasible communication pathways – this will be possible following the RTNET upgrade with requirements specified in AEMO's update to NEM data communications standard. – Dependency: Establish operational data exchange for participation in the distribution network discussed in this section [Monitoring and situational awareness]. • Implement a Wide Area Monitoring System (WAMS) enabling time-synchronised monitoring of dynamic behaviour across the power system. – AEMO currently implementing a project to ingest NSP PMU data into AEMO systems. Requires data concentration and storage provision, and application development. – Dependency: Relies on PMUs and associated communication links. See RTNET Upgrade project discussed below in this section [Monitoring and situational awareness].

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Dependency: Required as inputs to decision-making tools in the control room [Operational processes], automated generator compliance and dynamic model validation [Power system modelling].
Operational communication and data exchange fit for increasing volume of generation, storage and new forms of participation in the distribution network	• Establish operational data exchange requirements and communications architecture for scheduled and semi-scheduled plant and new forms of participation (such as aggregation) in the distribution network to be able to receive control commands from AEMO. – Through continued development of AEMO's NEM Power System Data Communication Standard to facilitate changes to the data communications architecture to allow for DNSP SCADA and newer forms of participation to directly connect to AEMO's EMS, and accommodate other communication protocols such as DNP3, and less cumbersome options compared to ICCP. – May also require uplift and development of some NSP and participant systems and communication links. – AEMO RTNET upgrade project [(Real-time network) operational system connecting NSP SCADA and PMUs to AEMO's EMS] is underway and will replace existing connections between AEMO's EMS and NSP SCADA systems in the NEM. The newer technology, and SDWAN design, will enable scalable integration of more service providers, and is a prerequisite for accommodating new connections to AEMO from other types of participants. – Implementation of DNP3 communication protocol capabilities for SCADA links to AEMO, and investigation of feasible options for bidirectional real-time data feeds to DER devices. • Establish operational visibility of non-scheduled generation in the distribution network and aggregator, retailer and DNSP actions that impact aggregate DER behaviour – including controlled load programs, dynamic operating envelopes and price-responsive behaviour. – Dependency: Discussed further in [Distribution].

A1.2.2 Operational processes

This table relates to Section 4.2.2 in the main report.

Table 22 Actions needed for operating at 100% instantaneous penetration of renewables – operational processes

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Ability to operationally forecast energy adequacy and quantify VRE variability and uncertainty over different timeframes	• Collaborate with DNSPs and participants to capture in AEMO's operational forecasting the impacts of distribution network and other constraints on the output of semi-scheduled plant, non-scheduled generation, and small-scale DER. – Impact of distribution network constraints are not currently visible to AEMO. – Dependency: Discussed further in [Distributed energy resources] and [Distribution]. • Redevelop AEMO operational forecasting infrastructure to enable the rapid development of tools and systems with increasing VRE and DER uptake. – Productionised data science environment, uplift in wind and solar forecast models, tools to quantify and visualise DPV variability. – *EF FY23 Action A15: Commence implementation of productionised data science environment to enable deployment of new machine learning models. Improve wind and solar dispatch forecasts by commencing uplift in AWEFS/ASEFS forecast models. Commence development of tools to quantify and visualise DPV variability.* • Extend AEMO operational forecasting capability to enable the assessment and scheduling of energy as well as capacity, required in the transition to a power system dominated by VRE and large amounts of non-scheduled plant.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Forecasting requirements will be very different, needing assessment of energy adequacy (GWh) over different timeframes, as well as the current focus on capacity (GW) adequacy at instances of time. • Shift from deterministic forecasts to probabilistic and consensus forecasting techniques to enable the quantification and management of uncertainty, variability and risk. – Probabilistic forecasting of plausible uncertainty in VRE and demand forecasts (ramp and variability), separate controllable/non-controllable components of demand forecast. – Implement shift to consensus forecasts utilising multiple independent forecasts and enable forecasting as a service (FaaS) with associated application interfaces and data storage. – Dependency: Requires weather monitoring data [Monitoring and situational awareness]. • Incorporate operational forecasting across a wider range of plausible uncertainty within operational look-ahead tools and automated studies. – Interfaces and dashboards for situational awareness. – Integration with automated study processes (DSA, EMS, VDS).
Ability to securely and reliably manage planned outages for maintenance and the augmentation required in the transition to 100% renewables	• Establish better defined processes for coordinated outage planning, limit advice and instructions across NSPs and AEMO, over time frames longer than 7 days. – Increasing need for coordination within and across regions, explicit limit advice and instructions on what is allowable during outage conditions. – More advanced planning and preparatory work required given range of complexities and considerations. – Operational protocols between AEMO and TNSPs may need to be reviewed. • AEMO to collaborate with TNSPs to assess possible procedural changes to enhance flexibility and adaptability in the outage management process as continuous outages may become harder to accommodate. – Shorter outage window may need to be considered, means to manage increasing likelihood of short notice cancellations or recall and shifting outages to night-time. – This would require contingency plans to be developed given they will involve the use of temporary protections, circuit breaker/bus bypasses, setting up temporary links to minimise duration and recall of outages. – Contingency plans should also incorporate plausible variability from planned cases and accurate representation of feasible recall times. • Develop enhanced tools and risk assessment approaches for AEMO and TNSP outage assessment studies. – New tools may be required for simulation across the complete outage period as spot checks for outage assessment may not be adequate. – High impact outages will need to be assessed and studied for various contingency scenarios. – Weather driven risk assessment criteria and forecasting will be required. • Develop structured mechanisms for ensuring adequate operational levers for managing system security during outage conditions. – Need for DPV control to allow and manage daytime outages and mitigate DPV disconnection risks. – Dependency: Emergency DPV curtailment is discussed further in [Distributed energy resources]. – Mechanisms to manage system services during outages, such as NSP contracting with generators or outage scenarios accommodated within NSCAS and System Strength requirements.
Dynamic security assessment and contingency analysis capability across	• Develop real-time EMT simulation capability for contingency analysis. – Dependency: Appropriate metrics for system strength and stability margin calculation.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
the range of stability phenomena – real-time and look-ahead	• Establish AEMO and NSP control room tools to utilise PMU data for real time stability assessment, monitoring and situational awareness. – Develop applications and enhanced dashboards and visualisation tools to support real-time decision making. – Dependency: Relies on PMU coverage and WAMS implementation [Monitoring and situational awareness]. • Establish look ahead Dynamic Security Assessment (DSA) capability across the range of system needs (including voltage, transient, small signal, frequency), accounting for risk and uncertainty over a variety of forward horizons. – Develop dashboards for monitoring, with enhanced visualisations and decision support tools, integrated within EMS, scheduling and dispatch processes. – Development of steady state constraints dashboard (PI, EMS). – Dependency: Requires generator and load dynamic response models [Power system modelling] – Dependency: Requires metrics and tools for stability assessment that can be applied using EMS data and in pre-dispatch timeframes [Power system modelling] – Dependency: Requires real-time EMT contingency analysis capability (discussed in this section [Operational processes]), operational forecasting over a wider range of scenarios (discussed in this section [Operational processes]). • Assess need for additional triggers for event reclassification to manage the impact of extreme weather on VRE and the potential for large, unforecast reduction in VRE output and other indistinct risks. – As part of the implementation of the Enhancing Operational Resilience Relation to Indistinct Events rule change., AEMO is consulting with industry on possible reclassification criteria to reflect the broadened definition of a contingency event framework to include indistinct events – such as earthquakes, space weather events, severe weather, wars, strikes and vandalism. – Reserve assessment [Operational processes] will need to cover the potential for plausible, unforecast changes in the supply-demand balance due to indistinct events. The consultation will also consider feasible operational levers available after an indistinct event is declared, which could include directions, constraints to manage inter or intra-regional power flows, or other changes to operational processes, prioritising options with the greatest net-benefit to the end consumer. – Dependency: reliance on widespread monitoring and fit-for purpose control room and support tools and processes to more accurately and precisely define and act upon indistinct events, lowering total cost to end consumers and maximising benefits [Monitoring and situational awareness].
Reserve assessment and management processes in place to balance VRE variability and uncertainty, and account for energy limitations	• Establish processes for short term capacity reserve assessment to help manage weather-driven variation within 30 minutes. – Managing unexpected, increasingly large and rapid changes in operational demand due to the impact of cloud cover on DPV generation occurring within 30 - 60 minute periods. This often cannot be predicted more than 30 minutes ahead, yet can be large relative to the largest supply contingency. – Following the ST PASA rule change there is now flexibility to shorten this period in the future if required. – Dependency: Requires more accurate modelling of supply-demand variability and uncertainty discussed in operational forecasting precondition above in this section [Operational processes]. – AEMC operating reserve rule change consultation considering a dispatchable raise reserve service procured ahead of time similar to contingency FCAS services in real-time and co-optimised with the other energy market services. Proposal is for reserves to procured 30 minutes ahead of time, with a 15-minute call time. Will require operator training and consideration in simulator test scenarios. – *EF FY23 Action A6: Technical advice to inform AEMC Operating Reserves rule change.* • Processes established for intra-day and longer-term (weeks to months ahead) reserve assessment, scheduling and management to take into account availability of stored energy and energy limited plant. – Will need to schedule and manage energy as well as capacity in order to quantify and manage uncertainty ahead of time.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Requires consideration of how energy limits need to be represented and modelled so participants can provide the relevant information in PASA timeframes and assessment tools can be built. – The first release of the ST PASA replacement project will be improving the modelling and scheduling of energy storage units, using currently available information such as state of charge and other modelling information. The longer-term goal is to improve this further by utilising further information from the participants, including self-forecasting. • Ensure greater flexibility in generator recall times for short-term resource adequacy assessment. – ST PASA rule change amends the definition of PASA availability to replace “specification of available capacity within 24 hours” with a requirement to specify the recall notice period for relevant plant. • Rate of change constraints on inter and intra-regional power transfers may need to be implemented to maintain flows within secure limits due to rapid price-driven changes in supply and demand. – Require ability manage rapidly varying VRE and storage so that network limits are not violated, significant run backs due to control scheme triggering, and tripping of large clusters of IBR due to protection operation of line protections. – Tie-line bias control may need to be considered if this is not possible. • Review adequacy of current semi-scheduled arrangements for periods when most generation online is semi-scheduled VRE. – Under these arrangements, semi-scheduled plant can rapidly increase generation up to the energy resource so long as there is no semi-scheduled cap enabled. – Rule changes may be necessary if this is assessed to not be manageable into the future, requiring semi-scheduled VRE to adhere to their dispatch targets at all times (i.e., operate as scheduled generation).
Significant uplift in industry training standards to ensure operator capability and sufficient training for new tools, procedures and processes	• AEMO control room and operational support staff require development and implementation of robust procedures and processes for the range of new operational tools and practices required in the transition to 100% renewables operation. • Training programs required for new procedures and processes, including delivery of plausible 100% renewables scenarios within AEMO’s Dispatch Training Simulator, to assist with understanding and managing power system behaviour in normal and abnormal conditions. • AEMO engagement with NSP’s and participants for operating staff training in power system operational challenges, new processes and tools required to meet their operational responsibilities and effectively coordinate across parties. • Progress options to implement benchmarking measures for participants through a standardised industry accredited training framework as proposed by AEMO’s Power System Training Framework.

A1.2.3 Power system modelling

This table relates to Section 4.2.3 in the main report.

Table 23 Actions needed for operating at 100% instantaneous penetration of renewables – power system modelling

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Models and data to establish confidence in the technical operating envelope of the power system under a range of plausible operating conditions	• Uplift AEMO processes and governance for managing power system data, models and tools. – Formalise internal accountabilities. – Establish appropriate corrective action feedback loops to identify and correct the root cause of quality issues earlier in the life cycle. – *EF FY23 priority Action A7: Uplift AEMO processes and governance for management of power system data, models, and tools, including uplift of model quality.* – Review scalability of AEMO power system data ingestion and information management processes with increasing volume of smaller new entrants. • AEMO and NSPs collaborate to establish and baseline power system data, model quality and model performance requirements. Develop and resource prioritised model uplift workplans. – Model issue resolution. – Provision of additional information to support enhancement to OPDMS. – Review model and data requirements. • Collaborate with industry and market bodies to ensure acceptable model provision, quality and performance. – Clarify participant roles and responsibilities. – Define acceptable model quality and performance requirements. – Regulatory reform to implement any necessary changes to access standards and model exchange requirements. – Suitable processes for identifying and addressing non-compliance. • Establish processes for OEM testing and validation of equipment performance for larger plausible disturbances to inform plant model development. – Require demonstration of type-testing in the connection process and suitable accountabilities for developers and OEMs. • Establish internal process to verify plant performance, including uplifting processes and tools for extracting data, necessary conversion and analysis, and for model validation using PMU data. – Dependency: Relies on PMU rollout [Monitoring and situational awareness].
Ability to scalably and accurately model a large number of scenarios in operational and planning timeframes	• Assess and implement a streamlined approach to grid model management to facilitate a step change improvement in the speed and accuracy of study case development. – Establish a ‘single source of truth’ high-fidelity master grid model for the current power system and representation of future grid developments to support planning, new connections and grid operations. – Utilise common data structures for exchanging data between applications and with NSPs and participants. • Develop processes and automated tools to enable fast and accurate application of any generator dispatch pattern or connection point demand forecast to study cases.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	• Assess high performance computing requirements for power system modelling, implement capability and establish efficient workflows across simulation tasks. • Develop a prioritised plan to address gaps in AEMO and NSP capability to effectively model the phenomena that will need to be studied in the transition to 100% renewables. – Assess volume of scenarios and kinds of issues that will need to be addressed. – Evaluate modelling methods and tools necessary to achieve this. – Focus on both remediating critical current issues (that could act as bottlenecks) and the development of new required methods and tools. • Develop and benchmark stability assessment methods and tools appropriate for assessing relevant power system phenomena in high IBR conditions. – Tools and metrics for screening assessment in planning timeframes. – Dependency: Required for future system studies discussed in this section [Power system modelling]. • Develop assessment tools that can be feasibly implemented using EMS data and available information in pre-dispatch time frames for real time and look-ahead stability assessment. – Dependency: Dynamic security assessment capability is discussed further in [Operational processes].

Future system studies to assess the secure technical envelope of the power system with reducing, and eventually no, synchronous fossil fuel generation online	• Perform targeted planning studies to assess system security issues across all power system phenomena with lower levels of synchronous fossil fuel generation.
	– Study impacts of synchronous fossil fuel generator exit on technical operating envelope including existing transfer limits.
	– Identify configurations impacted by reduction in synchronous fossil fuel generation (whether units online, or dispatched MW) to inform critical operational milestones on the way to 100% renewables.
	• Undertake a program of power system studies to assess power system security in the NEM at times of 100% renewable generation and assess future system requirements with fewer large synchronous generators.
	– *EF FY23 Action A2: Initiate a program of power system studies to assess power system security in the NEM at times of 100% renewable generation.*
	– Characterise plausible future100% renewable dispatch conditions, and intermediate hold points, develop study cases for analysis.
	  – Initial findings to be presented in 100% sensitivity run in AEMO's 2022 System Security Reports.
	  – Further studies to be conducted on other plausible scenarios.
	  – Investigation into use of generic modelling options to conduct dynamics studies to for future inertia needs and transient stability.
	– Screening studies for different stability phenomena to identify potential system security issues during times of 100% instantaneous renewable penetration requiring further investigation.
	– More detailed studies (where required) to better understand and confirm certain issues and identify feasible mitigation options.
	• Embed ongoing studies of potential future operational scenarios and events (critical outages, ramping events etc) into network planning process, through system security reports, connections studies, and ongoing joint planning activities.

Studies to develop limit advice and assess system adequacy to enable operational transition to first 100% periods	• TNSP studies to inform limit advice required for AEMO development of constraint sets and operational procedures. – Dependency: Requires TNSP limits advice [Transmission]. • Detailed assessment of system needs and required services to transition into and out of high renewable generation periods. – Key considerations include ramping adequacy, restart requirements for thermal plant, a regional transfers, FCAS requirements, EFCS adequacy • Collaboration with NSPs to assess key high-impact, low-probability non-credible risks and establish mitigation measures.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Assess and establish contingency plans for HILP non-credible risks and issues difficult to identify in studies. • Processes to monitor risk exposure, with 'roll back' measures in place if risk exceeds operational risk tolerance. – Requires monitoring and look-ahead 'what-if' risk assessment tools. • Assess and validate of constraints with real-time stability assessment tools, and system events as they occur, as hold points are relaxed. – Dependency: requires appropriate DSA tools across relevant stability phenomena [Operational processes].

A1.3 Resource adequacy and capability

A1.3.1 Utility-scale VRE

This table relates to Section 4.3.1 in the main report.

Table 24 Actions needed for operating at 100% instantaneous penetration of renewables – utility-scale variable renewable energy (VRE)

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Connect and securely integrate increasing volumes of VRE	• Development, construction, and connection of increasing volumes of new VRE generation. • Develop whitelist register for OEM products such as inverters, generators, synchronous condensers, Battery Energy Storage Systems (BESS), and power plant controllers. – *EF FY23 Action A16: Collaborate with stakeholders through the Connections Reform Initiative to determine suitable implementation plan.* – Refer to Connections Reform Initiative (CRI) workstream OEM Data and Modelling – To explore opportunities to improve the information fidelity and quality of data and models provided by Original Equipment Manufacturers (OEMs) including consideration of OEM whitelisting. – Dependency: Participant model provision to AEMO and NSPs, model quality and performance – discussed further in [Power system modelling]. • Develop mechanisms to efficiently leverage ability to adjust and tune generator and network asset controls in real time or over life of connection. – *EF FY23 Action A34: Investigate feasibility of leveraging ability to adjust and tune generator controls in real time or over life of connection.* – Refer to Connections Reform Initiative (CRI) workstream Investment Certainty – to introduce a suite of complementary reforms that create a more stable investment environment with reduced risk of changes or delays between project commitment and revenue. Includes an ongoing ability (i.e., after R1) for NSPs and AEMO to modify plant to meet system planning objectives. This stream is led by the Clean Energy Council (CEC). • Power system modellingSimplify connection and registration processes for hybrid generation facilities. – *EF FY23 Action A35: Explore options to simplify connection and registration processes for hybrid generation facilities.* – Refer to Connections Reform Initiative (CRI) workstream Introducing BESS Behind Existing Generation – To explore the opportunity to 'cordon off' existing plant from reopening a GPS when adding a battery to an existing generation system. • Develop clear guidance on use of EMT and RMS analysis in generator performance study assessments. – *EF FY23 Action A46: Develop clear guidance on use of electromagnetic transient (EMT) and root mean square (RMS) analysis in performance study assessments.* – Refer to Connections Reform Initiative (CRI) workstream Guidance on use of RMS and EMT Tools - To provide clearer guidance on when to assess plant performance using EMT vs. RMS tools (i.e. PSCAD vs PSSE) to avoid unnecessary work and accelerate connections process. – Dependency: Participant model provision to AEMO and NSPs, model quality and performance – discussed further in [Power system modelling].
Confidence in VRE plant performance during plausible disturbances and operating conditions	• Review performance standards for new VRE plant to identify streamlining opportunities to suit the volume of connections expected, while ensuring that the future power system can be operated securely and is sufficiently resilient to extreme condition. – AEMO has commenced a review of technical requirements for connection (NER Schedules 5.2, 5.3 and 5.3a).

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	• Collaborate with the AER, NSPs and participants to establish more scalable and effective processes for compliance monitoring and enforcement of generator performance standards. – Automated platform to replace current manual process. – Appropriate access rights and tracking. • Uplift of plant operators' ability to meet operational performance requirements, especially for cases where plant was designed, installed and commissioned by other parties.

A1.3.2 Distributed energy resources

This table relates to Section 4.3.2 in the main report.

Table 25 Actions needed for operating at 100% instantaneous penetration of renewables – DER

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Clearly defined operational roles and processes for managing system security and coordination across parties at times of high DER penetration	• Establish roles and responsibilities between AEMO, DNSPs, TNSPs and participants for managing bulk power system security in a high DER future, and associated planning and operational processes. – Key priorities initially for managing extreme abnormal system conditions with increasing DPV uptake – starting with under-frequency load shedding, last resort DPV curtailment, and system restart. – Dependency: Will require operational procedures to be developed and implemented across parties, including defined operational interfaces between bulk power system and distribution network operation, discussed further in [Distribution]. – *EF FY23 Action A12: Identify and progress regulatory reforms to clearly define AEMO, NSP, and participant responsibilities for system security in a high DER, low synchronous generation power system – starting with under-frequency load shedding (UFLS), last resort curtailment, system restart.* • Establish clear roles and responsibilities across the energy sector for remote interactions with DER devices. – *EF FY23 Action A44: Collaborate with industry to consider use cases for different parties remotely interacting with DER devices. Progress policy development on governance, roles and responsibilities, and compliance.* • Establish coordination architecture and processes for secure and reliable AEMO-NSP-participant interactions required with increasing DER and flexible load management and aggregation. – Foundational operational data exchange processes and standards for a highly decentralised power system and operational coordination architecture for AEMO-NSP-aggregator interactions. – *EF FY23 Action A26: Collaborate with stakeholders to review operational data exchange needs for AEMO, DNSPs, and industry to support increasing DER uptake and new forms decentralised participation.* – Dependency: Will require processes for distribution network limits being reflected in aggregated participation, and visibility and predictability of these limits at the system level, discussed further in discussed further [Distribution].
Basic level of controllability for a sufficient proportion of the DPV fleet	• Ongoing AEMO assessment of minimum load and DPV contingency thresholds for system security.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Minimum supportable load thresholds driven by need to maintain synchronous generating units online for essential system services for stability (system strength, FCAS, inertia, and voltage control). – Maximum DPV generation thresholds driven by impact of DPV contingency disconnection on stability limits and (possibly in the future) aggregate DPV ramping. • Establish effective emergency DPV shedding schemes, operational roles and procedures in each NEM region, before minimum system load challenges emerge. – *EF FY23 Action A11: Advocate for and progress introduction of emergency backstop DPV curtailment mechanisms in all NEM mainland regions. Specify technical requirements and operational coordination processes. Advocate for consistency in regional approaches, where possible.*
DER behaviour during disturbances quantified and managed	• AEMO and TNSP review of interconnector and intra-regional limits and FCAS requirements to account for the impact of DPV disconnection during disturbances (and associated constraint equations updated) including assessment of any new limits that could arise. – Requires transient stability studies for a range of different demand and DER conditions (and outage scenarios) with appropriate DER representation. – AEMO ongoing work to develop models that better represent DER and load dynamic behaviour during disturbances, and collaboration with TNSPs to enable and support their use. • Short term measures to improve installation compliance of new DPV inverters to AS4777.2:2020 reducing potential DPV disconnection during disturbances (including amendment of the standard). – Anticipate at least 95% compliance is required. – *EF FY 23 Action A10: Collaborate with industry on identified non-compliance risks for small-scale inverters' performance during disturbances. Collaborate with market bodies on enduring frameworks, roles and responsibilities for DER installation and performance compliance.* – Ongoing review and refinement of performance standards for small-scale DER installations necessary to improve compliance in the implementation of the new AS4777.2:2020. • Establish strong governance frameworks for assessing and enforcing ongoing compliance of DER inverters to meet performance requirements. – AEMC Review into Customer Energy Resources Technical Standards is considering compliance with, and enforcement of, consumer DER technical standards in the NER, the interpretation of standards by NEM participants and other relevant stakeholders and interactions between the NER and other regulatory regimes. The initial focus will be on experiences of implementing existing NER obligations relating to AS 4777.2:2020. – *EF FY 23 Action A10: Collaborate with industry on identified non-compliance risks for small-scale inverters' performance during disturbances. Collaborate with market bodies on enduring frameworks, roles and responsibilities for DER installation and performance compliance.* • Establish suitable monitoring data access frameworks and tools for sufficient aggregate visibility of DER behaviour during disturbances and for compliance assessment. – Project MATCH, an ARENA funded UNSW collaboration with AEMO and Solar Analytics is currently developing tools to better investigate DER behaviour during disturbances and their compliance to Australian Standards. • AEMO to collaborate with DNSPs to establish effective and consistent disturbance withstand performance standards for <5 MW connections in the distribution network. – *EF FY23 Action A21: Collaborate with distribution network service providers (DNSPs) to understand current status of performance standards for <5 MW connections, and identify any uplift required.* – Dependency: Define performance standards for EVs and different charging arrangements for disturbance withstand, grid support and network connection requirements [Structural demand shifts].

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Sufficient visibility and predictability of DER behaviour	• Establish DER device and distribution low voltage (LV) network monitoring and data access framework. – Dependency: Required for distribution network planning (see [Distribution]), AEMO operational forecasting (see [Operational processes]), and future system studies (see [Power system modelling]) – Collaborate with UNSW on Project MATCH to engage with OEMs and data providers to grow pool of data available for analysis, model validation and forecasting. – Collaborate with DNSPs on requirements for monitoring data needs for a high DER future. Contribute to ESB Data Strategy. – AEMC's metering review provides recommendations and options to accelerate smart meters in the NEM, to provide greater visibility of the LV network. – ESB's Data Strategy is seeking to enhance network visibility for market planning. – *EF FY23 Action A41: Continue to engage with OEMs and data providers to grow pool of data available for analysis, model validation and forecasting. Collaborate with DNSPs on requirements for monitoring data needs for a high DER future. Contribute to ESB Data Strategy.* – *EF FY23 Action A42: Develop implementation options for a register of EVSE standing data, including data collection and storage processes.* • AEMO collaborating with DNSPs to enhance confidence in DER register data, including robust data entry, validation and compliance arrangements. – *EF FY23 Action A38: Highlight known data quality and completeness issues with DER register data by validating against alternate data sources. Advocate for more robust validation processes at the data collection stage for new DER installations. Advocate for stronger compliance arrangements for data entry.* • AEMO developing accurate models of DER and load behaviour under different conditions for steady state and dynamic power system studies. – AEMO to collaborate with NSPs to agree on the appropriate locational representation and level of aggregation for DER in system studies.
Enabling consumer participation and provision of demand side flexibility	• Align DER incentives with network and system needs. – Pricing and other incentives such as feed-in tariffs and subsidies for DER installations need consideration and alignment with technical system needs. • Develop technical specifications for energy and FCAS provision from aggregated DER, and associated device performance and aggregation-level requirements for price responsive DER. – *EF FY23 Action A22: Consider the requirements for energy and FCAS provision from aggregated DER within the delivery of reform initiatives.* • Establish minimum DER device requirements for interoperability (including electric vehicles [EVs]). – Collaboration between DNSPs, service providers and aggregators to establish interoperability requirements within AS4777, including alignment with CSIP-AU. – *EF FY23 Action A36: Collaborate with industry on minimum device capability for coordination and aggregation, and power system operational use cases in a high DER future.* • Define performance standards for DER cybersecurity and interoperability. – Establish minimum device-level requirements for cyber security for DER, Internet of Things (IoT) and other internet-enabled devices. – Establish methods to use interoperability to determine device performance, compliance and firmware capabilities. – *EF FY23 Action A28: Advocate for and collaborate with industry on foundational device capabilities, configuration, and networking practices for internet-connected DER devices.* – Establish failsafe behaviour requirements of DER for secure and reliable power system operation. – *EF FY23 Action A29: Assess with industry, effective DER device configuration and behaviours under loss of communication and other contingency scenarios in a high DER future.*

A1.3.3 Structural demand shifts

This table relates to Section 4.3.3 in the main report.

Table 26 Actions needed for operating at 100% instantaneous penetration of renewables – structural demand shifts

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Fit for purpose performance requirements and connection processes for new loads, confidence in their operation during all operating conditions	• Define performance standards for EVs and their different charging configurations, to provide disturbance withstand, grid support and network connection requirements. – *EF FY23 Action A37: Collaborate with industry on disturbance withstand, grid support and grid connection requirements for EV and EV supply equipment (EVSE). Inform EV grid integration efforts.* • Establish appropriate performance requirements for new loads, implemented through NSP connection processes. – *EF FY23 Action A39: Establish a working group to determine and scope any necessary regulatory changes to support appropriate performance. requirements for new loads. AEMO's 2022/23 review of technical requirements for connection (NER clause 5.2.6A) is seeking to consider whether anticipated load developments warrant changes to technical standards for loads*. • Establish appropriate and efficient connection frameworks for new large loads to connect, considering potential adverse interactions with other IBR plant or impacts on power system stability, plus impacts to local system strength requirements.
Planning for energy adequacy and flexibility requirements to consider possible structural demand shifts	• Understand changing demand and daily and seasonal profiles of new loads (and correlated loads) and assess their impacts on resource adequacy and system flexibility. – Increased demand from continued electrification (e.g. heating, transportation). • Improve visibility of evolving load categories and their associated behaviours, for use in both long-term and short-term forecasting. • Scenario planning to assess impacts on network resulting from events such as sudden load reductions, load closures, or consumer grid defection. – Scenario planning for sudden exit or withdrawal of plant. • Coordination and stakeholder engagement to plan for new large loads and electrification, to ensure that energy adequacy and flexibility requirements can be met. • Investigate capability and willingness for loads to assist in meeting power system requirements, such as 'soak up' of excess VRE and DPV generation.

A1.3.4 Transmission

This table relates to Section 4.3.4 in the main report.

Table 27 Actions needed for operating at 100% instantaneous penetration of renewables – transmission

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Sufficient new transmission built to enable renewable development, sharing between regions and support system security	• Urgently progress delivery of new transmission infrastructure as outlined in ISP Step Change Scenario. – Jurisdictional mechanisms (such as the NSW Transmission Acceleration Fund, the Victorian Renewable Energy Development Plan and the Commonwealth Government's Rewiring the Nation policy) can support the delivery of these projects.
TNSP planning and investment is coordinated and efficiently enables secure and reliable system operation with progressively reduced numbers of synchronous generators online	• Pre-emptive planning for earlier than expected changes in coal plant operation or large load closures. – Where possible, consider early closure scenarios in AEMO's system security reports and through joint planning with TNSPs. – Consider specific scenarios for ensuring re-secure of the power system where relevant for critical outages on the power system. • Coordinated planning for system requirements for anticipated key operational milestones with the progressive reduction in synchronous fossil fuelled generation online in each region, in the transition to 100% renewables operation. – Identification and ongoing refinement of key operational milestones in each region.
Resilient transmission network design and system performance outcomes	• Undertake General Power System Risk Review annually to review a prioritised set of risks, events, and conditions that could lead to cascading outages or major supply disruptions. Review the adequacy of current approaches to managing these risks and options for their future management. – In the 2023 GPSRR AEMO plans to assess the following high impact low probability non – credible contingency events: ▪ Loss of line 62: 330 kV Wagga – Jindera and line 63: 330 kV Wagga – Darlington Point. ▪ Tamworth double 330 kV busbar trip (Sections 1 and 3) due to circuit breaker (CB) failure of bus coupler CB 5102. ▪ Non-credible loss of Bayswater – Mount Piper (5A3) and Mount Piper – Wollar (5A5) 500 kV lines. • REZ design process to consider increasing contingency size associated with increasing power transfers from VRE centres. • Collaborate with NSPs to review interactions between various NSP control schemes to ensure they remain fit for purpose as the power system topology, resource mix and operational conditions evolve. • Establish performance criteria for synchronous condensers, grid forming IBRs and other stabilising plant, not currently subject to NER Schedule 5.2 requirements. – Access standard review is considering changes to technical standards based on plant type rather than registration category. – *EF FY23 Action A23: Promote the addition of synchronous condenser capability in new and existing synchronous generator investment and retirement decisions.* • AEMO and TNSPs to consider through joint planning how a coordinated approach on network planning for resilience could be achieved. – Include consideration of how outages are considered in planning frameworks, AEMO definitions, processes and potentially rule change proposals. – Consider specific 'N-1-1 scenarios' for planning to better accommodate increased outages from major transmission projects being installed, and risks from aging thermal generators.

A1.3.5 Distribution

This table relates to Section 4.3.5 in the main report.

Table 28 Actions needed for operating at 100% instantaneous penetration of renewables – distribution

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
DNSPs able to determine and securely manage their technical operating envelope, connecting and integrating DER and VRE within their networks	• DNSP access to smart meter and DER monitoring data required for situational awareness, development of DER and LV network models and DER hosting capacity assessment. – Being considered in AEMC Metering Review and ESB Data Strategy. – EF FY23 Action A41: Continue to engage with OEMs and data providers to grow pool of data available for analysis, model validation and forecasting. Collaborate with DNSPs on requirements for monitoring data needs for a high DER future. Contribute to ESB Data Strategy. • Ongoing assessment of distribution network operating envelope with continued DER uptake and increasingly complex network operation. – Uplift in DNSP modelling tools and data, to facilitate hosting capacity assessment and state estimation, to ensure secure operating environments can be maintained with increasing DER uptake. – Several DNSPs have programs underway to improve visibility of their LV assets, including dedicated network monitoring, access to smart meter data (currently being considered in the AEMC's regulatory framework for metering services), and third-party monitoring data. – Dependency: Requires visibility and predictability [Distributed energy resources]. • Efficiently plan and manage network hosting capacity, both network and behind-the-meter strategies, to connect and integrate DER and VRE and enable consumer choice. – DNSPs to implement dynamic operating envelopes to enable increased hosting capacity for DER. • Connect and integrate larger embedded DER systems, and utility-scale renewable and storage capacity in MV and sub-transmission networks. – Implementing operational systems and communications upgrades necessary for utility-scale plant in the distribution network to be integrated with AEMO's EMS and receive control commands for dispatch and scheduling. – Improve connections process for sub-30MW generator connections to ensure requirements align with system needs and ensure specifications are commensurate with their size. – *EF FY23 Action A25: Assess functional requirements for communication architecture in the future power system. Explore options to efficiently, securely, and scalably meet functional requirements.* • Establish an agreed approach for representation of DER in network topology representations, adopted and utilised by NSPs, AEMO, aggregators and other coordinating parties. – *EF FY23 Action A33: Advocate for need, and collaborate with NSPs and service providers on approach.*
Effective planning and coordination at the transmission-distribution interface	• Establish with DNSPs distribution network and DER modelling and analysis requirements for planning coordination with TNSPs and AEMO to assess system needs at the transmission-distribution interface and at system level. – Establish modelling expectations for how distribution network and DER will be aggregated and represented for transmission and system-level studies. Dependency with consistent nodal representation of DER within the distribution network, discussed in [Distributed energy resources]. – Clarity on roles and responsibilities for Volt-VAr management at the transmission-distribution interface to allow for tractable modelling and representation, and operational coordination.

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
	– Ongoing assessment of protection adequacy with reducing fault levels and impact of reducing negative sequence current injection on protection schemes. • Collaboration between AEMO and DNSPs towards establishing integrated planning processes for managing and enabling DER uptake. – Dependency: Managing system security challenges associated with increasing DPV uptake, and appropriate mitigation measures. Refer to [Distributed energy resources]. – Account for distribution network hosting capacity and identify potential flexibility opportunities in the distribution network within system-level planning. – *EF FY 23 Action A11: Advocate for and progress introduction of emergency backstop DPV curtailment mechanisms in all NEM mainland regions. Specify technical requirements and operational coordination processes. Advocate for consistency in regional approaches, where possible.* • Assess impact of increasing DPV and DER on existing feeder protection schemes.
Clearly defined operational responsibilities at the boundary between distribution network and bulk power system operation	• Define operational boundaries and interface requirements between distribution network and bulk power system operation, for managing power system security and operational coordination in a high DER future. – Distribution network roles and responsibilities for system security to provide pathways for DNSPs to plan for and establish necessary operational capabilities and management systems. – Processes for DNSPs to scalably determine and keep up to date distribution network limits for aggregated DER participation and communicate these limits to aggregators so they are reflected in bids. – *EF FY23 Action A40: Assess functional requirements for setting, communicating, and managing network limits with increasing levels of aggregated participation. Consider roles and responsibilities of actors.* – Establish an agreed approach for representation of DER in network topology representations, adopted and utilised by NSPs, AEMO, aggregators and other coordinating parties. – *EF FY23 Action A33: Advocate for need and collaborate with NSPs and service providers on approach.* • Establish operational coordination and data exchange requirements between AEMO and DNSPs for situational awareness, and operational visibility and forecasting DER and other resources in the distribution network. – Data exchange and functional requirements for accounting for impact of DNSP dynamic operating envelopes within system-level DER forecasting. – *EF FY23 Action A32: Inform development of system integration, data exchange and functional requirements for dynamic operating envelopes.* – Awareness of DNSP controlled-load program capability and activation. – Impact of distribution network constraints on non-scheduled and semi-scheduled plant, and flexible export arrangements on DPV generation forecasts. – Operational visibility of larger non-scheduled DER (200kW to 5 MW) within the distribution network. – *EF FY23 Action A31: Explore and assess feasible visibility options and AEMO-DNSP system integration actions.*

A1.3.6 Firming

This table relates to Section 4.3.6 in the main report.

Table 29 Actions needed for operating at 100% instantaneous penetration of renewables – firming

Preconditions for first 100% periods	Action needed for operating at 100% instantaneous penetration of renewables
Sufficient flexible capacity available to cover intra-day VRE and DPV variability and uncertainty	• Build dispatchable capacity and firming to meet intraday and longer duration energy requirements. – ESB capacity mechanism consultation considering measures to explicitly value dispatchable capacity, alongside the energy market, to incentivise investment in flexibility required to firm renewables over different timescales. • Assess energy adequacy requirements for extended low VRE generation periods. – Will require scenario-based simulations and account for the requirement meet other power system security requirements such as voltage control, stability, system strength. – AEMO to consult on the addition of extended low wind and solar generation across NEM regions in Energy Adequacy Assessment Projection (EAAP) guideline consultation in early 2023. • Establish appropriate resource adequacy assessment metrics to better reflect reliability risk in the transition from a primarily capacity-limited thermal power system to a more energy-limited, high renewable power system. – Reliability Panel to review the form of the Reliability Standard in 2023 to include a tail risk metric in combination with the current expected unserved energy metric. • Measures to ensure a sufficient proportion of generation and load included in scheduled dispatch mechanisms to provide adequate operational flexibility and automated system dispatch. – Dependency: Develop processes to assess intraday ramping requirements and uncertainty from 5 min up to hours ahead to account for increasing DER and VRE. See [Operational processes].

A2. List of tables and figures

Tables

Figures

A3. Abbreviations

Abbreviation	Term in full	Abbreviation	Term in full
AC	Alternating Current	**ISP**	Integrated System Plan
AEMC	Australian Energy Market Commission	**JPC**	Joint Planning Committee
AEMO	Australian Energy Market Operator	**kV**	Kilovolt
AER	Australian Energy Regulator	**LV**	Low Voltage
AGC	Automatic Generation Control	**MASS**	Market Ancillary Services Specification
ARENA	Australian Renewable Energy Agency	**MV**	Medium Voltage
ASEFS	Australian Solar Energy Forecasting System	**MVAr**	Megavolt-amperes reactive
AWEFS	Australian Wind Energy Forecasting System	**MW**	Megawatt
BESS	Battery Energy Storage System	**NEM**	National Electricity Market
CB	Circuit Breaker	**NER**	National Electricity Rules
CER	Consumer Energy Resources	**NSCAS**	Network Support and Control Ancillary Services
DC	Direct Current	**NSP**	Network Service Provider
DER	Distributed Energy Resources	**OEM**	Original Equipment Manufacturer
DNSP	Distribution Network Service Provider	**OFGS**	Over Frequency Generation Shedding
DPV	Distributed photovoltaics	**OTR**	Operations Technology Roadmap
DSA	Dynamic Security Assessment	**PASA**	Projected Assessment of System Adequacy
EF	Engineering Framework	**PFR**	Primary Frequency Response
EFCS	Emergency Frequency Control Scheme	**PMU**	Phasor Measurement Unit
EJPC	Executive Joint Planning Committee	**PSFRR**	Power System Frequency Risk Review
EMMS	Electricity Market Management System	**PV**	Photovoltaics
EMS	Energy Management System	**PVNSG**	Photovoltaic Non-scheduled Generation
EMT	Electromagnetic Transient	**REZ**	Renewable Energy Zone
ESB	Energy Security Board	**RMS**	Root Mean Square
EV	Electric vehicle	**RoCoF**	Rate of Change of Frequency
EVSE	Electric Vehicle Supply Equipment	**RSS**	Restoration Support Services
FCAS	Frequency Control Ancillary Services	**SCADA**	Supervisory Control and Data Acquisition
FCESS	Frequency Co-Optimised Essential System Services	**SRAS**	System Restart Ancillary Services
FOS	Frequency Operating Standard	**STPASA**	Short Term Projected Assessment of System Adequacy
FSA	Frequency Stability Assessment	**SWIS**	South West Interconnected System
FY	Financial Year	**TNSP**	Transmission Network Service Provider
GPS	Generator Performance Standards	**TSA**	Transient Security Assessment
GPSRR	General Power System Risk Review	**TWh**	Terawatt hours
GW	Gigawatt	**UFLS**	Under Frequency Load Shedding
GWh	Gigawatt hour	**VDS**	VAr Dispatch Scheduler
HILP	High Impact Low Probability	**VRE**	Variable Renewable Energy
HV	High Voltage	**VSA**	Voltage Security Assessment
IBR	Inverter-based Resources	**WAMS**	Wide Area Monitoring Systems
IEEE	Institute of Electrical and Electronics Engineers	**WEM**	Wholesale Electricity Market