Energy Catalyst

Topic 7 – Power System Architecture

2024/25 Interim Report

Commonwealth Scientific and Industrial Research Organisation

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Contents

1. Introduction

G-PST Stages 1 – 3 of Topic 7 were undertaken in a context where Power Systems Architecture (PSA) and Model-Based Systems Engineering (MBSE) were still considered relatively new and somewhat abstract concepts. While extensive stakeholder engagement provided opportunities to expand awareness of both PSA and MBSE and forge the beginnings of a 'community of practice', as applied research projects considered a few steps removed from immediate implementation meant that the stakes were significantly lower.

With the support of CSIRO and AEMO, Stages 1 – 3 were advanced in the recognition that as ultra-complex systems, modern power systems such as the NEM and WEM are experiencing an unparalleled level of transformation. The working hypothesis has been that navigating such a level of complex transformation would benefit from the application of formal Systems Engineering-based methodologies employed by other complex sectors (including Aerospace, Defence, ICT, Mining, Rail, etc.) to:

- **Tame complexity:** provide established tools that enable the decomposition and 'taming' of the underpinning structural complexity inherent to transforming GW-scale power systems;
- **Enhance engagement:** empower more informed, multi-stakeholder participation by making critical content explicit and tractable which would otherwise remain opaque and intractable; and,
- **Improve outcomes:** increase decision quality, timeliness and traceability to increase the potential for full benefits-realisation and avoiding the propagation of unintended consequences.

During the last 3 – 4 years, the pace and complexity of Australia's grid transformation has continued to escalate to the point where the value of PSA and MBSE are not only recognised, but their application to real-time issues is now being actively advocated for by system operator, regulatory and distribution business staff alike.

While there are several explanations for this, perhaps the most plausible is that Australia's power sector, consisting of the multiple segments or siloes of the end-to-end supply chain, is now hitting what may be called a 'complexity wall'. In other words, while the more traditional 'issue-in-isolation' approach to problem solving continues to be applied, the structural and boundary-spanning nature of many issues requiring scalable, long-term solutions have made limits of many conventional tools and approaches to change more tangible.

For example, this evolving context has highlighted the practical relevance of the PSA and MBSE tools and methodologies to an expanding number of parallel initiatives, including:

1. **DCCEEW National Consumer Energy Resources Roadmap**[1]
2. **AEMO CER/DER Functional Requirements Co-design**
3. **AEMC Distribution System Operator (DSO) and Distribution Markets initiatives**
4. **DCCEEW National Electricity Market Review**
5. **ARENA/AEMO CER/DER Data Exchange Co-design**

Unsurprisingly, this significantly more dynamic context has created both opportunities and challenges. On one hand, the heightened interest has demonstrated the value of Australia's commitment to leveraging global best practice through the G-PST initiative. On the other hand, this has involved the G-PST Topic 7 team in providing key entities with an extensive range of briefings and engagements, supported by significant customised, actionable information (examples of which are provided herein).

[1] https://www.energy.gov.au/energy-and-climate-change-ministerial-council/working-groups/consumer-energy-resources-working-group/national-cer-roadmap

Scope Variation

The original Stage 4, Topic 7 scope was focused on moving from the earlier Reference Architecture in Stage 2 to the collaborative development of a longer-term Detailed Architecture in Stage 4.

Given the above range of initiatives underway, in early 2025 AEMO advised their preference to focus their staff and external collaboration efforts on resolving the full set of CER/DER Functional Requirements x 8 for both the Immediate-term and Medium-term horizons (i.e. 2025/26 and <2030 respectively).

AEMO further advised their preference for the parallel CSIRO-funded work to continue establishing the architectural foundation for addressing the CER/DER Functional Requirements x 8 for the Longer-term (2035+) horizon. AEMO recognises this needs to be advanced in parallel as the development of future-scalable solutions involves significant additional breadth and complexity, including interrogation of the structural changes required for the NEM to be made capable of supporting plausible futures such as the ISP 2050 Step Change scenario.

Accordingly, to avoid distracting AEMO staff and collaborating DNSPs from the priority of addressing the near-term CER/DER Functional Requirements, the Stage 4, Topic 7 work program has been adapted as follows:

- Defer the later phases of Detailed Architecture development, potentially to G-PST Stage 5 (i.e. Phases 3 & 4 of the original scope).
- Significantly expand the foundational elements of the G-PST Stage 4 scope (i.e. Phase 2) into five distinct research report due to their direct practical relevance to:
    - Underpin AEMO's next priority for the CER/DER Functional Requirements work (i.e. 2035+); and,
    - Provide an integrated set of reference materials relevant both to AEMO and all the Commonwealth initiatives currently underway.
- The full set of five research reports together with an integrative Executive Summary will be delivered as a single report in the final Phase 5 of G-PST Stage 4.
- The foundational elements of G-PST Stage 4 were originally planned as summary desktop scans (i.e. Reports 2A – 2C). Under the scope variation, the project will now deliver the following integrated set of five research reports and MBSE prototyping:
    - Report 1: Future Customer & Societal Objectives
    - Report 2: Emerging Trends Driving Transformation
    - Report 3: Systemic Issues & Transformation Risks
    - Report 4: Distribution System Operator (DSO) Models
    - Report 5: Transmission-Distribution Coordination (TDC)
    - MBSE-based prototype modelling of key DSO and TDC interactions.

  As noted in Figure 1 below, the target audience for this integrated set of content has been expanded to include AEMO and all the current Commonwealth processes. Given that DSO and TDC are key topics in the wider set of Commonwealth processes, the substantial expansion of the relevant reports has provided a high-impact opportunity to co-design their content with the AEMO and DNSP staff participating in them.

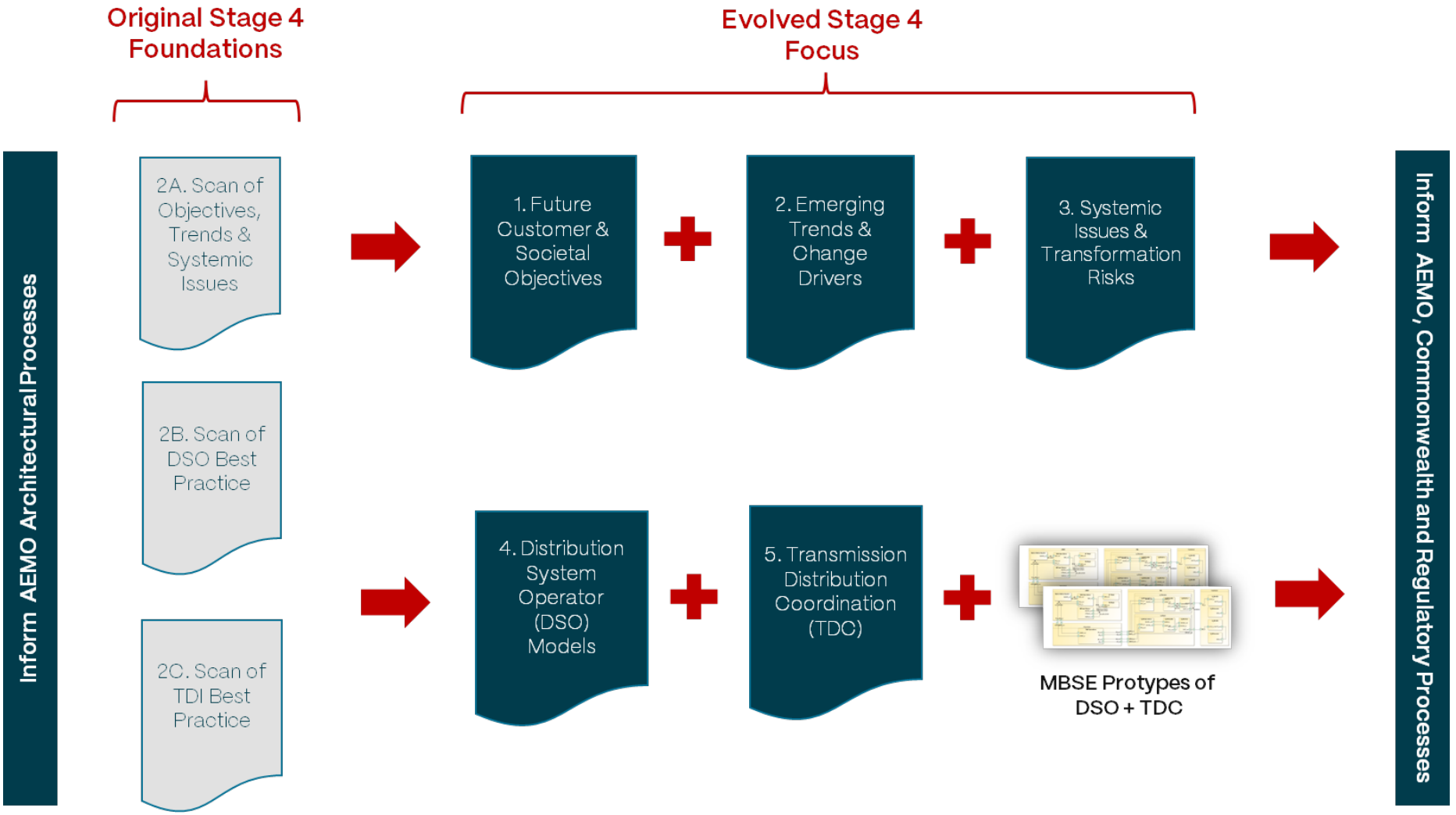

Figure 1 – A high-level illustration of how foundational elements of the original Stage 4 scope have been adapted to underpin immediate priority focus areas for both AEMO and the various Commonwealth government led initiatives.

2. Research completed

Recognising the significantly more engaged and dynamic context described above, the following sections of this report have been expanded to outline the number and intensity of briefings and engagements with key decision-making entities, supported by the provision of significant customised information.

#	Activity	Status	Update, results, and insights
PHASE 1: Project Alignment & Stakeholder Engagement (Jun 2024 – Dec 2024)			
1.1	Establish project Steering Group consisting of representatives of CSIRO, AEMO and GHD	Ongoing	Membership established, inaugural meeting completed and a weekly schedule of meetings established and ongoing.
1.2	DCCEEW National CER Roadmap team	Complete	A significant number of meetings were undertaken with DCCEEW representatives and other responsible parties within the National CER Roadmap program of work. An integrated 40-page set of advice was developed for DCCEEW by the Topic 7 team in consultation with CSIRO and RACE for 2030. The content was well received and significant portions of which were integrated into the National CER Roadmap document by DCCEEW.
1.3	AEMO CER/DER Functional Requirements team.	Ongoing	Weekly alignment meetings with AEMO's CER/DER Functional Requirements (FR) initiative were established early in Stage 4. While this was originally for information exchange and alignment, the practical relevance of the PSA and MBSE tools became increasingly apparent, supported by the advocacy of several DNSP staff involved in the FR initiative. Following trial application of the PSA/MBSE tools to the EDPV-C use case, the collaboration appears to be evolving toward a larger, multi-institutional program of work facilitated by Energy Catalyst and potentially integrated with the G-PST program of work for the direct, practical application of PSA and MBSE tools to the transformation of the NEM. Representatives from DNSPs who both assisted with instantiating structural arrangements for EDPV-C and attended subsequent workshops were particularly supportive of the co-design process undertaken.

1.4	AEMC Distribution System Operator (DSO) and Distribution Markets initiatives	Ongoing	The AEMC was assigned as the responsible entity for advancing the DSO and distribution-level market work packages under the National CER Roadmap program. Given both the critically important nature of these topics and the relevance of the Topic 7 body of knowledge, a series of in person and online briefings of the AEMC team have been provided, for example: 241022 Energy Catalyst - Structural Context of DSO.pdf. Additional PSA informed advice was also provided on the practical topic of assigning DSO roles and responsibilities which requires structurally-informed insight to avoid the limitations of largely qualitative approaches: Energy Catalyst - Definition and Assignment of Roles & Responsibilities.pdf
1.5	AER Policy-led CER/DER Sandbox Initiative	Complete	In late 2024, the AER Chair Clare Savage initiated a series of by-invitation working sessions to explore CER/DER Policy-led CER/DER Sandbox options. Beyond the largely issue-in-isolation approach to sandbox projects to date, the G-PST body of knowledge was represented by the Topic 7 team. This enabled unique contributions that highlighted the need for structurally-informed, whole-system approaches to CER/DER integration.
1.6	Determine best approach with Subject Matter Expert reference groups and engage as needed in a manner that is aligned with AEMO CER/DER Functional Requirements work.	Complete	As noted above, broad engagement has been undertaken with DNSPs, AEMC, AER and AEMO, and through international networks. Given the volume of engagement that has significantly expanded with the above processes, the Topic 7 team has generally worked to leverage these initiatives rather than risk further duplication of effort and stakeholder overwhelm.

#	Original Scope	Expanded Variation Scope
PHASE 2: Expanded core research development (Nov 2024 – Apr 2025)		
2.1	**Description:** Rapid review and update key input materials developed in G-PST Stage 2: ○ Customer & Societal Objectives for future power systems; ○ Emerging Trends driving change in GW-scale power systems; and, ○ Systemic Issues that require targeted structural interventions to resolve non-scalable features. **Deliverable:** ○ **Overview Report 2A** Stakeholder briefing pack on Customer & Societal Objectives, Emerging Trends and Systemic Issues.	**Description:** Given the accelerating pace of change, the growing profile and practical application of the Stage 4 work, and the relevance of the foundational content to informing all Commonwealth processes, a more expansive review and update of the following will be presented in three complementary volumes as per the descriptions below. **Target Audience:** ○ AEMO staff and participants in CER/DER Functional Requirement workshops. ○ All Commonwealth and regulatory/market processes currently focused on NEM transformation option. **Deliverables:** ○ **Report 1 - Customer & Societal Objectives** Updated set of current and emerging customer and societal objectives to provide a robust basis for stakeholder prioritisation and trade-off choices relevant to NEM transformation efforts. The content developed in Stage 2 is compared against more recent publications by key organisations and feedback from customer advocates is incorporated to provide a key reference source for all processes. ○ **Report 2 - Emerging Trends Driving Change** A review of the Australian and global literature has identified over 40 additional Emerging Trends which are harmonised with the updated set of >60 trends mapped in Stage 2. All change drivers are described and their implications for the power system considered. The expanded content is configured in a newly updated structure for greater ease of use as a reference source for all processes. ○ **Report 3 - Systemic Issues & Transformation Risks** Informed by the expanded set of Emerging Trends, the original set of ten are reviewed and updated with a further two Systemic Issues identified. The content is further enhanced with structured mapping of the relationship between each Emerging Trend and the Systemic Issues together with a synopsis of overarching challenges and risks presented by them.

3. Outstanding activities

#	Original Scope	Expanded Variation Scope
PHASE 2: Expanded core research development (Nov 2024 – Apr 2025)		
2.2	Desktop review of Australian and global best practice resources relevant to Distribution System Operator (DSO) models including analysis of transferrable insights into NEM context.	**Description:** Distribution System Operator (DSO) models are advancing faster in other parts of the world than Australia despite its record-breaking adoption of DPV by millions of consumers. The National CER Roadmap project has highlighted this gap at a policy level and the expanded G-PST Stage 4 report will provide an extensive treatment of the topic from technical and structural perspectives. **Target Audience:** o AEMO staff and participants in CER/DER Functional Requirement workshops. o DCCEEW and AEMC staff advancing the DSO Workstream under the National CER Roadmap initiative. **Deliverable:** o **Report 4 – Distribution System Operator (DSO) Models** Executive Summary 1 Report Context, Purpose & Scope 2 Report Development Approach 3 Policy Context: National CER Roadmap 4 Transformational Context: More dynamic, bi-directional and interdependent future grids 5 Changing Grid Dynamics: The growing importance of the 'demand-side' for whole-system planning and operations 6 Related but Different: Understanding DNSP and DSO commonalities and key distinctions 7 Future Grid Enabler: DSO models a key structural enabler of High-CER/DER power systems 8 Policy Enablers: The strategic policy landscape supporting the emergence of DSO models

		9 Alternative DSO Models: The relationship between policy objectives and the evaluation of DSO structural alternatives 10 DSO Relationships: Key structural and functional relationships between the DSO and the wider power system 11 Detailed DSO Functions: Exploring the core functions that DSOs are responsible for 12 Evolutionary Phases: Stepwise transition pathways to progressively establishing DSO models 13 Roles & Responsibilities: Structurally-informed methods for the objective, future-ready assignment of functions 14 Additional Questions: Common stakeholder questions about DSO 15 DSO Benefits: The societal and whole-system benefits DSO deployments are already delivering 16 Recommended Priority Actions 17 Conclusion
2.3	Desktop review of Australian and global best practice resources relevant to Transmission – Distribution Interface (TDI) models including analysis of transferrable insights into NEM context.	**Description:** Transmission-Distribution Coordination (TDC) is integrally related to DSO models a related capability required by a high-CER/DER power system. Together, both function to support enhanced system balancing, stability and power quality outcomes in an increasingly bidirectional power system. The expanded G-PST Stage 4 report provides a substantive treatment of the topic from technical and structural perspectives in a manner that will directly inform the National CER Roadmap initiative and its DSO Workstream. **Target Audience:** o AEMO staff and participants in CER/DER Functional Requirement workshops. o DCCEEW and AEMC staff advancing the DSO Workstream under the National CER Roadmap initiative. **Deliverable:** o **Report 5 – Transmission-Distribution Coordination (TDC)** Executive Summary 1 Report Context, Purpose & Scope 2 Report Development Approach

		3 Changing Grid Dynamics: The growing importance of T-D Coordination for whole-system planning and operations 4 Future Grid Enabler: T-D Coordination is a key structural enabler of High-CER/DER power systems 5 Design Considerations: Key considerations for effective T-D Coordination model design 6 Data Exchange: Considerations for enabling secure and scalable data and information flows 7 Core Functions: Examining key T-D Coordination functions, timeframes and roles 8 TDC Benefits: The societal and whole-system benefits TDC is expected to deliver 9 Recommended Priority Actions 10 Conclusion
2.4	Desktop review of Australian and global best practice resources relevant to Visibility and Operational Coordination models including analysis of transferrable insights into NEM context.	Relevant visibility and operational coordination content integrated into the significantly expanded Reports 4 & 5.
PHASE 3: Adapted MBSE Modelling		
3.1	Consistent with the above restructure of Phase 2 areas of research focus, targeted MBSE-based modelling will focus on the following representations. • Structural Representations o Prototype whole-system architecture that enables expanded DSO functionality with supporting T-D Coordination/Interface • Functional Representations o High-level data transformations and flows to support whole-system coordination o High-level sequenced, time-gated and recurring SO – DSO operational interactions leading up to dispatch	

PHASE 4: Final Report (Apr - May 2025)	
4.1	Develop a draft Stage 4 report structure with indicative content for review and feedback by CSIRO/AEMO.
4.2	Develop penultimate Stage 4 report content for review and feedback by CSIRO/AEMO.
4.3	The full set of five research content and MBSE modelling, together with an integrative Executive Summary, will be delivered as a single report containing the following at the conclusion of Stage 4. o Report 1: Future Customer & Societal Objectives o Report 2: Emerging Trends Driving Transformation o Report 3: Systemic Issues & Transformation Risks o Report 4: Distribution System Operator (DSO) Models o Report 5: Transmission-Distribution Coordination (TDC) o MBSE-based prototype modelling of key DSO and TDC interactions.

4. Progress against the Roadmap

The G-PST Research Roadmap identified opportunities for Australian research to support and accelerate the electricity system transformation across nine topics. Topic 7, focused on Architecture, identified a significant need and opportunity for the use of systems-based methodologies such as Power Systems Architecture to help 'tame' the deep complexity inherent in Australia's transforming power systems and to enable more holistic solutions. The Roadmap framed this work as foundational to efficient and timely decision-making (refer Figure 2).

In 2024, the need for such tools has only increased as technology solutions that support whole-system coordination, such as Dynamic Operating Envelopes, have matured through various research and demonstration projects. This is because the efficacy of such solutions is dependent on the underpinning structure in which they are deployed. To enable their full potential capabilities in a scalable and secure manner, consideration of the systems architecture is critical.

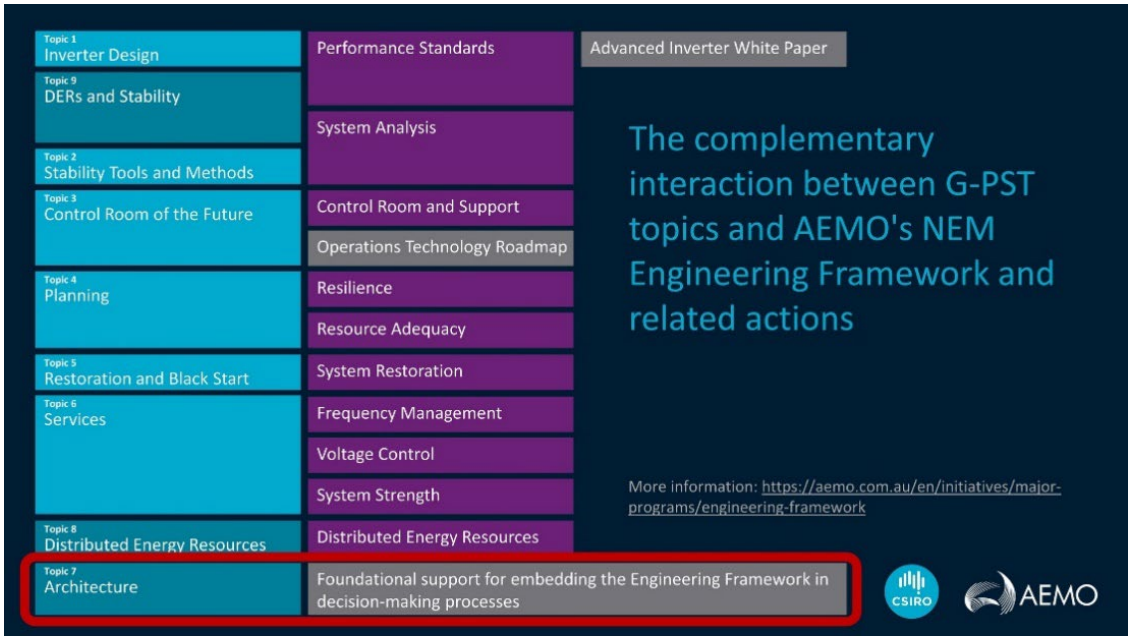

Figure 2 - Systems Architecture-based disciplines are recognised as foundational to the overall G-PST program of applied research

In the legacy or 'brownfield' grid context, this requires

- An acknowledgement of the complex couplings and dynamic interactions that exist between the different components and actors of the system and the purposes for which these structural choices were originally made;
- Formal processes for systematically mapping these relationships through the representation of the seven system structures noted above;
- A growing shared appreciation among system actors of the relevant Systems Architecture principles that enable diverse stakeholders to interrogate current structures and evaluate policy and other design choices that materially impact future structural choices; and,
- The application of fit -for-purpose tools that support the identification and targeted resolution of non-scalable constraints embedded in or arising from the inherited structural arrangements.

5. Research relevance to Australia

Building out the tools and capabilities to support rigorous architectural analysis of Australia's energy transition has and continues to be the purpose and rationale of G-PST Topic 7. While Stages 1 – 3 of Topic 7 were undertaken in a context where PSA and MBSE were still considered relatively new and somewhat abstract concepts, this context is now shifting quite substantially.

As highlighted above, the practical relevance of the PSA and MBSE tools and methodologies is now being noted and leveraged by various parties engaged with the parallel policy initiatives being advanced by the Commonwealth and market/regulatory bodies (DCCEEW, AEMO, ARENA, AEMC).

This encouraging development appears to be driven by rapidly expanding systemic complexity now being confronted by the sector. This is especially pronounced with the growing range of matters that span multiple traditional supply chain 'siloes' from System Operator through TNSPs, DNSPs, Energy Retailers, etc.

A tangible recent example of this development was AEMO's successful pilot of applying PSA and MBSE tools, in collaboration with several DNSPs, for analysing, enhancing and harmonising Australia's five different implementations in three states of the DPV Emergency Backstop (EDPV-C) use case.

Figure 3 – The cohort of AEMO, DNSP and Topic 7 staff participating in the EDPV-C trial application of PSA and MBSE

6. Recommended research priorities

Collaboration with AEMO staff on G-PST Topic 7 has been strong throughout Stages 1 – 3, and this has further strengthened during the execution of Stage 4 in 2024/25. The deepening engagement has been driven by AEMO's recognition of the PSA and MBSE tools practical value for addressing the complex, end-to-end CER/DER Functional Requirements in the near, medium and long-term futures.

Over this same period, the Commonwealth and market/regulatory bodies initiated several major reform initiatives that are directly relevant to the Topic 7 work. These include:

- DCCEEW National Consumer Energy Resources Roadmap
- AEMO CER/DER Functional Requirements Co-design
- AEMC Distribution System Operator (DSO) and Distribution Markets initiatives
- DCCEEW National Electricity Market Review
- ARENA/AEMO CER/DER Data Exchange Co-design

While the above are distinct initiatives, each has architectural dimensions that would benefit from a common set of near, medium and long-term architectural reference materials. The practical relevance of the PSA and MBSE tools is also being noted and leveraged by various parties engaged with these parallel initiatives.

While overwhelmingly positive, the more dynamic environment in 2024/25 has necessitated extensive engagements, briefings and scoping discussions with AEMO and various other parties to ensure the Stage 4 scope adapted to most effectively align with the evolving landscape. While this has proved time and resource intensive, it has also enabled additional clarity to emerge on AEMO's preferences for how AEMO and CSIRO investments are coordinated for maximum complementarity and to avoid duplication.

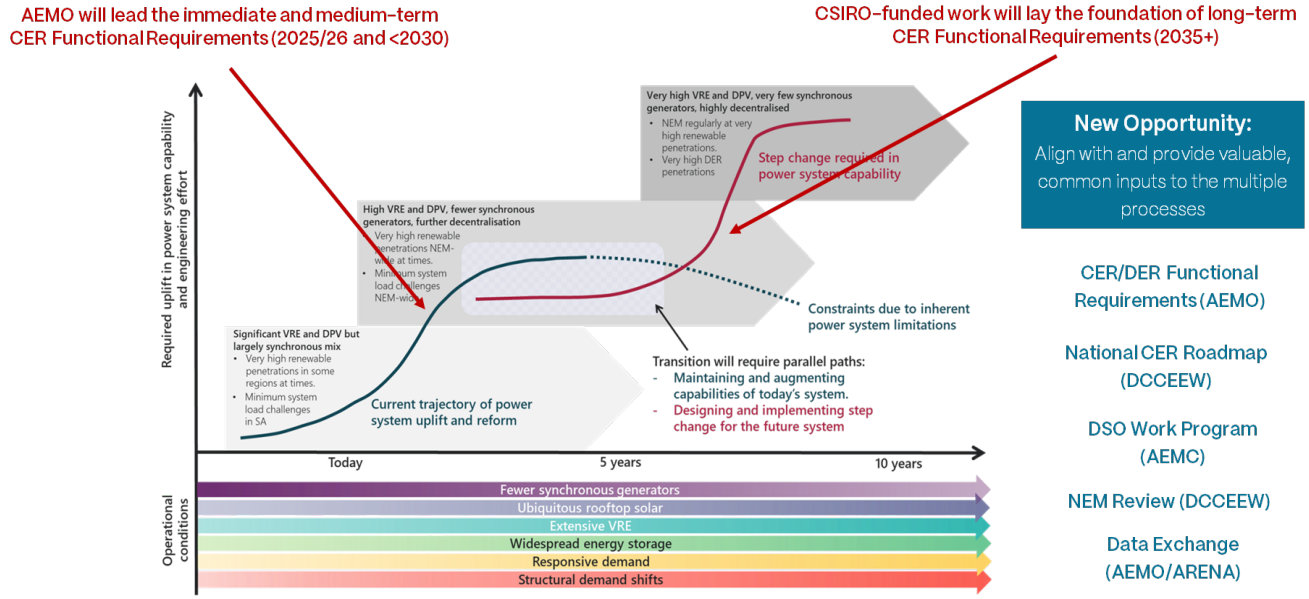

Figure 4 – Discussions with AEMO have provided clarity on how investments by CSIRO and AEMO may be coordinated to maximise complementarity and avoid duplication[2]

[2] Image: Engineering Framework – Interim Roadmap, AEMO, 2021; adapted from A Gambit for Grid 2035 – A systemic look into the disruptive dynamics underway, Pacific Energy Institute, 2021

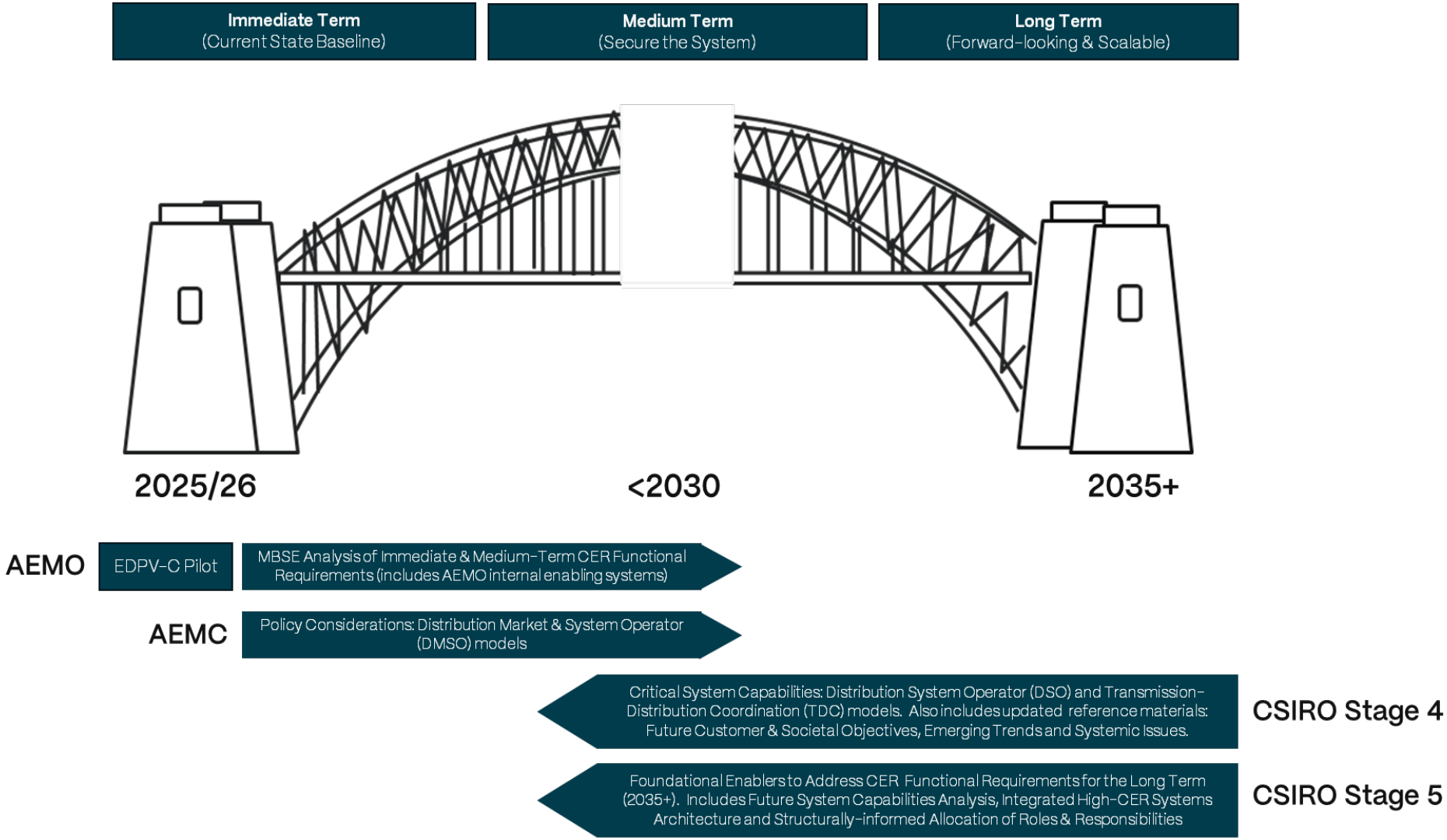

Figure 5 – The complementary relationships between CSIRO-funded Topic 7 (Stages 4 & 5) enabling futureproofing of solutions for the Long-Term (2035+) and the AEMO and AEMC-funded work focused on the Immediate and Medium-Terms (2025/26 and <2030 respectively).[3]

[3] Image: Adapted from Engineering Framework – Operational Conditions, AEMO, 2021

Relevant to Figures 4 & 5 above, following is an outline of how the respective bodies of work will complement each other to both advance the deep systems integration of CER/DER at scale and provide valuable physics-based inputs into the several Commonwealth processes running in parallel.

AEMO-funded Work: Immediate and Medium-term focus

Reflecting the practical value of the PSA and MBSE tools, AEMO has expressed a preference to directly fund the analysis and mapping of the Immediate-term (2025/26) and Medium-term (<2030) CER Functional Requirements and their supporting AEMO internal enabling systems.

Importantly, AEMO recognises that a key distinction of addressing these two nearer-term time horizons is the wider system structures of the NEM will remain largely as-built, with only limited changes being made during these time periods.

CSIRO-funded Work: Long-term focus

Informed by the various ISP 2050 scenarios and parallel Commonwealth initiatives, however, AEMO recognises that more substantial changes to the NEM's architectural structures will be required to ensure future scalability beyond 2035+. For example, as the system continues to evolve toward a more hybridised, high-CER/DER future, formalised Distribution System Operator (DSO) models, Transmission-Distribution Coordination (TDC) and advanced data exchange models will need to be structurally integrated.

Given the technical complexity, multiple stakeholders impacted and the finite time available, AEMO recognises that the Long-term work funded by CSIRO needs to be advanced in parallel with the Immediate and Medium-term work funded by AEMO. This will both provide valuable future-oriented insight to the Immediate and Medium-term efforts (to reduce the need for rework later) and provide a robust foundation for comprehensively addressing the Long-term CER Functional Requirements (2035+).

Building upon the prior stages of CSIRO-funded work, it is proposed that Stage 5 will have maximum practical value by addressing the following interrelated topics. These three elements are critical to both underpinning scalable solutions for AEMO's CER Functional Requirements in the Long-term (2035+) and providing physics-based inputs into the parallel Commonwealth policy processes. Based on current discussions, there is also potential for supplementary funding to CSIRO from other parties to enable this scope.

1. **Future System Capabilities Analysis (2035+)**
    - Map systemic differences between 2050 scenarios
    - Identify systemic commonalities across 2050 scenarios
    - Cross-check with Emerging Trends & Systemic Issues analysis
    - Identify least regrets system requirements for 2035+
    - Map relevant existing system capabilities
    - Analysis of key capability gaps critical to enabling transition beyond 2035
    - Identify least regrets system capabilities for 2035+

2. **Detailed Architecture for a High-CER/DER Power System (2035+)**

    Informed both by the Future System Capabilities Analysis and progressive outputs of relevant Commonwealth and other parallel initiatives:

    - Undertake a detailed review of the NEM Step Change Reference Architecture developed in G-PST Stage 2;

- Employ PSA and MBSE tools to collaboratively develop a 2035+ Detailed Architecture that maps the whole-system structural and functional relationships required between the following entities:
    - System Operator (AEMO);
    - Transmission Network Service Providers (TNSPs);
    - Transmission-Distribution Interfaces (TDIs);
    - Distribution System Operators (DSOs);
    - Distribution Network Service Providers (DNSPs);
    - Distribution-level Markets;
    - CER/DER Aggregators & VPPs; and,
    - Data Exchange structures.

3. Structurally informed Allocation of Roles & Responsibilities

Informed by the above, apply formal clustering analyses (graph partitioning, design structure matrix, etc) to provide an objective, scalable and structurally informed approach to the allocation of future system Roles & Responsibilities. This requires the following activities:

- Define each new capability (or capabilities) needed to meet new power system requirements.
- Decompose all new capabilities into sets (clusters) of functions.
- In conjunction with existing system functionalities, consolidate the functions list so that it consists only of unique, non-overlapping functions (mathematically, create an orthogonal set). Information on existing capabilities, functionalities, and components/systems are necessary inputs.
- Partition the functions into clustered sets or groups. The clustering criteria are largely technical in nature and every function must cluster to one and only one function group.
- Define discrete roles, ensuring that each functional group maps to one and only one role. This step will surface details such as access to infrastructure needed for Step 6.
- Informed by the detailed industry structure documentation developed in the previous Detailed Architecture step, map roles to entities and assign responsibilities, ensuring that each role can only map to one entity (while any entity can have several role).
- Confirm inter-entity integration to ensure that functionalities which reside in separate entities but must coordinate effectively to fulfill capabilities have the necessary means to do so.