Global Power Systems Transformation (Stage 2)

TOPIC 7:

Power Systems Architecture

Reference Architecture of Australia's National Electricity Market (NEM)

May 2023

Prepared for:

Topic 7 – Power Systems Architecture:

Integrated methodologies and activities for navigating the systemic complexity of Australia's power system transformation, deepen stakeholder engagement and social license and help align the new technology, regulatory and market design developments required for a high-VRE / high-DER future.

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The research presented in this report was funded by CSIRO, Australia's national science agency, and carried out as part of CSIRO's contribution to the initiatives of the Global Power System Transformation (GPST) Consortium. This research supports Australia's transition to a stable, secure and affordable power system and contributes to critical research identified by the Consortium required to accelerate the decarbonisation of our electricity grid. More details can be found at https://www.csiro.au/en/research/technology-space/energy/G-PST-Research-Roadmap.

Further Information

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ACKNOWLEDGEMENTS

"If I have seen further, it is by standing on the shoulders of giants…"

Sir Isaac Newton (1642-1727)

The study of power system transformation as it experiences deep decarbonisation and digitalisation is – unsurprisingly – both complex and challenging. For this reason, the development team wish to acknowledge the 'giants' whose seminal work and vision laid the foundation for this project.

For example, the Grid Architecture research funded by the U.S. Department of Energy over almost a decade, spearheaded by Dr Jeffrey Taft and his colleagues at Pacific Northwest National Laboratory (PNNL) including Dr Ron Melton and Dr Seemita Pal, remains unparalleled as a foundational body of insight.

In the context of Australia's accelerating power system transformation, the vision of CSIRO and AEMO in supporting the nation's contribution to the Global Power System Transformation (G-PST) initiative is recognised for its foresight and ambition.

In addition, the project has greatly benefited from the insightful engagement of several CSIRO, AEMO and GHD staff and collaboration with an outstanding International Expert Panel from the United States, United Kingdom and the European Union. Valuable contributions have also been provided in collaborative workshops involving many Australian stakeholders representing consumer groups, network businesses, energy retailers, government departments and regulators.

Ultimately, addressing such complex challenges requires the forging of new navigational capability that can be shared by a diverse and expanding community of practice. To that end, the level of active engagement by many, and the range of valuable insights and suggestions shared, have been critical to the development of this report.

INTERNATIONAL REVIEWS

Countries around the world are transitioning to decarbonised energy systems. Abundant and cheap renewable electricity from wind and solar means decentralisation is a trend that is here to stay, and this is turning traditional power system architecture on its head. This Power Systems Architecture work is timely and provides the tools, logic and engagement framework to help ensure that citizens' energy values, needs and preferences can be met in increasingly complex and local future low-carbon energy systems. The sooner it can be implemented, the better.

Dr Jeff Hardy

Director, Sustainable Energy Futures Ltd
United Kingdom

The energy transition is one of the largest transformations faced by humanity over the last several decades. It requires rethinking and re-organizing the power system, including its underpinning structures, the interactions of multiple agents and the integration of many new technologies to meet new system requirements.

The Power Systems Architecture (PSA) approach is unique as it brings multiple perspectives together, and incorporates the insights of global experts, to help address policy-makers and customers' expectations of our future power systems. The proposed framework provides a unique Systems Architecture-based approach that proceeds from an overall system view to detailed technical solutions and includes iterative loops between the various phases of development. The PSA framework has relevance not only for Australia's rapid grid transformation but potentially in many other jurisdictions facing similar challenges.

Dr. José Pablo Chaves Ávila

Deputy Director for Research Development
Institute for Research in Technology
Comillas Universidad Pontificia, Spain
Work Package 11 Leader: European Union OneNet project
Work Package 7 Leader: European Union Beflexible project

Australia's electricity system is on the critical path to achieving its energy transformation objectives. This Power System Architecture report provides holistic, proven methodologies to examine the complex set of dynamic relationships among devices and entities in a significantly more distributed electricity system. As with other countries facing a step change, thoughtful actions taken this decade will decide whether longer term decarbonization, resiliency and affordability goals are realized. The methods and the resulting pathways analysis in this report enables a robust discussion among stakeholders to determine how to effectively achieve the desired outcomes.

Paul De Martini

Executive Director, Pacific Energy Institute
United States

This thorough Reference Architecture of Australia's National Electricity Market will have both local and international relevance. It will be a valuable resource for thinking about markets and evolving market and regulatory institutions within the larger, holistic context of electric system transformation. Markets and price signals are the nervous system of our complex social systems, including the complex cyber-physical-social electric system, and as that system evolves, having clear market processes to communicate information in the transforming system will be essential for delivering customer and societal objectives.

Lynne Kiesling, Ph.D.

Director, Institute for Regulatory Law & Economics,
Center on Law, Business, and Economics
Northwestern University
United States

This timely Reference Architecture report clearly positions Australia as a global leader in the transition of electric service to a clean energy future. When massive drivers of change confront the traditional ultra-complex power system — in this case the need to decarbonize, combined with an explosion of cost-effective distributed energy technologies — trying to adapt via incremental changes is like taking a road trip with no destination and no visibility to the possible consequences of any given decision. That's where Power Systems Architecture (PSA) offers a coherent body of principles and methods for describing the whole system, revealing the interactions among its components, and tracing the impacts of structural and policy changes.

But PSA has its own learning curve, and until recently it has been largely unknown among policy makers, system operators and other key actors in the power industry. This is where the present report steps into the gap and makes a compelling contribution. By working through the application of PSA to the Australian energy market, the report offers Australia's policy makers a map for navigating the whole-system transition, and offers the global industry a demonstration of the power of architectural analysis for navigating complex system change.

Lorenzo Kristov, Ph.D.

Principal Market Architect
Electric System Policy, Structure, Market Design
United States

The report provides critical insights into the scale of the challenge ahead, detailing rapidly emerging trends and their impacts on electricity grids, some of the most complex systems ever made. Power Systems Architecture provides a tool to address these issues by exploring the strategic framework, providing key observations, and laying out a pathway towards meeting current and future needs. This is applicable for all involved in the energy transition, and will be useful in the context of Great Britain as we implement changes in governance, planning, and operations to realise our ambitious aim of creating a net-zero power system by 2035.

Francis Mosley

Senior Innovation and Systems Engineer
Ofgem
United Kingdom

The Ultra-Large-Scale (ULS) complexity of national scale electric power systems makes their transformation to meet 21st Century requirements vastly more difficult than a more piecemeal model of change, successfully applied in more stable periods, can now accommodate.

This report applies several elements of the comprehensive set of Power System Architecture techniques that can empower system planners, engineers, and regulators to apply a more holistic approach to modern grid transformation. Most critically, a detailed understanding of the underpinning structure of a legacy grid is key and starts with documenting the multiple grid structure classes in the 'as built' system, as shown in this report. Systematic synthesis of consumer expectations, emerging trends, and public policies in the context of multi-scale structure yields grid change specifications whose implications can be methodically traced throughout the grid at any scale.

The use of Power System Architecture in full is essential to transforming 20th Century power grids into decarbonized 21st Century grids.

Jeffrey D. Taft, Ph.D.

Fellow, Pacific Energy Institute
United States

EXECUTIVE SUMMARY

Australia's GW-scale power systems are experiencing one of the world's fastest grid transformations, impacting all vertical layers of the system including bulk power, transmission, distribution and energy retail. Most importantly, Australian customers are both actively participating in and directly impacted by these profound transformational shifts.

Australia's grid transformation is characterised by the accelerated withdrawal of the nation's dispatchable synchronous generation fleet and the mass-deployment of Variable Renewable Energy (VRE) generation, both utility-scale wind and solar and world-leading levels of rooftop solar photovoltaics. The Australian Energy Market Operator (AEMO) has highlighted that by 2025, the National Electricity Market (NEM) is projected to have sufficient renewable resource potential to completely serve demand during certain time windows.

Looking out further to 2050, when compared with the already world-leading levels of today, AEMO's widely accepted Step Change scenario anticipates that the NEM will need to accommodate VRE and DER/CER at multipliers of 9x and 5x respectively! This represents a transition from a past of a few hundred transmission-connected generators to a future involving tens of millions of highly diverse resources participating across several vertical layers of the power system.

Enabling a Secure, Cost-efficient & Flexible Power System

This is uncharted territory for GW-scale power systems anywhere in the world. As these integrated, physics-based systems experience increasingly volatile operating environments, and the traditional sources of system flexibility and services are progressively withdrawn…

> *Bulk energy, transmission and distribution systems – and the rapidly expanding fleet of distributed resources – will need to function far more dynamically and holistically to enable secure, cost-efficient and flexible operation of the end-to-end power system.*

With this in view, digitisation, interoperability, dynamic firming, transport electrification, enhanced asset utilisation and DSO models all have much promise. What is often poorly understood, however, is that all these solutions, and many others, cannot reach their full potential without an integrated approach to ensuring the underpinning structural relationships or 'architecture' of the grid are future-ready. This is fundamentally important because, while innovations such as energy storage and transport electrification may be more tangible and 'newsworthy', the Systems Architecture of any complex system always has a disproportionate impact on what the system can reliably and cost-effectively deliver.

As identified in the Stage 1 report, for some years now the United States, United Kingdom, European Union and Canada have been examining how the underlying architecture of their power systems may need to change. Given the pace and scale of Australia's grid transformation, a focus on Power Systems Architecture becomes pivotal as the NEM is required to perform more and more functions that were inconceivable when its architecture was originally settled in mid-20th century.

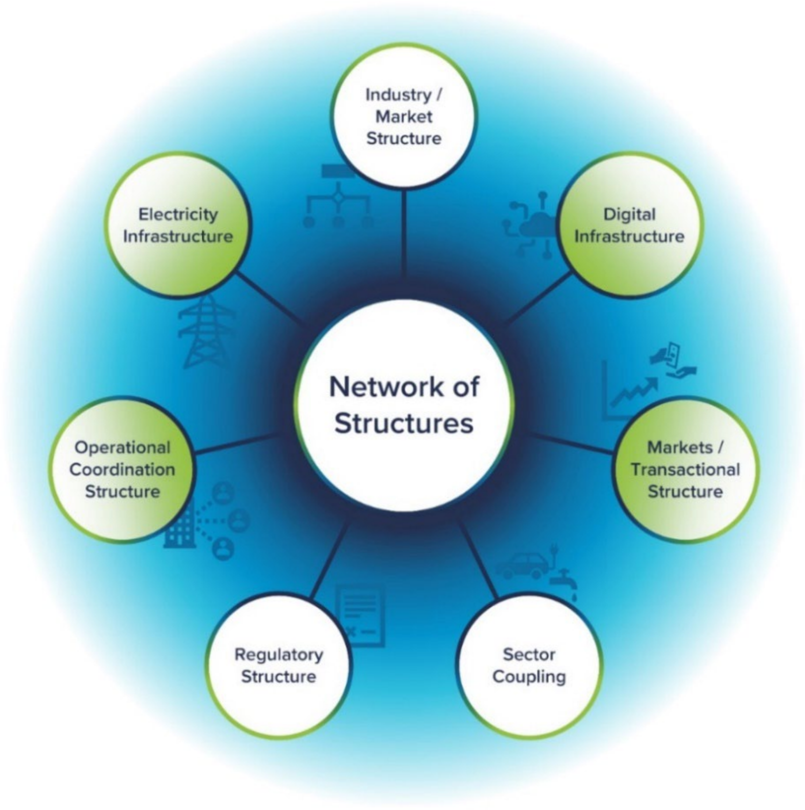

Figure I: The Network of Structures model provides a unique, whole-system view of the seven architectural structures that constitute a modern power system[1]

Power Systems Architecture 101

Some find the concept of Systems Architecture quite abstract. Simplistically, however, if the boxes in a block diagram represent the various components of a system, the structure or 'architecture' is represented by the lines that connect the boxes.

At a very practical level, where the underpinning architecture of a system is well aligned with its current or future purpose, all the components will function effectively together, and the system will exhibit resilience, cost-efficiency and scalability. Conversely, where the architecture is misaligned with current or future needs, technology integration becomes increasingly costly, investments may be stranded, and full benefits realisation becomes increasingly tenuous.

Power Systems Architecture (PSA) is a generic term for an integrated set of tools that support the structural transformation of legacy power systems to meet future policy and customer expectations. While PSA may also be applied to 'greenfield' power systems, a key application of PSA is the identification of the *minimum* structural interventions required to achieve the *maximum* uplift in the future-readiness of a legacy or 'brownfield' power system such as the NEM.

[1] The Network of Structures concept was originally developed by Pacific Northwest National Laboratory.

With strong parallels to the modernising aerospace sector before it, a decarbonising power sector is now experiencing unprecedented levels of complexity that exceed many of our traditional tools and navigational approaches. Applicable in any jurisdictional context or market structure, PSA methodologies should therefore be understood primarily as part of an 'expanded toolkit' for interrogating grid transformation pathways (rather than a rigid mechanism to provide '*the* answer').

In particular, as an integrated set of tools, PSA provides:

- **Whole-system insight** over 5, 10 and 20-year time horizons, enabling the interrogation and mapping of current, emerging and future power system priorities, objectives, functions and enabling structures that may emerge under a range plausible future scenarios;

- **Evidence-based tools** to identify, analyse and shortlist key transformational options through the combination of Systems Architecture, Network Theory, Control Theory, Systems Science and Model-based Systems Engineering (MBSE) supported by Strategic Foresight, Behavioural Science and Energy Economics; and;

- **Future-resilient decision making** by surfacing hidden structural constraints early which may otherwise drive future issues such as computational constraints, latency cascading and cyber-security vulnerabilities, providing greater assurance that new investments will be scalable and extensible under all plausible futures.

Forward-looking & Action-oriented

Given the pace of change now unfolding, Australia needs actionable insight for navigating the real-time transformation that is also scalable to the needs of the future, such as those illustrated by AEMO's Step Change scenario. Therefore, to ensure the Reference Architecture is both future-oriented and supports urgent near-term action, Stage 2 has been framed around the following two questions:

- **Q1. Critical Enablers:** What architectural settings might be required for the NEM to be capable of operating securely, cost-effectively and flexibly 'end-to-end' in a future similar to AEMO's Step Change scenario?

- **Q2. Decision Quality:** How might this perspective support the identification of 'least regrets' actions that enhance the scalability of near and medium-term investments to ensure they enable such longer-term futures?

Report Structure: Four Key Sections

With this high-level framing, development of the NEM Reference Architecture was advanced through the delivery of the four major sections of this report as outlined below in Figure II. As an inherently complex undertaking, this development approach enabled progressive review by, workshopping with and feedback from CSIRO and AEMO staff, the International Expert Panel and a diverse range of Australian stakeholders.

SECTION 1	**Customer & Societal Objectives** for future power systems
SECTION 2	**Emerging Trends** that are driving change in GW-scale power systems
SECTION 3	**Systemic Issues** that impede progress and require architectural interventions
SECTION 4	**Emerging System Structures** derived from mapping the 'as built' architecture of the NEM and the plausible architectural settings required to accommodate a 'Step Change' type of future

Figure II: The four major sections of the NEM Reference Architecture report

Considered together, these four sections illustrate how Power Systems Architecture provides a holistic and systematic methodology for supporting the structural transformation of legacy power systems to meet future policy and customer expectations. For example, as ultra-complex 'societal-technical-economic systems', any credible consideration of future architectural options for power systems such as the NEM must be informed by what customers and policy makers communicate that they expect from them.

As such, **Section 1 – Customer & Societal Objectives** provides a synthesis of eight major expectations of future power systems that were derived from a meta-analysis of the Australian and global literature and corroborated by stakeholder workshops. While a subsequent Detailed Architecture process would also involve a structured process of societal prioritisation of these objectives and trade-off choices, they have provided foundational insights to guide the development of the NEM Reference Architecture.

Ensuring that an ultra-complex societal system like the NEM is future-ready becomes increasingly critical during a time of large-scale transformational change. Therefore, **Section 2 – Emerging Trends** examines over sixty (60) such drivers of change that are influencing and accelerating the transformation, and then mapped under ten major categories. Each trend is stated, followed by a summary of its observable characteristics and systemic implications, including where they may impact one or several tiers/layers of the power system (e.g. bulk power, transmission, distribution, energy retail and/or customer resources). While such analysis will never be exhaustive, it does highlight the magnitude of change impacting power systems such as the NEM.

Given the sheer volume of Emerging Trends now impacting power systems, attempting to navigate change by largely or solely focusing on individual drivers, use cases and/or isolated treatments rapidly becomes unwieldy and inefficient. Therefore **Section 3 - Systemic Issues** distils a finite set of ten (10) cross-cutting conditions that arise as the many Emerging Trends converge to present increasing risks to the security, flexibility and cost-efficiency of the power system. Once again, while the list is not exhaustive, it does highlight specific transformational steps that cannot ultimately be enabled without targeted architectural interventions. In other words, the Systemic Issues identified are of a nature that cannot be addressed by the accretion of individual technology innovations and/or regulatory changes.

The analysis undertaken in Sections 1 – 3, together with structural insights provided by the range of Systems Architecture-based tools, then underpin a structural analysis of the NEM in **Section 4 - Evolving System Structures**. This becomes increasingly critical where any ultra-complex system, such as the NEM, is required to perform more and more functions that were largely inconceivable when its original architecture was settled many decades earlier. As noted earlier, while individual technology innovations may be more tangible and 'newsworthy', the Systems Architecture of any complex system always has a disproportionate impact on what the system can reliably and cost-effectively deliver.

With this in view, the structural analysis of the NEM contained in Section 4 focuses on the following three areas:

- **As-built architecture:** For the first time, mapping in a single document how the seven structure classes are configured in the 'as built' NEM.[2]
- **Transition architecture:** Illustrating one of the possible approaches to a hybrid architecture for the NEM and considering its strengths and weaknesses.
- **Step Change architecture:** Illustrating a Layered Architecture example of the NEM and considering its strengths and weaknesses in a future similar to AEMO's Step Change scenario.

Importantly, the structural analysis provided in Section 4 enables the identification of legacy and proposed structural settings that may not be well aligned with the rapidly emerging needs of the NEM. Where key constraints are not addressed, costly scaling and systemic fragility issues will arise that erode the security, flexibility and cost-efficiency of the system.

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[2] In the developed world, GW-scale power systems such as the NEM emerged and evolved over many decades. It is common to find that no single set of documents exists which accurately represent how all seven inter-dependent structures that underpin a modern power system are configured and interfaced in the 'as built' legacy system. While this may be of limited consequence during times of slow change, it becomes increasingly problematic in the context of large-scale transformation.

Key Observations & Next Steps

The NEM is one of Australia's most critical systems. This seminal Reference Architecture provides an expanded and whole-system perspective on the current, transitional and plausible future operational contexts of the NEM. A set of Key Observations derived from its development are set out in the report Overview, and the work is supported by a detailed glossary of terms that enable greater precision of communication between diverse stakeholders.

Developed through the application of the global best practice methodologies identified in Stage 1, the Reference Architecture is somewhat like an illustrative 'prototype' of a highly complex system. As such, while it does not presume to provide '*the* answer', it does illustrate how the integrated set of PSA methodologies enhance shared insight and the ability to collectively reason about such a complex system in profound transformation.

Consistent with Systems Architecture practice, the development of this NEM Reference Architecture is a precedent step to enabling the co-design and execution of a subsequent Detailed Architecture phase. For a nationally critical system such as the NEM, this subsequent phase would involve significant additional analysis and an expansive program of multi-stakeholder participation designed to enhance alignment and the social license for beneficial change.

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1. PROJECT INTRODUCTION

Australia is experiencing one of the fastest Power System[3] transformations on the planet. The nation provides a window on the energy future for many global jurisdictions.

The combined impacts of the '4 x Ds' – decarbonisation, digitisation, democratisation and decentralisation – are driving Australia's unparalleled transformation. These, in turn, are being accelerated by a complex range of societal, technological, economic and commercial shifts, many of which transcend the direct control of traditional power sector regulatory and governance mechanisms.

Compared with 2021 levels, for example, the Australian Energy Market Operator's (AEMO) widely recognised Step Change scenario of 2050[4] anticipates that the National Electricity Market (NEM) may need to accommodate major transformative shifts, including:

+ **9x Centralised VRE:** A nine-fold increase in the installed capacity of utility-scale Variable Renewable Energy generation (from 15GW to 140GW);
+ **5x Distributed DER/CER:** Almost a five-fold increase in the installed capacity of Distributed Energy Resources, large volumes of which are customer owned (from 15GW to 70GW);
+ **3x Dispatchable Firming Capacity:** A three-fold increase in installed Firming Capacity that can respond to a dispatch signal; and,
+ **99% Electric Vehicles:** Almost the entire passenger vehicle fleet electrified.

Such a future represents a materially – if not radically – different operational environment to that of the past and present. Given the widely recognised plausibility of AEMO's Step Change scenario, provisioning the NEM for such eventualities cannot be safely relegated either to the distant future or the collective 'too hard basket'.

Even more pressing is that these transformational impacts are already manifesting today. For example, significant segments of the NEM are already experiencing periods where 100% of instantaneous demand is served by non-traditional variable sources. AEMO has also noted that by 2025 the nation's GW-scale Power Systems must be capable of operating reliably and securely in such conditions, which are expected to increase in frequency and duration.[5]

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[3] Numerous defined terms are identified by capitalisation in the report body. A detailed glossary is of approximately 200 definitions is provided in Appendix D.

[4] Inputs, Assumptions & Scenarios Report, AEMO, 2021

[5] Engineering Roadmap to 100% Renewables, AEMO, 2022

1.1. Expanding the toolkit for navigating Australia's grid transformation

CSIRO, Australia's national science agency, and the Australian Energy Market Operator, AEMO, are leading Australia's contribution to the Global Power System Transformation (G-PST) consortia. The G-PST initiative covers nine topics that are directly relevant to enabling the progressive, secure and efficient decarbonisation of Australia's GW-scale Power Systems.

This report was developed under G-PST Topic 7: Architecture (Stage 2). Through the application of Power System Architecture (PSA) methodologies, it provides a seminal Reference Architecture of the National Electricity Market (NEM) as it experiences profound transformation.

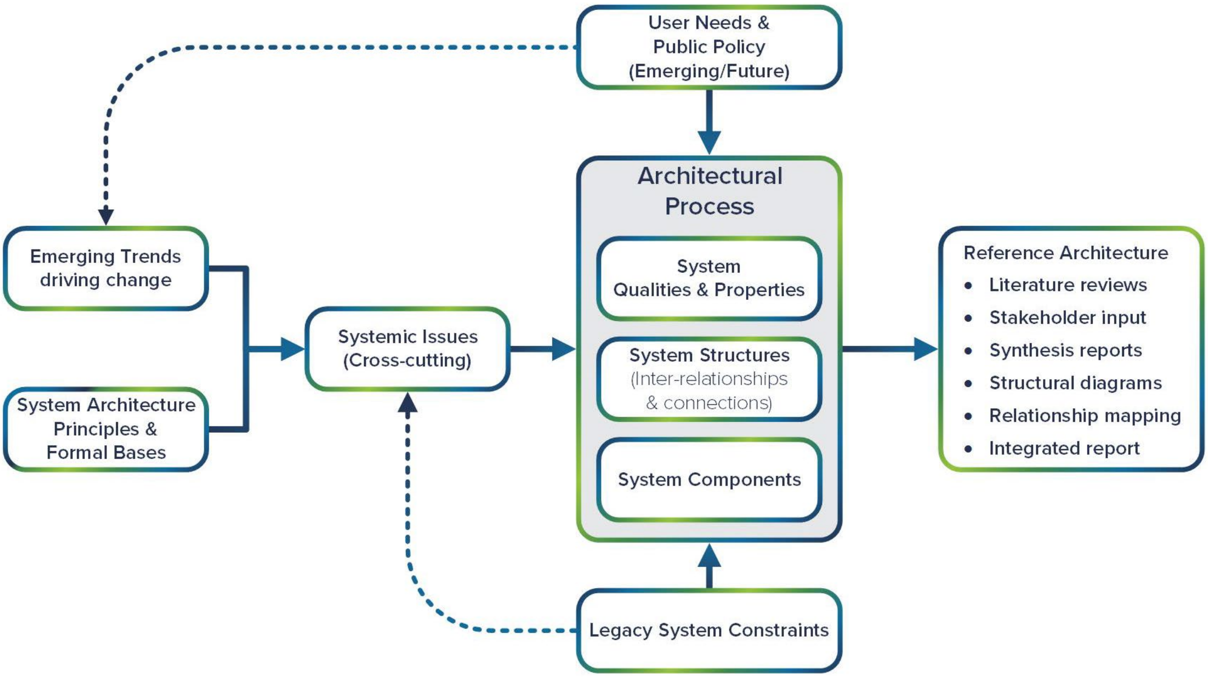

Figure 1: Power Systems Architecture provides a systematic methodology for supporting the structural transformation of legacy Power Systems to meet future policy and customer expectations[6]

At the highest level, the PSA methodologies applied may be summarised as:

> *An integrated set of disciplines that support the structural transformation of legacy Power Systems to meet future policy and customer expectations, by:*
>
> + *Providing formal tools that enable the decomposition and 'taming' of massive complexity that is inherent in transforming Power Systems;*

[6] This model has been adapted from the seminal work undertaken by Pacific Northwest National Laboratory.

- *Empowering more informed, multi-stakeholder participation by making critical content explicit and tractable which would otherwise remain opaque and intractable; and,*
- *Increasing decision quality, timeliness and traceability to increase the potential for full benefits-realisation and avoiding the propagation of unintended consequences.*

It is important to note that such formal and systematic methodologies are now becoming vital. This is because Power Systems – arguably some of the most complex and critical systems ever created by humanity – are now experiencing a pace and scale of transformation never previously experienced, and that will likely take a decade or more to fully play out.

With strong parallels to the modernising aerospace sector before it, a decarbonising power sector is now experiencing unprecedented levels of complexity that exceed many of our traditional tools and navigational approaches.

Key Concepts A

Structure

Every functioning System created by humans has an underpinning Structure. The Structure of a System consists of the formal, stable relationships and interdependencies that exist between the numerous Components of the System and enable it to reliably achieve specific purposes.

Architecture

The term Architecture is formally used in Systems Science to refer to holistic conceptual model that details how the many Components of a System are linked or related together by an underpinning Structure. The purpose of the conceptual model is to make explicit how all the physical, informational, operational, and transactional Components function together as a whole. This supports more robust reasoning about System capabilities, behaviours and transformational options.

Simplistically, if the boxes in a Block Diagram represent the Components, the Structure is represented by the lines connecting the boxes. Although the individual Components are often more tangible and easier to see, studying the underpinning Structure of a complex System is critical as it will always have a disproportionate impact on what the System is ultimately capable of.

Where the underpinning Architecture is well aligned with the current and/or emerging purpose of the System, the Components will function effectively together, and the System will exhibit Scalability and Extensibility. Where the Architecture is misaligned with current or future needs, technology integration becomes increasingly costly, investments may be stranded, and full benefits realisation placed at risk.

1.2. A progressive, holistic and transferrable body of work

In this context, Stage 1 of the G-PST Topic 7 project reviewed the various approaches employed globally to evaluate the underpinning Structures of GW-scale Power Systems and examine how an orderly transition may be supported toward Net Zero Emissions (NZE) future. Published in early 2022, the report surveyed over twenty global initiatives and approaches to provide an Action Plan for applying best practices in Australia.

This Stage 2 report has been developed to demonstrate how the best practice methodologies identified in Stage 1 may be practically applied in Australia. It does so by delivering a seminal Reference Architecture[7] of the NEM that considers both its legacy structures and plausible future state and intermediate transition requirements. Importantly, the development of such a Reference Architecture is somewhat like an initial 'prototype' of a highly complex system. As such, it does not presume to provide '*the* answer'. However, it does provide a powerful mechanism for shared insight and collective reasoning about such a complex system as it experiences unparalleled transformation.

This is particularly critical as the impacts of transformation are now transcending the traditional boundaries of bulk power, transmission and distribution. For example, as rooftop solar PV becomes near ubiquitous, new Forecasting, Visibility, Controllability and Minimum Demand Management challenges increasingly require whole-system collaboration and solution-development to address.

In this context, a key aim of this work is to demonstrate how systems-based methodologies such as Power Systems Architecture can help 'tame' the deep complexity inherent in our legacy Power Systems and enhance the development of more holistic solutions. As such, while focused largely on the NEM, the methodology is universally transferrable to all legacy Power Systems experiencing deep decarbonisation.

1.3. Future-oriented insight designed to enhance near-term action

Australia needs actionable insight for navigating today's transformation. To enhance economic efficiency and customer outcomes, however, near-term action must also be scalable to the needs of the future, such as those illustrated by AEMO's widely recognised Step Change scenario.

Therefore, to ensure the Reference Architecture is both future-oriented and supports urgent near-term action, Stage 2 has been framed around the following two questions:

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[7] Around the developed world, GW-scale Power Systems such as the NEM emerged and evolved over many decades. It is therefore common to find that no complete and agreed single set of documents currently exists representing how all seven inter-dependent structure classes which make up a modern grid are configured and function across all interfaces.

- **Q1. Critical Enablers:** What architectural settings might be required for the NEM to be capable of operating securely, cost-effectively and flexibly 'end-to-end' in a future similar to AEMO's Step Change scenario?
- **Q2. Decision Quality:** How might this perspective support the identification of 'least regrets' actions that enhance the scalability of near and medium-term investments to ensure they enable such longer-term futures?

Engagement with a diverse range of Australian stakeholders has highlighted that both questions are essential. As noted above, while the longer-term future of the NEM is likely to be extremely different from today, significant regions are already experiencing very different operating conditions from those conceived by the architects of the 20th century grid.

Applying the PSA methodology also allows the early surfacing of complex structural issues that cannot ultimately be resolved without architectural interventions. In the immediate term, this enables evaluation and selection of the transitionary steps that are scalable across all plausible futures. In the longer term, it has the potential to deliver many $-billions of savings to Australian consumers through more informed and resilient investment decisions both now and in the future.

1.4. Reference Architecture structure and development process

The development of a seminal Reference Architecture of the NEM is – not unexpectedly – an inherently complex undertaking. For this reason, its development has been advanced through the delivery of four major Sections which function as key building blocks.

Consistent with the PSA methodology illustrated in Figure 1 (above), the following topics have been sequentially addressed:

SECTION 1	**Customer & Societal Objectives** for future power systems
SECTION 2	**Emerging Trends** that are driving change in GW-scale power systems
SECTION 3	**Systemic Issues** that impede progress and require architectural interventions
SECTION 4	**Emerging System Structures** derived from mapping the 'as built' architecture of the NEM and the plausible architectural settings required to accommodate a 'Step Change' type of future

This development approach enabled progressive review by, workshopping with and feedback from CSIRO and AEMO staff, the International Expert Panel and diverse Australian stakeholders on Sections 1 - 4. Considered together, these four sections illustrate how the PSA methodology helps systematically decompose some of the otherwise intractable complexity of grid transformation. This enables a quality of analysis, stakeholder engagement and collective decision making that would be otherwise difficult or impossible.

1.5. Scope and limitations of a Reference Architecture process

As noted above, this project is focused on the first formal stage of applying a Systems Architecture-based methodology to develop a Reference Architecture of the NEM. A Reference Architecture provides an initial, prototypical model of an ultra-complex System and its evolving context. This helps diverse stakeholders – often for the first time – to visualise how the entire System is holistically structured and better understand some of the options for change.

It is important to reiterate, however, that the development of a Reference Architecture of the NEM is similar to creating an initial 'prototype' of a complex system and its evolving context. While it provides a powerful new mechanism for collective reasoning about the system, it will necessarily contain gaps and inaccuracies that must be addressed in the subsequent Detailed Architecture phase.

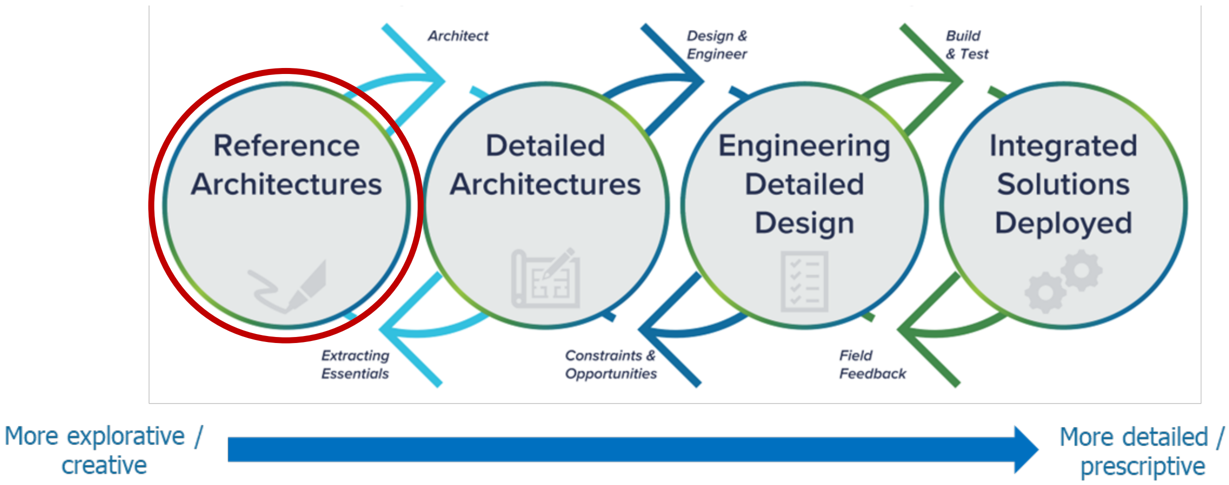


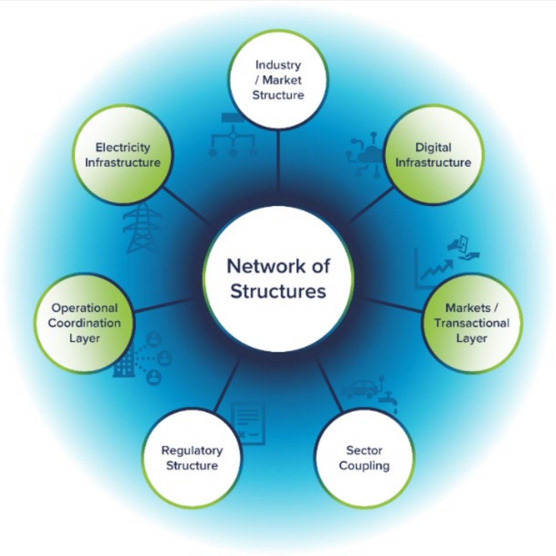
Figure 2: Reference Architecture development is a key first step in the application of Systems Architecture disciplines to an ultra-complex System.

Key Concepts B

The Grid as a 'Network of Structures'

A modern Power System is not one system, but an ultra-complex web of seven distinct, interdependent structures. When viewed from a whole-system perspective, it becomes clear that the Power System is a Network of Structures[8] consisting of:

1. Electricity Infrastructure (Power Flows);
2. Digital Infrastructure (Information/Data Exchange);
3. Operational Coordination Structure;
4. Markets / Transactional Structure;
5. Industry / Market Structure;
6. Regulatory Structure; and,
7. Sector Coupling Structures (Gas, Water, Transport, etc).



Many of these Structures have evolved progressively over decades in the context of a highly centralised, unidirectional Power System. These legacy systems are subject to hidden and overt interactions, cross-couplings, constraints and dependencies which impede change. While the 'system-of-systems' paradigm from software engineering is somewhat useful, being largely focused on Components, it does not adequately represent the complex multi-structural properties evident in a modern Power System.

The Network of Structures paradigm provides invaluable perspective for the detailed analysis, mapping, and optimisation of current and future Systems Architecture requirements. This is critically important as the underlying Structure of any complex System establishes its essential capabilities and limits and has a disproportionate impact on what it can reliably and cost-effectively perform.

[8] The Network of Structures concept was originally developed by Pacific Northwest National Laboratory.

1.6. Guiding principles and characteristics

Following are a set of key principles and characteristics of the Power Systems Architecture discipline that have guided the development of this report.

1. **Stakeholder / User-centric:** All architectural considerations must be grounded in a detailed knowledge of the current and emerging expectations of relevant stakeholders, including customers, policy makers and system actors, to ensure the System is able to deliver a balanced scorecard of stakeholder outcomes.
2. **Contextually Informed:** Systems Architecture methodologies give priority to examining the full range of Emerging Trends that are driving significant change together with the resulting Systemic Issues that must be addressed if stakeholder expectations of the future System are to be achievable.
3. **Principles-based:** System Architecture methodologies are grounded in established principles and formal bases, ensuring conceptual integrity through consistent, traceable and verifiable processes, enhancing multi-stakeholder trust, and minimising the potential for unintended consequences.
4. **Structural Focus:** Systems Architecture methodologies give particular attention to the underpinning structure or 'architecture' of a complex System due to the disproportionate influence it has on what the system can safely, reliably and cost-efficiently do (i.e. the 'performance envelope' of the system).
5. **Whole-system Perspective:** Systems Architecture methodologies provide a holistic view of the entire System as the primary basis for considering the interdependencies between its many Tiers/Layers, Subsystems and Components.
6. **Decadal Time Horizon**: By identifying structural options that enhance (rather than constrain) multi-year optionality, Systems Architecture methodologies ensure the System is Robust, Adaptable, Scalable and Extensible across a range of alternate future scenarios and maximise the 'future-proofing' of investments.
7. **Technology Agnostic:** By focusing on the required outcomes of the current and future System, Systems Architecture actively identifies alternative implementation pathways, supports technology innovation and avoids dependence on any particular proprietary solution.
8. **Complexity Management:** By making explicit the underpinning structures of a legacy system, Systems Architecture enables inherent complexity to be decomposed, legacy structural constraints to be identified, and proposed changes to be accurately targeted and avoid complexity escalation.
9. **Subsystem Analysis:** By providing formal analytical tools, Systems Architecture enables the detailed interrogation of all current Subsystems and Components, their individual Form and Function, Boundaries, Interfaces and Functional Interdependencies to holistically consider potential future enhancements.

10. **Stakeholder Empowerment:** By providing an objective and evidence-based set of tools that can be learned, Systems Architecture empowers diverse stakeholders – both technical and non-technical – to collectively reason about current and future options and better contribute to key trade-off decisions.

1.7. Defined terms and key concepts

Modern Power Systems are intrinsically complex, especially where they are experiencing profound transformation. In addition, while the application of Systems Architecture disciplines is more common in many other sectors, its application to Power Systems is relatively new to many in the power sector.

Therefore, Appendix D contains a detailed glossary of approximately 200 defined terms which are identified in the report body by capitalisation. In addition, a number of Key Concept boxes are provided throughout the report to help illuminate the content.

Key Concepts C

Systems Architecture

A formal part of Systems Engineering, which enables objective, collective reasoning about the underpinning Structure or Architecture of a complex System, together with its Components, Interfaces, Feedback Loops and other behaviours.

This is particularly important as the Architecture of a System always has a disproportionate and irreducible influence on what the System can reliably and efficiently perform. As such, a System is not the sum of its parts, but the product of the interactions of those parts as enabled by its underpinning Architecture.

While having a major impact on the performance of any System, Architecture is usually less tangible and harder to discern than the Components of the System. Therefore, the Systems Architecture discipline provides formal tools for examining how all the Components of a system are related together by the underpinning Architecture, the Emergent behaviours that arise through their interactions, and the most robust options for making changes where required.

Systems Architecture disciplines, therefore, help stakeholders visualise and make more informed decisions about the relationships embedded in the legacy System, including how they might best be adapted to ensure the System is ready to meet future needs.

1.8. How PSA Stage 2 Advances the PSA Stage 1 Research Roadmap

The Research Plan developed in G-PST Stage 1 for Topic 7 set out a process including both the full Reference Architecture & Detailed Architecture phases required to achieve the necessary level of detail, granularity and multi-stakeholder alignment.

Customised around time and resource availability for G-PST Stage 2, this report reflects an accelerated loop through the first four phases of the Topic 7 Research Plan at the level of a Reference Architecture process only. This provides an initial suite of high-level products that foster stakeholder coherence, alignment and the opportunity for timely forward movement.

As illustrated earlier in Figure 2 (above), the formal Systems Architecture approach commences with the more explorative and creative Reference Architecture process (far left). This enables the subsequent co-design and execution of the Detailed Architecture phase which is critical for developing significantly more granular analysis of a highly complex system in the context of much wider, multi-stakeholder collaboration.

The Reference Architecture, therefore, functions as something of a 'working prototype' of the subsequent Detailed Architecture process. It provides a seminal set of documents and structural diagrams that capture the essence of the relationships, linkages and interdependencies embodied in the complex system under consideration. In the case of grid transformation, this provides an initial 'lower stakes' means for diverse and often conflicted stakeholders to become familiar with the PSA tools and develop a shared appreciation of why the Detailed Architecture process is necessary and how it would be advanced.

2. OVERVIEW OF REPORT SECTIONS

2.1. Section 1 – Customer & Societal Objectives

Power Systems are complex techno-economic systems that have a critical societal role. Given the many essential functions they perform in a modern economy – and the growing potential for customer participation – any credible consideration of future architectural options must be informed by what customers and policy makers are expecting of their future Power Systems.

The PSA discipline is fundamentally stakeholder and user-centric. Therefore, this report provides a synthesis of Customer & Societal Objectives for future Power Systems as expressed in the Australian and global literature and corroborated by stakeholder workshops. Its findings are foundational to the entire Reference Architecture development process as it provides a diversity of insights as expressed by external stakeholders including end-user customers (residential, commercial, and industrial) and public policy makers.

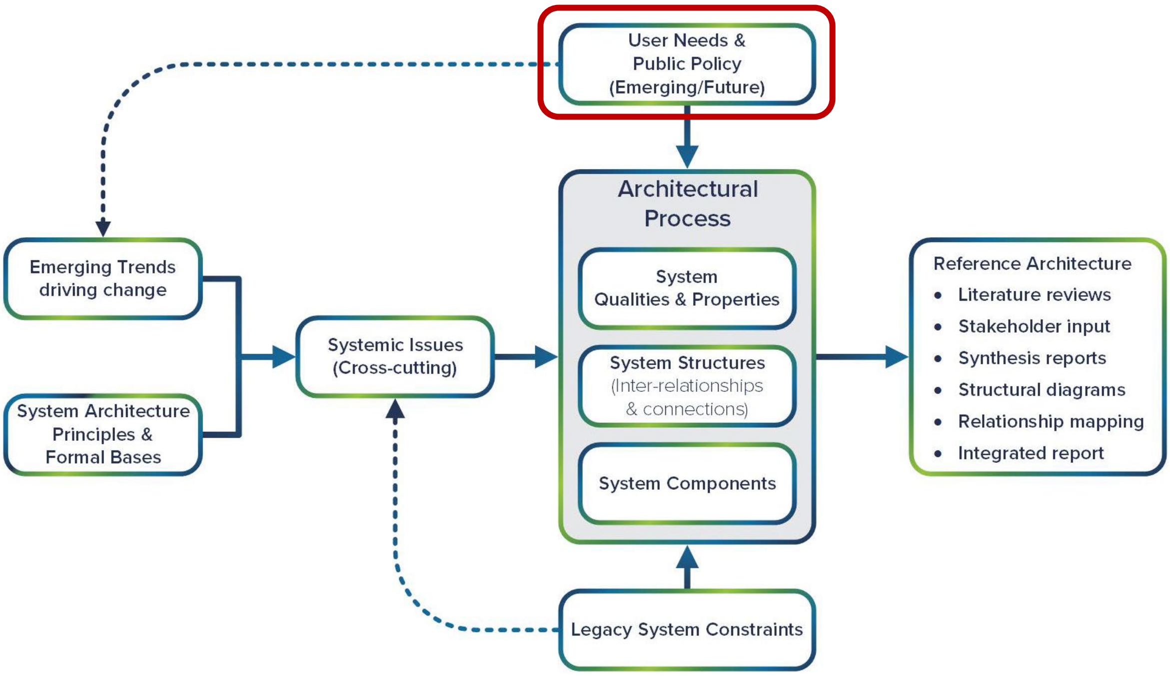


Figure 3: Examining Customer & Societal Expectations for the future Power System is a foundational step to applying formal Power Systems Architecture methodologies.

Eight key objectives emerged from the Australian and global literature. Like society itself, it is acknowledged that a complex tapestry of relationships exists between the various objectives, several of which will impact other objectives. As such, the practical application of the various objectives would require a process of societal prioritisation and trade-offs.

A consolidated summary of the diverse set of future customer and societal objectives for Power Systems that emerged from the literature are provided below. Customers and policy makers variously state that the future power system must be:

1. **DEPENDABLE**: Safe, secure, adequate, reliable and resilient;
2. **AFFORDABLE**: Efficient and cost-effective;
3. **SUSTAINABLE**: Enables 2030 and 2050 decarbonisation goals;
4. **EQUITABLE**: Broad accessibility of benefits and the fair sharing of costs;
5. **EMPOWERING**: Advances customer and community agency, optionality, and customisation;
6. **EXPANDABLE**: Enables electrification of transport, building services and industrial processes;
7. **ADAPTABLE**: Flexible and adaptive to change, including technological, regulatory and business model innovation; and,
8. **BENEFICIAL**: Socially trusted, public good/benefits, commercially investable and financeable.

Figure 4: Eight themes of Customer & Societal Expectations for future Power Systems

As a Reference Architecture process, it is important to note that the societal process of prioritising these objectives would be addressed in a subsequent Detailed Architecture phase. In this context, the objectives are outlined to provide a summary of key traits that future power systems would, to varying degrees, need to exhibit to satisfy customers and policy makers, and which therefore should inform and guide planning and design decisions.

2.2. Section 2 – Emerging Trends

While most of the nine G-PST topics focus on individual technology categories, G-PST Topic 7 is somewhat unique. This is because it applies a whole-system focus on the underpinning Structures (or 'Architecture') of the Power System which are integral to enabling the many individual technologies to function efficiently and securely as a System.

Given this whole-system view, an intentional framing around the scenario of 2050 considered most plausible by Australian stakeholders was chosen as a means for examining the scale of change that the NEM Architecture may need to accommodate. At a practical level, this also provides valuable, future-resilient insight to guide urgent, near-term action.

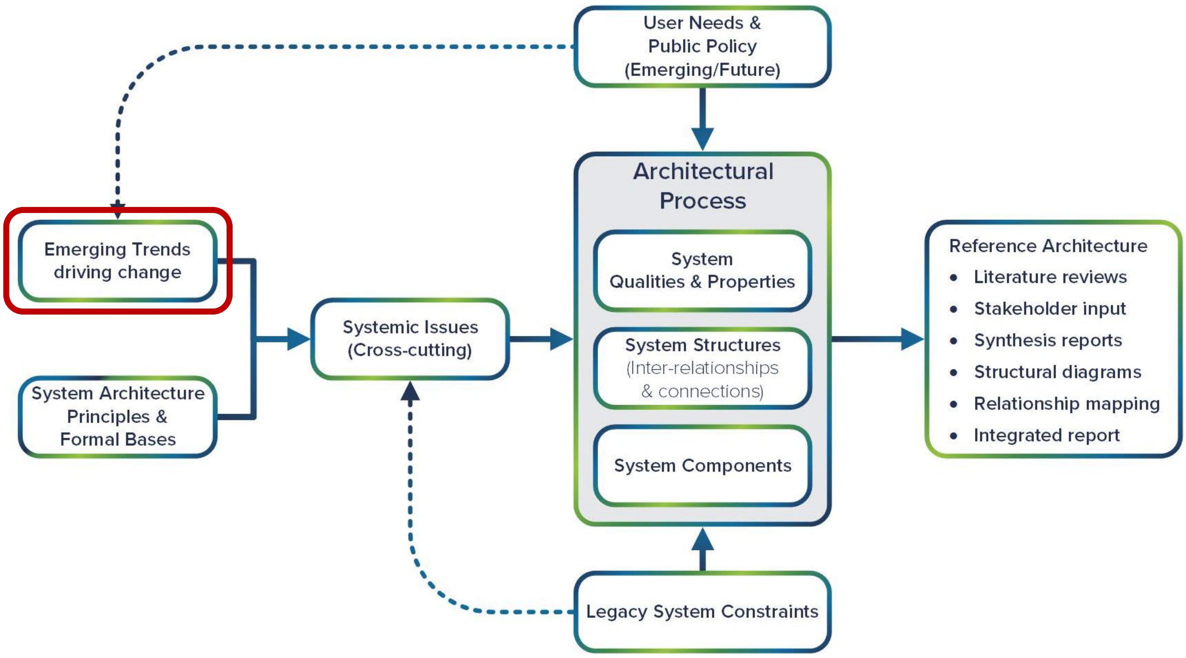


Figure 5: Mapping of the Emerging Trends driving change is a key step in applying the formal Power Systems Architecture methodologies.

Ensuring that the Systems Architecture of an ultra-complex societal system like the Power System is future-ready is vital at a time of large-scale transformational change. The veracity of such a process requires the detailed evaluation of Emerging Trends which function as the key drivers of change impacting the Power System. While this includes trends that directly impact one or several tiers/layers of the system (e.g. bulk power, transmission, distribution or retail), the distinctive focus of the Topic 7 project is considering the whole-system impacts and potential responses.

For the purpose of this report, Emerging Trends have been defined as follows:

Drivers of change that may significantly influence the evolution of Australia's GW-scale Power Systems over the next decade and beyond.

These drivers present challenges and impediments and/or new opportunities and potentialities that are either probable or plausible (not simply possible).

While some may be endogenous to the Power System, they are typically exogenous and include the impacts of evolving Customer & Societal expectations of future Power Systems.

As illustrated in Figure 5 above, the mapping of Emerging Trends is a key part of the formal Power Systems Architecture process. It is informed by the analysis of a wide range of policy, customer, technology, and other relevant developments and is a key input to mapping the cross-cutting Systemic Issues that must be addressed in the configuration of any future Systems Architecture, which are explored in Section 3.

Consistent with the whole-system orientation of the PSA discipline, over sixty Emerging Trends are mapped to the most relevant of the following ten categories. Each trend is stated, followed by a summary of its observable characteristics and implications.

1. Power System Structure
2. Operating Context
3. Generation Diversification
4. Load / Demand
5. Control Dynamics
6. Data & Communications
7. System Planning
8. Operational Forecasting, Management & Coordination
9. Markets & Commercial
10. Sector Coupling / Network Convergence

2.3. Section 3 – Systemic Issues

As Power Systems continue to decarbonise, they become orders of magnitude more dynamic and volatile. At its epicentre, the transformation involves moving from a few hundred large, dispatchable merchant generators to a future involving tens of millions of highly variable Energy Resources. In a major shift from 20th century norms, the proportion of system services sourced from this vastly more numerous and diverse fleet of Energy Resources will continue to increase year on year.

The importance of Systems Architecture disciplines, therefore, cannot be overstated where a complex legacy system is required to perform an expanding range of entirely new functions.

Key Concepts D

Operational Coordination

The systematic operational alignment of utility and non-utility assets to provide electricity delivery. It can also refer to structured mechanisms by which millions of diverse Energy Resources (merchant and private) operate both to serve individual priorities ('local selfish optimisation') and cooperatively participate to address common Power System issues.

As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, the proportion of synchronous generation declines, and decarbonising Power Systems experience unprecedented levels of Volatility, ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require:

> *Bulk energy, transmission and distribution systems – and the rapidly expanding fleet of distributed resources – to function far more dynamically and holistically across the end-to-end power system.*

Combined with exponential growth in Energy Resource numbers, types and ownership models, and the correlation between the economic value of grid services delivered and the physics-based needs of a Power System (which dynamically vary, both temporally and spatially), more advanced Operational Coordination models become critical to:

- Enhance dynamic Interoperability across the Transmission-Distribution Interface (TDI) due to the Power System's growing dependence on Energy Resources located both up and downstream:
- Support more granular 'market-control' alignment to incentivise and activate targeted provision of grid services in the form of Electric Products when and where most needed;
- Co-optimise the provision of grid services across the vertical Tiers/Layers of the Power System to both enhance operations and maximise the Electric Product Value for participants;
- Mitigate or avoid legacy Architectural Issues[9] that impede the Scalability, Extensibility and Resilience of Operational Coordination models; and,
- Ultimately enable transition to a more holistic Transmission-Distribution-Customer (TDC) model of Operational Coordination customised to local industry structure arrangements.

Co-optimisation

Co-optimisation is a structured approach to ensuring that Energy Resource services dispatched and/or financially incentivised in one vertical Tier/Layer of the Power System (e.g. Bulk Power, Transmission or Distribution System) are not driving unintended negative consequences in other Tiers/Layers of the system.

[9] Refer Key Concepts E

Consistent with Systems Science, this is because the original structure of any complex system will establish its essential capabilities and limits (i.e., its 'performance envelope').

In other words, compared with even a significant number of incremental improvements made to any complex system, well-targeted changes to its underpinning structure will typically deliver a disproportionate uplift in what it can reliably and cost-effectively do.

Given the less tangible but no less influential role of the underpinning Power System structures, Section 3 converges on a non-exhaustive list of ten Systemic Issues that will require architectural treatments if the NEM is to be efficiently and effectively transitioned. These are defined as follows:

Systemic Issues are cross-cutting conditions and/or structural settings that:

+ *Currently exist in the NEM and/or will arise from the convergence of various Emerging Trends (Section 2); and,*
+ *Will require architectural interventions if the emerging Customer & Societal Expectations of the NEM (Section 1) are to be enabled in a secure, cost-efficient, timely and scalable manner.*

Importantly, as Figure 6 (below) illustrates, the Power Systems Architecture approach is both holistic and externally aware. While *not* presuming the list of Systemic Issues examined to be exhaustive, the process of shortlisting them is critical to defining the 'problem space' to which architectural interventions must holistically respond.

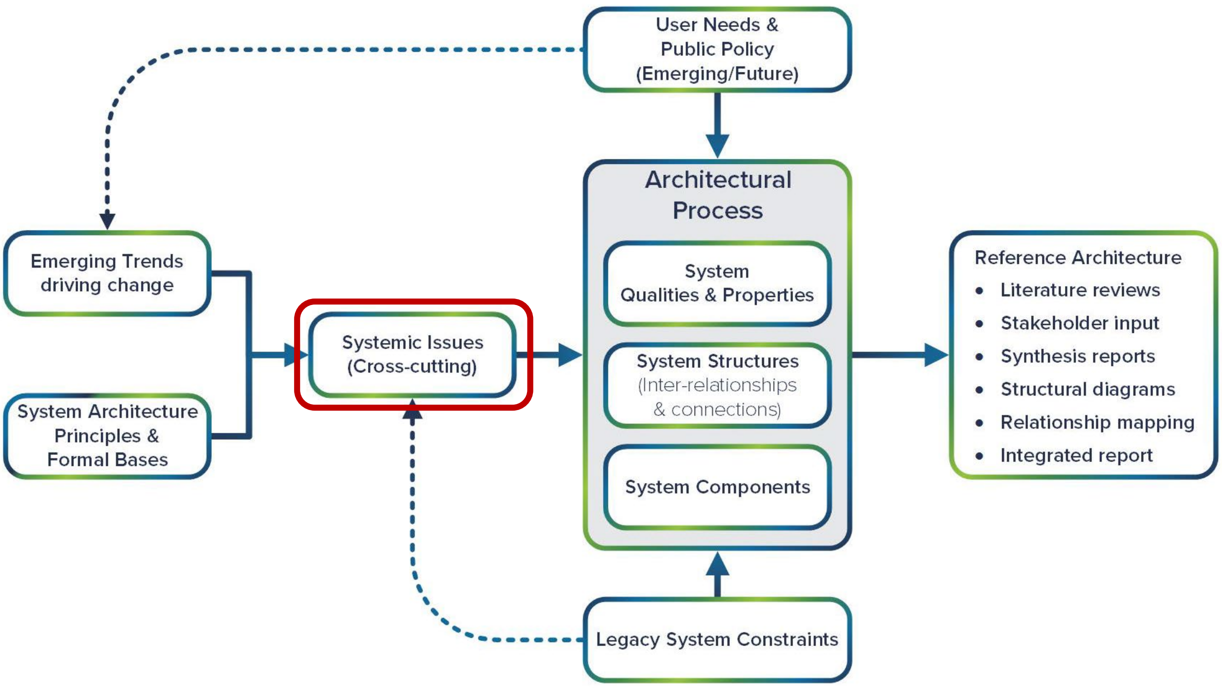


Figure 6: Converging on a set of cross-cutting Systemic Issues (Section 3) is a key step that informs the targeting of architectural interventions (Section 4).

For further consideration, the ten Systemic Issues identified are grouped under the three categories described below:

1. **Transition Constraints:** Fundamental considerations that influence many aspects of Australia's Power System and may impede our collective ability to navigate its transformation in a timely, efficient and technically robust manner.
2. **Core Structural Issues:** Structural and technological shifts that will become increasingly necessary to underpin Australia's Power System transformation from hundreds of centralised to tens of millions of ubiquitous energy resources.
3. **Future-ready Roles and Responsibilities:** Key considerations about how roles, responsibilities and detailed system interfaces may be provisioned to cost-efficiently manage the whole-system operation of decarbonising Power Systems that experience massive increases in volatility, complexity and operational dynamics.

The ten Systemic Issues that have been clustered under these three categories and examined in this report are outlined as follows:

+ **Transition Constraints:**
    - **Escalating Complexity Risk:** As an ultra-complex system experiencing profound change, the Operability of the NEM faces increasing risk where the growth of structural complexity is not formally and holistically managed.
    - **Benefits Realisation Risks:** The lack of both detailed structural mapping of the legacy Power System and shared transition methodologies exacerbates complexity and the potential for multi-stakeholder disagreement, slowing the realisation of $-billions of whole-system optimisation benefits for customers.
+ **Core Structural Issues**
    - **Profound Structural Shifts:** As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, legacy structural settings experience growing stress in a context where no single entity is responsible to holistically ensure the end-to-end Systems Architecture is future-ready.
    - **Inadequate Visibility:** The lack of a comprehensive approach to whole-system Visibility, especially of the growing fleet of LV-connected Energy Resources, risks compromising the Predictability and Resource Adequacy analysis of the NEM.
    - **System Coordination Risks:** More advanced, whole-system Operational Coordination is required in a decarbonising Power System that experiences growing Volatility and requires the beneficial participation of millions of Energy Resources to balance supply and demand and provide grid services.

- **Modelling Integrity Risks:** As Power Systems experience changes impacting technology mix, operational volatility and underpinning architectural structures, the usefulness of existing models must be constantly evaluated to ensure they are fit-for-purpose in a transformational context.
- **Cyber-security Vulnerabilities:** Layered cyber-security defences require the identification and treatment of non-cyber structural vulnerabilities to achieve a Power System that is inherently more resistant to cyber-attack.
- **Multi-party Data Sharing Risks:** Comprehensive options analysis and the formal application of Systems Architecture disciplines is required to mitigate non-trivial data sharing risks including Scalability, Extensibility, Cyber-security and Anti-resilience issues.
- **DER/CER Flexible Export Risks:** Greater whole-system perspective is required in the further development of DER/CER flexible export solutions to mitigate potential instability issues and non-linear behaviours, ensure capacity allocation equity, and achieve full benefits realisation.

+ **Future-ready Roles & Responsibilities**
    - **Roles & Responsibilities Risks:** High-resolution analyses of Power System structures, multi-entity relationships and data flows – in the current, future, and transitionary states – are key to identifying holistic, least-regret and future-ready options for evolving Roles & Responsibilities.

Finally, it is important to note from the above Systemic Issues definition recognises their relationship with the wide range of Emerging Trends that are driving change (Section 2). Further, they have been shortlisted on the basis that, where unaddressed, the Customer & Societal Objectives for the future NEM (Section 1) are unlikely to be achieved in a secure, cost-efficient, timely and scalable manner.

2.4. Section 4 - Evolving System Structures

Over the next decade, the expanding number of participating Energy Resources and the increasing complexity of Operational Coordination will continue to grow by orders of magnitude. Informed by Sections 1 – 3, some characteristics that are already well recognised include:

+ The NEM's transition from hundreds of participating Energy Resources to tens of millions;
+ Increasing Volatility throughout and across all Tiers/Layers of the Power System (including Bulk Power, Transmission and Distribution Systems) with the transition to highly variable generation; and,
+ Power System digitalisation driving the transition from slow data sampling to fast streaming data, vast data volumes and a declining tolerance for latency.

In this context, Interoperability standards, Two-sided Markets and Dynamic Operating Envelopes (DOEs), for example, are all expected to play key roles in supporting Australia's future Power Systems.

Key Concepts E

Architectural Issues

Following are seven important structural issues that the System Architecture discipline addresses that will otherwise negatively impact the Operability and Resilience of decarbonising Power Systems:

1. **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System's operational hierarchy.
2. **Coordination Gapping**: An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation.
3. **Hidden Coupling:** Two or more control entities with partial views of System State issue simultaneous but conflicting coordination signals to a DER/CER or Component of the Power System.
4. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
5. **Computational Time Walls:** Where excessive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines will hit a computational 'time wall' at some point where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time.
6. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
7. **Back-end Integration Constraints:** Multiple vertical silo structures found in many supply-chain organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others.

However, where the legacy 'as built' Structural settings are not well aligned with the rapidly emerging future needs of the NEM, costly scaling and fragility issues will arise, such as: latency cascading, computational constraints and time wall effects, and cyber-security vulnerabilities. These in turn will progressively erode the Reliability, Resilience and Efficiency of the NEM and exacerbate upward cost pressures.

A range of analytical methods have been successfully applied to evolving individual elements of the NEM over the last several decades. The magnitude and pace of transformation now unfolding, however, presents a new class of decisions that are architectural in nature and will require architectural interventions to resolve.

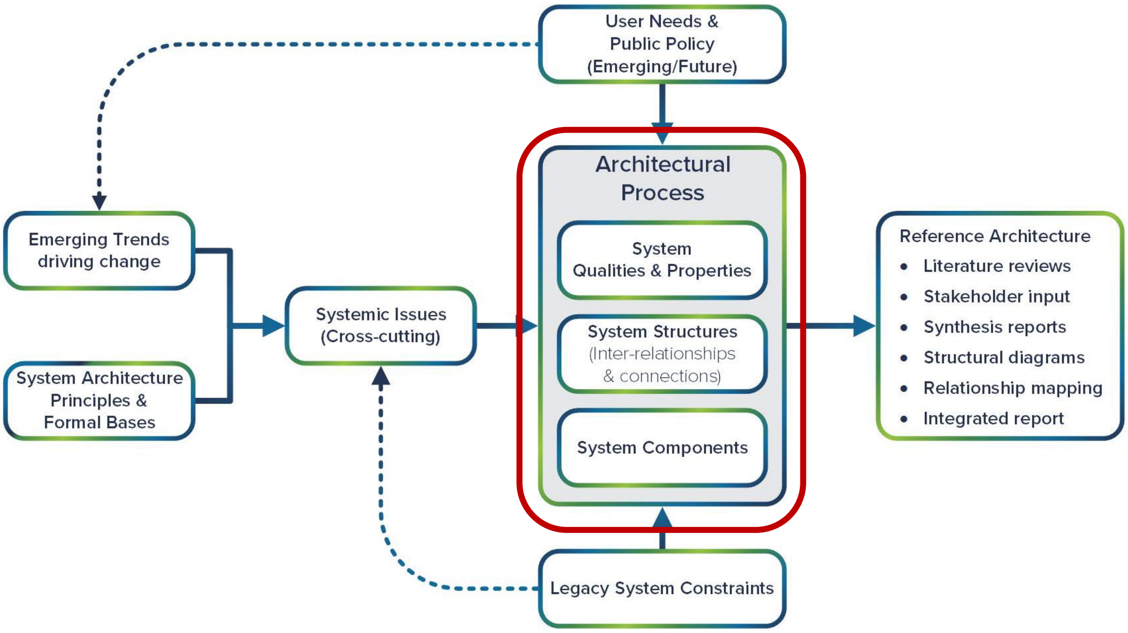


Figure 7: The architectural process of Section 4 draws upon the range of inputs developed earlier in the project to particularly focus Emerging System Structures.

In profound transformation, architectural interventions are unavoidable because the original 'as built' Structure of any complex System always establishes its essential capabilities and limits (i.e. the 'performance envelope' and functionality of the System).

Where any highly complex legacy System like the NEM is required to perform an expanding range of entirely new functions, the application of Systems Architecture disciplines is pivotal to the timely identification of the minimal structural interventions required to deliver maximal System capability uplift. Compared with any number of incremental changes, targeted enhancements to the underpinning Architecture will deliver a disproportionate uplift in what a complex System experiencing transformation can reliably and cost-effectively do.

As Figure 7 (above) illustrates, Section 4 draws upon and integrates a range of inputs examined and presented in Sections 1 – 3. In the context of a Reference Architecture project, it gives particular attention to the 'as built' and plausible future Structures that are likely to be necessary to underpin NEM operations. It does so by:

+ Providing an overview of the approach taken to interrogating the seven interdependent structure classes that constitute modern GW-scale Power Systems;
+ Examining and illustrating how these seven structure classes are configured in the 'as built' NEM – something not available in any other single set of artefacts;
+ Providing an overview of the approach taken to considering and illustrating the plausible future Architecture(s) of the NEM;

+ Illustrating a Hybrid Architecture of the NEM and considering both strengths and weaknesses; and,
+ Illustrating a Layered Architecture example of the NEM and considering both strengths and weaknesses.

Finally, it is important to reiterate that the development of a preliminary Reference Architecture is somewhat like an initial 'prototype' of a highly complex system. It provides a powerful mechanism for shared learning and collective reasoning about the system but will, by its nature, contain gaps that need to be addressed in subsequent phases of work.

3. KEY OBSERVATIONS

The development of this seminal Reference Architecture provides additional whole-system perspective of the entire NEM in its current, transitional and plausible future operational contexts.

Developed through the application of the best practice methodologies identified in Stage 1, the Reference Architecture is somewhat like an initial 'prototype' of a highly complex system. As such, it does not presume to provide '*the* answer'. However, it does provide a powerful mechanism for shared insight and collective reasoning about such a complex system as it experiences unparalleled transformation.

Following are several key observations derived from the development of the Reference Architecture with reference to several current challenges, how Power Systems Architecture can help and potential next steps.

3.1. Current challenges

This development of the NEM Reference Architecture in Sections 1 – 4 has highlighted a range of emerging challenges, including the following:

1. As Power Systems such as the NEM emerged and evolved over many decades, it is common to find that no complete and agreed set of documents exists representing how all seven inter-dependent structure classes[10] constituting a modern grid are configured, how they dynamically interact, and which party or parties (if any) is responsible for ensuring the structures remain fit-for-purpose in a changing context.

2. In Australia and around the world, the transformation of GW-scale Power Systems is being driven by a wide and diverse range of Emerging Trends, many of which are converging into cross-cutting Systemic Issues that will increasingly impact the security and efficiency of the end-to-end system, and that cannot ultimately be addressed in isolation, or in the absence of more holistic architectural approach.[11]

3. As decarbonising Power Systems experience growth in operational Volatility, Complexity and inter-dependence with various Sector Couplings (e.g. water, transport, gas, etc.), the ability of more linear, conventional models of planning, investment decision-making and regulatory reform to guarantee the future Scalability and Extensibility of proposed investments is increasingly under challenge.

[10] Refer Key Concepts B - The Grid as a 'Network of Structures'

[11] Refer Sections 2 and 3 of this report.

4. Where there are no widely agreed, objective and fit-for-purpose methodologies for performing structural analyses of the end-to-end Power System (supported by a shared set of key definitions), inappropriate tools and techniques can and have been applied that do not provide the required architectural rigour and risk further exacerbating complexity and stakeholder misalignment.

5. The complexity of Operational Coordination[12] in a Power System transitioning from hundreds to tens of millions of participating Energy Resources that are located across several Tiers/Layers of the grid, is expanding by orders of magnitude, the impacts of which are further compounded by constraints that are embedded in the legacy structural arrangements.

6. Where a transition of the NEM broadly consistent with AEMO's Step Change scenario continues, the expanding range of Architectural Issues[13] already emerging will only continue and increase where the structural constraints embedded in the legacy NEM architecture (and some proposed hybrid models) remain unaddressed.

7. The timely and detailed consideration of critical new Power System functions and capabilities, such as Distribution System Operator (DSO) models and Transmission-Distribution Interface Mechanisms (TDIM) will require, and is currently impeded by the lack of, whole-system architectural analysis and supporting methodologies.

8. The rigorous consideration of future-ready Roles & Responsibilities, and their many Interfaces between subsystems, will similarly require, and is currently impeded by the lack of, whole-system architectural analysis and supporting methodologies.

9. A diversity of customer and societal objectives for their future Power Systems exist[14], some of which present significant architectural implications that will require considered trade-off processes if a sufficiently balanced scorecard of outcomes acceptable to both diverse stakeholders and system operators is to be achieved.

10. In an emerging context where Bulk Power, Transmission and Distribution Systems – and the expanding fleet of distributed resources – will need to function far more holistically and dynamically together, no entity has responsibility for ensuring the readiness of the end-to-end NEM Systems Architecture[15] for enabling such a future.

[12] Refer Key Concepts D – Operational Coordination

[13] Refer Key Concepts E – Architectural Issues and Section 4 of this report.

[14] Refer Section 1 of this report.

[15] Refer Key Concepts C – Systems Architecture, noting this includes but is not limited to technology Interoperability and related standards development.

3.2. How Power Systems Architecture can help

The application of formal Power System Architecture (PSA) methodologies, in combination with conventional tools and techniques, can profoundly enhance the ability to develop holistic and future-ready approaches to Power System transformation. This is because PSA:

1. Provides powerful techniques to interrogate and manage the Ultra-Large-Scale (ULS) complexity of transforming Power Systems, informed by ULS theory, Systems Architecture, Network Theory, and other related disciplines.

2. Enhances multi-stakeholder participation and trust by providing formal and transferrable methodologies, templates and frameworks that can be employed by diverse stakeholders to collectively examine and more effectively reason about transformation options and trade-offs.

3. Enables planners, regulators and market/system operators to describe both current and potential future Power System structures in a holistic and uniform manner, which enables more precise interrogation of desired System characteristics before committing large investments to effect change.

4. Supports 'least regrets' decision making to enhance the future Scalability and Extensibility of major investments by enabling the early detection and avoidance of significant Architectural Issues which would not otherwise be discovered until long after investments had been made.

5. Widely agreed, objective and fit-for-purpose methodologies for structural analysis of the end-to-end Power System provides all entities working on individual Components or Subsystems of the NEM with greater latitude to innovate, a better comprehension of how their work interfaces with the rest of the System, and greater assurance that unintended consequences will not emerge to hamper or invalidate their work.

6. Provides empirically based approaches for moderating the complexity of advanced Operational Coordination, expanding the future readiness of the System as it transforms toward a context involving many millions of participating Energy Resources located across several Tiers/Layers of the Power System.

7. Enables a robust and step-wise approach to the consideration of alternative Distribution System Operator (DSO) models and Transmission-Distribution Interface Mechanisms (TDIM), including their respective merits in the current and plausible future states, and the potential range of transitional pathways between them.

8. Enhances far more detailed consideration of Roles & Responsibilities, together with their granular system Interfaces and interdependences over several time horizons, through the application of whole-system architectural analyses and supporting formal methodologies.

9. Provides an objective and transparent set of methodologies that key entities may apply to validate the optimality, future readiness and stakeholder benefits of proposed solutions in support of enhanced stakeholder engagement, trust and social license for change.

For these reasons, it is not just important, but crucial, that the structural issues addressed by Power System Architecture be systematically considered as a key element of provisioning the NEM to meet current and future needs.

3.3. Next Steps

The development of this Reference Architecture provides an initial, prototypical model of the complex structural relationships that underpin the NEM. This provides stakeholders with an initial demonstration of how Systems Architecture-based methodologies enable more effective collaboration on, and reasoning about, alternative transformation pathways.

Consistent with Systems Architecture practice, the development of such a Reference Architecture functions as a precedent step to enabling the co-design and execution of the subsequent Detailed Architecture phase. For an ultra-complex system such as the NEM, this subsequent phase is critical for developing significantly more detailed analysis of a highly complex system in the context of much wider, multi-stakeholder collaboration.

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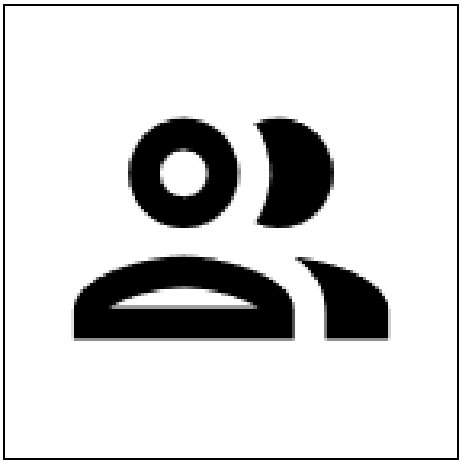

SECTION 1: CUSTOMER & SOCIETAL OBJECTIVES

Authors:
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SECTION 1: CONTENTS

1. SECTION 1 INTRODUCTION

1.1. Purpose Section 1

Power Systems are complex techno-economic systems that have a critical societal role. Given the many essential functions they perform in a modern economy – and the growing potential for customer participation – any credible consideration of future architectural options must be informed by what customers and policy makers are expecting of these systems in the future.

The PSA discipline is fundamentally stakeholder and user-centric. Therefore, this report provides a synthesis of Customer & Societal Objectives for future Power Systems as expressed in the Australian and global literature and corroborated by stakeholder workshops. Its findings are foundational to the entire Reference Architecture development process as it provides a diversity of insights as expressed by external stakeholders including end-user customers (residential, commercial, and industrial) and public policy makers.

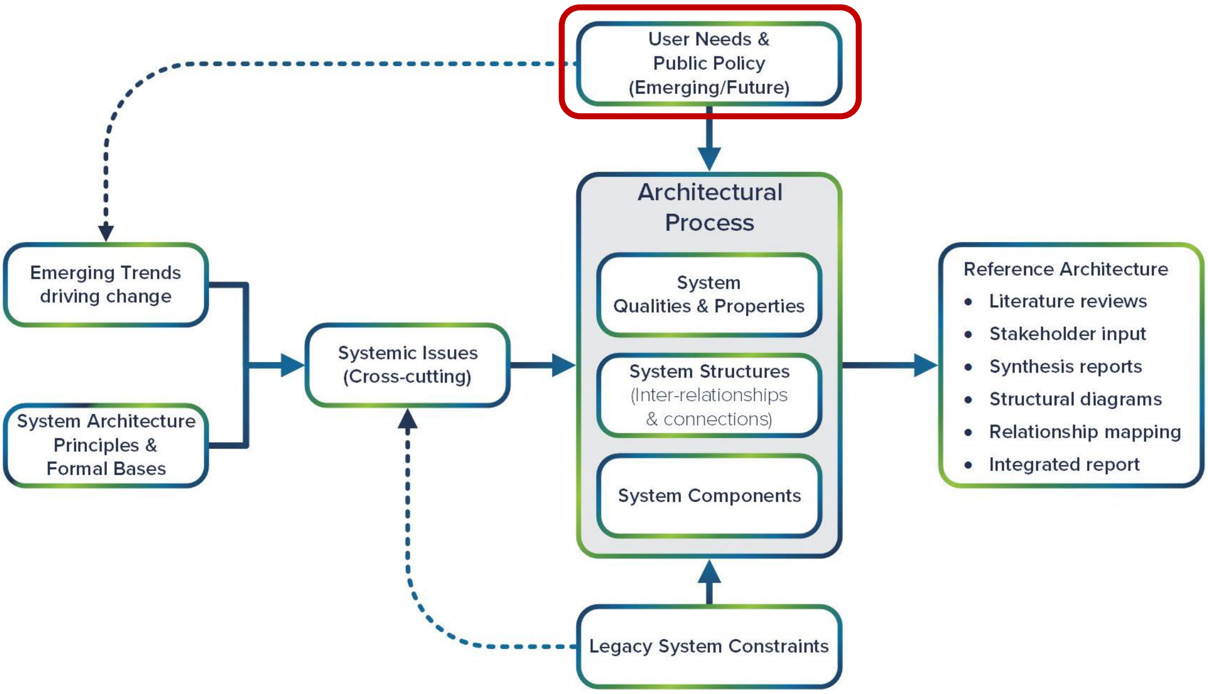

Figure 1: Examining Customer & Societal Expectations for the future Power System is a pivotal step in applying formal Power Systems Architecture methodologies.

Eight key objectives have emerged from the Australian and global literature. Like society itself, it is acknowledged that a complex tapestry of relationships exists between the various objectives, several of which will impact other objectives. As such, the practical application of the various objectives would require a process of societal prioritisation and trade-offs.

As a Reference Architecture process, it is important to note that the societal process of prioritising these objectives would be addressed in a subsequent Detailed Architecture phase. In this context, the objectives are outlined to provide a summary of key traits that future power systems would, to varying degrees, need to exhibit to satisfy customers and policy makers, and which therefore should inform and guide planning and design decisions.

1.2. Research Approach

This literature review is based on the analysis of the 37 most relevant primary sources from customer advocates, academia, and industry, originating from Australia, North America, the United Kingdom and the European Union (refer Appendix A). Strategen has shortlisted these sources from an expansive range of potential reference materials to ensure diversity of representation, content relevance and future orientation.

In forming the proposed Objectives, consideration was given to:

+ Ensuring the 'voice of the customer', as represented in the literature, is the evidence base for identified objectives;
+ Providing a diversity of perspectives from customer / end-users and policy makers;
+ Ensuring each objective is as distinct as possible (while some overlap is unavoidable).

In seeking to fairly report the findings, no opinion is offered on the appropriateness or otherwise of these objectives.

2. IDENTIFIED FUTURE OBJECTIVES

A consolidated summary of the diverse range of future customer and societal objectives ("Objectives") for the power system that emerged from the literature are provided below. Customers and policy makers variously state that the future power system must be:

1. **DEPENDABLE**: Safe, secure, adequate, reliable and resilient;
2. **AFFORDABLE**: Efficient and cost-effective;
3. **SUSTAINABLE**: Enables 2030 and 2050 decarbonisation goals;
4. **EQUITABLE**: Broad accessibility of benefits and the fair sharing of costs;
5. **EMPOWERING**: Advances customer and community agency, optionality, and customisation;
6. **EXPANDABLE**: Enables electrification of transport, building services and industrial processes;
7. **ADAPTABLE**: Flexible and adaptive to change, including technological, regulatory and business model innovation; and,
8. **BENEFICIAL**: Socially trusted, public good/benefits, commercially investable and financeable.

Figure 2: Eight themes of Customer & Societal Expectations for future Power Systems

3. KEY FINDINGS IN DETAIL

3.1. General Observations

Based on the range of primary sources identified in Appendix A, the following general observations can be made:

+ The increasing choice customers are expected to encounter in the future, primarily due to the rapid rise in demand side participation and digitalisation enabling more sophisticated on-premise energy management, is a key focus of much of the literature. However, increasing choice presents both challenges and opportunities for customers.

  Opportunities include increased optionality in products and services offered by energy service providers, such as the ability to trade-off previously bundled features for financial benefit. Challenges include the vulnerability faced by those who, for a variety of reason, don't or can't choose energy solutions that reduce cost and increase convenience. In this context, much of the literature provides a treatment of customer engagement with, and agency in the choices that will and should be available to them in the future power system. Simple, no-nonsense options for affordable energy provision as an essential service was often advocated. It is expected that many people won't want their interaction with energy providers to be all that different to that of water, internet, or mobile phones today.
+ Related to the above, a comparative scarcity of discussion on first order qualities such as the safe, secure, adequate, reliable, and resilient supply of electricity to customers was noted. Limited reference to these qualities is perhaps best explained by the simple fact that they are intrinsic to the foundational purpose of the electricity grid, and therefore are assumed as a given in any future power system. Even so, these future objectives are self-evident and therefore have been included in the below list of plausible future objectives from a customer and sectoral perspective.
+ Prominent in the literature is the assumption that automation will be a key feature of customer-facing energy solutions in the future. This conclusion is based on the prevalence of demand side participation, such as time-shifting loads, coupled with customers busy lives and unwillingness to give time and energy to the many micro-choices that they would otherwise need to make without automation pre-configured with user preferences.
+ Trust and transparency issues were highlighted across source documents, most commonly in the context of system actors working in the best interests of customers. An oft-repeated assertion was that system operators have historically viewed customers as untapped resources for system services, rather than diverse people with differing values, preferences and expectations which affect how they engage with the power system. To maximise demand side flexibility in a system with intermittent renewables, customers will need greater confidence, both when evaluating prospective providers, and when they're

dealing with their contracted provider, that their values, preferences, and expectations are met.

+ Further to the above, the literature surveyed identified the need to rethink customer 'safety nets' as enshrined consumer rights and protections laws. Particular attention was given to ensuring vulnerable consumers aren't left behind due to circumstances outside their control. It was often argued that energy service providers will need to be more proactive about supporting their disadvantaged customers, including renters and those under shared roofs (apartments, town houses, business complexes, warehouses). This consideration also applies to how demand side participation programs are designed and implemented. Disadvantaged and vulnerable customers should be provided fair and equitable access and financing options to participate in load management programs.

3.2. Overview of Dominant Themes

The following summarises the common themes from the literature within each plausible future objective.

3.2.1. DEPENDABLE: Safe, secure, adequate, reliable, and resilient

As noted above, reference to self-evident objectives of the power system were less common in the literature as they are often assumed. However, sources did note that in a modern society dependable energy is an enabler of an expanding range of other services. As increasingly electrified, automated and digitised businesses and lifestyles expand their reliance on these services, a dependable power system is of even more critical importance [1] [2] [3]. Sources also maintained that electricity should continue to be considered an essential service into the future, even as consumer sovereignty over their own energy production and consumption increases [4] [5]. As an essential service, ultimate responsibility for a dependable power system for all will continue to reside with government [5]. Commentators also noted that as the power system modernises and becomes more automated, digitised, better coordinated and less centralised, the potential for improving reliability, resilience, and the time taken to restore services increases, and should therefore be prioritised to the benefit of customers [4] [6]. However, digitisation also introduces new challenges and vulnerabilities, such as data privacy and cyber-security, which must be addressed to provide a safe and secure system [7].

> *Consumers can rely on having affordable energy for comfortable homes and competitive businesses.*
>
> ECA - Strategic Plan 2021-2024, October 2021
>
> *Energy companies improve energy affordability for customers to the point that customers consider energy to be good value, and there is significant evidence supporting this collective customer sentiment.*
>
> Energy Charter - Maturity Model, September 2020

3.2.2. AFFORDABLE: Efficient and cost-effective

Affordability was recognised in the literature as a priority objective with significant scope for improvement in the future power system [2] [4] [8] [9] [10] [11]. As a baseline, Energy Consumers Australia's recent Energy Consumer Sentiment Survey indicates cost of electricity supply has the lowest level of satisfaction across all retailer measures assessed (Figure 3) and the value for money of electricity services as equal lowest across all services assessed (Figure 4) [12]. Various sources also highlighted that many emerging features of the future power system are tightly coupled with affordability, such as automation, demand-side flexibility, cost-reflective tariffs, unbundling of energy services, energy efficiency [1] [4] [8] [11].

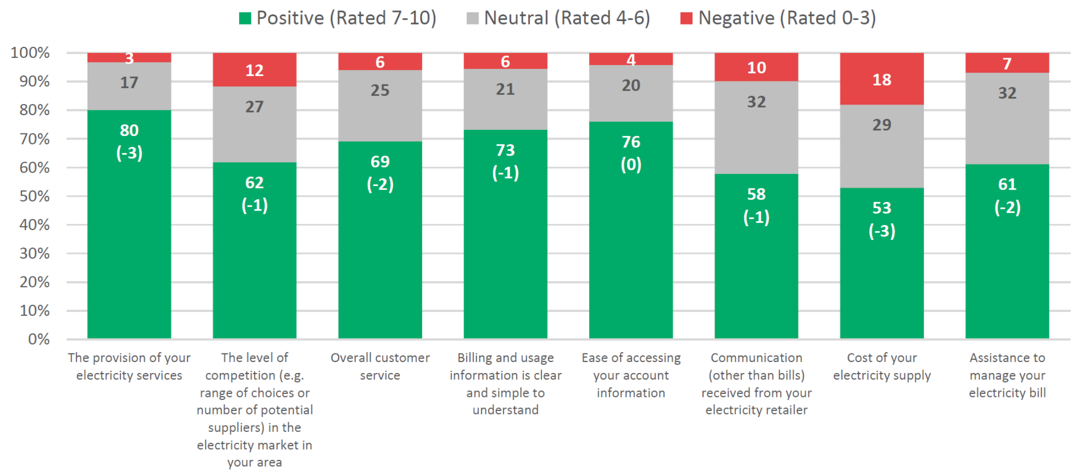

Figure 3: Satisfaction with Retailer Measures: Electricity[12]

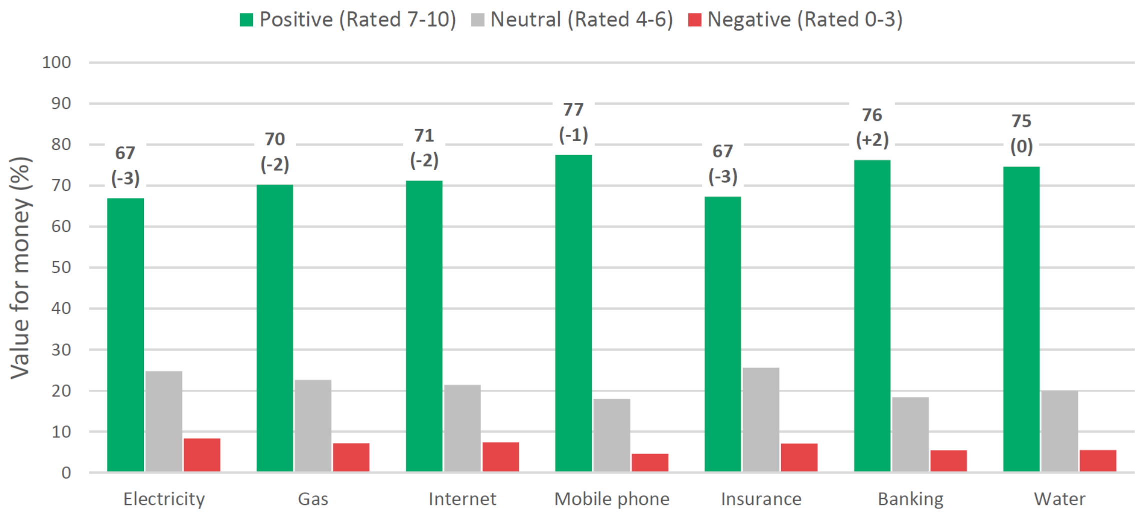

Figure 4: Value for money of all services [12]

Efficient investment in utility-scale infrastructure and utilisation of existing transmission and distribution were also raised across multiple sources as a key determinant of affordability for customers that will continue to require rigorous attention [3] [4] [7] [11] [13] [14]. Some sources discussed the need for customer's perception of value of their energy services to better align with the costs they incur [15], and similarly, that customers are confident that competition and cooperation across the supply chain are resulting in increased affordability [4] [10] [16].

3.2.3. SUSTAINABLE: Enables 2030 and 2050 decarbonisation goals and related technologies

> *Energy companies have improved the customer experience of organising, transacting, consuming, and providing energy. There is optimised, effective, and easy access to useful and portable data that empowers customers to make energy decisions that provide individual and societal benefit.*
>
> 2020-09 Energy Charter - Maturity Model
>
> *Data regarding customers' energy usage patterns is carefully, privately, and securely collected. This data is readily and easily interpretable for customers, such that they feel meaningfully informed and confident making decisions which will positively impact both themselves and the collective society.*

Customers increasingly acknowledge shared responsibility for the power system to decarbonise and are motivated to adapt their energy use accordingly. As such, enabling customers to conveniently choose to procure their electricity from sustainable and affordable sources was a common theme in the literature [3] [8] [16] [17] [18] [19] [20]. Energy efficiency, energy productivity, and the environmentally responsible building and decommissioning of energy infrastructure and components were also highlighted as contributing to a sustainable power system [3] [13]. Finally, sources noted that customers want clear, transparent, and accountable reporting on the environmental impact of their own choices and those of their providers [3].

3.2.4. EQUITABLE: Accessibility of benefits and fair sharing of costs

Ensuring equitable outcomes in a rapidly changing power system presented as another key priority for customer advocates [3] [5] [16] [20]. Several sources identified the need to ensure the benefits of a future modernised power system are distributed fairly across all customers, such that those with limited access to new energy products and services do not incur a disproportionate share of the costs of operating that system [8] [11] [21] [22]. Fit-for-purpose consumer protections featured in the literature as an important mechanism to ensure those participants in the power system with limited access are not disadvantaged [9] [14].

Another emerging challenge identified is minimising complexity and providing relevant information on offerings in a clear and concise manner [16] [11]. As the customer base diversifies, and energy products and services proliferate, it is important that all customers, regardless of their experience or knowledge, have easy and simple information and fair access to platforms and product/service offerings most suited to their circumstances [13]. This may include personalised and accessible quantitative data to inform decision making [4].

3.2.5. EMPOWERING: Advances customer and community agency, optionality, and customisation

The literature highlighted that, as the power system evolves and customers diversify in their preferences and priorities, facilitating customer and community agency will be a key challenge, opportunity and priority [8] [9] [11] [23] [24] [25] [26]. The design of new energy products and services and emerging technologies will need to carefully consider how they can empower customers to make informed choices, while at the same time not overwhelm them with micro-decisions that impact their lifestyle or business operations [5] [8] [14] [9]. This will require human-centred design and continuous feedback from their customer base as has been demonstrated by other sectors [2] [19].

It was also noted across various sources that empowerment includes:

+ Simple and intuitive platforms and user-interfaces for interacting with energy "events", products and services, including presentation of key data for decision making [4];
+ The ability to configure technologies, products and services to align with user and household preferences, routines and expectations [9] [7] [17] [27];
+ Enabling customers to easily compare offerings across competing providers and platforms [5] [13] [19]; and,
+ To retain simple no-frills arrangements should customers choose to do so [9] [12].

Similarly, sources suggested that communities will also have increasing optionality for meeting their energy needs, such as community batteries, virtual power plants, co-located small-scale generation and storage facilities, but will require the regulatory environment and policy settings to enable such solutions [4] [3] [14]. Finally, the literature observed that advancing customer agency will require all stakeholders, including government bodies, businesses, and individuals to have an agreed and coherent understanding of what customer agency and empowerment is, and to embed that in relevant policy and regulation [9] [23].

3.2.6. EXPANDABLE: Enables electrification of transport, building services and industrial processes

With the predicted levels of load growth in Australia, an expandable power system is critical. The literature affirmed that efficient supply-side investment in utility-scale generation, transmission and storage will be required to meet this objective [4] [11]. However, sources also identified the need to promote load flexibility for supply and demand balancing with much larger penetrations of VRE, supported by the strategic integration of energy storage across all levels of the power system and to moderate utility scale investment and avoid over-build [4] [7] [11] [14] [13].

In parallel, sources asserted the need for customer and industry facing energy product and service offerings and platforms to mutually benefit consumers and the operation of the power system. The literature pointed to managed EV charging as an example of an opportunity to enhance the orderly expansion of the power system through temporal and spatial load diversification – if offerings mutually benefit customers and the operation of the power system [17].

Other factors influencing expandability in the literature were operational scalability, data and communications infrastructure (and cyber security), and new and improved consumer-based appliances and other products with integrated energy management such as time-shifting load [4] [8] [7].

3.2.7. ADAPTABLE: Flexible and adaptive to change, including technological, regulatory and business model innovation

The literature reflected on the necessity of effective regulation, standards and policies that promote a highly interoperable and coordinated power system that can simultaneously accommodate a diverse range of business models, products, platforms and services while maintaining the security and stability of the system [7] [8] [21] [23]. This will enable customers to adopt new and innovative energy products and services offerings and new technologies as they emerge . In addition, enabling customer churn through an adaptable system will support customer-centred business model and product innovation through competition [3] [21]. Sources also noted that 'least regrets' decisions that enable the power system to be resilient to broad range of plausible futures reduces the risk of stranded assets and other costs involved with the transition [3]. Similarly, staged implementation of reforms to the power system that consider the long-term effects on optionality for customers was recommended [3] [8].

> *Technical standards for hardware enable informed and competitive consumer choice to more interoperable and easily accessible product and services options.*
>
> Energy Consumers Australia - Social License for DER Control FINAL v2.0, December 2020.

3.2.8. BENEFICIAL: Socially trusted and public good

Third party control and automation of privately owned energy assets is an important feature of a modern power system that, done well, benefits customer and the system. However, the literature emphasised that without social licence for control of privately owned assets, participation in such programs will be reduced, and potential cost-saving benefits to the system forgone [16] [21]. Specifically, customer-facing actors such as aggregators and retailers will need to manage concerns around loss of control, data security, privacy, and disruption to daily routines to be

> *To obtain a social licence, close to 100% of consumers with DER subject to control must perceive the benefits of the control to outweigh the private costs.*
>
> ECA - Social License for DER Control FINAL v2.0, December 2020

granted the social licence to operate these assets [8] [21].

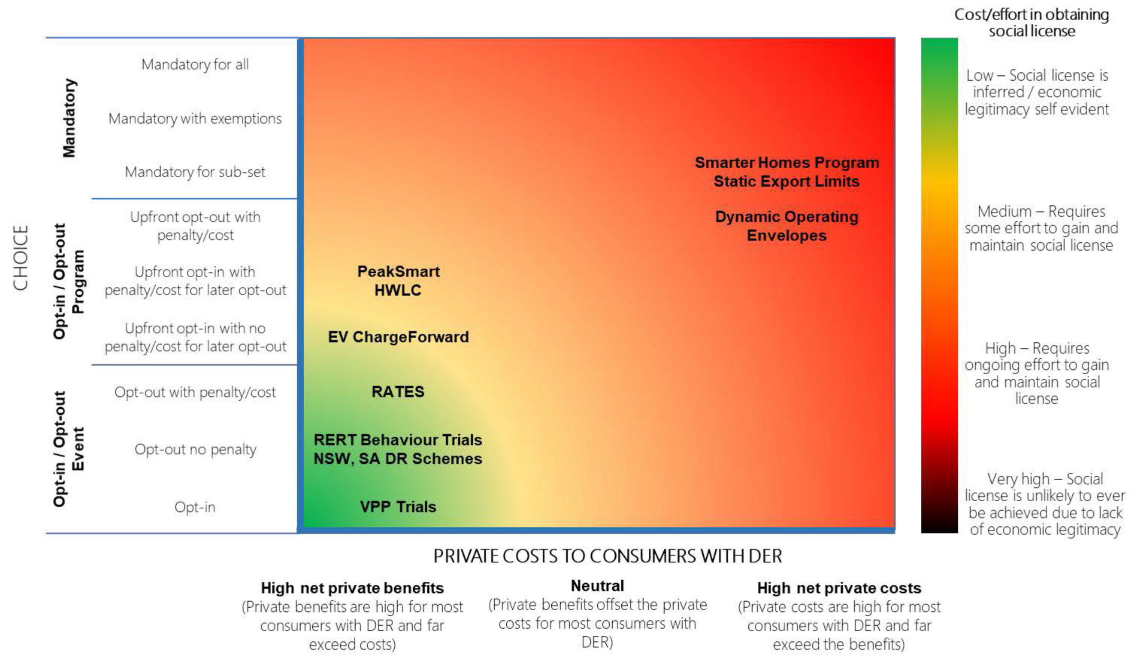

Figure 5: DER Control Programs Social Licence Assessment [21]

All parties will need to build trust by emphasising customer agency in the design of their platforms and systems and in their engagement with customers. Promoting and educating customers on the societal good that comes from enrolling their assets in programs that support the efficient operation of the power system will also be important [7] [14] [19]. Finally, sources concluded that the degree to which customer voice, concerns, and lived experience are reflected in customer facing product and service offerings will be the degree to which social license is obtained, which will in turn impact the success of such programs [19] [2].

4. SYNTHESIS MATRIX

The following tables provide supporting content to the plausible future objectives outlined above. Note that each entry may be applicable to several objectives, but for simplicity has only been listed against one objective. For consistency, each excerpt has been reframed to read as a future oriented objective. In many cases, the future objective has been inferred from current or nearer-term priorities described in the source content that are applicable to longer-term objectives for the power system.

DEPENDABLE: Safe, secure, adequate, reliable, and resilient	
Source	Stated or Inferred Objectives (Future Tense)
2022-06 ECA -– Energy Consumer Sentiment Survey -– Small Business	Small businesses are satisfied with their interaction and experience of the power system across the following areas: provision of electricity, customer service, billing platforms and arrangements, value for money, time to restore following outages, advances in technology, future reliability, ability to access information and tools, ability to make choices, confidence in the market, and dispute resolution.
2022-04 ESB -– Customer Insights Collaboration Workshop 2 -– Exploring the issues	Data regarding the customers'' energy usage patterns and interfacing with energy management platforms is carefully, privately, and securely collected. This data is readily and easily accessible and interpretable for customers, such that customers are meaningfully informed and able to and feel confident making decisions which will positively impact both themselves and the collective society.
2022-02 Our Power – A vision for clean, affordable, dependable energy for all	Ensure that the energy system can operate safely and securely regardless of how energy is produced. Engage with people and communities on investment and services so that energy is delivered in line with expectations, particularly when it comes to price, reliability and resilience. Improve the resilience of people, communities, businesses and institutions as well as the energy system to manage the increasing frequency and intensity of severe weather events as well as cybersecurity and other unforeseeable or 'black swan' events such as Covid-19. Develop metrics for resilience, especially relating to localised long duration outages caused by severe weather events. Ensure the transparency of reliability, security and resilience data to inform decision-making and efficient investment.

DEPENDABLE: Safe, secure, adequate, reliable, and resilient	
Source	Stated or Inferred Objectives (Future Tense)
	Strong and well-supported regulators to work with people, communities and energy participants to design, implement and oversee affordable, clean dependable energy.
2021-12 PEI –– Customer Load Management Evolution & Revolution	Customer impacts and disruptions caused by load management are imperceptible as they operate autonomously.
2021-10 ECA – Strategic Plan 2021-2024	Consumers experience cheaper and more reliable electricity supply from a modern power system that incorporates hardware and software that increases the speed and breadth of communication, artificial intelligences that delivers improved optimisation and responsiveness, monitoring and data that make delivering electricity more efficient. Households and small businesses benefit from a modernised system that can reduce the frequency and duration of power outages and restore service faster when outages do occur.
2021-01 ECA - Future Energy Vision Research - Households	Technology enables customers to automate when things turn on and off to save energy and money.
2020-11 ACOSS –- New Energy Compact Consultation Draft 5	Consumers can depend on energy system resilience and efficiency across the supply chain, efficient energy use and new technologies and services are promoted for the benefit of people and the environment.
2020-11 ACOSS - New Energy Compact Consultation Draft 5	The power system is flexible, innovative, responsive, and based on consumers' expectations.
2020-05 Monash –- Ron Ben-David on Two Sided Markets	Energy is provided to customers as an essential service. Similar to other essential services, the provision is reliable, sustainable, and affordable, and enabled by effective policy.
2019-10 FFRC -– Electrification in a Peer-to-Peer Society	Energy is perceived as ubiquitous and abundant by participants in the energy system, which changes how they use energy personally, what business models arise, and how the system is coordinated.

DEPENDABLE: Safe, secure, adequate, reliable, and resilient	
Source	Stated or Inferred Objectives (Future Tense)
2015-12 CSIRO & ENA -– Customer-centric Networks	Customer''s value electricity solutions that provide secure and reliable electricity, given their dependence on increasingly automated and digitised economy and lifestyle

AFFORDABLE: Efficient and cost-effective	
Source	Stated or Inferred Objectives (Future Tense)
2022-03 ECA - Feedback on the Draft AER Consumer Vulnerability Strategy	Rigorous attention is paid to ensure there is efficient investment and effectively utilising the capacity of the transmission and distribution networks as part of a collective commitment to improve affordability for consumers.
2022-03 ECA - Feedback on the Draft AER Consumer Vulnerability Strategy	The overall cost to serve is minimised through an effective balancing of energy products and services affordability and consumer protections.
2022-02 Our Power – A vision for clean, affordable, dependable energy for all	Ensure that investment in, and the operation of, the energy system is economically efficient and avoids wasting money and resources. There should be fair and efficient allocation of costs, which should be borne first by the beneficiaries of the energy transition. There should be fair allocation of risks, which should be borne by those who are best able to manage and mitigate them in the interests of energy users. Ensure that the energy system can operate safely and securely regardless of how energy is produced. Engage with people and communities on investment and services so that energy is delivered in line with expectations, particularly when it comes to price, reliability and resilience. Improve the resilience of people, communities, businesses and institutions as well as the energy system to manage the increasing frequency and intensity of severe weather events as well as cybersecurity and other unforeseeable or 'black swan' events such as Covid-19. Provide incentives and prioritise energy solutions relating to energy demand including energy efficiency. Improve the utilisation of existing generation and network infrastructure. Enable energy management technology and behaviour that enhances outcomes for energy users and reduces the costs of the energy system. Develop metrics for resilience, especially relating to localised long duration outages caused by severe weather events. Ensure the transparency of reliability, security and resilience data to inform decision-making and efficient investment.

	Strong and well-supported regulators to work with people, communities and energy participants to design, implement and oversee affordable, clean dependable energy.
2021-12 Race for 2030 - Tariffs for Rewarding Flexible Demand	Customer friendly cost reflective tariffs and incentives enhance flexibility of household electricity use and generation, resulting in increased capacity for renewable generation and reduced costs for consumers, while still maintaining affordability for high cost-to-serve locations. Incentives are appropriately designed around household diversity, abilities, opportunities and values and availability of controllable discretionary loads to time-shift via automation or otherwise.
2021-12 PEI - Customer Load Management Evolution & Revolution	The power system is affordable, and fair to the people with the least resources and opportunities.
2021-10 ECA - Strategic Plan 2021-2024	Consumers can rely on having affordable energy for comfortable homes and competitive businesses. Greater automation offers stress-free and seamless time-shifting in ways that consumers barely notice, leading to lower bills. Demand side solutions moderate investment in new bulk generation and storage, backed by a robust understanding of consumers. Consumers experience cheaper and more reliable electricity supply from a modern power system that incorporates hardware and software that increases the speed and breadth of communication, artificial intelligences that delivers improved optimisation and responsiveness, monitoring and data that make delivering electricity more efficient.
2021-01 ECA - Future Energy Vision Research - Households	Energy is affordable: household consumers are satisfied that what they are being is fair and reasonable and represents value for money. Technology enables customers to automate when things turn on and off to save energy and money.
2020-09 Energy Charter - Maturity Model	Energy companies improve energy affordability for customers to the point that customers consider energy to be good value, and there is significant evidence supporting this collective customer sentiment.

	Investment decisions are demonstrably optimised for the benefit of the customers by the given company, which is working cooperatively across the supply chain.
2020-05 Monash - Ron Ben-David on Two Sided Markets	Efficient allocation (or rationing) of services, including reliability of electricity supply, to the parties who attach the greatest value to those services, reduces the cost of electricity for all consumers.
2015-12 CSIRO & ENA - Customer-centric Networks	Customers are offered value options allowing them to trade off electricity service featuresv that were previously standardised, in exchange for a financial benefit, such as being more responsible for their own reliability of supply (by choosing to install on-site energy storage, for example).

SUSTAINABLE: Enables 2030 and 2050 decarbonisation goals	
Source	Stated or Inferred Objectives (Future Tense)
2022-02 Our Power – A vision for clean, affordable, dependable energy for all	Energy sources that negatively impact the health and wellbeing of people and communities are avoided and as are those detrimental to the environment in their production and use (including global heating, coal dust, diesel particulates, noxious fumes from burning coal and gas, wood smoke, and groundwater pollution) Incentivise energy solutions that improve the health and well-being of people - for example, by improving the energy efficiency and energy productivity of homes, hospitals, schools, offices and other workplaces. Implement policies and strategies in line with the transition to net zero emissions by a date consistent with the scientific evidence to limit global warming to 1.5 degrees, including incentives to decarbonise, prioritising investment in zero-emissions technology and deploying clean energy production. Be transparent and accountable in reporting on environmental performance. Ensure people, businesses and communities can play a role in the transition to zero-carbon energy.

SUSTAINABLE: Enables 2030 and 2050 decarbonisation goals	
Source	Stated or Inferred Objectives (Future Tense)
	Build and dispose of energy infrastructure and components in a socially responsible and environmentally sustainable way.
2021-01 ECA - Future Energy Vision Research - Households	Customers can choose to source their electricity from sustainable sources at cheaper prices.
	Energy is clean: energy comes from sustainable carbon-free energy sources.
2020-11 ACOSS - New Energy Compact Consultation Draft 5	Consumers assume a shared responsibility for the power system to achieve Net Zero Emissions through the sustainable production and use of energy.

EQUITABLE: Broad accessibility of benefits and the fair sharing of costs	
Source	Stated or Inferred Objectives (Future Tense)
2022-06 ICL - Applying strategic foresight and human centred design to business model innovation	Business models are aligned with what consumers find desirable, as uncovered by human centred design.
2022-06 ECA - A fit-for-purpose consumer agency and protection	Consumer protection and rights are comprehensively covered by consumer law and aligned with the two-way dynamic functioning of the power system. Consumers have universal access to free and independent dispute resolution whatever their arrangements for consuming and producing electricity.
2022-04 ESB - Customer Insights Collaboration Workshop 2 - Exploring the issues	Energy companies develop equitable and productive automation processes that reduce costs for customers and businesses and enable customers' agency and reduce barriers to entry. These automation processes are collaboratively developed in parallel with relevant hardware to ensure coherent and modular implementation and integration of interoperability practices and standards. Landlords are incentivised to install/provide flexible DER/demand response technologies on their properties to enable increased access for tenants to meaningfully participate in energy markets and demand response incentive programs. Effective processes are in place to ensure both landlord and tenant benefit from the use and consistent maintenance of the technologies.
2022-03 ECA - Feedback on the Draft AER Consumer Vulnerability Strategy	The overall cost to serve is minimised through an effective balancing of energy products and services affordability and consumer protections. Reviews and amendments to consumer protections are forward-looking and focus on the needs of and benefits to consumers in the relevant energy markets. Changes to consumer protections address the reality that not all consumers have the capacity to engage in their respective energy markets and/or have poor home energy efficiency because of housing construction decisions. Energy companies reduce platform and product/service offering complexity and enhance the level of accessibility customers have to energy.

EQUITABLE: Broad accessibility of benefits and the fair sharing of costs	
Source	Stated or Inferred Objectives (Future Tense)
	Customers are provided with better information about service scope and quality and feel greater confidence that they will be treated fairly and supportively by the energy companies they are dealing with. Energy companies implement initiatives like proactive reporting on quality-of-service metrics and customer engagement programs and move away from relying on the threat of disconnection for forcing customers to engage with them. Governments play a critical and positive role in addressing the impact of energy costs on people's lives and livelihoods and ensuring that the changes in the energy system do not widen the energy divide between those with resources and access to technology and those without. Governments play a key role in building the resilience of households and small businesses to address market barriers, while also equipping them to participate in emerging markets equitably, easily, and affordably. Households that do not have energy efficient housing and appliances, rooftop solar PV or home battery storage, do not face disproportionately higher energy bills. Significant efforts are made to ensure that all consumers are able to understand which technologies or services will generate benefits to them, that they have the financial means and/or support to procure them, and that they have the technical literacy to use them in the right way to secure those benefits. Those under financial pressure are and feel supported in any attempts to adjust their energy use behaviours where these are made for public benefit, such as participating in demand response schemes, and these people are not hurt by any direct monetary tariff changes which they are unable to adapt to due to their circumstances. Dispute resolution and enforcement are foundational to the energy system so that consumers have clear mechanisms for redress across the new market structures, and regulators have the appropriate authority and resources to monitor consumer outcomes, and address non-compliance swiftly.

EQUITABLE: Broad accessibility of benefits and the fair sharing of costs	
Source	Stated or Inferred Objectives (Future Tense)
	Energy companies significantly improve their identification of vulnerable customers. Consumers are more likely to experience negative outcomes depending on: + Individual characteristics (eg digital literacy, poor health, cognitive impairment etc); + Market factors (such as poorly designed products, complexity, information asymmetry); and + Their situation (such as losing a job, relationship breakdown, or renting). While the circumstances contributing to vulnerability are multi-dimensional and complex, there are two key areas that address diversity and help cut through complexity. Governments engage with retailers to not only better understand the information they collect, but how they're using that data to aid consumers. The second is that energy companies work with vulnerable consumers to develop equitable assistance offerings. The historical focus on financial hardship as the main determinant of vulnerability has meant that the sector has been slow to engage with consumer voices who may experience vulnerability in different ways. Governments strengthen protections and rights for consumers facing payment and financial difficulty. Protection and rights are appropriate to the myriad of ways intermediaries are marketing energy supply, energy services and technologies that enable consumers to use, store or generate energy. They apply whether electricity is bundled with telecommunications, internet, insurance, finance and credit or tenancy. There are multiple intermediaries including retailers, aggregators, home energy management system suppliers and networks through connection agreements.
2022-02 Our Power – A vision for clean, affordable, dependable energy for all	Ensure energy rules, policies and measures are designed to enable access to clean, affordable, dependable energy for everyone. Ensure energy rules, policies and measures do not disadvantage people if they cannot or do not want to participate in new energy products and services. Be honest, ethical and transparent to build trust. Understand and engage with people, businesses and communities to meet their needs, provide real choices and improve outcomes. Provide education to inform and support people to access and manage energy to meet their needs. Enable real choice and decision-making by ensuring options and tools are ethical,

EQUITABLE: Broad accessibility of benefits and the fair sharing of costs	
Source	Stated or Inferred Objectives (Future Tense)
	clear, transparent, learnable, in plain language and accessible. Enable people, businesses and communities to contribute to society, economic development and a sustainable environment. Give energy users control over how their data is used and shared in a way that is consistent with community expectations as well as privacy and other legal frameworks. Ensure energy service platforms are open and people can move between them without being locked in, to support innovation and provide real choices. Implement human-centred co-design processes when developing new policy, regulation, services and products, to ensure diversity of energy users views and needs. Ensure adequate protections are in place to enable full participation in the energy system. Ensure that people understand their responsibilities and the impacts on others of their energy choices.
2021-12 Race for 2030 - Tariffs for Rewarding Flexible Demand	Energy service providers have considered approaches to vulnerable customers and design flexibility schemes such that they are not disadvantaged or adversely impacted.
2021-10 ECA - Strategic Plan 2021-2024	Consumers participate in demand-side decision-making in ways that prioritise reward over punishment and which do not ask them to trade-off core needs, such as being warm in winter and cool in summer. Utilities also benefit, enjoying improved security, reduced peak loads, increased integration of renewables, and lower operational costs. Energy services are individualised, and accessing electricity as an essential service is no longer provided as one-size-fits-all. A least-cost future energy system is enabled by providing genuine choices and control to households and small businesses, who have a range of motivations, abilities and opportunities to contribute to, and benefit from, technologies, new energy services and markets.
2021-05 US DOE - A National Roadmap for Grid-Interactive Efficient Buildings	The building design and construction industry have deep expertise in energy and incorporate relevant technologies and design tools into projects, maximising customer choice, smart building capability, customer convenience, control and safety.

EQUITABLE: Broad accessibility of benefits and the fair sharing of costs	
Source	Stated or Inferred Objectives (Future Tense)
2021-01 ECA - Future Energy Vision Research - Households	Energy is inclusive: Household consumers are empowered by readily available information about the energy system and their choices. Customers on limited incomes have access to assistance or subsidies to pay for their energy use. Energy is affordable: household consumers are satisfied that what they are being is fair and reasonable and represents value for money.
2020-12 ECA - Social License for DER Control FINAL v2.0	DER control programs equitably distribute net private benefit to ensure that consumers that don't have the ability to install DER (such as renters, or households living in dwellings without access to adequate roof space) are still able to participate.
2020-09 Energy Charter - Maturity Model	Energy companies have improved the customer experience of organising, transacting, consuming, and providing energy. There is strong evidence of customers agreeing that they get fair outcomes and that the general customer experience exceeds their expectations. There is optimised, effective, and easy access to useful and portable data that empowers customers to make energy decisions that benefit them individually and their society. Energy companies put customers at the centre of their business models. There is a demonstratable culture of collaboration and innovation, both internally and with organisations across the supply chain and with other stakeholders delivering positive customer outcomes. Energy companies support customers who are facing vulnerable circumstances. This includes early identification of customers who are at risk of vulnerability with effective intervention processes in place that consistently prevent customers falling into hardship. Products and services are tailored to reflect the specific needs of customers who are at risk of vulnerability, with outcomes measured and incorporated into product or services design. Energy companies partner with external community service groups and agencies, their supply chains, and other stakeholders to

EQUITABLE: Broad accessibility of benefits and the fair sharing of costs	
Source	Stated or Inferred Objectives (Future Tense)
	improve outcomes for customers at risk of vulnerable circumstances. There is overwhelming evidence to show that customers at risk of and struggling through vulnerable circumstances are highly satisfied with and have their expectations exceeded by the customer experience process.
2020-05 Monash - Ron Ben-David on Two Sided Markets	There is an increase in fairness, through the elimination of cross-subsidies and prohibitions that protect consumers from certain types of conduct that harm effective competition
2019-10 FFRC - Electrification in a Peer-to-Peer Society	Engaging with energy is readily understandable to modern consumers as it is conceptually similar to other existing familiar peer-to-peer exchange platforms like social media, and shares many of the same features (self-organisation, absence of traditional hierarchies and social structures, open collaboration, self-expression, bottom-up creativity). Inferred
2015-12 CSIRO & ENA - Customer-centric Networks	Diverse customers representing a range of different expectations and priorities, not necessarily correlated with income levels, can access preferred products and services through new business models and financing tools.

EMPOWERING: Advances customer and community agency, optionality, and customisation	
Source	Stated or Inferred Objectives (Future Tense)
2022-06 ECA - A fit-for-purpose consumer agency and protection	Consumer agency is enshrined in the regulation of the power system. Business models arise from out of familiarity with how energy services are bought - starting with consumers' diverse needs and preferences including: convenience, minimising entities consumers contract with, shared services such as local storage and bulk hot water, pricing optionality so consumers can manage their own risk.
2022-04 ESB - Customer Insights Collaboration Workshop 2 - Exploring the issues	Energy companies have a customer-centred approach to their business models that is tested with customers and has the endorsement of customers. The approaches continuously seek improvement and innovative ways to adapt to ensure better collective and individual benefits for the business, its customers, and the wider power system. Demand response transactive mechanisms are structured so that the customer feels satisfied with any compensation for/cost to make adjustments to their lifestyle and routine.
2022-03 Origin Energy - 2022 Investor Briefing	In-house VPPs and other customer engagement solutions provide a seamless and coherent interface to low carbon energy management in the home and helps reduce the household's overheads. The software solutions provide the customer with easily accessible, interpretable and meaningful data analytics regarding their energy efficiency and usage. These software solutions are end-to-end platforms that span billing, customer relationship management capability, forecasting, and market interactions and metering, where the availability of functionality is limited by customer preference rather than provider offering. The implementation of billing functionality should enable visibility, transparency and forecasting capabilities provide meaningful and easily accessible billing information to the customer. The software solution are cloud-based, and provide real-time analytics and machine learning-enabled data-based decision support.

EMPOWERING: Advances customer and community agency, optionality, and customisation	
Source	Stated or Inferred Objectives (Future Tense)
	Customer happiness is measured using innovative ratings structures and productivity measured by secure and private interface usage data analytics.
2022-03 ECA - Feedback on the Draft AER Consumer Vulnerability Strategy	Energy companies enable potential and existing customers to make informed tariff and consumption choices. Suppliers provide consumers with information, services, and/or tools that help customers: + Understand the key features of the product/service offering, including any charges, fees, and associated payments + Make informed choices about how they manage their costs and consumption, including when and how much energy they consume, and other significant relevant quantified factors, such as efficiency and flexibility. Further, energy companies provide consumers with clear and accessible information that helps them understand that they can switch their current product/service offering and supplier. Customer agency goes beyond simply regulating suppliers and the information they need to provide, and transitions to considering what is needed for consumer decision making and building customer confidence and trust. Revised energy market structures provide a wide range of competitive, affordable, and accessible options for consumers.

EMPOWERING: Advances customer and community agency, optionality, and customisation	
Source	Stated or Inferred Objectives (Future Tense)
2021-12 Race for 2030 - Tariffs for Rewarding Flexible Demand	Incentives are appropriately designed around household diversity, abilities, opportunities and values and availability of controllable discretionary loads to time-shift via automation or otherwise. Consumers are comfortable with using enabling technologies to manage flexible loads, such as inputting default energy use priorities and choices for autonomous management, integrating smart appliances into home energy setup, and remote activation of discretionary loads. Consumers have access to accurate and understandable energy/aggregator offering comparison services to aid in decision making, including details on incentives that reward flexibility and assistance to configure household for flexibility. Consumers use advanced but simple monitoring tools that provide visualisation of energy use (and/or generation) which support households in understanding the energy use and costs of their appliances and in assessing the impact of load-shifting.
2021-10 ECA - Strategic Plan 2021-2024	Demand side solutions moderate investment in new bulk generation and storage, backed by a robust understanding of consumers. Advanced metering makes consumption more transparent, allowing consumers who wish to do so to be more actively involved in the energy market. User-friendly phone apps can make real-time decision making around energy consumption as quick and easy as checking your bank balance or arranging a date.
2021-09 ECA - Foresighting Forum - System Design Webinar	Consumers are granted autonomy as to the degree of participation and the decisions they make about supporting grid objectives. People and communities are empowered to implement local solutions to their energy needs.

EMPOWERING: Advances customer and community agency, optionality, and customisation	
Source	Stated or Inferred Objectives (Future Tense)
2021-05 US DOE - A National Roadmap for Grid-Interactive Efficient Buildings	Customers understand and are compelled to adoption by the value proposition of Grid-Interactive Efficient Buildings as capital costs decrease and maintenance requirements are better understood. Customers understand and are comfortable with the risks of investment in Grid-Interactive Efficient Buildings and participation in the greater energy system through a mature familiarity with technologies assisted by broad dissemination of relevant information that supports decision making. Federal, state, and local codes and regulations regarding energy devices and systems are aligned and consistent, decreasing Grid-Interactive Efficient Building project costs and complexity.
2021-01 ECA – Future Energy Vision Research - Households	Energy is simple: energy offerings, bills and plans are straight forward and simplified, with relevant accessible information available. Households are equipped to avoid wasteful use of energy in the home. Customers are provided analysis of in-home energy use such that they can adapt energy usage, such as knowing which appliances are driving up costs. Technology challenged customers can access simple explanations to understand energy use, and ways to reduce waste and save money. Households can easily split bills through a i.e. through a providers online billing platform. Energy is easy to manage through apps, real-time information and smart technology and automating energy saving operation. Customers are provided visibility on real-time energy usage and cost so they can adjust behaviours. Customers have easy access to information regarding the range of options to participate in energy initiatives particularly as they relate to climate change.

EMPOWERING: Advances customer and community agency, optionality, and customisation	
Source	Stated or Inferred Objectives (Future Tense)
	Prospective house buyers are provided standardised data and information on the energy efficiency and energy assets operating in houses they are assessing. Customers can choose cheap no-frills energy plans. Customers can easily understand their bills and compare plans across different companies.
2020-09 ICL - The need for aligned vision and supporting strategies to deliver NZE grids	The vast majority of customers are engaging effectively in demand side management programs. This mass participation is enabled by appropriately designed markets and technical infrastructures (e.g., smart meters and batteries) to deliver demand side management without the loss of individual comfort or experience or societal benefits.
2020-05 Monash - Ron Ben-David on Two Sided Markets	Consumers can efficiently, and with minimal pressure, process the choices they face, and feel confident in making the decision that is best for their personal circumstances that balances societal needs. The degree to which customers monitor electricity precises and decide how or when to participate is entirely based on their preferences of engagement frequency and intensity, rather than limited by the service or product offering of the businesses and technologies with which they are interacting.
2019-10 FFRC - Electrification in a Peer-to-Peer Society	The energy system is democratised as users are empowered to realise their personal and societal ambitions for energy, aided by the ability to form peer networks of like-minded energy users and jointly act in line with their values and priorities.
2018-12 NREL - Electrification Futures Study	Energy companies have advanced consumer choice models for an expansive list of end-use technologies, to provide insights on the drivers of electric technology adoption. These models capture economic trade-offs between different technologies, customer preferences and behaviour, supply chain and infrastructure impacts, risks, financing, and integrated challenges and opportunities. These consumer choice models inform policymakers, guide R&D strategies that lower costs and improve desirability and motivate engineering design to influence appropriate adoption.

EMPOWERING: Advances customer and community agency, optionality, and customisation	
Source	Stated or Inferred Objectives (Future Tense)
2015-12 CSIRO & ENA - Customer-centric Networks	Customers can compare competing electricity solutions based on each option's ability to perform the combination of 'jobs' that they uniquely want done (including functional and financial 'jobs' as well as social and emotional 'jobs') Customers are offered energy solutions that are highly customised and delivered in the emotionally and socially engaging ways that customers already expect from service providers outside the energy sector. Customers are offered simple, accessible choices, with the option of bundled products and services that conveniently combine technologies, data access and/or entertainment
2014-05 CSIRO - Applying behavioural economics to understand energy consumer decision-making and behaviour	Energy companies and policymakers ethically and effectively utilise social psychology learnings to inform the development of more efficient marketing, more user-friendly platform interfaces and processes, and more customer-focused regulation development. Research indicates that Consumer choices and behaviour are to a large extent understood to be driven by cognitive biases, heuristics and other 'predictably irrational' tendencies. For example, people use mental shortcuts to cut through complexity, they dislike losses more than they like gains, prefer lower value certainties over higher-value risks, evaluate things in relative rather than absolute terms, and are heavily influenced by the people around them. However, these cognitive biases and motivational factors are often overlooked by practitioners and policymakers seeking to promote energy efficiency and conservation. To ensure cost-effectiveness and maximise return on investment, the objective is that energy companies and policies take these phenomena into account when developing strategies for encouraging renewable and sustainable energy use, and for motivating pro-environmental behaviour more broadly. By understanding these predictable deviations from economically rational behaviour, policymakers will be better placed to craft interventions that successfully bridge the gap between pro-environmental knowledge, values, attitudes and intentions, and the everyday energy-related behaviour of consumers.

EXPANDABLE: Enables electrification of transport, building services and industrial processes	
Source	Stated or Inferred Objectives (Future Tense)
2022-06 Caltech Energy - Cutting US global warming gas emissions in half by 2030	Current consumer-based products that have high demand are replaced with demand-flexible products at the end of their lifetime over the next 5-10 years. These products include water heaters, pumps, dishwashers, cars, etc. End-users and consumers are educated and empowered to make more and better decisions around making their own household net zero. If each household has their own net zero plan, then the community will collectively achieve it as a cumulation of micro-incremental step functions.
2021-10 ECA - Strategic Plan 2021-2024	Localised, community-centred forms of generation, while more complex, are critical to a more robust system that is less radial and more networked. Community batteries, virtual power plants and co-located small-scale generation and storage facilities are embedded within communities. Power comes from a large number of diffuse and diverse sources such that the system is less vulnerable to failure caused by a single catastrophic event and therefore more resilient.
2021-10 UoM - EV Charging Consumer Survey	Managed EV smart charging is widely adopted, supported by: + Clear and simple communication of monetary savings on offer. + Third-party management and control that is performed via Apps that increase users' sense of control over charging and decrease their feeling of uncertainty. + Clarity in data sharing and user privacy policies. + Consumer awareness of environmental and community benefits. + A perception that public charging is an easy and accessible backup plan.
2021-09 ECA - Foresighting Forum - System Design Webinar	Mechanisms to identify and understand consumer aspirations, expectations, concerns and emerging issues are in place.

ADAPTABLE: Flexible and adaptive to change, including technological, regulatory and business model innovation	
Source	Stated or Inferred Objectives (Future Tense)
2021-01 ECA - Future Energy Vision Research - Households	Energy service providers align and adapt their products and services with the evolving and changing values across life-stages and generations.
2020-12 ECA - Social License for DER Control FINAL v2.0	Technical standards for hardware enable informed and competitive consumer choice to more interoperable and easily accessible product and services options. Hardware standards positively dictate the way in which consumers interact with their DER systems in terms of provision of information and manual over-rides to enable permanent or event-based opt-in or opt-out. The increased choice provided by well-designed hardware standards also reduces the effort/costs of gaining and maintaining a social licence. DER control programs are supported by technical standards that play a key role in ensuring that hardware and software limitations do not restrict the ability for consumers to opt-out, or that they don't increase the costs of opting-in. Interoperability and modular interfacing standards and practices are prioritised and enforced, so that DER controlled exclusively by proprietary communications technologies does not occur. A lack of interoperability has the potential to lock a consumer with DER into a particular service arrangement. Should the consumer wish to change service provider, or integrate multiple DER systems from different brands, they may find that this is not technically possible without completely replacing one or all of their DER systems. A lack of interoperability has the potential to increase the costs of the DER control program by effectively forcing a consumer to stay with a higher cost or lower value provider. For example, a consumer with a non-interoperable solar and battery system who is receiving unacceptable service from the party undertaking the control, may have no option but to opt-out completely from the DER control program (or buy a new solar and battery system).
2020-11 ACOSS - New Energy Compact Consultation Draft 5	The power system is flexible, innovative, responsive, and based on consumers' expectations.

BENEFICIAL: Socially trust, public good/benefits, commercially investable and financeable	
Source	Stated or Inferred Objectives (Future Tense)
2022-06 ECA - Energy Consumer Sentiment Survey - Households	Households are satisfied with their interaction and experience of the power system across the following areas: provision of electricity, customer service, billing platforms and arrangements, value for money, time to restore following outages, advances in technology, future reliability, ability to access information and tools, ability to make choices, confidence in the market, and dispute resolution. Electricity suppliers have sufficient trust from consumers to be happy to hand over control of their load/devices.
2022-03 ESB - Customer Insights Collaboration Workshop 1 - Defining the problem	All customers can realise the value of flexible demand and DER for both individual and collective benefit. The barrier of perceived complexity of DER demand response processes is removed or mitigated. Customers' effective understanding of these processes is enabled by clearer language, communication, and information and technology that is designed to be user friendly. Customers realise the value of flexible demand through more relevant incentives. These incentives respond to customer needs and improve the customer experiences. Energy companies provide different incentives for different customers, where the incentives are tailored to suit the customers' circumstances and financial and energy goals. Barriers such as lack of value certainty and transparency are removed or mitigated by providing clear, informative, and easy to understand information which is easily accessible on user friendly platforms. Further, there are significant improvements to the customer experience through the building of trust in energy companies and the building of consumers' confidence in their choice and capability to participate.
2022-03 ECA - Feedback on the Draft AER Consumer Vulnerability Strategy	Consumer voice and lived experience inform and refine regulatory design and change.

2021-12 Race for 2030 - Tariffs for Rewarding Flexible Demand	Energy service providers have built trust with consumers and broadly addressed concerns over participation in flexibility schemes, including time constraints, loss and risk aversion, status quo bias, low perceived benefit, information or choice overload, more pressing priorities, decreased comfort or convenience, safety risks, lack of control or autonomy, data security or loss of privacy.
2021-12 PEI - Customer Load Management Evolution & Revolution	Customers are encouraged to participate in problem-solving and program design processes to produce mutually valued outcomes for customers and the power system.
2021-10 IEA - Social License to Automate	The dynamics of trust and other social dimensions are favourable to user engagement with automation technologies used in demand side management.
2021-10 ECA - Strategic Plan 2021-2024	Consumers are willing participants in flexibility schemes, agreeing to adjust their energy use in ways that help their community, themselves, and the system. The process of doing this is simple and frictionless and does not require expert knowledge or high-level engagement. Consumers have sufficient trust in the system and goodwill towards key actors within it that they respond to system events when invited. They have a clear understanding of what they are being asked to do and what their options are, and the way they respond is intuitive and easy.
2021-09 ECA - Foresighting Forum - System Design Webinar	Clear and valuable information is available to inform energy choices as they navigate the changing energy landscape.
2021-05 US DOE - A National Roadmap for Grid-Interactive Efficient Buildings	Technology maturity has grown such that customers have confidence to invest in Grid-Interactive Efficient Buildings without fear of obsolescence.
2021-04 Upowr - Customer Segmentation Research and Design for DER Orchestration Programs	DER/CER orchestration programs, including how they are communicated and understood (the why), cater to and appeal to a broad range of customer types from "innovators" to "laggards", as they are aligned with customer motivations, emotions and values. This has resulted in deep participation in such programs, increased technology adoption, and greater contribution of distributed assets to whole-of-system objectives.
2020-12 ECA - Social License for DER Control FINAL v2.0	A social licence to control DER is acquired, and results in individual consumers perceiving the private and public benefits of DER control to be greater than the private costs. The social license increases

participation in voluntary DER control programs and the uptake of DER more broadly. Further, where a social licence for mandatory programs is obtained, it increases compliance and therefore decreases non-compliance and enforcement costs. The government or institution enabling the DER control (through policy, regulation or via programs) requires the licence. This body may not ultimately be directly doing the control, however, it generally regulates the way in which the third party must undertake the control, communicate with and reward consumers and provide data and information to monitor the effectiveness of the DER control program.

The three different levels of social licence for control of DER are obtained by parties which reasonably require a social license to manage their respective initiative:

+ Acceptance: Whereby the consumers subject to DER control perceive that the private benefits of the control outweigh the private costs of the control.
+ Approval: Whereby to the extent practicable, consumers and consumer representatives perceive that:
+ The benefits of the DER control are allocated according to their views of fairness
+ The institution enabling the DER control program engages in two-way dialogue with consumers (both those subject to control and those receiving the broader system benefits of the control).
+ Psychological Identification: Whereby consumer representatives and the institution enabling the DER control program develop enduring regard for each other over the course of DER control program design, implementation, evaluation and modification.

The cost/effort required to gain and maintain a social licence for control of DER is directly related to the consumer's choice (in terms of the mandatory/voluntary nature of the program) and the extent to which the private costs are outweighed by private benefits for all consumers with DER subject to control. The more mandatory and the higher the private costs, the more difficult it is to achieve a social licence.

To obtain a social licence, close to 100% of consumers with DER subject to control must perceive the benefits of the control to outweigh the private costs. This is achieved where the program enables the energy system (public) benefits to be directly transferred to the DER consumer via an incentive payment, rebate or bill reduction or by personalising the public value to infer an indirect or perceived benefit. In consideration of the role of choice, the level of participation/uptake required to deliver the benefits

	must be taken into account. Mandatory participation has the potential to drive the greatest uptake and therefore deliver the greatest benefit. However, where a DER control program is made mandatory, a social licence must be obtained from close to 100% of consumers with DER subject to control. DER consumers tend to fall into four main categories when it comes to the perceived private cost and benefits of DER: Derives personal satisfaction in adopting modern technology and automation and perceives little to no disbenefit of control Willing to absorb any private costs where the DER control provides for financial benefits and/or solves a practical problem Places a high value on social/environmental outcomes, perceives DER control as in alignment with these values, and is therefore willing to absorb reasonable costs Place a high value on social/environmental outcomes but perceives DER control (and often technology generally) as in conflict with these values and is therefore unlikely to adopt DER control. Consideration of these four groups, in terms of the make up of each for any given DER control program, is a critical component in the processes of obtaining a social licence and/or increasing uptake and effectiveness.
2020-11 ACOSS - New Energy Compact Consultation Draft 5	The power system is consumer focused, and everyone can access clean, affordable, dependable energy.
2020-05 Monash - Ron Ben-David on Two Sided Markets	Market mechanisms and structures operate in a manner which reflects the broader society's standards of fairness. Great care is taken by energy companies and policymakers to understand and articulate the community's standard of fairness, and to ensure that market design, development, and implementation are built out of and satisfy these standards. Further, consumers have confidence in the alignment and integration of these standards throughout the whole process. Market designers, policy makers and regulators have access to tools that allow models and related assumptions to be tested in high definition, and experimental economics applies laboratory methods to economic questions. At the same time, behavioural economists help market designers peer into market participants' true decision-making processes. Likewise, economic theorists in the fields such as industrial organisation, game theory and institutional design apply their own assumption-bending techniques to theoretical models of proposed markets. The full arsenal of economic methods are openly deployed in search of

	comprehensive questions and equally comprehensive, satisfactory, and community confidence building answers.
2018-05 ThinkPlace - Demand Response Consumer Insights Report	Demand response mechanisms: + Enable families to easily adapt their energy use habits and routines + Connect people with energy management techniques that are of interest and benefit to them + Support experimental learning and self-improvement to allow consumers to optimise their energy management + Balance the desire of people to contribute to the greater good with equitable energy balancing + Balance the perceived and actual effort with the perceived and actual significance of demand response + Allow customers to connect their individual demand response to longer-term energy user patterns and affirm customers that they are valuable contributors to the results of collective demand management + Tap into Australians' dominant social preferences if it is to attract and engage them, and change their long-term behaviour + Allow users to share their experience of the program with family/friends and let them know the operational methodology and positive impacts it brings

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STRATEGEN

SECTION 2: EMERGING TRENDS

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Contents

1. SECTION 2 INTRODUCTION

1.1. Purpose of Section 2

The various G-PST topics bring a strong future orientation to power system challenges and then mostly focus on a specific technology category. G-PST Topic 7 is somewhat unique, however, as it applies a whole-system perspective to the entire Power System and its underpinning Structure (or 'Architecture'), which provides the basis for the many technologies to function as a System.

Given this whole-system view, an intentional framing around the 2050 scenario considered most plausible by stakeholders helps interrogate the potential scale of change that the Architecture of the Power System may need to accommodate. As noted above, most practically it also provides valuable, future-resilient insight that guides urgent, near-term action that is prudent and efficient.

Ensuring that the Systems Architecture of an ultra-complex societal system like the Power System is future-ready is vital at a time of large-scale transformational change. The veracity of such a process requires the detailed evaluation of Emerging Trends which function as the key drivers of change impacting the Power System. While this includes trends that directly impact one or several tiers/layers of the system (e.g. bulk power, transmission, distribution or retail), the distinctive focus of the Topic 7 project is considering the whole-system impacts and potential responses.

For the purpose of this report, Emerging Trends have been defined as follows:

> *Drivers of change that may significantly influence the evolution of Australia's GW-scale Power Systems over the next decade and beyond.*
>
> *These drivers present challenges and impediments and/or new opportunities and potentialities that are either probable or plausible (not simply possible).*
>
> *While some may be endogenous to the Power System, they are typically exogenous and include the impacts of evolving Customer & Societal expectations of future Power Systems.*

As illustrated in Figure 1 below, the mapping of Emerging Trends is a key part of the formal Power Systems Architecture process. It is informed by the analysis of a wide range of policy, customer, technology, and other relevant developments and is a key input to mapping the cross-cutting Systemic Issues that must be addressed in the configuration of any future Systems Architecture, which are explored in Section 3.

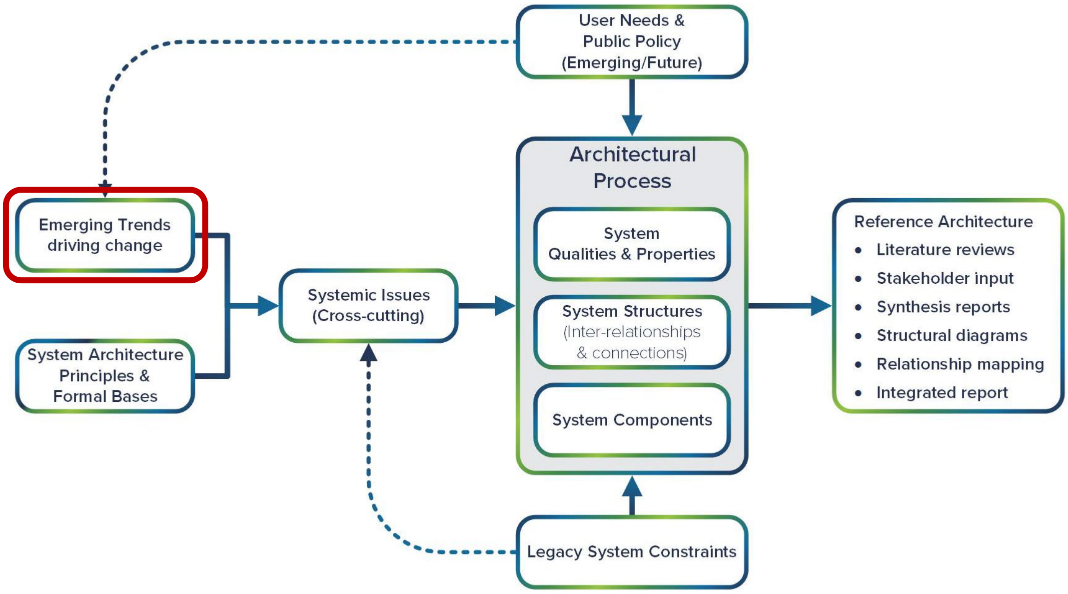


Figure 1: Mapping of the Emerging Trends driving change is a key step in applying the formal Power Systems Architecture approach[16].

1.2. Report Structure

Informed by Section 1: Customer & Societal Objectives for Future Power Systems, this report examines over sixty Emerging Trends which are impacting Power Systems today and expected to drive change over the next decade and beyond.

Consistent with the whole-system orientation of the PSA discipline, Emerging Trends are mapped to the most relevant of the following ten categories. Each trend is stated, followed by a statement of its observable characteristics and then a summary of its implications.

Structure

1. Power System Structure
2. Operating Context
3. Generation Diversification
4. Load / Demand
5. Control Dynamics
6. Data & Communications
7. System Planning
8. Operational Forecasting, Management & Coordination
9. Markets & Commercial
10. Sector Coupling / Network Convergence

[16] Adapted from Pacific Northwest National Labs Foundational Report on Grid Architecture, available at https://gridarchitecture.pnnl.gov/media/white-papers/Grid%20Architecture%20%20-%20DOE%20QER.pdf

2. EMERGING TRENDS

2.1. Power System Structure

<table>
<tr><th>Emerging Trend</th><th>Implication/s</th></tr>
<tr><td colspan="2">2.1.1. Australia's power systems are becoming more diverse and dynamic</td></tr>
<tr><td>Australia's GW-scale power systems have historically been heavily dependent on coal-fired generation which consisted largely of various forms of utility-scale, synchronous resources. System management focused on the security constrained economic dispatch of merchant resources to meet customer demand, which was comparatively predictable.

This situation has changed starkly over the last decade with unprecedented levels of deployment of weather-dependent Variable Renewable Energy (VRE) and Distributed PV (DPV). This expanding fleet of resources:
• Largely consists of various types of Invertor-based Resources (IBR);
• Includes many different types of generation, storage and flexibility resources; and,
• A significant proportion of these resources were not installed for the primary purpose of functioning as a merchant resource.

In parallel, based on current projections, 60% of Australia's coal-fired generation capacity will have been withdrawn by 2030, with the entire coal-fired fleet withdrawn by 2043.

Simultaneously, significant demand volatility is also being introduced by the operational behaviour of DPV, creating additional challenges and opportunities for the instantaneous balancing of supply and demand.</td><td>With increased penetrations of VRE and DPV and the related increasing volatility at all levels of the system, the underlying nature of the power system is changing fundamentally.

AEMO has noted that by 2025, the NEM is projected to have sufficient renewable resource potential to completely serve demand during key time windows. Looking further out, AEMO's Step Change scenario anticipates that by 2050 the NEM will need to securely accommodate the following:
• 9x Centralised VRE: Nine-fold increase in installed capacity of utility-scale wind and solar generation (from 15GW to 140GW);
• 5x Distributed VRE: Almost a five-fold increase in the installed capacity of DPV generation (from 15GW to 70GW);
• 3x Dispatchable Firming Capacity: A three-fold increase in installed firming capacity that can respond to a dispatch signal; and,
• 99% passenger vehicle electrification.

In addition, the implementation of new resource types is driving significant increases in the speed at which grid events occur, both at transmission and distribution

In this context, the System Operator and network service providers all face much greater levels of uncertainty, dynamics and complexity. This will require a significantly expanded range of capabilities in support of more advanced forecasting, planning, analytics, visibility, controllability, incentivisation, etc.</td></tr>
</table>

2.1.2. Power systems are transitioning from hundreds to tens of millions of participating energy resources

Australia's power systems are being reshaped by the combined impact of the '4Ds': decarbonisation, digitisation, democratisation and decentralisation. This involves a complex range of societal, technological, economic and commercial forces, many of which are outside the direct influence of traditional power sector regulatory and planning mechanisms.

At a macro level, it involves the transition from hundreds of large, dispatchable, merchant generators to a vastly more heterogenous range of participating resources. As noted above, this involves a massive uplift in the volume of utility-scale VRE and rooftop DPV that the system will depend on. Similarly, it involves a dramatic expansion in dependence on a wide range of technologies including Battery Energy Storage Systems (BESS) and Distributed Energy Resources (DER).

In summary, Australia's power systems are transitioning from hundreds of large, transmission-connected generation resources to tens of millions of highly diverse and heterogenous resources that are near ubiquitous across transmission and distribution systems.

The growth in system complexity arising from this vastly more diverse, dynamic, numerous and inter-dependent base of resources is without parallel in the history of Australia's power systems.

Ensuring least-cost societal outcomes in a context where power systems are becoming more complex will require significantly enhanced Operational Coordination to unlock new system optimisation opportunities.

For example, as coal-fired generation is withdrawn, a growing proportion of Essential System Services (ESS) and system flexibility will need to be sourced from diverse energy resources variously connected across Australia's HV, MV and LV systems. Given the temporal and spatial sensitivity of power system requirements, this will require computationally scalable approaches that incentivise and activate:

- the right physics-based service (energy, power, essential system services);
- at the right time (seasonal, days, hours, minutes, seconds, microseconds); and,
- at the right network layer / location (bulk power, Tx system, Dx system, Dx feeder).

Importantly, service provision must be co-optimised such that energy resources dispatched and/or financially incentivised at one layer of the system are not driving unintended and undesirable consequences at other layers of the power system.

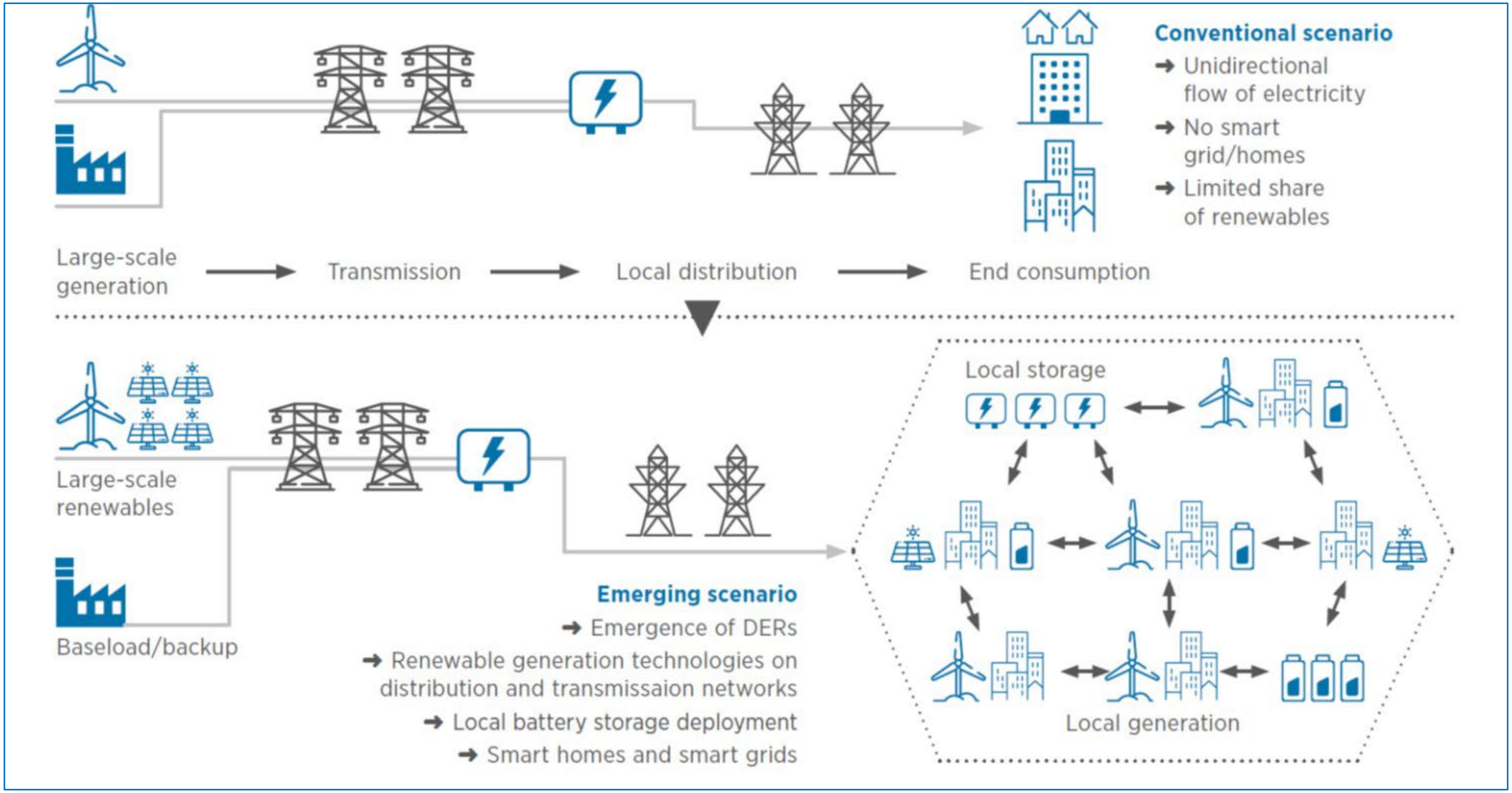


Figure 2: Power systems are transitioning from hundreds to tens of millions of participating energy resources and the traditional 'supply-side / demand-side' bifurcation is eroding

2.1.3. The traditional 'supply-side / demand-side' bifurcation is eroding for many power systems

Australia's 20th century power system was structurally configured around a very clear 'supply-side / demand-side' bifurcation and unidirectional real power flow operation. Transformational forces such as the '4Ds' are, however, reshaping global power systems and fundamentally eroding this paradigm central to legacy power system structural settings.

As noted above, legacy power systems were largely designed around a fleet of MW-scale generators. The 'supply-side' of the system consisted of these large generators connected to the HV transmission system providing bulk electricity to the system. Customers located on the 'demand-side' of the system were largely connected to LV distribution systems and considered passive receivers of energy services.

While remaining the location of major load centres, distribution systems are now also hosting an ever-expanding fleet of energy resources. This is being driven by mass deployment of energy resources that is largely agnostic to historic bulk power, transmission, and distribution system boundaries. Many of these resources are highly relevant to the operational management of the entire power system as sources of generation, system buffering (storage), flexibility and the provision of ESS.

With both the erosion of the traditional 'supply-side / demand-side' bifurcation and the increasing levels of volatility introduced by variable resources, a significantly more integrated approach to system management will be required to ensure secure operation at least cost.

In this context, advanced Operational Coordination models must enable bulk energy, transmission and distribution systems – together with deep demand-side flexibility – to function in a more holistic and dynamically independent manner than previously required.

Importantly, unlocking the efficiencies of 'demand-side' participation – estimated to be worth $20 – 30bn over the next two decades, will require the successful incentivisation and mass activation of the expanding fleet of privately owned resources.

This will require comprehensive 'market-control' alignment at all layers of the power system to efficiently incentivise, automate and coordinate the necessary physics-based services from a diverse range of resources (due to the inseparable cyber-physical-economic nature of the power system).

Importantly, multiple entities may play different roles in enacting this multi-layered coordination. Ensuring secure and least cost operation of the entire power system, however, will require advanced Operational Coordination models (underpinned by appropriate cyber-physical architectural choices), that are computationally scalable to accommodate many millions of resources across all layers of the power system.

2.1.4. With the ongoing deployment of DPV, minimum system demand continues to decline

A key illustration of the impact of the traditional ‘supply-side / demand-side’ bifurcation eroding is the volume of load now served by LV-connected DPV in an expanding frequency of time windows.

Driven by Australia’s high uptake of rooftop DPV, operational demand is now reaching record minimums. For example, in one 30-minute interval in 2021, 43% of underlying demand in the entire mainland NEM was supplied by LV-connected DPV. This is currently forecast by AEMO to reach up to 77% by 2026.

The state of South Australia has one of Australia’s highest levels of DPV deployment. It has already experienced 100% of underlying demand being met by DPV, which AEMO forecasts will exceed 100% of demand for the first time later in 2022. When this occurs, South Australia, which has a peak demand of over 3GW, will see operational demand pushed below zero as demand for the entire region is supplied by DPV!

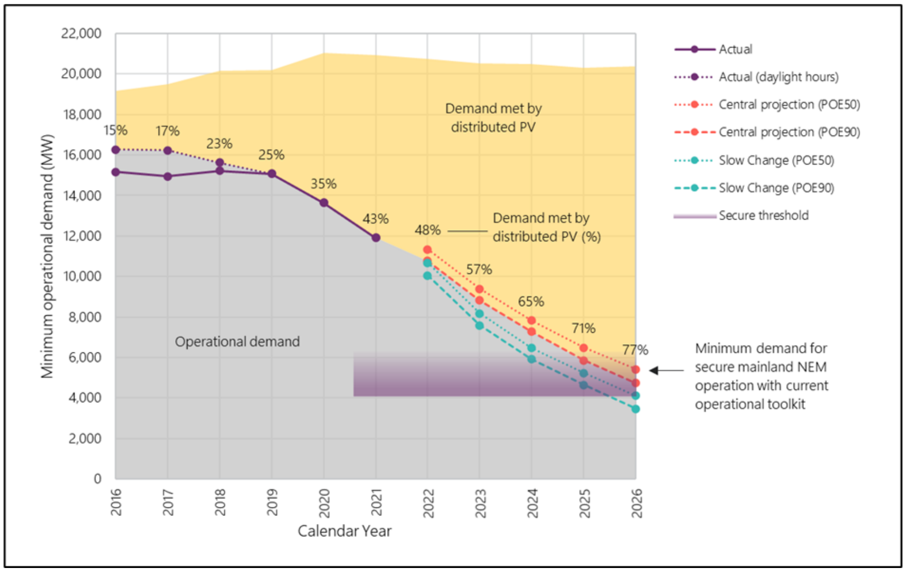
By 2025, AEMO forecasts that there will be time windows where LV-connected DPV will supply up to 70-80% of underlying customer demand across all mainland-NEM regions.

Despite Australia’s world-leading level of DPV uptake, the proportion of new installations participating in aggregation remains relatively low. While market bodies are developing frameworks that incentivise participation in ‘two-sided markets’ to enable DER / DPV to respond to real-time prices, capabilities to manage down DPV export are needed in the shorter term to maintain system security.

In September 2020, South Australia became the first Australian jurisdiction to require all new DPV installations to have the capability to be remotely disconnected in emergency conditions. Currently, outside South Australia, there is no ability to actively manage the minimum system load impacts of DPV in the other mainland-NEM regions, though other jurisdictions are expected to follow suit.

Figure 3:

AEMO Minimum Operational Demand Projections:



2.1.5. The scale and diversity of energy storage deployed across all layers of the power system is accelerating

A significant development in an increasingly volatile power sector is the advent of increasingly cost-competitive energy storage. As a form of 'buffering', different types of energy storage can provide a new range of services across different functional time horizons, including:

- Shallow / ESS (< 4-hours);
- Medium / Intraday shifting (4 – 12-hours); and,
- Deep / RE drought (> 12-hours).

This is especially noteworthy as, unlike most other supply chains, power systems have not traditionally had buffering mechanisms to manage volatility. In supply chain logistics systems, for example, the buffers are warehouses. In gas and water systems, the buffers are storage tanks. In communication systems, they are called jitter buffers.

Given that the power system and its regulatory frameworks were developed in the absence of viable, large-scale energy storage options, significant changes may be required to effectively integrate this category of resource. For example, the Australian Energy Market Commission (AEMC) recently made several changes in support of this, including:

- A new registration category, the Integrated Resource Provider (IRP), that allows storage and hybrid generation and storage systems to register and participate in a single registration category rather than under two different categories;
- Clarity for the scheduling obligations that apply to different configurations of hybrid systems, including DC-coupled systems, so that operators of these systems have the flexibility to choose whether to be scheduled or semi-scheduled;
- Allowing hybrid systems to manage their own energy behind the connection point, subject to system security limitations;

	• Clarifying that the current approach to performance standards that are set and measured at the connection point will apply to grid-scale storage units, including when part of a hybrid system; and, • Transferring existing small generation aggregators to the new category and enabling new aggregators of small generating units and/or storage units to register in this category.
2.1.6. Power system functions are evolving and impacting traditional organisational roles and responsibilities	
With increased penetrations of VRE, IBR and DERs, the underlying nature of the power system is changing fundamentally. To maintain the stability and functionality of the power system, the key system actors are having to adapt in ways that are not comprehensively provided for in the traditional governance arrangements.	Where power systems are experiencing fundamental change and unprecedented levels of volatility, a significant range of new or evolved system functions and related roles and responsibilities will be required. For example, emerging system dynamics will require detailed consideration of: • Distribution System Operator (DSO) models, and potentially, Distribution Market Operator (DMO) models; • Advanced Transmission Network Service Provider ('A-TNSP') models; • Transmission-Distribution Interface (TDI) designs capable of advancing whole-of-system responsiveness, flexibility and interdependence; and, • System Operator (SO), A-TNSP and DSO relationships. Importantly, given that the Laws of Physics are blind to the structural demarcations currently embedded in the NEM, each of these emerging functional roles must be considered holistically to ensure the desired 'whole-system' outcomes are achieved.

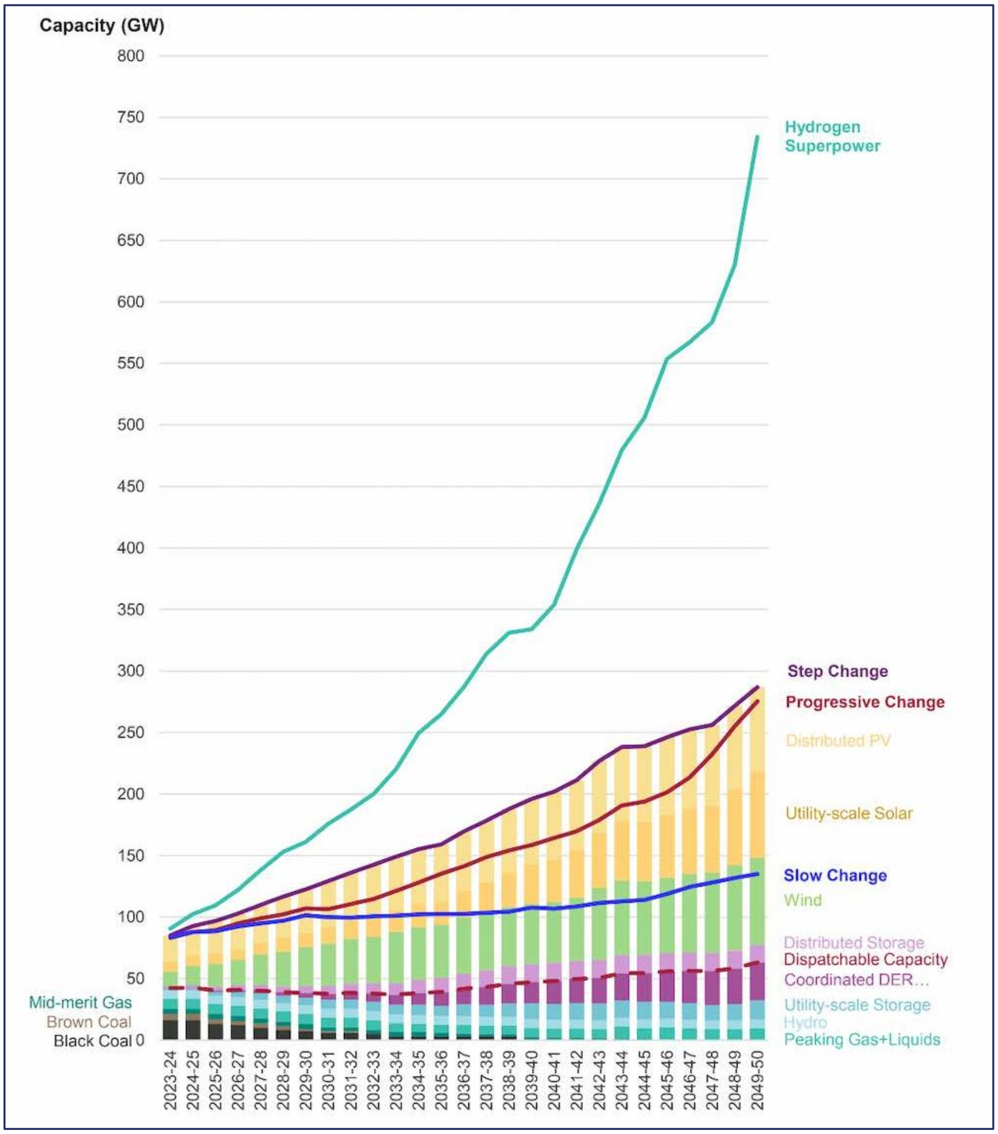


Figure 4: Unprecedented levels of NEM capacity expansion anticipated to 2050 under AEMO's Progressive Change, Step Change and Hydrogen Superpower scenarios

2.2. Operating Context

Emerging Trend	Implication/s
2.2.1. An unprecedented volume of new system capacity is now required	
Australia's COP26 commitments involve a significant dependence on large-scale electrification. In particular, there is an expanding focus on the electrification of transport, industrial processes and building services to replace more carbon-intensive fuels such as natural gas and petroleum. Under AEMO's Step Change scenario, the capacity of the NEM would need to nearly double between 2022 and 2050. Under the Hydrogen Superpower scenario, the capacity of the NEM would need to increase eight-fold in the same period to support hydrogen export production.	The unprecedented volume of new system capacity required within a finite timeframe presents major challenges and risks in terms of approvals, social license, funding and construction. As a national and multi-stakeholder undertaking, extensive stakeholder collaboration will be required to maximise alignment, mitigate duplication of effort and substantially expand the necessary social license required for timely progress. In addition, given the critical issue of energy affordability (refer 2.2.2 below), it will be essential that all materially significant existing and emerging system optimisation options are fully examined. The construction of new capacity should be contingent on all optimisation options having been exhausted. Given this system expansion will occur at a time of accelerated investment in other forms of national infrastructure, investment coordination to alleviate supply chain constraints, project cost escalation and schedule slippage will be critical.
2.2.2. Energy affordability is under increasing challenge due to geo-political, extreme weather, system dynamics and expansion	
While electricity affordability had been improving in recent years, this has been impacted by energy market shocks intersecting with broader increases in costs-of-living. Recent surges in wholesale electricity and gas prices are putting immediate upward pressure	Multiple factors are expected to place continued upward pressure on power system costs. These include: • Rising inflation; • Increases in the cost of capital;

on retail prices available to consumers. These surges reflect the combined impacts of:

- reduction in thermal generation resulting from unplanned outages and higher costs
- impacts from the ongoing war in Ukraine, which has led to significant pressure on coal and gas prices globally
- extreme weather in NSW and Queensland, which has affected coal supplies and electricity demand
- increasingly 'peaky' demand driving up the cost of hedging for retailers.

Costs may decline and stabilise in the medium-term but there is currently more upward than downward pressure in the system.

- Global supply chain disruptions;
- Labour shortages; and,
- The scale and pace of the power system expansion requirements.

Given the massive scale of transmission build that Australia will require, consideration of all options for whole-system optimisation will be critical for moderating the total investment, the cost of which will ultimately flow to customers, governments and taxpayers.

2.2.3. Power system infrastructure is being impacted by an increased frequency and intensity of extreme events including bushfires, high winds, and flooding

Power system infrastructure has been challenged by a range of exogenous factors over the last decade, including an increased frequency and intensity of extreme events such as bushfires, high winds, and flooding.

While this is confronting traditional methods for system planning, construction, operation, outage management and outage recovery, regulatory frameworks continue to focus primarily on reliability.

Legacy power systems were developed with a focus on a few key requirements, among them reliability, safety, and affordability.

Current mechanisms do not provide the sector with adequate means to identify or plan investments, specify more resilient system architectures, or create alternate designs that enhance power system behaviour in the face of infrequent but high impact events.

The distinction between reliability and resilience is an important one. Reliability is focused on the average system performance and seeks to minimise outage duration and frequency during normal conditions. By contrast, the capacity of a power system to prepare for and recover from infrequent but extreme events is generally referred to as resilience.

As such, existing definitions and methods make it very difficult to isolate root causes,

	identify investments and carry out planning clearly related to specific elements of the overall power system. New definitions are required to provide greater precision to guide cost-effective action. For example: • Reliability must change from a backwards-looking conflation of power system behaviour with externalities to a forward-looking approach as used in other sectors such as aerospace and electronics. • Resilience must change to be about the grid's ability to avoid, withstand or adapt to external stresses. An enhanced focus on system resilience will be key to expanding the range and cost-efficiency of resilience options considered. Supported by commensurate regulatory treatments, investment mechanisms and planning tools, this will enable options ranging from traditional grid hardening to more advanced adaptive and modular approaches to system resilience.
2.2.4. The number and size of new actors exerting control on the power system without fully appreciating the systemic implications is expanding	
A growing number of large, multi-national 'new energy' actors in various nations are managing many GWs of DER and EV load. These aggregators and super-aggregators manage their DER and EV fleets in response to various market signals and other commercial drivers. Given the growing scale of these actors, the risk of significant system impacts arising due to a failure to fully appreciate the systemic implications is significantly expanding.	To the extent that such entities influence or participate in real time power system operation, formal Roles & Responsibilities must be defined, and coordination mechanisms created that function within a comprehensive and scalable structure. Planning processes must be able to obtain appropriate information regarding the non-utility entities and their intended operations. Appropriately secure communications systems, methods, and standards must match both utility needs and third-party roles and capabilities.

	For shorter-term purposes, this presents operational challenges as multiple entities with different and potentially conflicting objectives make decisions independent of one another, without a common or complete view of the operational environment of the resources under control. Addressing this dilemma requires that resource controllers are provided the necessary data to make complimentary decisions. Over longer time horizons, the System Operator, network service providers, policy makers and regulators will require an ever-expanding range of data for their planning, investment and strategic functions.

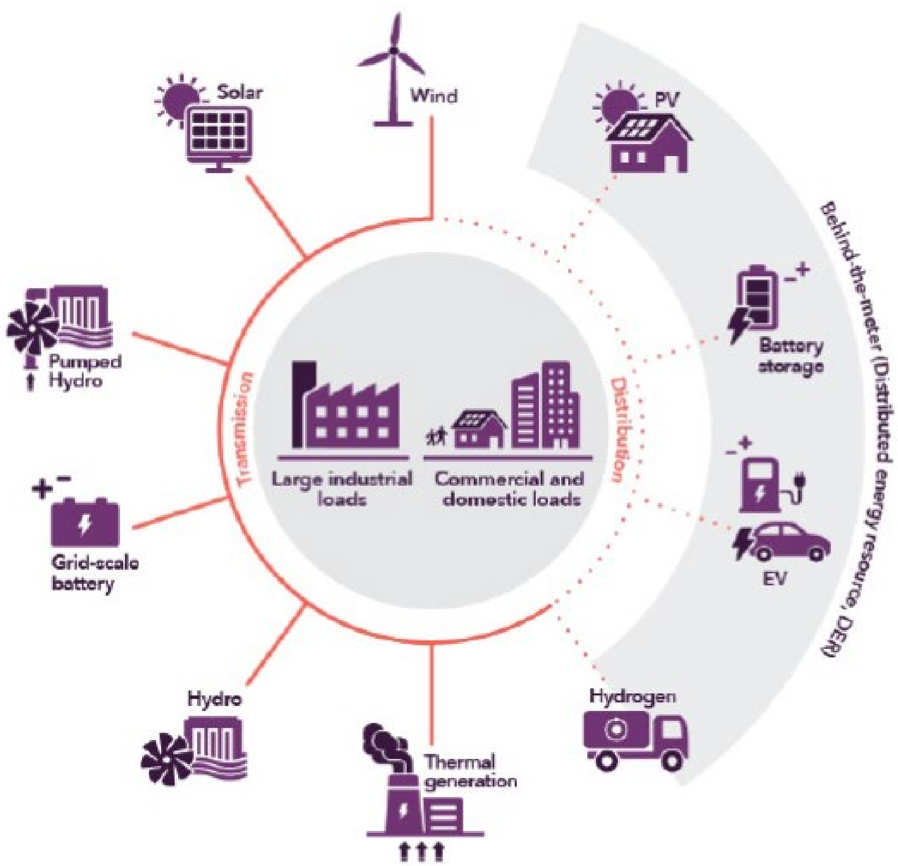


Figure 5: The impact of interactions between the power system and individual and aggregated customer resources is increasing

2.3. Generation Diversification

Emerging Trend	Implication/s
2.3.1. Withdrawal of traditional generation and replacement with utility-scale VRE is being accelerated by market forces and policy imperatives	
The withdrawal of Australia's coal-fired, synchronous generation fleet is accelerating, with the original closure dates typically being brought forward from original announcements. Based on current announcements, 60% of conventional generation capacity will have been withdrawn by 2030. The entire coal-fired fleet will have been withdrawn by 2043. In parallel, Australia is installing utility-scale Variable Renewable Energy (VRE) faster than at any time in history.	The current record rate of utility-scale VRE deployment will need to be maintained every year for a decade to triple VRE capacity by 2030 – then almost double it again by 2040, and again by 2050. Synchronous generation is typically the largest source of firming flexible energy and Essential System Services (ESS) by a wide margin. Therefore, as the proportion of asynchronous Inverter-based VRE generation increases, resource availability must be managed carefully to ensure that sufficient alternative sources of firm, flexible capacity and ESS come online. It is noteworthy that in a modern power system, many of these services may be provided by resources located on both the supply and demand sides of the system. In addition, alternative inverter control methods such as those offered in Grid-Forming Inverters (GFMI) will increasingly be required to help achieve a secure, stable, reliable, IBR-dominated power system. This, in turn, will require new control methods as well as new protection schemes.
2.3.2. New VRE deployments are facing significant network connection risks	
In the past four years, 121 new large-scale wind and solar projects have connected to the NEM with many more on the way. This is driving a wave of major new transmission projects to carry the generated energy to market.	As the withdrawal of coal generation accelerates, it is increasingly urgent that these transmission projects advance. This will require new approaches to coordinating investments and resource mix, and the development of Renewable Energy Zones

Given the scale of VRE deployment, a critical challenge is the timely and least-cost delivery of major transmission projects that will support the changing generation mix. These large and complex projects have been prone to delays and cost-increases through planning and approval stages and are occurring in an environment of upward pressures on network costs.	(REZ) for the prioritised siting of new VRE capacity will be a key focus. Furthermore, given the massive scale of transmission build anticipated, additional consideration of options for whole-system optimisation will be increasingly valuable for moderating the scale and sequencing of new transmission construction.
2.3.3. VRE deployments are facing curtailment risks due to congestion management issues	
Given the scale of VRE deployments and the related transmission capacity issues that are emerging, network congestion is becoming an increasing challenge. This is resulting in VRE generation being curtailed off the network for periods of time.	Significant work will be required to mitigate market disruptions arising from curtailment risks to VRE generation as the coal-fired generation fleet retires. This may include a range of considerations including: • New variable transmission circuit structures; • Variable flow control; • Expanded buffering / energy storage; and, • Moderation of build through targeted system optimisation.
2.3.4. Gas-powered generation is increasingly prominent as a transitionary source of flexible generation but is facing gas shortfall risks	
As the coal-fired generation fleet is progressively withdrawn, new sources of flexible generation are increasingly required to meet demand in daily peak periods and/or when the output utility-scale VRE and other generation sources is low.	Without significant increases in long-duration storage and demand response, gas-powered generation will likely be the key source of flexible generation in the medium term. Looking further out, the Step Change scenario also anticipates a longer-term role for gas-powered generation with up to 10GW of capacity in 2050. Gas shortfalls could, however, constrain the availability of gas generators and/or lead to higher prices. These shortfalls pose direct risks to gas system security in the event that

	inventory at storage facilities falls below the minimum levels required to support gas flow from them. Curtailments of this sort ultimately then restrict flexible generation availability, which highlights the challenges associated with closely interconnected markets.
2.3.5. High levels of DPV adoption by residential, commercial and industrial customers are driving rooftop solar toward becoming near ubiquitous	
Many of Australia's states have experienced world-leading levels of roof-top Distributed Photovoltaics (DPV) adoption, initially by residential customers and increasingly by commercial and industrial customers. In this context, rooftop DPV is anticipated as being a ubiquitous feature of Australia's future power system. The time windows in which some distribution network elements must operate with >70% of instantaneous demand being served by local DPV will continue to increase in frequency and duration.	The generation model of the power system is shifting from a traditional centralised, transmission-connected paradigm to an increasingly hybridised system as the proportion of distribution-connected generation expands. This shift changes power system operations drastically, introducing bi-directional power flows and other effects not included in original power system design assumptions.
2.3.6. Energy resources are bifurcating into two locational classes: Centralised / HV-connected and Distributed / LV-connected.	
Historically, the generation fleet was largely connected to the transmission system, which functioned as a one-directional, bulk delivery system. As noted above, an additional class of generation is now emerging at significant scale which is highly distributed and connected to Australia's LV distribution systems. This is a fundamental and profound structural change to the power system and one that has developed organically, not as a result of design.	The bifurcation of Australia's generation fleet into two major locational classes involves a dramatic shift as follows: • From a wholly centralised generation fleet located at one end of the power system; • To an increasingly hybridised generation fleet that is located at both ends of the power system. As noted above, this changes power system operations drastically. And because the change was not planned, the underlying grid systems are not aligned with this major

<table>
<tr><td></td><td>structural shift, except to the extent that minor incremental changes have been made.

Major revision of power system control and coordination is needed to fully realise the benefits and mitigate the risks of this fast-emerging new paradigm.</td></tr>
<tr><td colspan="2">2.3.7. Energy resources are bifurcating into two primary functional/investment classes: Merchant resources and Customer/private resources</td></tr>
<tr><td>Historically, the generation fleet largely consisted of merchant resources installed for the primary or singular purpose of providing energy and services to the relevant markets.

By contrast, an additional class of customer / private generation and energy resources is now emerging at significant scale. While these resources will typically have under-utilised capabilities that would be of value to the power system, they were not primarily deployed as merchant resources.</td><td>Australia risks duplication of investment in its electricity system where the under-utilised capacity of customer / private energy resources is not efficiently and equitably unlocked.

Being installed primarily for customer purposes, however, compared with merchant resources, large scale provision of services will involve:
• Different motivational dynamics and engagement approaches;
• New procurement and remuneration models; and,
• Advanced automation to ensure the right physics-based services are provided when and where required most.

In other words, power systems will increasingly need to be able to accommodate energy resources that they cannot directly control. This introduces a new dynamic class of constraints into the power system control challenge, as well as new observability issues.</td></tr>
<tr><td colspan="2">2.3.8. Essential System Services (ESS) are increasingly required from alternative sources</td></tr>
<tr><td>Essential System Services (ESS) help keep the power system in a safe, stable, and secure operating state. These critical services, which have traditionally been by-products of synchronous generation, include inertia,</td><td>In a power system dominated by IBR-based VRE generation and DER, new sources of ESS will be required. This will require new:</td></tr>
</table>

frequency regulation, system strength and operating reserves. As the proportion of conventional synchronous generation sources decline, inertia, frequency, system strength and operating reserve services must be provided by alternative sources, both centralised and decentralised.	• Frequency support services arrangements, including performance parameters for very fast frequency response and siting and capacity requirements of FFR resources; • Voltage support services arrangements, including identification of conventional Volt/Var/OLTC equipment capabilities operating in an IBR-dominated system and orchestration requirements for distribution-connected energy storage systems; • Performance assessment metrics, including evaluation of existing metrics used to assess the quality of ESS and their suitability in an IBR-dominated power system; and, • Financial domain, including the sustainable integration of new sources of ESS into the market and coordinating DER-provided ESS with bulk power and transmission requirements.
2.3.9. System flexibility and firming services are increasingly required from alternative sources	
As the generation fleet transitions, the proportion of system flexibility and firming services that can be provided by traditional supply-side resources is decreasing. In addition, system balancing is considerably aggravated by stochastic generation sources such as VRE, the operation of which is ultimately inconsistent with the standard 'load-following' paradigm of power system control. Beyond direct balancing issues, unmanaged oversupply of VRE output is also driving voltage regulation problems, transmission congestion issues, negative marginal prices and curtailment-related investment issues.	Power systems dominated by VRE and DPV generation will require new sources of system flexibility and firming on both supply and demand-sides of the system. Supply-side sources of flexibility and firming services include: • Existing hydro generation, both storage and run-of-river types, which rely on natural inflows rather than pumping to operate; • New utility-scale Battery Energy Storage Systems (BESS) and Pumped Hydro Energy Storage (PHES) options across various capacities, typically spanning 6- 48 hours of energy in storage;

	• Existing and new gas-fired generation will be crucial for complementing BESS and PHES capacity during periods of peak demand, particularly during long 'dark and still' weather periods. • As the maturity of zero-emission gas turbines improves and input fuel costs fall, their participation in the NEM will also need to be supported with relevant policy levers. Refer to 2.4.6 and 2.4.7 for demand-side sources of system flexibility.
2.3.10. A power system dominated by IBR-based generation is increasingly requiring the deployment of alternative inverter types	
Power electronic connected generation, also known as inverter-based resources (IBR), are increasingly the dominant means to connect new generation to the Australian electricity grid. To date, almost all applications of IBR have been based on Grid-following Inverter technology (GFLI). Essentially, this means that these energy sources rely on other resources, mainly thermal and hydro synchronous generation, to set grid voltages and frequency.	As synchronous generation is progressively withdrawn, the availability of essential grid services to manage voltage and frequency is increasingly at risk. Alternative inverter control methods such as those offered in Grid-Forming Inverters (GFMI) will help achieve a secure, stable, reliable, IBR-dominated power system and compliment other sources of grid services such as synchronous condensers. Development of these methods requires exploration of control strategies, protection schemes and modelling approaches for IBR-dominated grids. This will need to include a particular focus on the contribution of advanced IBRs to frequency stability, voltage stability, real and reactive power flow control, and interaction mitigation and oscillation damping between aggregated IBRs.

2.4. Load / Demand

<table>
<tr><th>Emerging Trend</th><th>Implication/s</th></tr>
<tr><td colspan="2">2.4.1. Structural shifts in demand / load composition are occurring and becoming more difficult to forecast</td></tr>
<tr><td> Loads are changing from simple passive forms to more active forms dominated by nonlinear power supplies and by increasing embedded intelligence. In addition, significant new sources of load are emerging from sector coupling such as the electrification of transport and industrial processes and the emergence of the green hydrogen sector. Decreases in traditional loads are also resulting from energy efficiency initiatives, large industrial closures, and consumer grid defection. </td><td> Enhanced approaches to load forecasting will be needed as new types of loads emerge, some traditional loads decline and the deployment of DPV and DER continues apace. This will need to include: More sophisticated computation of alternative load scenarios that may arise from different customer investment choices;
Ongoing, advance monitoring of the emergence of significant new / non-traditional sources of load;
Ongoing monitoring of potential decreases in traditional loads; and,
More advanced and ubiquitous deployment of short and medium horizon solar resource forecasting relevant to DPV output.</td></tr>
<tr><td colspan="2">2.4.2. The deployment of Distributed Photovoltaics (DPV) at scale is hiding real demand and exacerbating ‘demand-side’ volatility</td></tr>
<tr><td> The deployment of DPV at scale is reducing net customer demand from the power system. However, due to the stochastic nature of DPV operation, the power system must still be capable of supporting the entire instantaneous load, with very short notice, where DPV output suddenly drops. </td><td> The operational behaviour of DPV effectively introduces new levels of apparent demand volatility. This is problematic for system balancing and obscures signals required to forecast needed capacity needed into capacity markets, potentially signalling that less traditional generation is needed than must be available to back up non-firm DPV. Increasingly, more advanced control methods will be required to provide a sufficiently integrated approach to bulk power and </td></tr>
</table>

	distribution systems coordination. This will also need to include short and medium horizon solar resource forecasting relevant to DPV output. Due to fast dynamics, this may require storage buffering with automatic control, since markets will not be able to respond quickly enough to handle fast power fluctuations. The above are expected to emerge in the context of industry efforts to define and mature new industry structures such as Distribution System Operator (DSO) models and Transmission-Distribution Interface (TDI) designs.
2.4.3. The intensity of the 'evening ramp' in demand is increasing in comparison to average midday demand	
Increasing penetration of both distributed and utility solar PV as a generation resource is causing an increasing need for non-solar resources to ramp up output as the sun sets to replace the fading solar production. The so-called 'evening ramp' occurs as the decline in solar PV output occurs quite rapidly in the late afternoon. There is an increasing need not just for replacement resources, but resources that can ramp up output to match both the drop-off of bulk solar and the increase in apparent demand (and during heating seasons real demand) as the sun sets. In addition, vehicle charging demand is increasing in the evening as the electrification of transportation grows, further exacerbating the effective of this ramping issue.	The penetration of solar PV complicates the makeup and operation of the generation resource set by introducing a non-controllable (albeit predictable) generation fluctuation that the power system was not designed to handle. Neither solar PV nor wind turbines are in themselves 'rampable', unless under curtailment. This is creating an expanding need to match resources and demand dynamically via rapid ramping capacity in the resource mix, multi-hour storage, load shifting, or other means to manage what is effectively an emerging volatility in generation. This also complicates day-ahead and intra-day grid management, as well as intermediate and long-term grid planning and investment strategies.

2.4.4. Overall system load growth (GWh) is expected to be unprecedented with the electrification of transport, industrial processes and building services	
Australia's COP26 commitments involve a significant dependence on the large-scale electrification of transport, industrial processes and building services to replace a range of more carbon-intensive fuels such as natural gas and petroleum. Significant efforts are currently underway across many sectors to advance decarbonisation through electrification.	The NEM currently delivers approximately 180 TWh of electricity to industry and homes per year. Based on AEMO's Step Change scenario, the capacity of the NEM would need to nearly double between 2022 and 2050 to meet the levels of electrification set out in the COP26 commitments. In the case of the AEMO's Hydrogen Superpower scenario, the capacity of the NEM would need to increase eight-fold between 2022 and 2050 in support of hydrogen export production. This would involve an unprecedented level of change and scale of investment over the coming decade with significant risks that will need to be carefully managed (refer 2.2.1 above)
2.4.5. The mass-electrification of transport will result in an entirely new phenomena of load, demand and storage portability at scale	
The transition to electric vehicles (EV) began relatively slowly in Australia but is now gaining pace. EV ownership is expected to surge from the late 2020s, driven by falling costs, greater model choice and availability, and more charging infrastructure. At the same time, EV batteries are increasing in size, weight and energy storage capacity, and increasing penetration is creating an entirely new phenomena of load, demand and storage portability at scale.	Most traditional network analysis and constraint analysis is currently based on the assumptions that: • Energy supply is provided by locationally fixed generation resources; and, • EV charging is primarily a load source during charging. This inadequately considers the potential significance of energy portability via road transport. Such potential may result in OEM solutions and employer benefits that, for example, encourage workers to charge their EV with 'free' solar PV at work and then discharge it to

<table>
<tr><td></td><td>power their home via Vehicle to Building (V2B) technology.

While this may not make a significant impact at first, as with solar PV it may result in significant shifts of energy via roads over time.</td></tr>
<tr><td colspan="2">2.4.6. System flexibility and firming services will increasingly need to be provided by demand-side resources</td></tr>
<tr><td>As the generation fleet transitions, the proportion of system flexibility and firming services that can be provided by traditional supply-side resources is decreasing.

In addition, system balancing is considerably aggravated by stochastic generation sources such as VRE, the operation of which is ultimately inconsistent with the standard 'load-following' paradigm of power system control.</td><td>As noted above, power systems dominated by VRE and DPV generation will require new sources of system flexibility and firming on both supply and demand-sides of the system.

Several key sources of high potential demand-side sources of flexibility include:
• Electrolysis for large-scale hydrogen production;
• Electrification of metals and minerals processing;
• Smart controls for commercial buildings;
• Behind the meter solar and battery storage;
• Electric vehicles; and,
• Orchestrated energy consumer devices, such as air-conditioners, pool pumps and heat pumps.

In addition, four forms of flexible demand have emerged as follows:
• Shape - Moving demand routinely according to a standard long-term pattern;
• Shift - Moving demand sporadically in response to an external signal;
• Shimmy - Moving demand over very short timescales in response to an external signal; and,
• Shed - Switching off equipment.</td></tr>
</table>

	These have use cases across different elements of the power system. For example: • Shift can be used to reduce demand and reduce pool price in the wholesale electricity market during high price events; • Shape, Shed, and Shift can reduce demand on electricity networks during peak demand periods, reducing the need for infrastructure upgrades and increasing network security; • Shed is the dominant provider in the Australian Reliability and Emergency Reserve Trader (RERT) scheme; and, • Shimmy can be used to provide short-term supply and demand balancing in the Frequency Control Ancillary Services (FCAS) market.

2.4.7. Customer technologies have increasing ability to provide flexibility, firming and ESS

Traditionally, customer loads were largely considered passive in terms of power system management and generally forecastable in terms of demand aggregated to the feeder level and above. Increasingly, loads are becoming more responsive with participation in various demand response programs. While demand response has been used for decades, in many cases this has focused on commercial and industrial customers and been activated through non-automated processes. With the development of smart appliances / devices and new interoperability standards, a growing proportion of residential, commercial, and industrial technologies located behind the meter have the latent ability to provide a range of services to the power system in exchange for a share of the value created.	Rather than being limited to supply-side sources, a proportion of flexibility services may be provided by Behind the Meter (BTM) resources in a modern power system. Unleashing the full potential of under-utilised customer resources, however, will require a new range of systems architecture enablers, communication links and financial incentives. Ultimately, the Operational Coordination of the power system will need to extend beyond the historic system boundary to efficiently manage the level of dynamic interactions at scale. This will require an 'extended grid' paradigm that actively involves BTM assets not owned by utilities) and the observability and controllability issues for grid will extend to include responsive loads.

2.5. Control Dynamics

<table>
<tr><th>Emerging Trend</th><th>Implication/s</th></tr>
<tr><td colspan="2">2.5.1. The power system is experiencing a significant loss of system rotational inertia and faces increasing challenges in managing frequency</td></tr>
<tr><td>As the power system decarbonises, frequency management is becoming more challenging due to the reduction in mechanical inertia.

In bulk power systems dominated by synchronous generators, the inertia response determines the initial Rate of Change of Frequency (RoCoF) after a contingency. The generator governor response assists in arresting the system frequency before the compensation mechanisms take effect, allowing frequency to be stabilised and restored to normal by reserves.

By contrast, wind turbines have low mechanical inertia, which is not always available, and solar PV has no inertia. Historically, NEM mainland inertia has never been below 68,000 megawatt seconds (MWs), however, by 2025 AEMO forecasts that inertia could drop to as low as 45,000 MWs.</td><td>As mechanical inertia decreases, an increased volume of frequency services, or services that can respond quickly in response to transient phenomena in a low inertia system will be necessary to arrest the change in frequency before technical limits are exceeded and risk system collapse.

Consistent Primary Frequency Response (PFR) provision will be required in the future to model system events, which is essential for system planning and ongoing management of power system security.

Further, understanding the behaviour of DER technologies, including how they impact system dynamics and existing primary, secondary, and tertiary frequency controls is becoming increasingly important as penetrations rise.</td></tr>
<tr><td colspan="2">2.5.2. Variable Renewable Energy (VRE) deployment at both HV and LV levels of the system is increasing volatility that can propagate in either direction</td></tr>
<tr><td>Volatility is a phenomenon that can occur on a wide range of time scales. While much focus is on very short-term effects, it is increasingly necessary to consider this as a multi-scale issue. For example:

• Variation on the scale of sub-seconds to minutes is increasingly a problem at the distribution edge, where no 'law of large numbers' effects exist to smooth out the variations – leading to voltage regulation</td><td>Volatility is both a technical and an economic problem for electric grid operators and customers. Traditional means of managing volatility via spinning reserves are becoming increasingly inadequate as the coal-fired generation fleet retires.

In most other kind of engineered systems or supply chains, it is standard to provide buffering mechanisms to manage volatility. In logistics systems, for example, the buffers are</td></tr>
</table>

issues at the local feeder and service drop levels.

- Fluctuations in apparent load in the seconds to minutes time scale can appear as fluctuations at the Transmission-Distribution Interface, including even reverse power flows caused by DPV export into the grid.
- Hourly to longer fluctuations in customer resources contribute to overall duck curve effects at the bulk level, which is how a ramping deficit can develop.
- Volatility of bulk solar and wind not only introduces volt/VAR and frequency / balance fluctuations that affect LV systems, they exacerbate market price volatility which ultimately affects customers.
- On a diurnal, and seasonal basis, changes in load and in availability of wind and solar constitute volatility on slower scales, affecting planning, investment and prices at both HV and LV levels.

warehouses. In gas and water systems, the buffers are storage tanks. In communication systems, they are called jitter buffers.

A grid dominated by VRE requires buffering to operate reliably. The scale, placement and control of such buffering elements is a key aspect of power system transformation.

2.5.3. The power system faces increasing challenges in managing voltage

As the power system decarbonises, the management of voltage is increasing in complexity. Key factors exacerbating this challenge include:

- Decreasing levels of synchronous generation being online;
- Increasing levels of Distributed PV (DPV);
- Increasing levels of VRE generation in distant locations;
- Low daytime customer demand;
- Structural changes in demand characteristics;

High VRE output is displacing synchronous generation, which has traditionally been a significant source of static and dynamic reactive power in key network locations. In addition, the growth of VRE generation in regional locations (where solar and wind resources are plentiful, but far from demand centres and existing transmission infrastructure) is increasing power transfer over long distances, which requires reactive support and the need for fast reactive response.

The growth of DPV installed behind the meter by households and businesses reduces demand on the transmission system, which

• Dependence on forms of manual control between power system entities; and, • Increasing volatility at the distribution edge, where DPV dynamics are not moderated by 'law of large numbers' effects.	causes voltage rise and reverse flows into the bulk system. This causes voltage rise on the distribution system, as power is fed back from the end of long feeders. In addition, as DPV has grown, falling daytime demand is increasing the usage of already ageing reactive plant which was originally sized to manage differences between night-time minimum and maximum demand. The increased need for reactive plant to manage daytime minimums for a greater proportion of the year also reduces the available critical maintenance windows during off peak periods. Increasing distributed generation is changing the reactive flow between the transmission and distribution system. This requires the System Operator to manually interact with distribution networks to adjust reactive power interchange at the Transmission-Distribution Interface (TDI). While there is increasing reactive capability connecting at the distribution system, in many cases, there may not be established processes to immediately act on the instruction.
2.5.4. The power system is experiencing faster system dynamics and decreasing latency tolerance	
Power system dynamics are increasing in speed by orders of magnitude as latency tolerance declines. The implementation of new power system capabilities has resulted in significant increases in the speed at which grid events occur. This is especially true with distribution networks but is also impacting transmission systems. In the last century, aside from protection, distribution control processes operated on a time scale stretching from about five minutes	Automatic control is becoming essential, and this brings with it the need to obtain data on the same times scales as the control must operate. This is the result of somewhat of a 'double impact': • Many more new devices to control; and, • Much faster dynamics for each device. This requires vast new data streams and increasing dependence on ICT for data acquisition and transport, analysis, and automated decision and control.

to much longer, and human-in-the-loop was (and still is) common. With the increasing presence of technologies such as IBR-based VRE and DPV and power flow controllers, active time scales are moving down to sub-seconds and even to milliseconds.	Existing person-in-the-loop control is therefore becoming unsustainable and existing control systems and related applications are becoming unable to keep up with real-time grid behaviour. Additionally, data acquisition is impacted since latency and latency skew become much more significant as control time cycles decrease

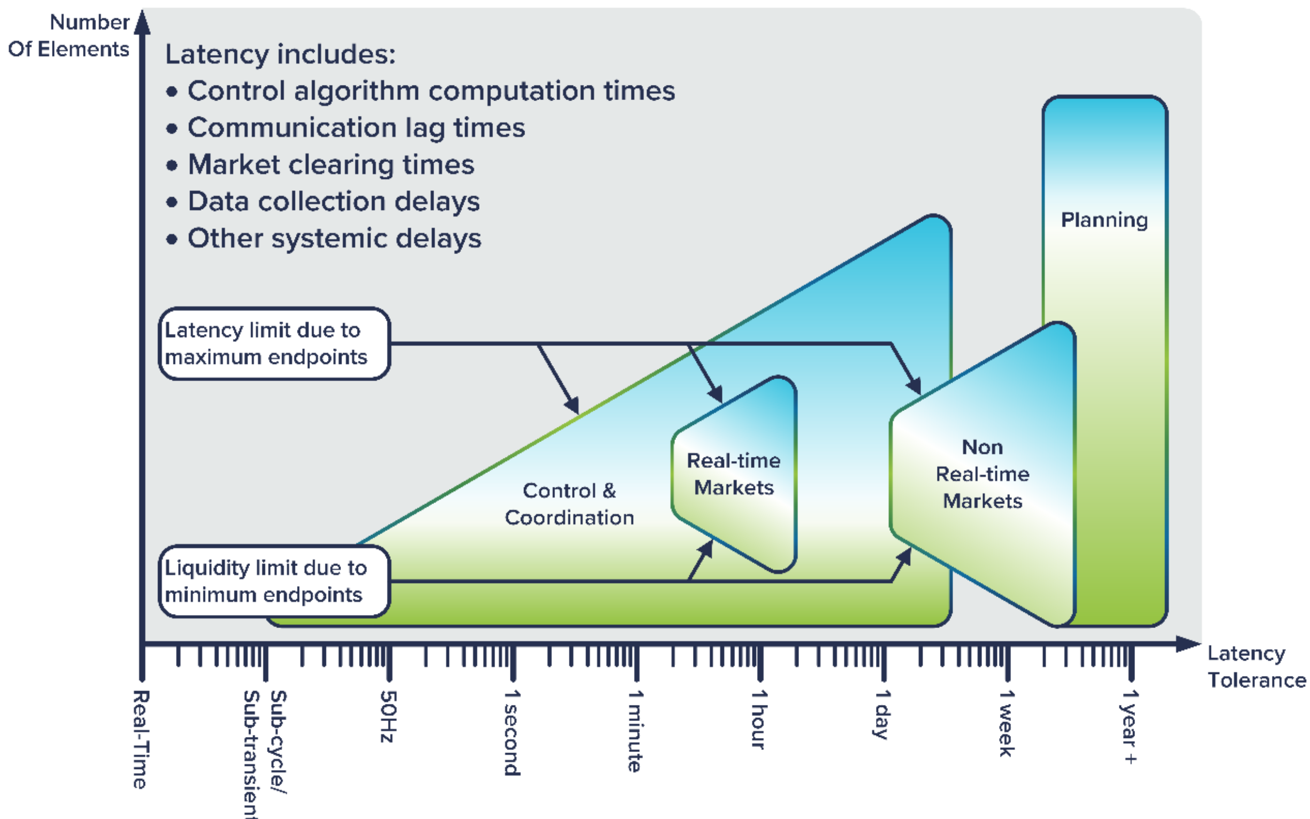


Figure 6: Market and control interactions as power systems experience faster system dynamics and decreasing latency tolerance

2.5.5. The number and complexity of new functions are growing significantly and are presenting a new level of computational and optimisation challenges

Power system control problems are becoming increasingly complex as we add new functions and requirements.

This is typically involving a growing diversity of objectives for system optimisation which, for example, may variously focus on:

- Load profile optimisation;
- Carbon emission optimisation;
- Volt/VAR optimisation;
- Variable grid structure control and logical multi-way power flow (to be resolved into real flows);
- Embedded storage management; and,
- EV charging optimisation, etc.

End users are also wanting to perform 'selfish' control optimisation that, in many cases, may conflict with optimal system control.

Large scale, multi-objective optimisation is increasingly required across multiple layers of the power system. This will be necessary to coordinate controls and optimise to various objectives. It will also need to consider complex constraints and solve distributed control problems.

The presence of large volumes of mixed DER ultimately constitutes an entirely new kind of optimisation and scaling challenge for power system control. Conventional power system control architectures, however, were not structured for such large scale, multi-objective optimisation needs.

Key challenges include the establishment of sufficient optimisation capacity to manage the huge numbers of constraints and conflicting objectives that must be accommodated across power system layers. Related computational loads will also grow exponentially and risk computational 'time walls' emerging.

2.5.6. Operational Coordination of millions of energy resources located across the Transmission-Distribution Interface is presenting significant new challenges

Modern power systems are increasingly requiring enhanced Operational Coordination mechanisms due to:

- The level of system volatility experienced as decarbonisation deepens;
- The number and diversity of participating resources as the system transitions from hundreds to tens of millions of energy resources;
- These resources becoming near-ubiquitous across all vertical layers of the power

Imperial College London (ICL) estimated the optimisation premium of whole-system-based coordination of demand-side flexibility to be in the order of 8.3% TOTEX annually for the UK power system.

Given the inseparable cyber-physical-economic nature of the power system, comprehensive 'market-control' alignment will be required to incentivise and activate service provision in a reliable and mutually reinforcing manner. The balance between market-like and control-like

system and blind to historical bulk power, transmission and distribution boundaries; and, • With the retirement of synchronous generation, increasing volumes of system flexibility, balancing and ancillary services will be required from the traditional demand-side of the system.	methods must evolve as the structure and dynamics of the power system change. Economic incentivisation and cyber-physical automation elements must be tightly coupled across each power system layer for energy, capacity, flexibility, and essential system services to be delivered when and where needed by the system. Ultimately, advanced Operational Coordination models must be capable of maintaining instantaneous supply and demand balance every millisecond of the year (refer also to 2.8.7 below).

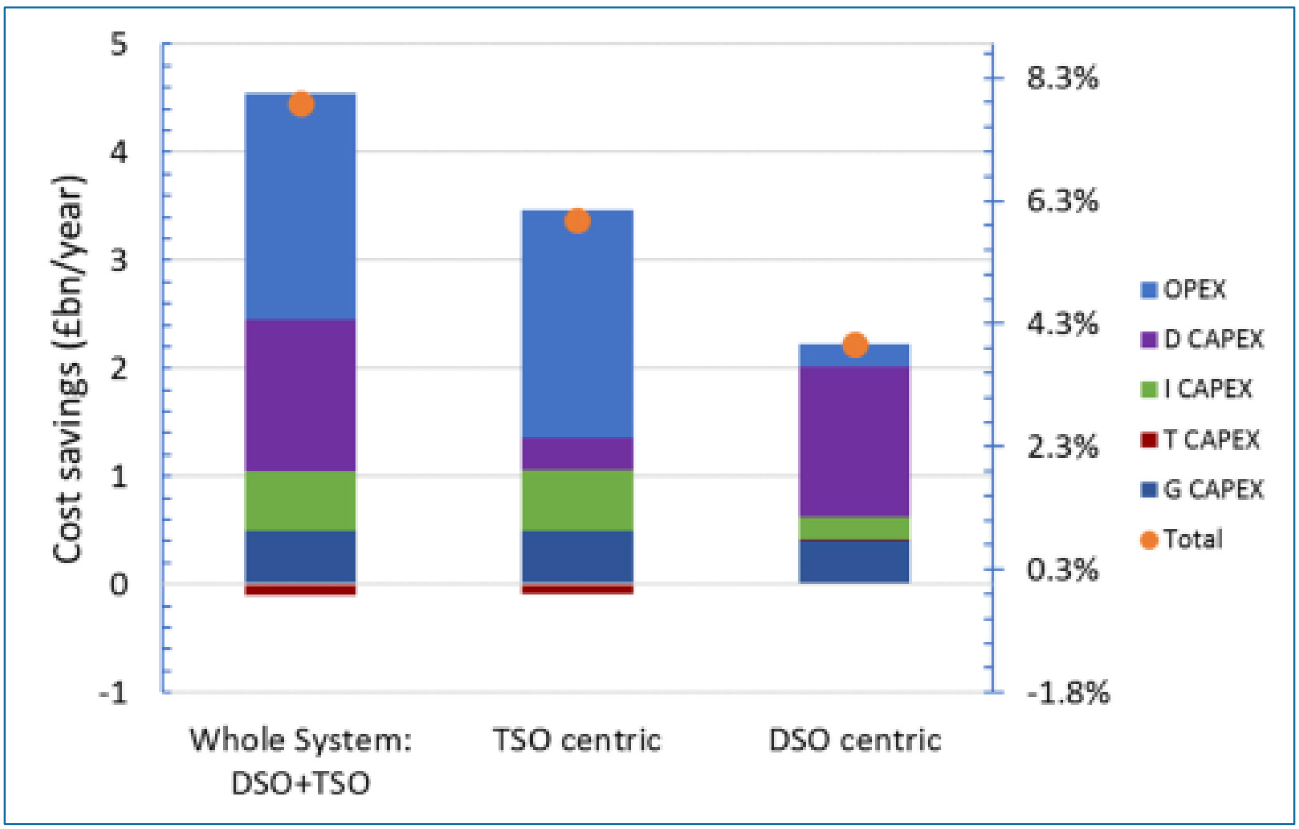


Figure 7: Potential benefits of improved transmission and distribution control interface modelled by Imperial College London

2.6. Data & Communications

Emerging Trend	Implication/s
2.6.1. Operational, market and customer data volumes and variety are rapidly expanding	
Increased data volumes and variety are being driven by a range of emerging characteristics of the power system. Most obviously, it correlates with massive growth in the number and dynamics of participating resources connected to the power system. Each of these resources may exchange two-way communication and multiple datasets with aggregator(s), retailer, OEMs/vendors, network service provider, third party energy management or smart home platforms and applications, cloud services, meteorological services, and other similar entities. Many of these data exchanges will occur concurrently, at high frequency and in real-time. Transmission and distribution networks are also producing orders of magnitude more data volumes as they deploy next generation high fidelity instrumentation with streaming sensing devices and asset monitoring equipment, in addition to newer data-rich protection, sensing and control systems needed to support Advanced Distribution Management Systems (ADMS). New distribution-level markets that are likely to emerge also require significant amounts of data, both physical and financial.	Historically, network service providers have often implemented communications systems that are dedicated to supporting a single application, such as an industrial SCADA system. These single-purpose networks are not readily scalable, are often difficult to manage, and their associated data not easily shared, even across internal business units. In addition, 'siloed' systems with back-end integration tend to be more brittle overall. By contrast, future infrastructure will increasingly need to be configured for entirely new levels of scalability and extensibility to ensure it can securely accommodate an increasing range of applications, participating entities and data volumes.

2.6.2. Power system, market and customer data are required by an expanding number of entities

The number of actors interacting with the power system to monitor and exert control over network-connected resources is growing. This includes aggregators, retailers, OEMs/vendors, network service providers, third party energy management or smart home platforms and applications, cloud services, and other similar entities. Data produced and consumed by each of these entities currently resides in disparate servers and data repositories, each with varying meta-data schemes, credentialing, and authorisation approaches. This further complicates the management of data flows, storage, versioning, access rights and credentialing, prioritisation, and similar considerations.	Existing systems that currently 'own' significant volumes of grid data that are increasingly also required by other systems may have to give way to more distributed arrangements that are not subject to inherent limitations of more siloed systems This will require new data flow and information sharing / processing architectures will be required to support coordination across this range and volume of actors.

2.6.3. The cyber-security of power systems and related datasets is becoming increasingly prominent

Power systems are moving from centralised, privately networked, single application control systems with hub-and-spoke communications to more distributed forms of control using vendor-developed solutions and multi-application digital infrastructure, with some data transiting public meshed networks. At the same time, the number of cyber-threats and sophistication of cyber-attacks is on the rise and power systems are far from immune. For example, in 2015, hackers successfully disabled 30 substations in Ukraine, disrupting electricity supply to 230,000 residents.	As digital infrastructure, data and the power system become more tightly coupled, the potential for large-scale disruption caused by cyber-attacks may exceed that of natural disasters and contingency events. Risk assessments and resilience planning are increasingly needing to give priority to cyber-security. Existing approaches to cyber-security in the power sector will need to continue to mature and an expanding range of new tools, methods, and processes will be needed. Third party systems providing customer-facing products and services could introduce avenues for cyber-attacks that cause system-wide disturbances. Alternately, in a situation where a particular product or service has significant uptake, exploiting vulnerabilities isolated to that product or service may be enough to

	destabilise parts of the network. For example, a hacker who gains access to the management system of all EVs of a particular make could potentially manipulate a large amount of load on short cycles to disrupt system operations. Aside from malicious actors, the redundancy of communications networks is also an important consideration. It could conceivably arise that OEM, vendor or other functions of the power system are dependent on digital connectivity that is in-turn dependent on the power system. During a power-outage those systems become inoperable potentially causing instability, for example, during black-start.
2.6.4. Inadequate access rights to operational data are becoming more problematic as the number of participating resources and associated platforms expands	
Energy service providers have been and are expected to continue to be aggressive in asserting their Intellectual Property as it relates to their fleet management systems and control of distributed resources, including EVs, aggregation, demand response and distributed storage. Electric Vehicle Supply Equipment (EVSE) vendors, for example, collect a large amount of data from their customers. Beyond enabling intelligent managed charging services, this is of significant commercial value as it can be used to enhance vendor platforms, target new products and services, and tailor solutions to their customers. Similarly, data associated with DPV is increasingly accessible to DER aggregators but is not so readily accessible by network operators. More generally, when useful data resides in proprietary platforms, system operators are unable to access otherwise valuable information for real-time operational decisions and longer-range planning functions.	A 2019 report commissioned by the UK Government, Innovate UK and Ofgem and compiled by the Energy Data Taskforce found that a lack of common data standards, no openly shared data repository, and a culture of data hoarding was preventing competition, innovation and new business models. It recommended that, given the power and potential of data, a culture of 'presumed open' be embedded across the sector. Reluctance to share data is expected to continue unless provisions are made for secure, authorised and controlled data access and management. Commercial entities may be willing to provide access to useful data, however, where suitable undertakings from the receiving party protect their interests. Such provisions would ideally be standardised sector wide, avoiding a patchwork of bi-lateral arrangements or a multitude of schemes that cause confusion. A shared and secure data platform backed by a universal credentialing may be one such option.

2.6.5. It is increasingly recognised that legacy power system architectures and data routings contain structural vulnerabilities that elevate cyber-security risks	
The legacy system architecture emerged in an era when digital infrastructure played a much more limited role in supporting the power system, particularly at the distribution level of the system. In recent years there has been a growing focus on cyber-based security considerations. While limited in Australia, some jurisdictions are recognising that legacy power systems also contain non-cyber structural vulnerabilities that heighten cyber-security risks.	Cyber-secure communications can be significantly enhanced by analysing legacy and alternative structural arrangements for data flows and communications routing. Such analysis can provide new architectural features that have inherent non-cyber capacities to resist cyber-attack. This may include the application of Resilience Algebra to identify structural configurations that are inherently cyber-threat resistant and support the placement buffering to resist/minimise the efficacy of cyber-attacks.
2.6.6. It is increasingly recognised that legacy power system architectures risk bottlenecking and latency cascading as endpoint and data volumes expand	
The power system was historically configured as highly centralised, and its control systems designed to align with this paradigm. In general, data has been routed to centralised systems for analysis that informs system operation and resource coordination. Massive volumes of data are produced as more sophisticated near real-time management is required in a context where the level of system dynamics, and the number and type of endpoints, are dramatically expanding. Several jurisdictions are now recognising that both legacy and hybrid power system architectures may face bottlenecking and latency cascading risks as endpoint and data volumes expand.	Centralised models of data flows and processing risk bottlenecking and latency cascading as the number of endpoints and volumes of data expand. Analysis of legacy and alternative structural arrangements, including options such as Layered Decomposition structural models will be required to ensure communications systems are scalable and extensible. Similarly, application-specific data and communications systems will need to shift to more data-centric approaches, whereby data is freed from siloes and its value unlocked by making it available to other consuming applications.

2.6.7. Significant interoperability efforts are increasingly at risk of being impeded without the parallel consideration of evolving systems architectures	
The maturity of existing DER interoperability systems and related technologies is limited when compared with the needs of a high-DER power system. Australia is currently contributing to international efforts to develop common communications protocols and technical standards for DER interoperability. 'CSIP-Aus' is an Australian adaptation to the Common Smart Inverter Profile (CSIP) IEEE 2030.5 Implementation Guide for Smart Inverters. The full benefits of this work, however, risk being impeded due to the absence of agreed and future-ready architectural configurations of the power system (i.e. cyber-physical structural settings that are scalable and extensible to plausible future scenarios).	While interoperability standards provide clarity about what and how data is exchanged between technologies, systems architecture is needed to formalise the relationships and structural interdependencies between the actors of a complex system and their related portfolio of technology and market structures. A holistic approach to interoperability, therefore, is inextricably linked to question of the evolving Roles & Responsibilities (R&R) required by the future power system. To realise the full potential of interoperability, systems architecture tools must be applied to analyse the cyber-physical constraints that pertain to existing and alternative future R&R configurations (in addition to mitigating the related risks of bottlenecking and latency cascading as above).

2.6.8. Significant interoperability standards development are underway but risk being superseded as by consumer-focused standards

As noted above, power system control mechanisms have been highly centralised and largely based on a command-and-control paradigm.

With the advent of DPV and DER, significant efforts are underway to develop relevant interoperability standards. Consistent with traditional approaches in the power sector, development of these standards is largely occurring in a utility-focused paradigm.

However, as customer agency and autonomy continue to expand, aided by ever-expanding distributed intelligence, products and services are moving toward consumer-focused standards that elevate customer agency and autonomy.

What traditional power sector standardisation approaches may not adequately appreciate is that DPV and DER are perhaps more analogous with consumer electronics technologies than traditional power system assets. For example, *ISO/IEC 15067-3:2012, Model of a demand-response energy management system* recently redefined the concept of demand response to include indirect incentives such as price changes to motivate customers to control demand locally.

This change reflects the transformation from utility-focused to consumer-focused standards. To this end, the name has been changed to *Model of an energy management system*, which removes 'demand-response' from the title to de-emphasize a focus on demand for power supplied mostly by a utility.

Beyond current interoperability efforts, greater focus will need to be given to the next generation of energy management standards that empower greater autonomy by consumers. For example, the revision of ISO/IEC 15067-3 specifies the framework for a system in homes and commercial buildings that enables consumers to manage their usage of electricity according to their priorities, budget and technology preferences.

As distributed energy technologies evolve, energy management will be enabled by on-premises control of power usage in response to fluctuations in power availability and cost from all sources, especially sources on the premises or nearby. Energy management equipment (hardware and software) will increasingly be built into mass consumer electronics products supplied by competitive suppliers.

2.7. System Planning

<table>
<tr><th>Emerging Trend</th><th>Implication/s</th></tr>
<tr><td colspan="2">2.7.1. Forecasting for system planning is facing new challenges in a more diverse and volatile power system</td></tr>
<tr><td>Traditional methods of forecasting remain necessary but are no longer sufficient as both load and generation output become more volatile and stochastic, while also remaining temporally and spatially sensitive.

Planning practices have traditionally adopted deterministic approaches to represent the long-term drivers of system expansion, historically associated with annual load growth, using simplified representations of system operation.

The increasing operational and technological complexity of power systems, as well as the levels of uncertainty about the future system, market, and policy developments, are diminishing the effectiveness of traditional approaches. Long-term uncertainty is also increasingly influenced by factors including emerging technologies and business models, policy environments, and climate change, which all represent daunting challenges to system reliability and resilience.</td><td>The planning and operation of low-carbon power systems dominated by IBR-based VRE generation and DER requires new modelling capabilities and tools.

This includes more sophisticated and flexible representations of the plausible futures, along with enhanced decision-making tools capable of optimising planning outcomes across multiple scenarios. New metrics and methodologies that account for the technical and economic risks faced by multiple stakeholders during the energy transition must also be included.

To the extent that bulk energy storage becomes an integral part of the power system, planning methods will need to evolve to properly represent what such technology can do for the grid. This will include how all other aspects of power system operation can and should change to take advantage of the inherent buffering capability of storage, as distinct to merely treating storage as 'generation with negative output' or attached ancillary service devices.

The interface between power systems and other energy systems and sectors (i.e., natural gas, hydrogen, transport) also needs to be properly designed to capture the impact of and flexibility created by multi-energy systems and sector coupling in planning studies and to prevent negative consequences of cross-coupling and cross-export of volatility.</td></tr>
</table>

2.7.2. It is increasingly recognised that conventional planning paradigms face new challenges as the end-to-end power system becomes more inter-dependant

Conventional planning processes have primarily focused on individual segments of the power system (e.g. bulk power, transmission, distribution). As the end-to-end power system becomes more dynamically interdependent, this is unlikely to fully unlock 'whole-system' optimisation benefits.

However, as noted earlier (refer 2.1.1 – 2.1.3), Australia's power systems are:

- Becoming more diverse and dynamic;
- Transitioning from hundreds to tens of millions of participating energy resources; and,
- Experiencing a progressive erosion of the traditional 'supply-side / demand-side' bifurcation.

In this context, many jurisdictions are recognising that conventional planning models are facing new challenges as power system complexity and interdependencies increase due to the profound structural changes impacting the power system.

Conventional planning tools and methods are increasingly unable to account for the structural changes and operational behaviour/control requirement changes needed to accommodate and capitalise on power system transformation.

Planning methodologies increasingly need to be cross-organisational and cross-functional. Enhanced analytic tools must be able to adequately represent the behaviour of newer technologies such as utility-scale VRE, various types of bulk energy storage and numerous DER types and configurations.

New integrated resilient planning methodologies and tools will also be needed to fully unlock the enhanced resilience potential afforded by the targeted implementation of new technology options.

Such integrated planning will need to span organisational boundaries and functions, including across the traditional but arbitrary Transmission – Distribution boundary.

<table>
<tr><th colspan="2">2.7.3. It is increasingly recognised that more integrated joint planning of sector coupling relationships will be required to realise optimisation opportunities</th></tr>
<tr><td>While many non-electric sectors have had dependencies on the electric sector (and vice versa) the importance of sector coupling is accelerating in the cases of transportation, buildings, and manufacturing.

As these sector convergence trends proceed, independent autonomous planning of the individual sectors is increasingly incapable of recognising joint opportunities for capturing functional requirements and potential operational and investment efficiencies.</td><td>Capturing these opportunities will require joint planning methods and cross-observability over sectors experiencing emerging coupling/convergence.

Data sharing for planning across sectors will be necessary, on time scales ranging from sub-minute to years, just as the planning processes must operate.

Further, the planning processes must mesh (synchronise) by accommodating planning and implementation process sequence requirements.

Regulatory processes must also allow and encourage cross-sector collaboration.</td></tr>
<tr><th colspan="2">2.7.4. It is increasingly recognised that more advanced planning automation is required to fully realise emerging system optimisation opportunities</th></tr>
<tr><td>Many jurisdictions are recognising that existing planning tools are lagging both the scale and pace of grid transformation and the rapid increase in optionality and system optimisation provided by new power system technologies.

For example, production planning tools often treat bulk energy storage as analogous to generation. New approaches are emerging that have far greater efficacy but the full benefits of such are not currently represented in the planning tools.

Increasingly faster grid dynamics (especially near the distribution edge) are shortening the time available to perform core operational planning and control functions.

Emergence of issues such as evening ramping in the presence of extensive solar PV are likewise rendering existing planning,</td><td>New and improved planning tools that combine production cost type analysis with advanced control simulations and include models for advanced components such as storage and IBR must be developed, along with the method and processes for using them.

Advanced Operational Coordination and new market-control approaches and tools must be developed to operate the future grid.

Existing roles and responsibilities must adjust to new grid capabilities and new roles and responsibilities must be created to address gaps between current grid capabilities and those needed in the future grid.</td></tr>
</table>

simulation, and evaluation methods less effective. Operational paradigms, control and coordination, and protection schemes are falling behind advances in device technologies, such as storage, inverters, and VRE. Existing market methods and tools are becoming ineffective as generation resources increasingly move toward low to zero marginal cost.	
2.7.5. Microgrid, energy storage and related technologies are maturing in a manner that enables power system planning that is more modular and resilient	
Microgrids and more general variable structure grids are emerging to develop a capability to modularise distribution systems. Bulk energy storage technologies are also emerging as key components of such grid architectures for purposes of stabilisation and grid outage ride-through. Various models for microgrid ownership and integration with distribution systems are also emerging. These include multi-user microgrids that make use of the distribution system versus wholly private microgrids that are attached only at a single point to a distribution system.	Integrated resilient planning is needed to characterise and organise such modular and variable structure grids. New methods for evaluation for grid resilience that support architecture and design decision-making are needed. New approaches to grid management and control and protection that take into account islanding, grid support from the microgrid are also needed.

2.8. Operational Forecasting, Management & Coordination

2.8.1. System Operators are experiencing new levels of uncertainty and complexity in managing the reliability, security, and stability of the power system	
Historically, management of the power system was oriented toward the security constrained economic dispatch of dozens or hundreds of merchant resources that were typically limited to various forms of synchronous generation. As the power system decarbonises, however, the Market/System Operator (M/SO) faces greater levels of uncertainty and complexity. With increased penetrations of VRE, DER and cross-coupling with other sectors, the underlying nature of the system is changing. While having a large variety of existing tools and methods to underpin their operating decisions, many of these tools are largely based upon power system phenomena relevant to synchronous machines. These changes will both limit the applicability of some existing tools and methods as well as dictate the development of new tools and methods to ensure the reliability, security, and stability of the power system.	Faster processes and new methods are required to identify the emerging issues brought on by the transitioning power system. New analytical tools that help evaluate the operation of an IBR-dominated power system must be developed. This includes tools to: • Mitigate uncertainty arising from changing system behaviour arising from the adoption of new technologies and the volatility of weather-driven generation • Capture the interactions and impact of IBR control algorithms that can be detrimental, or beneficial, to the power system's stability and performance; • Conduct stability analyses, which are particularly challenging with time-domain analysis tools; and, • Aid real-time decision making and management of power system security.

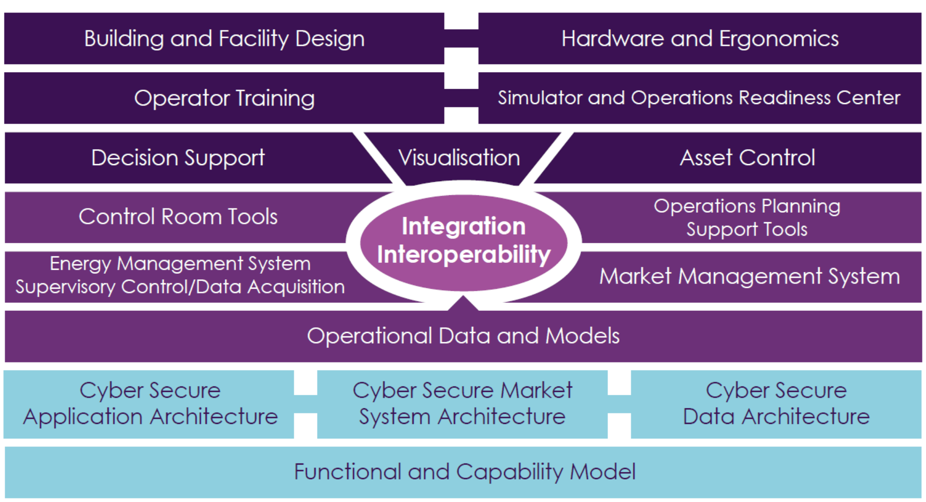


Figure 8: AEMO Control Room of the Future and Future Operations Framework

2.8.2. Conventional control room capabilities are facing a wide range of emerging demands that require significant capability uplift	
Many M/SO control rooms were designed early in the era of large-scale electricity grid interconnection, beginning in the 1970's and they haven't significantly changed since. Market systems have not materially changed since market start in 1998, and security assessment tools are rapidly becoming obsolete in a power system increasingly dominated by IBR-based VRE generation. As such, this will become particularly pronounced for maintaining energy supply through large and highly volatile weather events, that are occurring more frequently.	Conventional M/SO control rooms cannot effectively manage future power system operations. A significant uplift in capability is required that will involve identification of wider industry needs, building on the existing projects in transmission and distribution operations and maximising national alignment. The uplift in control room capabilities and their integration with the wider system are expected to require a particular focus on: • Functional & capability model and underpinning architectures; • Data modelling, data streaming and standardisation; • New advanced analytics and visualisation tools; • Energy and Market Management Systems and real-time simulation • Operator capabilities, process digitisation and human factors; and, • Buildings, facilities and hardware.
2.8.3. System restoration and black start arrangements are becoming significantly more complex	
As the number of system actors and energy resources increases, and much of the synchronous generation fleet retires, system restoration / 'black start' arrangements are becoming significantly more complex. This is because conventional processes have been largely designed for a power system dominated by synchronous machines. With increased penetrations of VRE, IBRs, and DERs, the huge growth in the number of	The following two new black-starting alternatives need to be evaluated. The first involves new specifications for grid-forming IBRs to enable them to directly black-start or to significantly assist with the restoration process. The other involves new methods, procedures, and analysis techniques to black-start a power system with various penetrations of IBRs, including up to 100%. This may require bulk

participating energy resources, and increasing coupling with other sectors, new systems and procedures will be required. Notably, as EV uptake increases, pro-longed outages may create a 'back-log' in demand, creating a risk that all EV chargers come on load with very low diversity.	energy storage devices as energy sources and temporary loads to prevent collapse during start-up.
2.8.4. Whole-system management is increasingly challenged by inconsistent levels of near real-time forecasting and visibility across distribution systems	
With increasing levels of DPV penetration comes increasing uncertainty for M/SO, transmission and distribution network planners and operators. DER embedded within the distribution network is generally not operationally visible to the System Operator or transmission system. Instead, it is observed as an aggregated fluctuation in demand at the transmission bulk supply points. This means that net demand seen by the M/SO varies drastically with the weather, affecting local settings such as frequency response or Volt-Watt functions. Together, this makes the task of operating and planning the power system economically, securely, and reliably, much more complex.	In a power system where DPV becomes ubiquitous, new approaches to forecasting, visibility, management and planning will be required. This will require new: • Short and medium horizon forecasting of DPV output; • Visibility of DER, including definition of the data flows required to ensure the System Operator has sufficient DER/net demand visibility across different time scales; • Control architecture of DER, including technology standards and the most suitable decision-making algorithm for each DER control approach; • DER communication requirements for monitoring and control, including determination of the most cost-effective infrastructure for communication, orchestration and the corresponding decision-making algorithms; and, • DER influence on system planning, including distribution network-equivalent modelling adequate for use in system planning studies.

2.8.5. Distribution networks are informally transitioning toward providing a range of Distribution System Operator (DSO) functions

With increased penetrations DPV and DER being deployed, the underlying nature of both distribution systems and the entire power system is changing fundamentally.

Traditional system functions and their related organisational roles and responsibilities were originally developed in a context that involved:

- A clear 'supply-side / demand-side' bifurcation and uni-directional real power flows;
- Load served by bulk, dispatchable and transmission-connected MW-scale generation;
- Significantly less system volatility due to negligible deployment of variable energy resources; and,
- Comparatively passive consumers.

With the phenomenon of DPV mass adoption by consumers has come the recognition that the traditional roles of distribution network management are needing to evolve.

Globally, this transition is commonly seen as a transition toward the need for an expanding range of functions under the rubric of a Distribution System Operator (DSO). This role is often considered most likely to emerge as an evolution of the existing distribution network businesses.

While alternative models exist, DSO functions are commonly seen as including some or all of the following:

- Implement advanced, scenario-based modelling of DER uptake and operation, bi-directional power flows and distribution system operations;
- Establish Distribution System State Estimation (DSSE) and near real-time visibility across the distribution network;
- Manage the network within the technical constraints and hosting capacity of distribution assets including computation and issuing of Dynamic Operating Envelopes (DOEs);
- Advance the transition to more cost and value-reflective pricing in broad-based tariffs and establish bilateral reserve contracts for short and long-term emergency support of distribution security;
- Implement Integrated Distribution Planning (IDP) to medium-long term network requirements, incorporating non-network / DER alternatives;

	• Actively identify opportunities for aging distribution feeders to be progressively replaced with Microgrid, individual Stand-alone Power Systems (SPS) and/or grid-connected Energy Storage solutions; • Analysis and evidence-based determination of the temporal and locational value of DER Services to the distribution system; • Establish and operate a Flexibility Market or Network Services Market that enables comprehensive 'market-control' alignment at the distribution layer; and, • Work collaboratively with the Market/System Operator (M/SO) and Advanced TNSP (A-TNSP) to manage the Transmission-Distribution Interface (TDI) relevant to the DSO's service territory.
2.8.6. Decarbonising power systems are experiencing increasing operational interdependencies across the Transmission-Distribution Interface (TDI)	
As the volumes of VRE and DPV generation incorporated into the power system materially increase, the level of dynamic operational interdependence across the Transmission-Distribution Interface (TDI) is increasing. This is requiring enhanced exchange of data and protocols for the integrated management of system and network operations critical to frequency control, voltage control, congestion management, etc.	Developing and embedding formalised roles, protocols and capabilities for integrated management across the TDI will typically require extensive effort, including: • Significant advancements in the policies, procedures, platforms, and infrastructure needed to achieve a coherent coordination across the TDI by the A-TNSP and DSO; • Expanded technological and organisational knowledge of the dynamics of managing transforming energy systems and new sources of flexibility; and, • New business models that incentivise and maximise the participation of a sizable proportion of the DPV and DER population.

2.8.7. Decarbonising power systems are requiring more advanced Operational Coordination models scalable to millions of participating energy resources

Due to the level of operational volatility experienced by lower-carbon power systems, the expanding volume of participating resources, and the diversity of their types, locations and ownership models, new models of DER coordination are being trialled.

As noted earlier this is particularly relevant as Australia's power systems are:

- Becoming more diverse and dynamic;
- Transitioning from hundreds to tens of millions of participating energy resources; and,
- Experiencing a progressive erosion of the traditional 'supply-side / demand-side' bifurcation.

Advanced Operational Coordination involves structured mechanisms for coordinating many millions of participating energy resources and embedded grid controls.

This must occur in a manner that ensures whole-system stability and enhances efficiency. It must also be co-optimised across all power system layers to ensure that energy resource services dispatched and/or financially incentivised in one layer of the power system (e.g. wholesale market, transmission or distribution system) are not driving unintended negative consequences in other layers of the system.

Given the inseparable cyber-physical-economic nature of the power system, close 'market-control' alignment is required to incentivise and activate service provision in a reliable and mutually reinforcing manner.

These economic incentivisation and cyber-physical automation elements must be coupled across each power system layer for energy, capacity, flexibility, and essential system services to be delivered when and where needed by the system (from days to milliseconds).

2.8.8. A significant proportion of small-scale IBRs currently behave undesirably when exposed to voltage depressions	
Studies have revealed that following large system disturbances, many DPV and DER inverters can behave unpredictably in response, which represents a threat to system security. Current benchmarking in Australia suggests that over 50% of IBR-based DPV behave undesirably, in terms of disconnection or power curtailment, when exposed to distribution voltage depressions such as those that occur during transmission level faults. Similar inverter technologies will drive energy storage systems, hybrid storage inverters, commercial and industrial systems, and vehicle charging. As such, the continuous assessment of inverter performance to the types of faults and grid disturbances they are exposed to is becoming increasingly critical.	The sudden, unexpected loss of DPV generation has historically been offset by the disconnection of load. However, with DPV generation increasingly the largest generation source during some time window, these disturbances now represent a net loss of generation during daylight hours. This can coincide with the loss of the largest single generating unit, increasing the size of the largest credible generation contingency. Without an accurate understanding of how inverters operate, it is difficult for the Market/System Operator (M/SO) to adequately prepare for and respond to disturbance events. This will require laboratory testing, in-field data analysis, and simulation to build a comprehensive understanding of DER behaviours during disturbances and apply this knowledge to broader system planning and operations. Also need appropriate standards and means to address inadequacies in existing installed base. With increasing DPV uptake, should this undesirable behaviour continue unabated, it will present unmanageable generation contingency sizes.

2.9. Markets & Commercial

Emerging Trend	Implication/s
2.9.1. The roles and efficacy of energy-only markets in a near zero-marginal cost future are increasingly under question	
As the world moves toward greater VRE generation and a near zero-marginal cost future, liberalised electricity markets face a crisis of purpose. Up to now, thermal generators - particularly natural gas-powered generators - have had a dual function, providing both physical stability and market stability to our electricity systems. The roles and efficacy of energy-only markets in a near zero-marginal cost future are coming under question and may need to be fundamentally redesigned to adapt. Key questions being asked include: • What role will wholesale energy-only market pricing play in the future? • How must electricity markets evolve to produce clear price signals and drive effective investment decisions?	While electricity systems may be able to function physically without natural gas, electricity market pricing will break down if other solutions don't replace the role that gas plays in setting wholesale spot market prices for electricity. How electricity markets are adapted in the long term may largely depend on which types of technology become the dominant firming solutions (e.g. zero-emissions gas, highly flexible demand, or energy storage). As such, market designers can't make decisions in isolation from technology. In addition, if net-zero electricity systems are to become a reality, they must take care that their reforms go beyond solving today's issues and ensure that their designs are compatible with likely technological development.

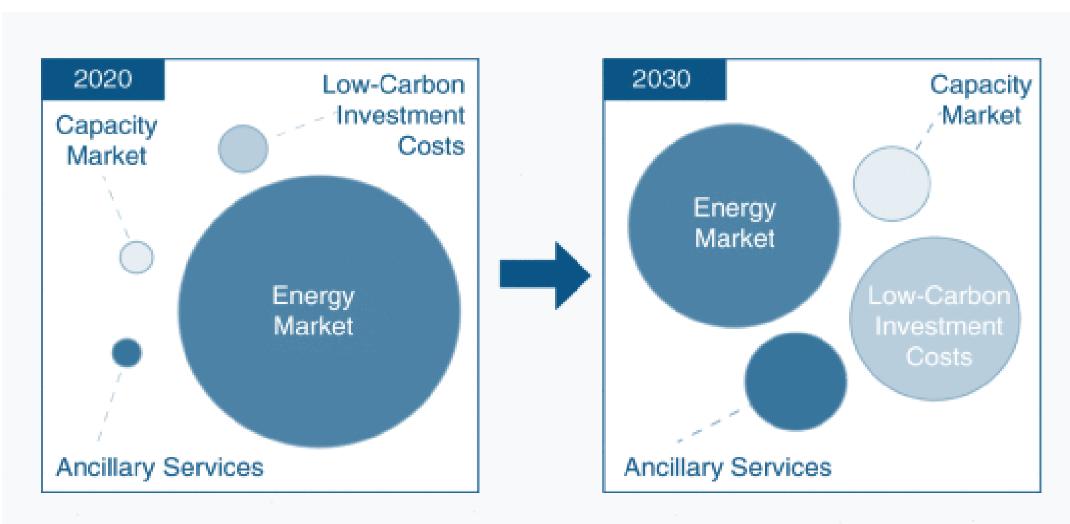


Figure 9: Qualitative illustration of market evolution in the European Union

2.9.2. New market arrangements that explicitly value capacity are being considered	
Transitioning to a lower-emissions generation profile involves higher levels of near-zero marginal cost VRE generation. However, under the current energy market arrangements, new investment in generation relies on expectations that wholesale prices will be at sufficient levels long enough to provide adequate confidence, certainty and returns to investors. Under current market arrangements, if the spot price is not high enough, and expectations of sustained future wholesale prices are not held with enough confidence, sufficient investment may not occur.	To support the quantum of new generation build required over the next decade, new market arrangements will be required that explicitly value capacity (separate from the energy price) to encourage investors to take long-term capacity risk. A combination of incentives are being considered to support the orderly retirement of thermal generators and timely investment in an efficient mix of resources (firm flexible generation, variable renewable energy and storage) to maintain reliability.

2.9.3. New market arrangements that explicitly value the provision of Essential System Services (ESS) are being considered	
Essential System Services (ESS) help keep the power system in a safe, stable, and secure operating state. These critical services, which have traditionally been by-products of synchronous generation, include inertia, frequency regulation, system strength and operating reserves. As the proportion of traditional generation sources decline, inertia, frequency, system strength and operating reserve services must be provided by alternative sources, both centralised and decentralised.	In a power system dominated by IBR-based VRE generation and DER, new market arrangements that explicitly value the provision of ESS will become critical. This will need to include the procurement of services such as frequency support and voltage support services from resources located on both the supply and demand-sides of the system.

2.9.4. New market arrangements that explicitly value the provision of flexibility and/or network services are being considered	
As the generation fleet transitions, the proportion of system flexibility and firming services that can be provided by traditional supply-side resources is decreasing. In addition, system balancing is increasingly aggravated by stochastic generation sources such as VRE, the operation of which is ultimately inconsistent with the standard 'load-following' paradigm of power system control.	Power systems dominated by VRE and DPV generation will require new sources of system flexibility and grid services on both the supply and demand-sides of the system. This may increasingly require flexibility markets to monitor energy flows and create dynamic market signals that motivate changes in supply and demand, supported by automated activation. Similarly, network services markets may also provide the means to procure physics-based services required to support network stability, power quality and economic efficiency.

2.10. Sector Coupling / Network Convergence

Emerging Trend	Implication/s
2.10.1. The electricity and gas sectors are experiencing greater interdependency	
New sources of flexible generation are replacing coal to meet demand in daily peak periods and when VRE output is low. Gas-powered generation is required as a transition technology as a key source of flexible generation in the medium term. Natural gas also has a key role to play in setting prices in today's wholesale energy-only electricity markets. Because of the way prices are set in these markets, gas prices have disproportionate influence on the price of electricity. As the entry of substantial VRE generation and storage causes coal-fired generators – and subsequently gas-fired generators – to close, it has the potential to undermine this mechanism.	As the withdrawal of coal generation accelerates, new approaches to ensuring strategic investments in gas-powered resources may be required to support transition. Given the price-setting role of gas, the eventual retirement of gas-powered resources will also need to be managed carefully to avoid high and unstable electricity prices. As traditional gas-fired generators withdraw from the market, zero-emission gas-fired generators could prove to be a major stabilising force in the NEM in future years. As the maturity of zero-emission gas turbines improves and input fuel costs reduce, their participation in the NEM should be encouraged with relevant policy levers.

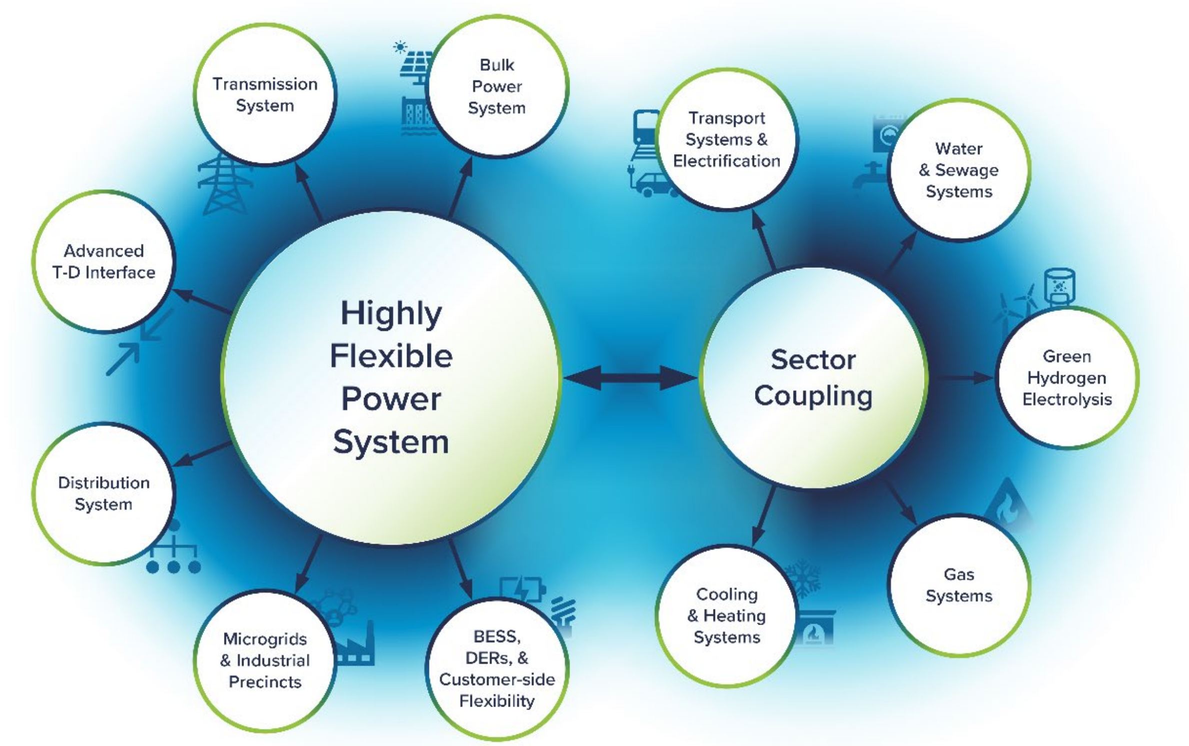


Figure 10: System optimisation benefits emerge through advanced sector coupling

2.10.2. Electricity and industrial processes are experiencing greater convergence	
Heavy industry and manufacturing facilities are actively exploring options for decarbonising industrial processes through electrification. Fossil fuel generated process heat is responsible for a significant share in Australia's emissions. Electrical heating technologies, such as industrial heat pumps, electromagnetic heating, electrical resistance heating, and electric arc heating will likely replace many carbon intensive industrial technologies for process heat used today. The use of Green Hydrogen is another indirect route to electrifying industry.	Industrial precincts and processes that actively electrify will significantly increase demands on both distribution and transmission networks. Wider industrial electrification will require significant amounts of additional firmed VRE generation. Many such industrial processes may be configured to function as major sources of system flexibility in exchange for financial incentives. In such cases there will be a need for more advanced coordination between industrial load centres, aggregators and power system control functions.

2.10.3. Electricity and transport are experiencing an entirely new level of convergence

The transition to electric vehicles (EV) began relatively slowly in Australia but is now gaining pace. EV ownership is expected to surge from the late 2020s, driven by falling costs, greater model choice and availability, and more charging infrastructure.

According to AEMO's Integrated System Plan, 99% of all vehicles are expected to be battery EVs in 2050 under the Step Change scenario.

Such a massive increase in EVs will require large scale deployment of residential, commercial and public charging facilities. This will present challenges for all parts of the power system.

An electrified transport fleet has the potential to significantly influence the shape and location of load – for better or worse. Effectively coordinated EV charging through incentives and automation may play a key role in system optimisation and better utilisation of excess VRE generation during the day. Conversely, poorly coordinated EV charging will exacerbate system constraints, augmentation costs and operational risks.

Integrating EV, EVSE and electrified transport generally with the electricity sector will be essential to both a stable power system. Without proactive enabling policy, standards, and customer-centric managed and incentivised charging schemes, system costs incurred to support EVs could increase consumer bills dramatically.

2.10.4. Electricity and building services are experiencing greater convergence

Like heavy industry and manufacturing facilities, commercial and residential building owners are actively exploring options for decarbonising building services through deeper electrification.

Building and water heating provided by gas or electric resistance sources are responsible for a significant proportion of Australia's building services emissions.

Precincts that actively electrify may increase demands on the local distribution network. Wider electrification will also require significant amounts of additional firmed VRE generation.

Where coupled with an appropriate building envelope configuration, some building services may function as a valuable source of system flexibility in exchange for financial incentives. In such cases there will be a need for more advanced coordination between participating buildings, aggregators and power system control functions.

	Beyond traditional demand-response programs, network-interactive buildings use increasingly using smart technologies and active DER to optimise energy use to meet occupant needs and preferences, reduce emissions and provide grid services in an automated manner.
2.10.5. Electricity and water systems are experiencing greater convergence	
Water infrastructure has long been substantively linked with the power sector. Like other sectors, the water sector is actively exploring options for decarbonising its operations. Many water sector functions including pumping, storing, desalination, treatment, distribution, and heating of both potable water and wastewater depend on the power system but may also function as a valuable source of system flexibility.	Where coupled with appropriate automation and water storage capacity, many water sector activities may be configured as a valuable source of system flexibility in exchange for financial incentives. In such cases there will be a need for more advanced coordination between participating services, aggregators and power system control functions. Given that the power and water sectors both involve critical societal systems, their convergence and interdependence will require detailed consideration of the potential risks and mitigations.
2.10.6. Power system and ICT technologies continue to converge	
The power system is increasingly dependent on distributed computing, data, and communications networks for both its operation and as a platform for enabling third-party energy services. This is particularly pronounced with the exponential growth of networked devices with embedded computing across a wide variety of devices, both utility-grade and consumer-grade. This convergence is also driven by the push toward customer agency in energy management that has accelerated consumer-facing applications and platforms and digital automation of energy in homes and businesses, often without 'offline' functionality.	As society continues to produce, consume, and depend on data-based digital services, the profound interdependencies between the power system and the ICT sector become ever more critical. As digital infrastructure, data and the power system become more tightly coupled, the potential for large-scale disruption caused by cyber-attacks may exceed that of natural disasters and contingency events. System planning and ongoing risk assessments increasingly need to give priority to more holistic approaches to both:

At the same time, ICT technology and infrastructure is becoming increasingly dependent on the electricity system. Data centres continue to grow in number and size – along with their overall share of electricity consumption. The deep interdependencies between the power system and both mobile telephony and internet service provision are also well known.	• Sector coupling risks and opportunities presented by power system / ICT interdependencies; and, • Application of advanced cyber-security tools and methods commensurate to the level of interdependency, including the structural routing considerations noted earlier.
2.10.7. Electricity and the emerging Green Hydrogen sector development has the potential for a transformational convergence	
Australia is aggressively pursuing the development of a major new Green Hydrogen export industry. AEMO's 'Hydrogen Superpower' scenario describes a future where underlying electricity consumption increases ten-fold from current levels primarily due to load growth from production for export.	Should the Green Hydrogen sector develop at the targeted rate and scale, interdependence with the wider power sector will increase dramatically. Key areas of convergence are likely to include: • Green Hydrogen providing a key source of long duration energy storage, balancing multi-day and seasonal disparity in renewable energy generation; • Electrolysis emerges as a productive use of surplus daytime electricity from VRE that would otherwise be curtailed, with the added benefit of smoothing the daily load profile; • Improved utilisation of transmission infrastructure in low load periods as VRE is transported to electrolysers; • Provision of an additional fuel source, either exclusively or blended with natural gas, for utility-scale electricity generation – primarily by peaking plants; • An alternate zero carbon fuel source for on-site backup power generators; and, • An alternative fuel source for heavy transport and machinery, and process heat for industrial applications that might otherwise be electrified.

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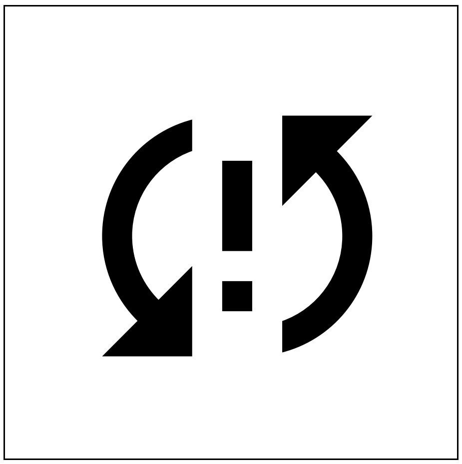

SECTION 3: SYSTEMIC ISSUES

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SECTION 3: CONTENTS

1. SECTION 3 INTRODUCTION

1.1. Purpose of Section 3

As Australia's Power Systems continue to decarbonise, they are becoming orders of magnitude more dynamic and volatile. At its epicentre, the transformation involves moving from a few hundred large, dispatchable merchant generation resources to a future involving tens of millions of highly variable Energy Resources. In a major shift from 20th century norms, the proportion of system services sourced from this vastly more numerous and diverse fleet of Energy Resources will continue to increase year on year.

The importance of Systems Architecture disciplines, therefore, cannot be overstated where a complex legacy system is required to perform an expanding range of entirely new functions. Consistent with Systems Science, this is because the original structure of any complex system will establish its essential capabilities and limits (i.e., its 'performance envelope'). In other words, compared with even a significant number of incremental improvements made to any complex system, well-targeted changes to the underpinning structure will typically deliver a disproportionate uplift in what the system can reliably and cost-effectively do.

Given the less tangible but no less influential role of the underpinning Power System structures, **Section Report 3 converges on a focused list of Systemic Issues that will require architectural treatments if the NEM is to be efficiently and effectively transitioned**. These are defined as follows:

> *Systemic Issues are cross-cutting conditions and/or structural settings that:*
>
> + *Currently exist in the NEM and/or will arise from the convergence of various Emerging Trends (Section 2); and,*
> + *Will require architectural interventions if the emerging Customer & Societal Expectations of the NEM (Section 1) are to be enabled in a secure, cost-efficient, timely and scalable manner.*

Importantly, as Figure 1 illustrates, the Power Systems Architecture approach is both holistic and externally aware. While *not* presuming the list of Systemic Issues examined to be exhaustive, the process of shortlisting them is critical to defining the 'problem space' to which architectural interventions must holistically respond.

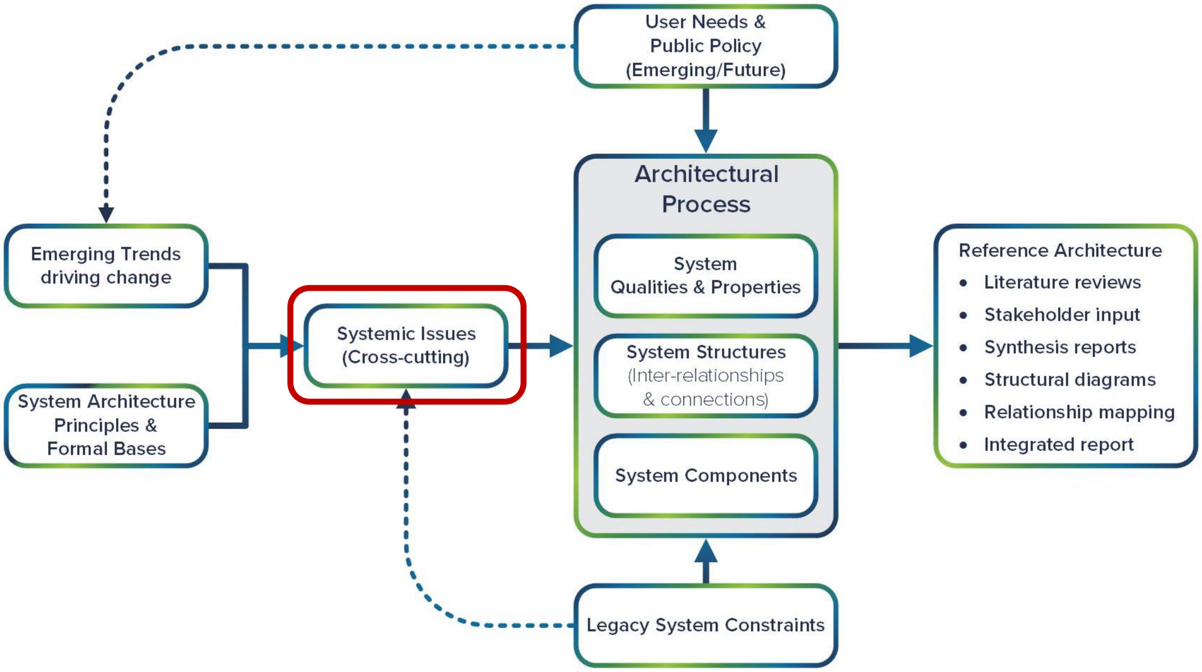

Figure 1: The Power Systems Architecture approach is both holistic and externally aware, being informed by a wide range of current and future-oriented insights drawn from credible sources and multi-stakeholder engagement.[17]

Finally, it is important to note from the above Systemic Issues definition recognises their relationship with the wide range of *Emerging Trends*[18] mapped earlier in the process. Further, they have been shortlisted on the basis that, where unaddressed, the *User Needs & Public Policy*[19] expectations of the future NEM are unlikely to be achieved in a secure, cost-efficient, timely and scalable manner.

[17] Image: Pacific Northwest National Laboratory (Adapted).

[18] Refer Section 2 of this report

[19] Refer Section 1 of this report

1.2. Report Structure

In this report, ten Systemic Issues have been grouped in to the following three categories which are described below:

1. **Transition Constraints:** Fundamental considerations that influence many aspects of Australia's Power System and may impede our collective ability to navigate its transformation in a timely, efficient and technically robust manner.
2. **Core Structural Issues:** Structural and technological shifts that will become increasingly necessary to underpin Australia's Power System transformation from hundreds of centralised to tens of millions of ubiquitous energy resources.
3. **Future-ready Roles and Responsibilities:** Key considerations about how roles, responsibilities and detailed system interfaces may be provisioned to cost-efficiently manage the whole-system operation of decarbonising Power Systems that experience massive increases in volatility, complexity and operational dynamics.

The ten Systemic Issues that have been clustered under these three categories and examined in this report are outlined as follows:

+ **Transition Constraints:**
    - **Escalating Complexity Risk:** As an ultra-complex system experiencing profound change, the Operability of the NEM faces increasing risk where the growth of structural complexity is not formally and holistically managed.
    - **Benefits Realisation Risks:** The lack of both detailed structural mapping of the legacy Power System and shared transition methodologies exacerbates complexity and the potential for multi-stakeholder disagreement, slowing the realisation of $-billions of whole-system optimisation benefits for customers.
+ **Core Structural Issues**
    - **Profound Structural Shifts:** As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, legacy structural settings experience growing stress in a context where no single entity is responsible to holistically ensure the end-to-end Systems Architecture is future-ready.
    - **Inadequate Visibility:** The lack of a comprehensive approach to whole-system Visibility, especially of the growing fleet of LV-connected Energy Resources, risks compromising the Predictability and Resource Adequacy analysis of the NEM.
    - **System Coordination Risks:** More advanced, whole-system Operational Coordination is required in a decarbonising Power System that experiences growing

Volatility and requires the beneficial participation of millions of Energy Resources to balance supply and demand and provide grid services.

- **Modelling Integrity Risks:** As Power Systems experience changes impacting technology mix, operational volatility and underpinning architectural structures, the usefulness of existing models must be constantly evaluated to ensure they are fit-for-purpose in a transformational context.
- **Cyber-security Vulnerabilities:** Layered cyber-security defences require the identification and treatment of non-cyber structural vulnerabilities to achieve a Power System that is inherently more resistant to cyber-attack.
- **Multi-party Data Sharing Risks:** Comprehensive options analysis and the formal application of Systems Architecture disciplines is required to mitigate non-trivial data sharing risks including Scalability, Extensibility, Cyber-security and Anti-resilience issues.
- **DER/CER Flexible Export Risks:** Greater whole-system perspective is required in the further development of DER/CER flexible export solutions to mitigate potential instability issues and non-linear behaviours, ensure capacity allocation equity, and achieve full benefits realisation.

+ **Future-ready Roles & Responsibilities**
  - **Roles & Responsibilities:** High-resolution analyses of Power System structures, multi-entity relationships and data flows – in the current, future, and transitionary states – are key to identifying holistic, least-regret and future-ready options for evolving Roles & Responsibilities.

1.3. Key Principles & Characteristics

Following are a set of key principles and characteristics of the Power Systems Architecture discipline that have guided the development of this report.

1. **Stakeholder / User-centric:** Systems Architecture methodologies are grounded in a detailed knowledge of the current and emerging future expectations of relevant stakeholders, including customers, policy makers and system actors, to ensure the System is able to deliver a balanced scorecard of stakeholder outcomes.
2. **Contextually Informed:** Systems Architecture methodologies give priority to examining the full range of Emerging Trends that are driving significant change together with the resulting Systemic Issues that must be addressed if stakeholder expectations of the future System are to be made achievable.

3. **Principles-based:** System Architecture methodologies are grounded in established principles and formal bases, ensuring conceptual integrity through consistent, traceable and verifiable processes, enhancing multi-stakeholder trust, and minimising the potential for unintended consequences.
4. **Structural Focus:** Systems Architecture methodologies give particular attention to the underpinning structure or 'architecture' of a complex System due to the disproportionate influence it has on what the system can safely, reliably and cost-efficiently do (i.e. the 'performance envelope' of the system).
5. **Whole-system Perspective:** Systems Architecture methodologies provide a holistic view of the entire System as the primary basis for considering the interdependencies between its many Tiers/Layers, Subsystems and Components.
6. **Decadal Time Horizon**: By identifying structural options that enhance (rather than constrain) multi-year optionality, Systems Architecture methodologies ensure the System is Robust, Adaptable, Scalable and Extensible across a range of alternate future scenarios and maximise the 'future-proofing' of investments.
7. **Technology Agnostic:** By focusing on the required outcomes of the current and future System, Systems Architecture actively identifies alternative implementation pathways, supports technology innovation and avoids dependence on any particular proprietary solution.
8. **Complexity Management:** By making explicit the underpinning structures of a legacy system, Systems Architecture enables inherent complexity to be decomposed, legacy structural constraints to be identified, and proposed changes to be accurately targeted and avoid complexity escalation.
9. **Subsystem Analysis:** By providing formal analytical tools, Systems Architecture enables the detailed interrogation of all current Subsystems and Components, their individual Form and Function, Boundaries, Interfaces and Functional Interdependencies to holistically consider potential future enhancements.
10. **Stakeholder Empowerment:** By providing an objective and evidence-based set of tools that can be learned, Systems Architecture empowers diverse stakeholders – both technical and non-technical – to collectively reason about current and future options and better contribute to key trade-off decisions.

2. SYSTEMIC ISSUES

The Power Systems Architecture (PSA) methodology draws upon multiple sources to analyse the emerging and future needs of a given Power System (as illustrated in Figure 1 above).

In the case of developing a Reference Architecture of the NEM, while not presuming the list of Systemic Issues identified to be exhaustive, shortlisting several key issues is critical to defining the 'problem space' that help guide architectural and other interventions. The shortlisting process has been guided by the following definition:

Systemic Issues are cross-cutting conditions and/or structural settings that:

- *Currently exist in the NEM and/or will arise from the convergence of various Emerging Trends (Section 2); and,*
- *Will require architectural interventions if the emerging Customer & Societal Expectations of the NEM (Section 1) are to be enabled in a secure, cost-efficient, timely and scalable manner.*

The ten Systemic Issues identified as a focus for this report have been grouped in to the following three categories, which are examined in more detail below:

+ Transition Constraints
+ Core Structural Issues
+ Future Roles and Responsibilities

Transition Constraints

Transition Constraints are fundamental considerations that influence many aspects of Australia's Power System and may impede our collective ability to navigate its transformation in a timely, efficient and technically robust manner. Two key Transition Constraints are now examined.

2.1. **Escalating Complexity Risks:** As an ultra-complex system experiencing profound change, the Operability of the NEM faces increasing risk where the growth of structural complexity is not formally and holistically managed.

Cross Cutting Issue

A modern Power System is not one system, but an ultra-complex web of seven distinct, interdependent structures. When viewed from a whole-system perspective, it becomes clear that a GW-scale Power System is a 'Network of Structures'[20] consisting of the:

Transition Constraints are fundamental considerations that influence many aspects of Australia's Power System and may impede our collective ability to navigate its transformation in a timely, efficient and technically robust manner. Two key Transition Constraints are considered below.

1. Electricity infrastructure;
2. Digital infrastructure;
3. Operational coordination structure;
4. Markets / transactional structure;
5. Industry / market structure;
6. Regulatory structure; and,
7. Sector coupling structures.

These seven different structures span internal supply chain boundaries and impact multiple system actors (e.g., Bulk Power, Transmission and Distribution Systems, Energy Retailers, Aggregators, Customers, etc.).

[20] Refer Key Concepts C

As some of the largest and most sophisticated 'machines' ever created by humanity, legacy Power Systems were already formally defined as Ultra Large-scale (ULS) Systems[21]. Today, however, Australia must provision its GW-scale Power Systems to operate at 100% instantaneous renewable generation – a feat AEMO recognises as globally unparalleled[22]. This requires vastly more functionality, more dynamic stability, more interoperability, more participating entities, more technologies, and more sector-couplings.

However, Systems Science[23] highlights that 'asking more' of an already complex system invariably drives an expansion in complexity. As MIT's Crawley et al note, additional complexity is unavoidably driven into a legacy system as more functionality and interoperability are required of it. [24]

Given the unparalleled cyber-physical-transactional interdependencies of modern Power Systems, the ability to undertake formal, whole-system structural analysis of proposed local and system-wide changes while still 'on paper' becomes critical. The failure to do so elevates the potential for unintended consequences, non-linear behaviours, runaway complexity, propagation of structural fragility and cost excursions.

An already highly sophisticated system experiencing transformation can ultimately exceed human cognition and even computational capacity.[25] This can result in initiatives designed to address local issues that drive unintended system level issues which are expensive to reverse.[26]

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[21] Feiler et al, Ultra-Large-Scale Systems: The Software Challenge of the Future, Carnegie Mellon, Software Engineering Institute, 2006. Refer to Key Concepts 2 for more information.

[22] Engineering Roadmap to 100% Renewables, AEMO, 2022

[23] Refer Key Concepts 1

[24] System Architecture, Crawley, Cameron & Selva, 2016

[25] Section 2.7 of the DER Market Integration Trials – Summary Report, ARENA, 2022 provides an early example of the complexity involved in developing holistic solutions.

[26] In addition, while technology trials support risk mitigation, the application of formal systemic analysis remains critical for even the most promising technologies at trial stage. This enables early identification of potential structural issues that are not evident at pilot or demonstration scale but will ultimately prevent reliable and cost-effective scaling if unaddressed.

Key Concepts A

System

A set of Components that are formally related together by a shared Structure to achieve outcomes that exceed the sum of the individual Components. As such, a System is not the sum of its parts, but the product of the interactions of those parts - a concept referred to as Emergence.

Simplistically, if the boxes in a Block Diagram are the Components, then the Structure or Architecture is represented by the lines that connect the boxes.

Importantly, the underpinning Architecture always has a disproportionate and irreducible influence on the essential limits of what a System can reliably and efficiently perform. Given this decisive impact on System performance, changing or enhancing any number of Components cannot ultimately compensate for a failure to address an underpinning Architecture that is no longer fit-for-purpose.

Components

A generic term for the uniquely identifiable elements, building blocks, devices and organisations which are related together by a Structure to enable the purposes of the System to be achieved. The term also includes mechanisms intrinsic to the functioning of the System that are both tangible and intangible, such as policy instruments, regulatory mechanisms, rate or tariff structures, etc.

Emergence

The desired outcome of a System which arises from the interactions between the Components that are enabled by the linkages, relationships and interdependencies embodied by the Architecture. Rather than being the sum of the behaviours of individual Components, Emergence is the product of all interactions as a systemic whole.

'Emergency' is also a related systems concept. It is an undesirable outcome that 'emerges' from a System as the product of dysfunctional interactions between the Components due to structural relationships that are not fit-for-purpose.

System Science

A multi-domain, integrative discipline that brings together research into all aspects of complex Systems with a focus on identifying, exploring and understanding the universal patterns and behaviours of Complexity and Emergence.

Contributing Factors

Operating Australia's GW-scale Power Systems is a real-time activity. It involves the control rooms and support functions across multiple entities and market participants who, aided by integrated technologies and decision support, must maintain a secure and reliable system every second of every day. As AEMO notes:

> *"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."* [27]

In the context of provisioning our Power Systems to operate at 100% instantaneous renewable generation, AEMO[28] highlighted the following three broad themes as pivotal:

1. **Power system security** – maintaining the secure technical operating envelope of the power system under increasing renewable penetrations.
2. **System operability**[29] – the ability to securely and reliably operate the power system and transition through increasingly complex operating conditions.
3. **Resource adequacy and capability** – building the resource and network capability to unlock the renewable potential and the flexible capacity to balance variability over different timeframes.

Importantly, these key priorities must be pursued in a manner fully cognisant of the impacts of the numerous Emerging Trends[30] that are simultaneously converging and escalating whole-system complexity. These include:

+ A rapidly escalating number and technical diversity of Energy Resources;[31]
+ The highly variable nature of many renewable Energy Resources;
+ Structural shifts in customer demand and the Volatility of load;
+ Increasingly volatile and stochastic behaviour of the end-to-end Power System;
+ A less dispatchable Power System and an increasing number and scale of actors capable of influencing system stability;
+ Erosion of the 'Supply-side / Demand-side' bifurcation as the traditionally dominant operational paradigm of the Power System;

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[27] Engineering Roadmap to 100% Renewables, AEMO, 2022
[28] Ibid
[29] Refer Key Concepts B
[30] G-PST Topic 7 – Section 2: Emerging Trends, Strategen Consulting, 2022
[31] Refer Key Concepts F

+ Faster system dynamics, bi-directional energy flows and multi-lateral logical relationships;
+ Mobility of load with the electrification of transport; and,
+ Deeper interdependencies with other industry sectors (gas, hydrogen, transport, water, etc).

As noted above, these drivers of change are impacting the complex web of seven interdependent structures that map across the various supply chain segments. As an integrated cyber-physical and transactional system, successfully navigating this unparalleled level of complexity requires dedicated tools for whole-system structural analysis not required in the past.

This is particularly important as the underpinning structures of any system – how all the elements and actors are formally linked together as an integrated system – will always have a disproportionate impact on what the system can safely, reliably, and cost-efficiently do. Somewhat like an intricate tapestry, changes to one structure will typically impact the functioning of the other structures in both intended and unintended ways and must therefore be managed carefully.

By contrast, in Australia's vertically disaggregated market structure, traditional models of change have addressed emerging issues with a primary focus on the most directly impacted supply chain segment. While this has been effective in a historic context of slower change, the nature, scale and pace of the Power System transformation now requires it to be supplemented with dedicated tools for navigating the structural complexities of the next decade. As noted above, the failure to do so will expand the potential for unintended consequences, non-linear behaviours, runaway complexity, and the propagation of structural fragility.

Finally, it is noteworthy that the ULS complexity of GW-scale Power Systems arises not only from their continental scale and number of Components and Endpoints; it is especially due to their multiple complicated Structures which are themselves interconnected in complicated ways. As a result, already highly complex ULS Systems are at significant risk of further exponential growth in complexity where it is not formally managed.

Solution Requirements

The significant escalation of complexity in Ultra-Large Scale (ULS) must be formally managed in a manner commensurate with the nature, scale and pace of change impacting the system. This requires a new level of whole-system insight and options-analysis enabled by formal disciplines and capabilities, including:

+ Detailed mapping of the current Power System 'as-built' structures and interfaces (which historically has never been rigorously specified or documented);
+ Fit-for-purpose analytical models that help 'tame' complexity, identify embedded structural constraints and cost-effectively 'stress test' proposed changes while still on paper;

+ Rigorous examination of alternative structural configurations to ensure investments deliver maximum future optionality and scalability and avoid unintended propagation of computational constraints, latency cascading and structural cyber-security vulnerabilities in the longer term; and,
+ Dedicated professional expertise specialising in the management of systemic and structural complexity, who function in close collaboration with a diverse range of traditional subject matter experts.

2.2. **Benefits Realisation Risks:** The lack of both detailed structural mapping of the legacy Power System and shared transition methodologies exacerbates complexity and the potential for multi-stakeholder disagreement, slowing the realisation of $-billions of whole-system optimisation benefits for customers.

Cross Cutting Issue

As with all Power Systems, a range of structural demarcations are embedded in the NEM based on historical precedent (e.g., bulk power, transmission, distribution, energy retail, etc.). Due to their direct relationship to formal roles and responsibilities, these demarcations have tended to provide the most natural framing for key change initiatives.

However, given that decarbonising Power Systems will require vastly greater levels of whole-system inter-dependence to unlock $-billions of customer savings, this increasingly presents a critical challenge for society.[32]

Despite the functional and regulatory demarcations embedded in any Power System, the laws of physics interact with the entire system blind to these boundaries. In the case of the NEM, these were largely established when it was solely a linear and unidirectional bulk delivery system.

In contrast the unidirectional bulk delivery system of the 20th century, it is widely recognised that rapidly decarbonising Power Systems require vastly greater levels of dynamic inter-dependence between both ends of the system.[33] As decarbonising Power Systems experience growing levels of Volatility, this dynamic inter-dependence be key for the instantaneous balancing of supply and demand, and the sourcing of Essential System Services.

Given the scale of this transformation, it is particularly noteworthy that the Systems Architecture of most as-built Power Systems has never been rigorously specified or documented in a common set of artefacts. Like most GW-scale Power Systems, the NEM evolved around a unidirectional bulk delivery paradigm over many decades.

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[32] A growing body of credible Australian and international sources are quantifying the massive scale of economic value at risk where 'whole-system' approaches to transition and Operational Coordination are not applied. For example:

https://www.iea-isgan.org/wp-content/uploads/2020/05/ISGAN_DiscussionPaper_Annex6_microVsMEGA_2020.pdf (pages 73-74)

https://smarten.eu/wp-content/uploads/2022/09/SmartEN-DSF-benefits-2030-Report_DIGITAL.pdf

https://arena.gov.au/knowledge-bank/valuing-load-flexibility-in-the-nem/

https://www.datocms-assets.com/32572/1629948077-baringaesbpublishable-reportconsolidatedfinal-reportv5-0.pdf

[33] For example: System Operation Collection, International Renewable Energy Agency, 2020; Coordination of Distributed Energy Resources; International System Architecture Insights for Future Market Design, Newport Consortia, 2018; and, Evaluation of Combinations of Coordination Schemes and Products for Grid Services, EU CoordiNet Project, 2022.

Key Concepts B

Complexity

A System is complex if it has many interrelated, interconnected, or interdependent entities and relationships. A high-level indicator of the complexity of any System is the amount of information required to describe its full range of functions and behaviours (i.e. words, formulae, lines of code, etc.).

It is important to note that additional Complexity is driven into a legacy System by 'asking more' of it: more functions, more interdependencies, more robustness, more flexibility, etc. This expansion of Complexity is always exacerbated by the addition of new Components and may ultimately require targeted modifications to the Structure through the application of Systems Architecture disciplines.

Ultra Large-scale (ULS) Complexity

Extremely large, ultra-complex Systems that consist of unparalleled volumes of: hardware and software; data storage and exchange; computational elements and lines of code; participants, stakeholders and end-users; and, multiple complicated Structures interconnected in complicated ways.

A ULS System also typically exhibits the following characteristics:

- Wide geographic scales (continental to precinct);
- Wide-time scales (years to microseconds);
- Long-term evolution and near continual deployments;
- Centralised and decentralised data, control, and development;
- Wide diversity of perspectives on the purpose(s) and priorities of the System;
- Inherently conflicting diverse requirements and trade-offs;
- Heterogeneous, inconsistent, and changing elements; and,
- Locational failures and response occur as a matter of normal operations.

Operability

Critical pre-requisites for secure and reliable operation of the Power System, which include a key focus on its Predictability and Dispatchability.

The Predictability of the Power System is the ability to:

- Measure or derive accurate data on energy demand, power system flows, and generation output across numerous time frames as key inputs into planning and operational decision-making; and,
- Forecast upcoming Power System conditions and have confidence in how the system will perform.

The Dispatchability of the Power System is the ability to configure system services, sourced from a diverse range of Energy Resources, in a manner that consistently maintains system security and reliability.

Related to the above, the Dispatchability of a particular Energy Resource is the extent to which its output can be relied upon to 'follow a target' issued by the Market/System Operator (MSO) and adhere to a pre-agreed dispatch schedule at some time in the future.

However, as an ultra-complex system that directly involves hundreds of supply chain actors and impacts almost every citizen, this presents key challenges for the collaborative navigation of change. The absence of both shared structural artefacts and formal transition methodologies significantly elevates the risk of stakeholder and solution misalignment, and reduced whole-system optimisation benefits for customers.

Contributing Factors

As noted above, GW-scale Power Systems are highly complex cyber-physical-transactional systems. However, as infrastructures essential to the functioning of a modern economy, they are most fundamentally critical societal systems. As they rapidly decarbonise, these physics-based systems must be provisioned to perform a range of functions that are significantly or dramatically different to twentieth century requirements.

While Australia is not unique, given the globally unparalleled pace and scale of the NEM's transformation, the following factors exacerbate the impacts of this cross-cutting issue:

+ At a practical level, the vast majority of power sector expertise is currently focused on the historical segments of the supply chain; there are comparatively few entities or resources that consistently focus on the end-to-end system (from customer to bulk power / bulk power to customer);
+ Each of the historical supply chain segments (e.g., bulk power, transmission, distribution, energy retail, etc.) has developed a depth of expertise in their own context but have a comparatively limited expertise in or comprehension of other segments;
+ The lack of shared, fit-for-purpose methodologies for structural analysis of the entire Power System result in the misapplication of applications[34] and/or an overdependence on subjective workshopping, neither of which provides the necessary empirical rigour nor the necessary detailed mapping of interfaces between all subsystems;
+ While there is currently a significant amount of effort focused on standards and interoperability, full benefits realisation will be at risk without a shared view of the emerging future architectural requirements[35] needed to support a future similar to AEMO's 'Step Change' scenario; and,

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[34] For example, while Enterprise Architecture (EA) and the Smart Grid Architecture Model (SGAM) may appear relevant, their inherent limitations must be understood. In the case of EA, the focus is primarily on the IT/OT system architecture *within* a particular enterprise. In the case of SGAM, it was developed to analyse discrete smart grid project use cases with a primary focus on only one of the seven structures that make up the Network of Structures (namely the Digital Infrastructure: Information/Data Exchange). Neither are designed to provide comprehensive architectural views of the as-built legacy Power System or potential alternative configurations to support future requirements.

[35] Architecture a must for interoperability - Six reasons why it's imperative, Dr John Loonsk, 2014

+ The absence of a shared, detailed mapping of the as-built Power System architecture compounds key knowledge gaps between the supply chain segments and makes navigating toward holistic, future-ready solutions significantly more difficult.

Solution Requirements

Efficiently navigating the scale of transformation impacting the NEM over the next decade to realise $-billions of optimisation benefits for customers requires a new level of whole-system, multi-stakeholder collaboration. Given the massive complexity of this undertaking, timely progress will require enhanced stakeholder alignment supported by shared methodologies for developing holistic, integrated solutions. In addition to the requirements outlined in Systemic Issue 2.1, this will require:

+ Objective, evidence-based methodologies that provide a 'neutral' set of tools that technical and non-technical stakeholders across the supply chain can learn, share and collaboratively apply to solve complex problems in a verifiable manner that builds trust;
+ Principles-based approaches that maximise latitude for innovative while also ensuring stakeholders can collaborate effectively to deliver holistic solutions with well-defined interfaces;
+ A range of open-source materials and analytical tools being made available that enable diverse stakeholders to individually evaluate and better contribute to options analysis;
+ A full set of agreed definitions and key concepts that enhance the quality and timeliness of stakeholder participation and solution co-design; and,
+ As stakeholder confidence grows, application of the same tools to collaboratively develop structural mapping of what the NEM will require to function reliably and cost-efficiently in a future similar to the AEMO Step Change scenario.

Ultimately this will provide significant efficiency gains in multi-stakeholder engagement through the management of complexity, more tangible trade-off choices and enhanced stakeholder buy-in. It should also be noted that the application of such tools and methodologies may need to focus on 'robust' rather than purely optimisation-based methods, since such methods can result in systemic brittleness.[36] In practice, this means that such a system can suddenly fail to operate in a reasonable way when operating conditions depart significantly from nominal.

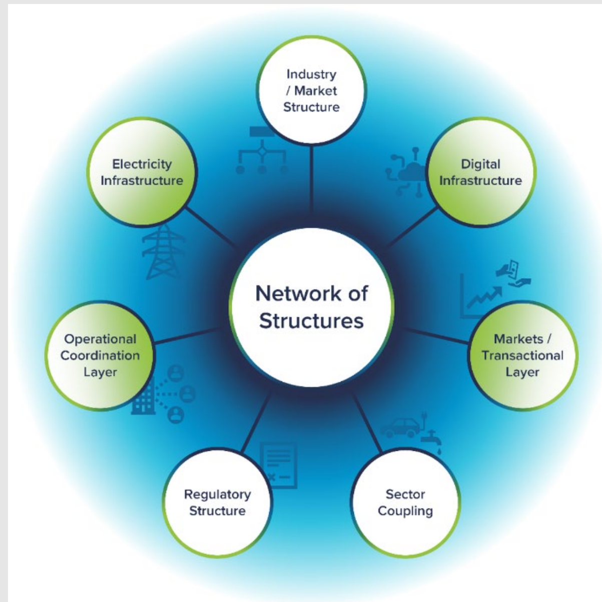
[36] A brittle system is a system characterised by a sudden and steep decline in performance as the system state changes. This can be due to input parameters that exceed a specified input, or environmental conditions that exceed specified operating boundaries. This is the opposite of a gracefully degrading system.

Key Concepts C

Network of Structures

A modern Power System is not one system, but an ultra-complex web of seven distinct, interdependent structures. When viewed from a whole-of-system perspective, it becomes clear that the Power System is a Network of Structures[37] consisting of:

1. Electricity Infrastructure (Power Flows);
2. Digital Infrastructure (Information/Data Exchange);
3. Operational Coordination Structure;
4. Markets / Transactional Structure;
5. Industry / Market Structure;
6. Regulatory Structure; and,
7. Sector Coupling Structures (Gas, Water, Transport, etc).



Many of these Structures have evolved progressively over decades in the context of a highly centralised, unidirectional Power System. These legacy systems are subject to hidden and overt interactions, cross-couplings, constraints and dependencies which impede change. While the 'system-of-systems' paradigm from software engineering is somewhat useful, being largely focused on Components, it does not adequately represent the complex multi-structural properties evident in a modern Power System.

The Network of Structures paradigm provides invaluable perspective for the detailed analysis, mapping, and optimisation of current and future Systems Architecture requirements. This is critically important as the underlying Structure of any complex System establishes its essential capabilities and limits and has a disproportionate impact on what it can reliably and cost-effectively perform.

[37] The Network of Structures concept was originally developed by Pacific Northwest National Laboratory.

Core Structural Issues

Core Structural Issues are structural and technological shifts that will become increasingly necessary to underpin Australia's Power System transformation from hundreds of centralised to tens of millions of ubiquitous energy resources. Seven such issues are now examined.

2.3. **Profound Structural Shifts:** As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, legacy structural settings experience growing stress in a context where no single entity is responsible to holistically ensure the end-to-end Systems Architecture is future-ready.

Cross Cutting Issue

The National Electricity Market (NEM) is transitioning from hundreds of large, dispatchable, synchronous generators to a future involving tens of millions of diverse and highly dynamic resources which are ubiquitous across all segments of the system. With the progressive withdrawal of conventional generation, a wide range of energy and system services will need to be sourced from both HV and LV-connected Energy Resources.

By contrast, Australia's GW-scale Power Systems developed over the last century around a 'Supply-side / Demand-side' bifurcation. This acted as one of the most dominant paradigms of the global electric sector and, although now in decline, continues to shape much of the thinking of the sector. In parallel, as this historic paradigm erodes, two new bifurcations of Energy Resources into locational and functional categories is occurring. While the visible effects are emerging gradually, these shifts involve some of the most profound structural changes to Power System operations in a hundred years.

Given the increasing Volatility of a decarbonising Power System, and the new bifurcation of Energy Resources into HV and LV-connected categories, a more holistic approach to system Operability across the Transmission-Distribution Interface (TDI)[38] becomes critical. Importantly, the underpinning cyber-physical-transactional structures of a Power System have a decisive impact on what it can reliably and cost-efficiently perform. As such, it cannot be assumed that the existing structures, designed for a highly bifurcated system, will be sufficiently Scalable or Extensible to accommodate such a level of transformative change. Nor may it be possible to provision the NEM for a 'Step Change' type future without a dedicated entity or process for ensuring the adequacy of the Power System's end-to-end underpinning architecture.

[38] Refer Key Concepts J

Contributing Factors

Erosion of a Defining Paradigm

Australia's GW-scale Power Systems developed over the last century around a 'Supply-side / Demand-side' bifurcation which acted as one of the most dominant organising principles of the electric sector. In its historical context, this paradigm served Australia well based on the following assumptions:

+ A 'Supply-side' of the system which consisted of a fleet of centralised MW-scale generators connected to the HV transmission system;
+ A 'Demand-side' of the system where the vast majority of customers were connected to the LV distribution systems and consumers of energy (i.e., not producers);
+ Unidirectional bulk Real Power flow from the 'Supply-side' to the 'Demand-side';
+ Almost all Essential System Services were provided by the fleet of dispatchable, synchronous, supply-side generators; and,
+ Dispatch of centralised generation was based on a Demand-following model where customer demand was considered the primary independent variable and generation ramped up or down in line with it.

The transformational forces discussed earlier, however, are reshaping global electric systems. The significance of the erosion of this paradigm, which played a pivotal role in shaping the legacy Power Systems' underpinning Architecture cannot be overstated. As AEMO has noted:

> *"As penetrations of passive DPV continue to increase and become significant at the regional level, the aggregated impact affects almost all core duties of the bulk system operator in some way…"*[39]

This is especially the case in Australia due to our world-leading scale and pace of Distributed PV (DPV) adoption by customers. While our distribution systems remain the location of major load centres, they are transforming to host an ever-expanding fleet of Distributed Energy Resources (DER/CER)[40] and Electric Vehicles (EV). Although its visible effects are emerging gradually, the overall trajectory involves one of the most profound changes in a century of grid operations. As such, all seven cyber-physical, transactional and regulatory structures illustrated by the Network of Structures[41] are experiencing increasing stress as this defining paradigm erodes, and system dynamics fundamentally change.

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[39] Renewable Integration Study Stage 1 Appendix A: High Penetrations of Distributed Solar PV, AEMO, 2020

[40] Refer Key Concepts F

[41] Refer Key Concepts C

Impacts of Two Emerging Bifurcations

It is noteworthy that mass adoption of DER/Customer Energy Resources (CER) and EVs in Australia is largely customer-driven and agnostic to traditional bulk power, transmission, and distribution system boundaries and planning conventions. In addition, the erosion of this structurally influential paradigm is occurring in parallel with the emergence of two new bifurcations of Energy Resources into new locational and functional categories as follows:

1. **Energy Resources are bifurcating into two locational classes.**

    + Firstly, Australia's fleet of Energy Resources is bifurcating into two major locational classes: Centralised and Decentralised. This involves an historically unprecedented shift:
    + From a past where over 95% of Australia's generation fleet was concentrated at one extremity of the Power System (HV-connected);
        - To a fast-emerging future where the generation fleet is bifurcated across two opposite extremities of the Power System. Under AEMO's widely accepted 2050 Step Change scenario, this will involve:
        - A progressive narrowing of the differential between HV-connected generation capacity in comparison to the volume that is LV-connected;
        - Significant regions of NEM increasingly needing to be capable of operating reliably during periods where 100% of instantaneous demand is met by Variable Renewable Energy (VRE)[42] sources, both HV-connected and LV-connected;
        - Several regions experiencing periods where 100% of instantaneous demand is met by LV-connected DPV, especially at solar zenith on days experiencing low levels of demand;
        - At other times, such as during the night, due to the somewhat 'tidal' characteristics of high-VRE / high-DER systems, these same regions must be capable of largely depending on utility-scale wind generation and other centralised Energy Resources; and,
        - Over time, the entire NEM must be provisioned to operate reliably for increasing numbers and durations of time where 100% of instantaneous demand is met by VRE, whether centralised, decentralised or a combination of both.

    Such changes are not peripheral. They are structural in character and drastically impact the physics-based Operability of any GW-scale Power System. It simply may not be safely assumed that as-built cyber-physical-transactional structures, forged around a

[42] Refer Key Concepts F

fixed 'Supply-side / Demand-side' paradigm, will be sufficiently Scalable or Extensible to accommodate such a level of transformative change.

1. Energy Resources are bifurcating into two primary functional/investment classes.

Secondly, Australia's fleet of Energy Resources is bifurcating into two primary functional/investment classes: Merchant and Private. This involves another historically unprecedented shift:

+ From a past where the generation fleet was largely merchant resources installed for the primary or singular purpose of providing energy and services to the relevant markets; and,
+ To a future where the proportion of private, customer-owned generation, storage and flexible capacity – as compared with traditional merchant resources – is trending upward.

Many of these customer-owned DER/CER and EVs have under-utilised capacity and capabilities that would be of value for providing Electric Products[43] to the wider Power System. However, as they were not primarily deployed as merchant resources, Australia risks a massive duplication of capital investment where this underutilised capacity is not efficiently and equitably unlocked.

Being installed primarily for customer purposes, however, the large-scale sourcing of this underutilised capacity will involve:

+ Significantly different motivational dynamics and engagement approaches;
+ Advanced forms of Visibility[44] and Operational Coordination[45] to ensure the right physics-based services are dynamically sourced when and where required most; and,
+ New procurement and remuneration models that are:
    - Capable of reflecting the dynamically changing temporal and spatial value of different Energy Products at much higher resolution than traditional tariff models; and,
    - Supported by advanced automation to ensure the customer experience is seamless, effortless, and consistent with contract conditions approved by the customer.

[43] Refer Key Concepts D

[44] Refer Key Concepts F

[45] Refer Key Concepts G

Key Concepts D

Electric Products

The core physics-based services provided by Energy Resources to the Power System are summarised under the '3Rs':

- **Real Power:** measured in MW, is the instantaneous rate at which electrical energy is generated, transmitted or consumed;
- **Reactive Power:** measured in MVAR, sustains the electrical field in alternating-current systems while maintaining voltage within the limits specified for safe operation (source or sink); and,
- **Reserves:** measured in MW, represent contracted commitments to deliver or reduce Real Power (MW) or Energy (MWh) at a point of time in the future.

All services provided by Energy Resources to any Tier/Layer of the Power System are derivatives of the 3Rs.

Electric Product Value

The sustainable economic value of Electric Products provided by merchant or private Energy Resources to support system operations, as an alternative to Power System augmentation.

The value of Energy Products is not static. In general, their value can be expected to increase where provision is highly correlated with the needs of the Power System at a given time and geographic segment or vertical Tier/Layer, which will vary dynamically.

As decarbonising Power Systems experience increasing Volatility, advanced forms of Operational Coordination will be necessary to help increase the strength of this correlation to enhance the dynamic provision of:

- **Energy Products**: The required '3Rs' physics-based service(s): Real Power, Reactive Power, Reserves;
- **Timing**: At the right time: days, hours, minutes, seconds, microseconds; and,
- **Location**: At the right geographic segment or vertical Tier/Layer of the Power System.

Legacy Structures, Functions & Roles Under Stress

Structurally, where the once dominant 'supply-side / demand-side' bifurcation is experiencing erosion, coupled with the increasing Volatility of a decarbonising Power System, a significantly more integrated and holistic approach to system Operability will be required to ensure secure and least-cost operation. In this context, the relationship between the upstream bulk power / transmission system and the downstream distribution system(s) becomes even more critical and dynamically interdependent.

The range of functions performed across the Transmission-Distribution Interface (TDI), therefore, must be expanded, formalised and increasingly automated. This will involve enhanced data exchange and the execution of formalised roles and protocols for the integrated management of system operations. It includes a focus on matters such as frequency control, congestion management, voltage control and involves appropriate levels of real-time or near real-time DER Visibility, Forecasting and Resource Adequacy analysis.

As noted above, the dispatch of centralised generation has been historically based on a Demand-following paradigm. To illustrate the significance of this erosion of the 'Supply-side / Demand-side' bifurcation, and the expanding role of the TDI, the international literature increasingly evidences the need for consideration of paradigm variants that include Supply-following features.[46]

Finally, as the Laws of Physics interact with the entire Power System blind to its historic demarcations and delegations of Roles & Responsibilities, in the context unparalleled structural shifts, no single entity is responsible for ensuring the adequacy of the end-to-end power system's underpinning architecture.

Solution Requirements

Given the once-in-a-century magnitude of transformation impacting GW-scale Power Systems such as the NEM, it is simply no longer tenable to advance transformational solutions that assume (whether explicitly, or perhaps more commonly, implicitly) a largely unchanged Supply-side / Demand-side bifurcation.

As this most dominant of historical paradigms continues to erode, transformational initiatives must honestly confront the full implications of this profound structural shift for the future Operability of decarbonised Power Systems. The vast increase in the Volatility experienced by a decarbonising Power System, and the emerging new bifurcation of Energy Resources into HV-connected and LV-connected categories, will require a fundamentally more holistic and structural approach to system coordination across the Transmission-Distribution Interface (TDI).

In summary, the fundamental nature of the unfolding transformation means that it is not possible to provision the NEM for a 'Step Change' type of future simply by the multiplication of issue-in-isolation solutions. It requires both the explicit acknowledgment of the inherently structural nature of the transformation and the need for a clear-eyed, holistic and formalised approach to ensuring its underpinning architecture are made future-ready.

[46] Supply-following paradigms are premised on future contexts where the major source of Volatility that impacts Power System operations is the output of highly variable wind and solar generation. In this case, large volumes of LV-connected flexible loads and resources are Orchestrated to dynamically follow the output of highly variable generation sources.

Key Concepts E

Structure

Every functioning System created by humans has an underpinning Structure. The Structure of a System consists of the formal, stable relationships and interdependencies that exist between the numerous Components of the System and enable it to reliably achieve specific purposes.

Architecture

The term Architecture is formally used in Systems Science to refer to holistic conceptual model that details how the many Components of a System are linked or related together by an underpinning Structure. The purpose of the conceptual model is to make explicit how all the physical, informational, operational, and transactional Components function together as a whole. This supports more robust reasoning about System capabilities, behaviours and transformational options.

Simplistically, if the boxes in a Block Diagram represent the Components, the Structure is represented by the lines connecting the boxes. Although the individual Components are often more tangible and easier to see, studying the underpinning Structure of a complex System is critical as it will always have a disproportionate impact on what the System is ultimately capable of.

Where the underpinning Architecture is well aligned with the current and/or emerging purpose of the System, the Components will function effectively together, and the System will exhibit Scalability and Extensibility. Where the Architecture is misaligned with current or future needs, technology integration becomes increasingly costly, investments may be stranded, and full benefits realisation placed at risk.

Scalability

An architectural characteristic that takes the future scale growth of a System into consideration. It is a systemic measure of the underpinning Structure's ability to accommodate significant increases in the number of Components and Endpoints without degrading System functions and/or requiring major modifications.

Extensibility

An architectural characteristic that takes the future extension of System functions and capabilities into consideration. It is a systemic measure of the Architecture's ability to extend System functions and capabilities, and the level of effort needed to implement the extension.

In the context of a Power System experiencing significant transformation, Extensible architectural and technology choices aim to be:

- Cognisant of the plausible future developments that the solution will need to enable or migrate toward;
- Capable of accommodating future requirements without impairing core, critical functionality; and,
- Capable of enabling cost-effective migration to longer-terms solution when required.

Taming Deep Complexity

ARENA's recent DER Market Integration Trials – Summary Report (2022) evaluated Australia's four major DER Market Integration Trials, namely Project EDGE, Project Symphony, Converge and Project Edith. It noted that the four projects were each seeking to coordinate and unlock different subsets of some, but not all, of the following core DER/CER functions:

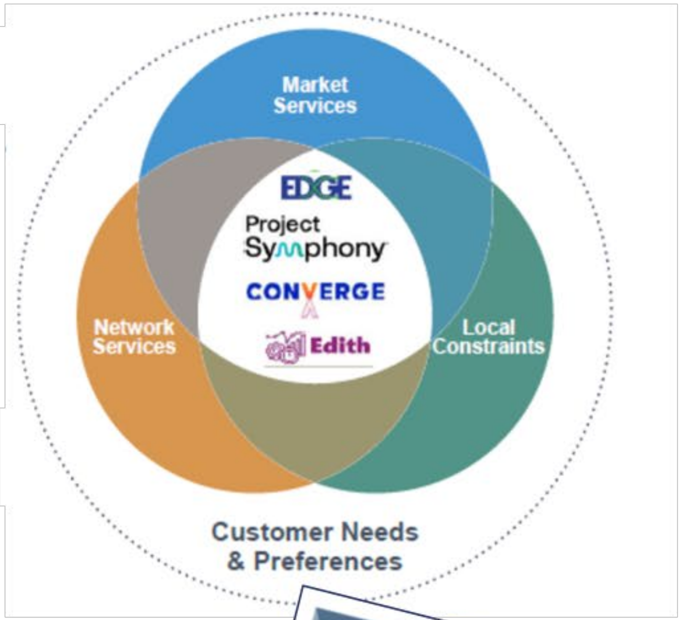
- Wholesale Market Services
- Network Services
- Local Constraints
- Customer Needs & Preferences

Highlighting the need for next-generation approaches for navigating the structural complexity involved in unlocking all four core functions, Section 2.7 of the ARENA report makes the following summary observations:

> *"Putting all four core functions together creates a **complex mix of actors and functions** involved in the operation of DER. One of the main focuses is **how the different actors receive access to, and transmit, information**…*

> *"Depending on the model, **various pieces of information may be required to go to multiple parties** or need to be **coordinated with other information**. Coupled with this is the need to **manage information flows** across **millions of devices, hundreds of traders,** and **12 separate distribution networks** in the NEM.*

> *"Not only does this **create complex requirements for market and network IT infrastructure** that hasn't been seen before, having more devices and actors in the system **poses the risk of additional cybersecurity threats** that will need to be mitigated…"*



Source: DER Market Integration Trials – Summary Report, ARENA, 2022 (emphasis added)

2.4. **Inadequate Visibility Risks:** The lack of a comprehensive approach to whole-system Visibility, especially of the growing fleet of LV-connected Energy Resources, risks compromising the Predictability and Resource Adequacy analysis of the NEM.

Cross Cutting Issue

Two critical aspects of Power System Operability are its Predictability and Dispatchability.[47] In a decarbonising system that is also experiencing significant growth in LV-connected DER/CER and transport electrification, the System Operator will require new levels of Visibility of this growing proportion of the Energy Resource fleet.

Having developed around a clear 'Supply-side / Demand-side' bifurcation, with over 95% of the generation fleet located on the 'Supply-side' of the system, AEMO has historically focused information and data acquisition where most of the Energy Resources were located. By contrast, as the NEM transitions to host one of the world's highest proportions of decentralised Energy Resources, AEMO will need increasingly granular and near real-time data, aggregated at the Transmission-Distribution Interface (TDI), from millions of DER/CERs and EVs for operational forecasts and whole-system Resource Adequacy analysis.

In the context of greater system Volatility as decarbonising Power Systems become more dependent on variable resources, higher speed dynamics are also driving the need for real or near real-time data. This requires more stringent bandwidth, latency, and packet loss requirements. Therefore, applying a holistic approach to identifying cyber-physical constraints embedded in the as-built system structures becomes critical. Once identified, holistic architectural strategies must be developed to validate the data required and address structural constraints in a manner acceptable to both AEMO and DNSP/DSOs[48].

Contributing Factors

Relevance of Visibility to Operability

AEMO operates the Power System through a security constrained, optimised dispatch process. In doing so, it is responsible to continuously quantify the limitations on the system to determine a technical Operating Envelope. This must actively consider the prevailing conditions of the Power System in general, and the generation fleet in particular, with a key focus on predicting the impacts of unexpected events.

Key operational functions that AEMO performs to maintain Power System security and reliability may be grouped into the following broad operational functions:

+ The central dispatch process;

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[47] Power System Requirements, AEMO, 2020

[48] Refer Key Concepts J

+ Short-term and medium-term planning;
+ Long-term planning; and,
+ Power System security monitoring and contingency planning.

Performing these functions requires sufficient Visibility of the Power System, enabled by diverse data sources, to effectively quantify how it might respond to a range of potential events. It also involves ensuring a sufficient portfolio of Energy Resources is continuously available to maintain real-time balancing of supply and demand, otherwise known as Resource Adequacy.[49] Further, it enables AEMO to develop and validate forecasting models to reflect a diversity of emerging operational and planning scenarios more accurately.

Historically, over 95% of Australia's generation fleet was located on the 'Supply-side' of the system and connected to the HV network. As such, it was normative for AEMO to focus its most granular information and data acquisition and analytics where most of the Energy Resources were located. In addition, the vertical disaggregation of Australia's electricity supply chain has meant that the System Operator has limited Visibility of the Low Voltage (LV) systems.

Operational Impediments

However, as the proportion of LV-connected generation, storage and flexible capacity continues to trend upward (compared to traditional HV-connected resources), without sufficient Visibility, AEMO's ability to perform the following core functions will increasingly be impeded and ultimately impact customer outcomes:

+ Quantify how the Power System is likely to behave and manage operations within the boundaries of the Technical Envelope;
+ Manage the Power System using the usual operational levers, as DER/CERs and EV charging are managed by consumers or their Aggregators;
+ Develop, calibrate, and validate its technical or business models, meaning AEMO will need to assume how future trends may deviate from past trends;
+ Predict variability in load due to DER/CER and EVs, increasing regulation Frequency Control Ancillary Services (FCAS) requirements and costs;
+ Predict system load and its response to disturbances as accurately as in the past;

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[49] Stable and secure operation of the Power System in any five-minute period requires adequate resources to be available at that time, and able to respond to disturbances and imbalances over different time durations. When working with MW-scale generators, much of the data relevant to Resource Adequacy is visible to AEMO. For example, the primary energy reserves for thermal plant, weather forecasts for renewables, and the inherent physical characteristics of synchronous generators important to operational stability and flexibility (such as inertia, primary frequency response droop control settings, ramp rates and ride-through capacity). This is similar for bulk generation Invertor-based Resources (IBR) but implemented through software and enforced by adherence to connection codes.

+ Have certainty in the effectiveness of emergency control schemes to manage Frequency, if DER/CER affected, and more accurately quantify and target the volume of load available to be shed; and,
+ Ensure a sufficient and economically efficient portfolio of Energy Resources, both HV and LV-connected, is continuously available for instantaneous balancing of supply and demand.

In addition, with the dynamics of the Power System changing, insufficient Visibility of DER/CER and EVs will affect the operational management of the Power System under extreme conditions. This may make segments of the Power System more prone to failure and impact the management of contingency events.

Conversely, international studies have found that greater Visibility provides the System Operator with more operational flexibility to efficiently manage the balance of supply and demand, and in planning against contingency events.[50] Further, it enables the development and validation of forecasting models that more accurately reflect the effects of DER/CER and EVs across all operational and planning timeframes.

Visibility / Data Requirements

Distribution networks in many parts of the world are hosting an ever-expanding range of connected devices and required to perform increasingly sophisticated functions. While specific data requirements will vary across the different types of DER/CER and EVs, Market/System Operators will increasingly require the following:

+ Standing data on the location, capacity, and technical characteristics of DER/CER and EV charging, in particular the inverters interfaced to the network;
+ Near real-time data with resolution of at least five minutes for operational forecasts, to 30 minutes for longer-term forecasts, are required from DER/CER and EVs, aggregated at the Transmission-Distribution Interface (TDI); and,
+ In the longer term, expanding data resolution concerning available LV-connected generation, storage and export capacity in support of whole-system Resource Adequacy.

Legacy Structural Constraints[51]

These requirements should be understood in the context of greater Volatility as decarbonising Power Systems become more dependent on highly variable generation. The resulting higher speed Power System dynamics directly drives the need for real or near real-time data. The delivery of data from source to use, therefore, becomes critical and bandwidth, latency, and packet loss requirements more stringent.

[50] As noted earlier, this data may be aggregated at the Transmission-Distribution Interface (TDI).

[51] This topic is more fully addressed in Section 2.5.

It therefore becomes critical to apply a holistic approach to identifying cyber-physical constraints embedded in the as-built Power System structures that impede accurate and timely data flows. Such constraints may arise from historical design precedents and various aspects of the structural separation arrangements of the NEM. In a historical context of much less dynamic interdependence across the TDI for Operability purposes, these impediments are commonly exacerbated by relevant data being managed by proprietary applications and structured in vertical siloes which escalate back-end integration delays and costs.

Once identified, holistic architectural strategies must be developed to validate the data requirements and address structural constraints in a manner acceptable to both AEMO and DNSP/DSOs. It is important to note that while this may initially involve a range of targeted initiatives, the failure to address legacy structural constraints in a holistic manner will not ultimately be compensated for by any number of 'issue-in-isolation' solutions.

Solution Requirements

In a context where LV-connected DER/CER and EVs are projected to continue strong upward growth as a proportion of all Energy Resources, the Operability of the NEM will require more sophisticated approaches to Visibility. Founded on low latency, real-time or near real-time data and analytics, key outcomes that will ultimately be required include:

+ Enhanced ability to forecast operational demand over a range of time windows and operating conditions, calibrated and validated on a continual basis;
+ Better quantification of the system Technical Envelope and more accurate identification of measures available to prevent exceedance of this envelope in credible contingency events;
+ Support the adequacy and enhanced economic efficiency of the portfolio of centralised and distributed Energy Resources available to maintain the instantaneous balancing of supply and demand;
+ The dynamic identification of an expanded range of options that enable the System Operator to:
    - Reduce the forecast reserve requirements;
    - Reduce the volume of regulation FCAS required;
    - Enhance overall rates of asset utilisation; and,
    - More accurately inform the volume of load available to be shed to manage Frequency, where impacted by DER/CER, under emergency conditions.

As noted above, enabling this will require the collaborative development of holistic architectural strategies that address legacy constraints and latency cascading in a manner acceptable to both AEMO and DNSP/DSOs and can be implemented in a step-wise manner over an appropriate duration of time.

Key Concepts F

Energy Resources

A universal term for all technologies that provide one or several of the Electric Products required by the Power System. It includes conventional Synchronous Generation, utility-scale Variable Renewable Energy (VRE), Distributed Energy Resources (DER/CER) and various forms of Energy Storage and Firming Resources.

Variable Renewable Energy (VRE)

A generic term for highly intermittent forms of generation powered by renewable resources that are inherently variable, such as wind and solar energy.

While some forms of Distributed Energy Resources (DER/CER) are considered VRE, the term is most commonly used to describe large, utility-scale applications of solar and wind generation.

In the absence of Firming Resources, large volumes of VRE can impact the stability of the Power System and exacerbate periods of misalignment between Demand and Supply.

Distributed Energy Resources (DER/CER)

A diverse range of small to medium scale Energy Resources that are either connected directly to the Distribution System (known as DER) or located behind the meter at residential, commercial and industrial customer premises. In some jurisdictions, the latter may be referred to as Customer Energy Resources or CER.

Active DER/CER are a multi-application resource capable of providing valuable Electric Products to the Power System. It includes the following types of technologies:

- Distributed Generation (DG): including Distributed Photovoltaics (DPV) and Embedded Generators;
- Energy Storage Systems (ESS): including small and medium-scale batteries;
- Electric Vehicles (EV);
- Smart Inverters; and,
- Flexible Resources: including various loads that are responsive, such as air conditioning, electric hot water storage, water pumping, industrial loads and EV charging.

Visibility

The degree to which information on Energy Resource characteristics and operational information is available to the Market/System Operator (MSO), Distribution System Operator (DSO), and other authorised third parties.

Examples including real-time or near real-time information on electrical demand, generation output, state of charge for Energy Storage, availability of Demand Response, system voltages and system frequency, and power flows on major network elements.

2.5. System Coordination Risks: More advanced, whole-system Operational Coordination is required in a decarbonising Power System that experiences growing Volatility and requires the beneficial participation of millions of Energy Resources to balance supply and demand and provide grid services.

Cross Cutting Issue

The consideration of advanced Operational Coordination mechanisms is perhaps one of the most critical issues facing global Power Systems that are experiencing deep decarbonisation, expanding decentralisation and unprecedented levels of Volatility.

Closely related to the topic of Operability, the concept of Operational Coordination also engages with the fast-emerging reality in many jurisdictions of a growing proportion of the Energy Resource fleet not being Dispatchable by traditional, hierarchical means. At the same time, however, ensuring the Adequacy, Security[52], Reliability and Cost-efficiency of such systems will require the Bulk Power, Transmission and Distribution Systems – together with deep Demand-side Flexibility – to function far more holistically together than they have in the past.

In Australia's highly decentralised grid transformation, advanced Operational Coordination models will be particularly important to provision the NEM both for a future similar to AEMO's Step Change scenario by 2050, and by 2025 be able to operate reliably during periods where 100% of instantaneous demand is met by variable sources. In a context where the NEM is also moving toward a future involving tens of millions of participating Energy Resources, advanced Operational Coordination models must be capable of providing Whole-system coordination that spans the Transmission-Distribution Interface (TDI).

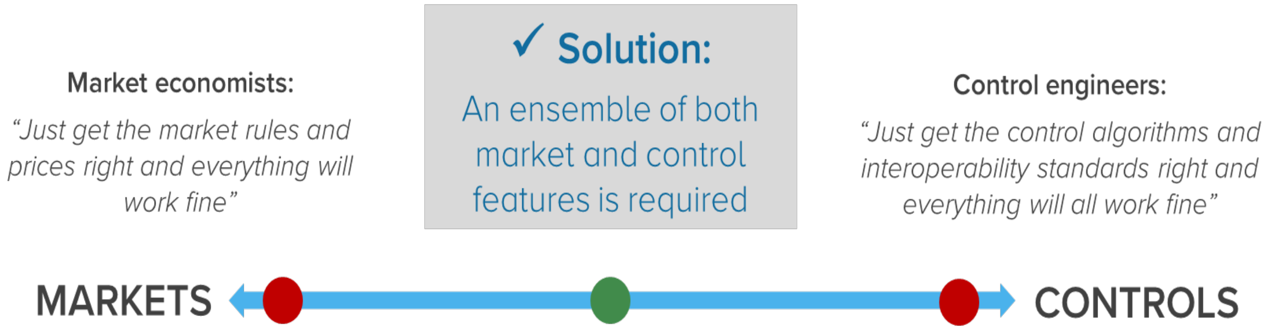

Figure 2: The 'markets vs controls' false dichotomy[53]

[52] Includes the management of Minimum Operational Demand

[53] Image: Adapted from Paul De Martini and Dr Jeffrey Taft

Further, as Energy Resource ownership and operational models evolve, advanced Operational Coordination will also require higher-resolution and more dynamic 'market-control' alignment to both provide an attractive '*quid pro quo*' and activate the efficient delivery of specific Electric Products when and where most needed by the Power System. Both elements are essential as well-designed markets operate as excellent sensors and optimisation engines, and technological controls are essential to secure timely and firm grid services that supports effortless customer participation.

Given the scale of change this involves, it is not rational to assume that the legacy structures of the Power System, developed last century for very different functional purposes, are capable of incrementally accommodating it. This is further compounded in the NEM by the clear structural separation that, over recent decades, has involved limited dynamic interdependence, interoperability and coordination across the supply chain. Where System Architecture considerations are not formally addressed in the development of holistic Operational Coordination mechanisms, costly scaling issues and structural brittleness will emerge that in turn reduce system reliability, resilience and economic efficiency.

Contributing Factors

Operational Coordination – Global Challenge & Opportunity

It is widely recognised that decarbonising Power Systems will increasingly require Bulk Power, Transmission and Distribution Systems – and deep Demand-side Flexibility – to function holistically to enable secure, cost-efficient operation.[54] As a result, Operational Coordination mechanisms configured for such a profoundly different Power System are perhaps one of the most pressing issues confronting the global sector.

For example, several major projects in the European Union include a strong focus on this topic[55] and AEMO's recent Engineering Roadmap to 100% Renewables[56] includes approximately twenty references to system coordination or derivatives thereof. Further, in commenting on critical priorities relevant to FERC Order 2222[57], the US Department of Energy's Electricity Advisory Board noted the following:

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[54] Refer to footnote 20 for example sources of both the need and the scale of economic value at stake.

[55] For example: System Operation Collection, International Renewable Energy Agency, 2020; Coordination of Distributed Energy Resources; International System Architecture Insights for Future Market Design, Newport Consortia, 2018; and, Evaluation of Combinations of Coordination Schemes and Products for Grid Services, EU CoordiNet Project, 2022.

[56] Engineering Roadmap to 100% Renewables, AEMO, 2022

[57] FERC Order2222 - Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators, Federal Energy Regulatory Commission, 2020

"One of the most critical requirements relates to the types of operational coordination needed across the transmission, distribution, and customer domains to enable DER aggregation for wholesale market participation while preserving system safety, reliability, and resilience…

"These activities should ultimately support development of a detailed coordination framework for each region to determine the roles and responsibilities of key actors and define information and data exchange requirements."[58]

Elsewhere, the same document nominates advanced Operational Coordination as one of the most critical issues raised by initiatives such as FERC Order 2222 given its relationship to system safety and reliability:

"Transmission-distribution-customer operational coordination processes (e.g., information and data exchange, including distribution utility DER visibility and controllability requirements) to preserve system safety and reliability, including evolution to more automated processes over time."[59]

In Australia, key characteristics of the journey to a Net Zero Emissions grid include the following, which only compound these wider concerns:

+ Structurally separated industry arrangements where the degree of dynamic interdependence, interoperability and functional coordination across the supply chain has been limited;
+ An accelerating transition from hundreds of large, dispatchable, synchronous generators to tens of millions of diverse and dynamic Energy Resources;
+ The erosion of the historically dominant Supply-side / Demand-side paradigm and the emergence of a context where Energy Resources are bifurcated into Centralised / Decentralised locational classes and Merchant / Private functional classes;
+ System security will require increasing levels of Flexibility, Balancing and Essential System Services from new sources as synchronous generators are withdrawn, including a growing dependance on LV-connected Energy Resources; and,
+ Despite growing levels of system Volatility, the Operability of the Power System will continue to require that supply and demand are instantaneously balanced every microsecond of the year.

[58] FERC Order 2222 – Recommendations for the U.S. Department of Energy, Electricity Advisory Board, 2021
[59] Ibid

Key Concepts G

Operational Coordination

The systematic operational alignment of utility and non-utility assets to provide electricity delivery. It can also refer to structured mechanisms by which millions of diverse Energy Resources (merchant and private) operate both to serve individual priorities ('local selfish optimisation') and cooperatively participate to address common Power System issues.

As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, the proportion of synchronous generation declines, and decarbonising Power Systems experience unprecedented levels of Volatility, ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require:

> *Bulk energy, transmission and distribution systems – and the rapidly expanding fleet of distributed resources – to function far more dynamically and holistically across the end-to-end power system.*

Combined with exponential growth in Energy Resource numbers, types and ownership models, and the correlation between the economic value of grid services delivered and the physics-based needs of a Power System (which dynamically vary, both temporally and spatially), more advanced Operational Coordination models become critical to:

- Enhance dynamic Interoperability across the Transmission-Distribution Interface (TDI) due to the Power System's growing dependence on Energy Resources located both up and downstream:
- Support more granular 'market-control' alignment to incentivise and activate targeted provision of grid services in the form of Electric Products when and where most needed;
- Co-optimise the provision of grid services across the vertical Tiers/Layers of the Power System to both enhance operations and maximise the Electric Product Value for participants;
- Mitigate or avoid legacy Architectural Issues[60] that impede the Scalability, Extensibility and Resilience of Operational Coordination models; and,
- Ultimately enable transition to a more holistic Transmission-Distribution-Customer (TDC) model of Operational Coordination customised to local industry structure arrangements.

Co-optimisation

Co-optimisation is a structured approach to ensuring that Energy Resource services dispatched and/or financially incentivised in one vertical Tier/Layer of the Power System (e.g. Bulk Power, Transmission or Distribution System) are not driving unintended negative consequences in other Tiers/Layers of the system.

[60] Refer Key Concepts H

Transmission-Distribution-Customer (TDC) Coordination

Provisioning the NEM for a Step Change type future, and the ability to operate reliably during periods where 100% of instantaneous demand is met by variable sources in 2025, will require more holistic approaches to Operational Coordination that are future-resilient due to high levels of Scalability and Extensibility.

As noted earlier, the NEM is moving toward a future where tens of millions of participating Energy Resources are bifurcated into Centralised and Decentralised locational classes (i.e. HV or LV-connected). In this context, secure and cost-efficient operation of the Power System will ultimately require Operational Coordination models capable of providing Whole-system or Transmission-Distribution-Customer (TDC) coordination.

Due to the wide locational spread of Energy Resources, the erosion of the Supply-side / Demand-side bifurcation and the somewhat 'tidal' behaviour of high-VRE / high-DER Power Systems[61], future Operational Coordination models will need to function 'by design' and at massive scale across the Transmission-Distribution Interface (TDI).

Higher-resolution 'Market-Control' Alignment

In addition, the tens of millions of Energy Resources will also fall into Merchant or Private classes in terms of their primary functional purposes. A significant proportion of these resources will also be highly variable and possess varying degrees of Dispatchability.

In a Power System experiencing growing Volatility, more advanced Operational Coordination will require more dynamic, higher-resolution 'market-control' alignment. This will be key to providing an attractive and efficient 'quid pro quo' and automate the contracted provision of Electric Products, enabling the targeted delivery of Power, Energy, and Essential System Services when and where most needed by the Power System.

The core rationale for such an approach is summarised as follows:

+ Well-designed markets operate as excellent sensors and optimisation engines; reduce transaction friction and cost; and, enable the Market/System Operator (MSO), emerging Distribution System Operators (DSO), consumers and 'prosumers' to reveal what they need and value at significantly higher levels of resolution; and,
+ Technological controls are required as markets alone cannot address all Power System dynamics and timeframes; and, automation is required to deliver Firm response and make the day-to-day experience of participating customers seamless and effortless.

[61] For example, several NEM regions are projected to experience an increasing number of periods where 100% of instantaneous demand is met by LV-connected DPV, especially at solar zenith on days experiencing low levels of demand. At other times, such as during the night, these same regions must be capable of largely depending on utility-scale wind generation and other centralised Energy Resources.

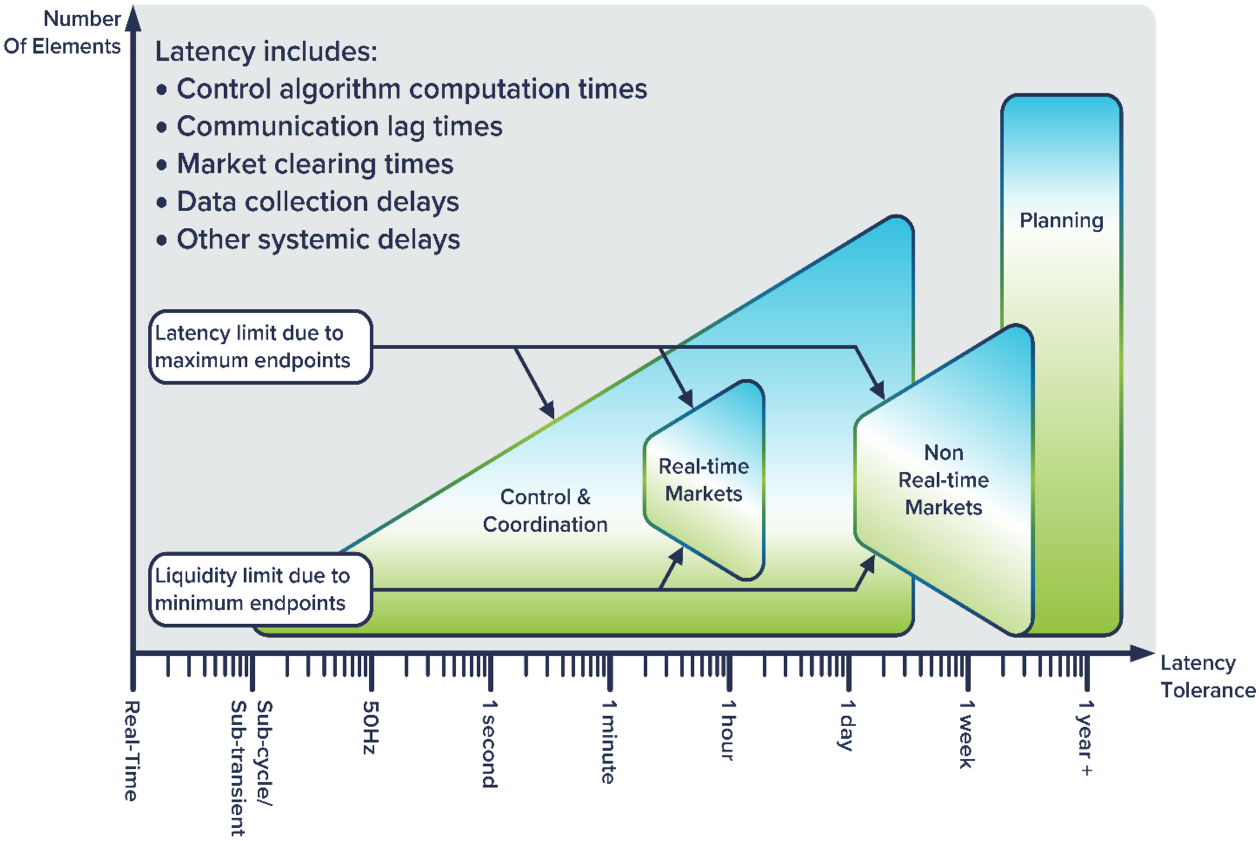

Figure 3: Advanced Operational Coordination mechanisms require 'Market-Control' alignment and complementarity across key layers of the Power System[62]

Structural Shifts Require Architectural Treatments

These changes are structural in character and drastically impact the Operability of any GW-scale Power System. In recognition of the scale and pace of change now confronting Australia's grids, AEMO has noted:

> *"Traditional, legacy approaches will need to be maintained in the near term, but inherent structural limitations will eventually constrain the pace of transition. Parallel to this, it is critical that designing a step change in power system capability starts today, due to… the risks if timely action is not taken and system operators do not have the tools to securely and reliably manage new operational conditions…"*[63]

Some related transformative influences that are already emerging in Australia include:

+ Increasingly fast dynamics at all Tiers/Layers of the Power System (including bulk power, transmission and distribution system and customer devices);

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[62] Image: Pacific Northwest National Laboratory (adapted)

[63] NEM Engineering Framework – Initial Roadmap, AEMO, 2021

+ An expanding number and diversity of entities that are influencing functions related to Operational Coordination;
+ Vast increases in data volumes generated by millions of Components, Energy Resources and Endpoints;
+ The transition from slow data sampling to fast streaming data; and,
+ Decreasing tolerance for latency in control systems due to the above-referenced fast dynamics.

In other words, it is not rational to assume that legacy Structures developed last century for very different set of functional purposes and expectations are capable of automatically accommodating this scale of change. Where System Architecture considerations are not well aligned with future needs, costly scaling issues will arise, such as latency cascading, computational constraints, time wall effects, and cyber-security vulnerabilities. These, in turn, reduce system reliability, resilience and economic efficiency.

Operability Risks Arise from Poor Architectural Practice

The Operability of Australia's increasingly complex and volatile Power Systems, involving millions of participating Energy Resources, will fundamentally depend on the holistic application of sound Systems Architecture practice.

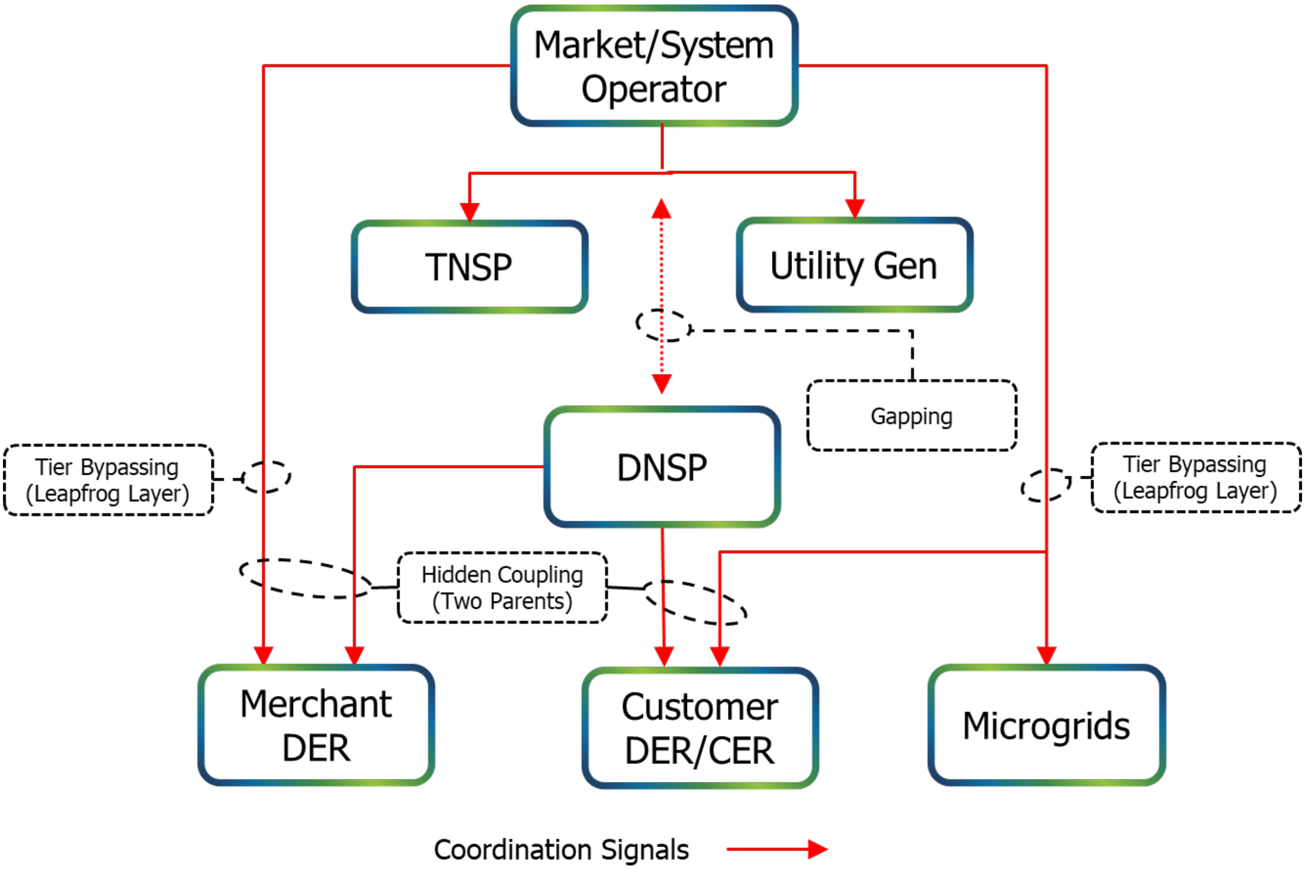


Figure 4: Examples of Systems Architectural errors that will impact Operational Coordination

Following are seven important structural issues that the System Architecture discipline surfaces which are relevant to enabling Operational Coordination in a high-VRE / high-DER future:

1. **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System operational hierarchy.

2. **Coordination Gapping**: An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation.

3. **Hidden Coupling:** Two or more control entities with partial views of System State issue simultaneous but conflicting coordination signals to a DER/CER or Component of the Power System (refer Figure 5).

4. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.

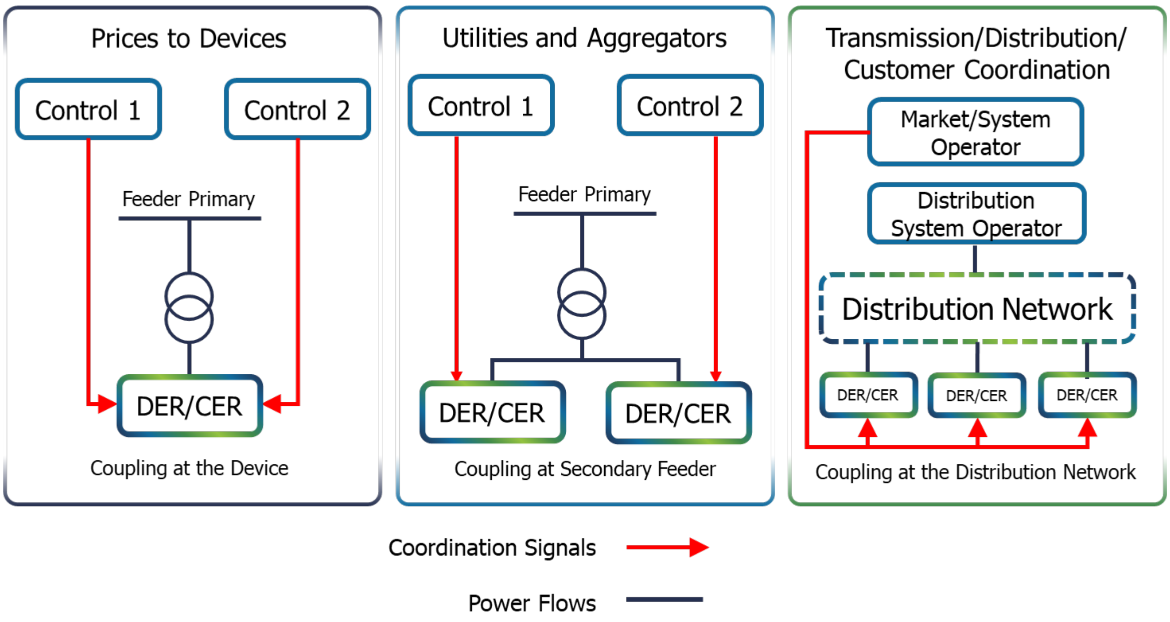


Figure 5: Different ways that Hidden Coupling can occur.

5. **Computational Time Walls:** Where massive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines risk hitting a computational 'time wall' where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time (refer Figure 6).

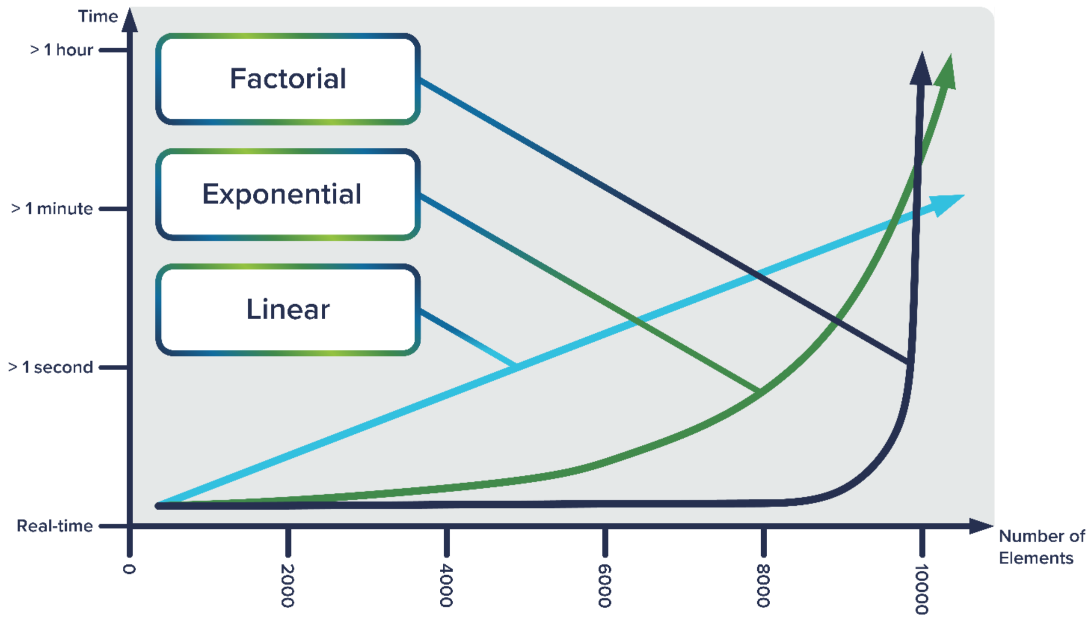
6. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.

7. **Back-end Integration Constraints:** Multiple vertical silo structures found in many organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others (refer Figure 7).

The Supporting Role of Platform-based or Layered Structures

Increasingly complex and dynamic systems experience growing fragility and anti-resilience where their underpinning legacy Architecture remains unduly centralised and based on an outdated, linear 'command and control' model – either explicitly or implicitly.

Layering is a valuable architectural approach that is applied widely in ultra-complex computing and communication systems as it enables the management of exponential complexity. Based on Layered Decomposition mathematics, the core capabilities of an ultra-complex system are configured into interoperable 'horizontal' surfaces or Platforms that enjoy far greater Resilience, Scalability and Extensibility. Given its complex cyber-physical-transactional characteristics, Layering is highly relevant to transforming Power Systems.



8.

Figure 6: Computational 'time wall' effects can occur quite suddenly. In the case of Factorial curve (black), no amount of computing resources will be adequate to solve the optimisation problems in a reasonable time once the breakpoint has been reached.[64]

[64] Image: Dr Jeffrey Taft

By contrast, in highly bifurcated traditional Power Systems core functions were arranged in 'vertical' structures and siloes (often with their own networks, sensors and computational systems). When experiencing significant change, these vertical structures exacerbate integration issues, compromise solution Scalability and Extensibility and result in more brittle, less resilient and higher cost outcomes.

The properties of a layered approach that make it superior for Power Systems that will host millions of participating Energy Resources connected to the LV-system include:

+ End-to-end system Visibility, Operational Coordination and Operability outcomes are significantly enhanced;
+ The relatively stable core system functions are kept entirely separate from applications, which be changed or upgraded more frequently without impacting the core functions;
+ Each tier/layer can insulate the tier/layer immediately above from changes in the tier/layer immediately below, and vice versa (i.e. preventing changes at one level from being propagated through the entire system);
+ The ability of third parties to create applications that leverage the Platform via open standard interfaces is enhanced; and,
+ Changes or upgrades in end-use or third-party applications are decoupled from impacting underlying core functions and capabilities.

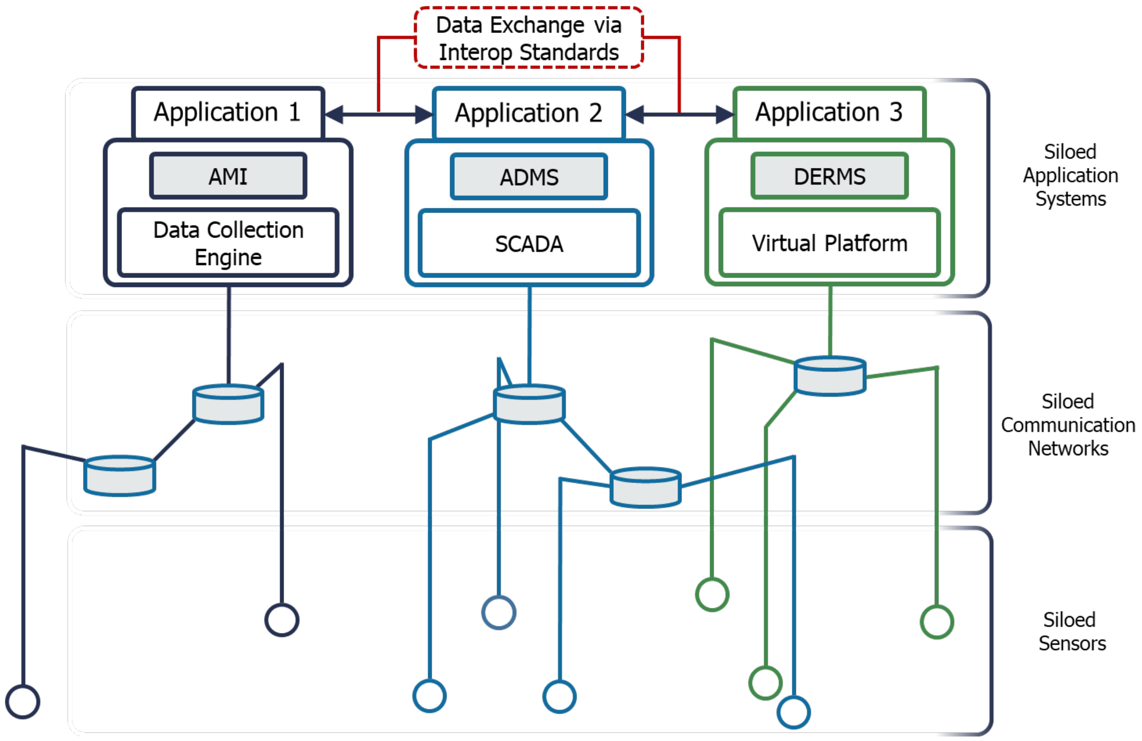


Figure 7: Back-end integration constraints arise due the multiple vertical silo structures found in many supply-chain organisational system.

Solution Requirements

More advanced and future-ready approaches Operational Coordination must be configured around a vastly greater emphasis on end-to-end Power System interdependency. This is a context where Bulk Power, Transmission and Distribution Systems – together with deep Demand-side Flexibility – must function far more holistically together to cost-efficiently management system operations.

Some of the key features of more advanced Operational Coordination models include:

+ Enhanced dynamic Interoperability across the Transmission-Distribution Interface (TDI) due to the Power System's growing dependence on Energy Resources located both up and downstream;
+ More granular 'market-control' alignment to incentivise and activate targeted provision of grid services in the form of Electric Products when and where most needed;
+ Co-optimised provision of grid services across the vertical Tiers/Layers of the Power System to both enhance operations and maximise the Electric Product Value for participants;
+ Mitigation of legacy Architectural Issues[65] that impede the Scalability, Extensibility and Resilience of Operational Coordination models; and,
+ Support the scalable transition to a more holistic Transmission-Distribution-Customer (TDC) model of Operational Coordination customised to local industry structure arrangements.

[65] Refer Key Concepts H

Key Concepts H

Architectural Issues

Following are seven important structural issues that the System Architecture discipline addresses that will otherwise negatively impact the Operability and Resilience of decarbonising Power Systems:

1. **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System's operational hierarchy.
2. **Coordination Gapping**: An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation.
3. **Hidden Coupling:** Two or more control entities with partial views of System State issue simultaneous but conflicting coordination signals to a DER/CER or Component of the Power System.
4. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
5. **Computational Time Walls:** Where excessive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines will hit a computational 'time wall' at some point where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time.
6. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
7. **Back-end Integration Constraints:** Multiple vertical silo structures found in many supply-chain organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others.

Layered Decomposition

A formally established mathematical technique employed in many technology sectors to solve Ultra Large-scale (ULS) optimisation problems characterised by highly coupled constraints.

In the case of Power Systems transitioning from hundreds to tens of millions of participating Energy Resources and experiencing growing levels of operational Volatility, Layered Decomposition provides an empirical basis for solving many critical Architectural Issues, including otherwise intractable Operational Coordination problems.

In contrast with more traditional hierarchical control, it enables highly complex problems to be decomposed multiple times into sub-problems, which then work in combination to solve the original problem in a manner that addresses long-term Scalability, Extensibility, Cyber-security and Resilience issues. Importantly, rather than 'competing' with other Architecture models currently or proposed for use in the power sector, Layered Decomposition provides a universal, canonical structure for unifying alternative models.

2.6. Modelling Integrity Risks: As Power Systems experience changes impacting technology mix, operational volatility and underpinning architectural structures, the usefulness of existing models must be constantly evaluated to ensure they are fit-for-purpose in a transformational context.

Cross Cutting Issue

Models are essential for both Power System planning and operations, with the latter being a key element of Operability in regard to the ability to forecast upcoming Power System conditions and have confidence in how the system will perform.

Numerous useful models have been developed over recent decades that are relevant to different functions and segments of the existing Power System supply chain. However, no single full-fidelity model of a GW-scale Power System such as the NEM exists. This means that many different models are used for interrogating different functions, with various models often being 'nested' such that the outputs of one can be used as inputs to another. Understandably the development of existing models has been based (explicitly or implicitly) on the historical structural and operational paradigms that are now experiencing profound change.

Power System governance, investment and operational decision processes continue to place significant confidence in the outputs of modelling. However, as Power Systems experience transformational forces impacting technology mix, operational volatility and inevitably the underpinning architectural structures, the usefulness of existing individual and nested models must be constantly reassessed. Further, to ensure the accuracy, trustworthiness and ongoing fitness of Power System models, it is essential that data and other inputs, and underpinning architectural assumptions, are transparent so that they can be verified and validated by all stakeholders.

Contributing Factors

Numerous useful models have been developed over recent decades that are relevant to different functions and segments of the existing Power System supply chain. The development of existing models has typically been based on the extant historical structural and operational paradigms. Further, no single full-fidelity model of a GW-scale Power System such as the NEM exists which means that many different models are used for interrogating different functions, with various models often being 'nested' such that the outputs of one can be used as inputs to another.

For example, existing models based on steady-state power flow conditions are typically employed for optimisation-based dispatch and capacity expansion planning tasks. The optimal power flow (OPF) problem is the canonical example of this type of task, yet even this one task may be formulated in many different ways, each of which addresses or abstracts away specific elements of the system. Single-line power flow models, for example, which are typically sufficient for transmission network dispatch and planning studies, are quite different from three- or four-line models used for distribution networks where unbalances and neutral currents regularly arise and have engineering consequences.

Similarly, time domain simulations, which are used for operational decision-making, fall into two main categories: root-mean square known as RMS-based models or full electro-magnetic transient (EMT) models. RMS-based models are computationally faster, but their accuracy decreases as the proportion of inverter-connected generation in a system increases. This is mainly because the control systems employed by inverter-based resources have dynamics in the range of several kHz that cannot be accurately represented by RMS simulation tools. By contrast, EMT models are able to represent these dynamics, but come with dramatically increased computational requirements and modelling detail.

The two examples above – optimal power flow and time-domain simulation – illustrate the diversity and interdependencies of various models. The power flows computed from the solutions to an OPF problem, for example, may be used as the steady state initial conditions for a time-domain simulation to assess system dynamic stability. By contrast, while the OPF solves a least-cost problem and can handle power flow constraints, it does not and cannot consider stability constraints; this is the task of time domain simulations.

Solution Requirements

Given the level of confidence placed in the outputs of Power System modelling, which often involves cascading interdependencies, it is critical that individual and nested Power System models remain holistically fit-for-purpose in a transforming context.

As Power Systems such as the NEM experience transformational forces impacting technology mix, operational volatility and inevitably the underpinning architectural structures, the usefulness of existing individual and nested models must be constantly reassessed. This will be essential to ensure the integrity of Power System governance, investment and operational decision processes.

Further, to ensure the accuracy, trustworthiness and ongoing fitness of Power System models, it is essential that data and other inputs, and underpinning architectural assumptions, are transparent so that they can be verified and validated by all stakeholders. A high level of transparency is also critical for eliminating anti-competitive practices that may arise due to modelling tool vendor lock-in.

2.7. Cyber-security Vulnerabilities: Layered cyber-security defences require the identification and treatment of non-cyber structural vulnerabilities to achieve a Power System that is inherently more resistant to cyber-attack.

Cross Cutting Issue

The progressive digitalisation of Power Systems, together with the rapid emergence of millions of Distributed Energy Resources (DER/CER), presents significant cyber-security challenges for the sector. Increasingly inter-dependent Power Systems that involve an expanding diversity of participating entities, data volumes and communication systems is significantly more vulnerable to malicious cyber-attack.

A range of important efforts are currently advancing in Australia to progress minimum cyber-security standards and technical designs for interoperability communications. These are also supported by efforts to identify suitable regulatory levers to ensure that minimum requirements are implemented. Given the criticality of secure Power System operations, best practice approaches to cyber-security require the implementation of a multi-layered approach. It is noteworthy, therefore, that a major commonality across the current risk mitigations is they are all cyber-based.

Achieving such a layered approach to Power System cyber-security also requires the inclusion of non-cyber structural analysis and treatments. Doing so is essential to provide powerful additional lines of defense and reinforce more conventional cyber-based solutions. Conversely, the failure to identify and treat non-cyber structural vulnerabilities significantly increases the available vectors of attack, resulting in a greater volume of attempted penetrations that must be prevented by cyber-based solutions as a final line of defense. Such a Power System is inherently less resistant to cyber-attack.

Contributing Factors

Expanding Range of Cyber-attack Vectors

Power Systems are facing an entirely new scale of cyber-security challenges as they become increasingly inter-dependent and interconnected. Both progressive digitalisation and the rapid diffusion of Distributed Energy Resources (DER/CER) involves an expanding range of participating entities, exponential increases in data volumes, and a wide diversity of communication systems. Such a system is, by definition, significantly more vulnerable to malicious cyber-attack and non-malicious cyber-fragility.

All plausible future scenarios of Australia’s Power System transition anticipate the continued deployment of DER/CER, in many cases at massive scale. While this brings with it numerous opportunities for DER/CER to provide a range of valuable grid services, it also involves growing dependance on these devices and the communications networks that connect them, including the internet.

Such configurations present a significant shift from the traditional dependance on dedicated industrial communications infrastructure such as SCADA control systems architectures. It transforms significant aspects of the Power System from a closed to an open system comprised of many diverse, autonomous and self-interested entities. For example, this will include the MSO, DNSPs, TNSPs, Energy Retailers, Aggregators, Technology OEMs, DER owners, etc.; all of which are dependent on a range of communication channels.

This transition introduces several vulnerabilities. First, the Power System will become much more vulnerable to disruptions to communications networks, whether they be malevolent or accidental. Second, it will be at risk to cyber-attacks conducted via DER/CER-related communications networks. These might be denial of service attacks or attempts to modify software or setpoints for the attackers' benefit. Alternatively, they may be attempts to extract valuable information about energy customers, system infrastructure, energy service providers or other Power System stakeholders. Third, the abundance of DER/CER will also be susceptible to software errors propagating through the system, such as bugs in firmware updates or systematic connection code violations, rendering large numbers unpredictable or unusable.

Active Focus on Cyber-based Security Considerations

Given the growing potential for malicious cyber-based attacks, ARENA's Distributed Energy Integration Program (DEIP) has established a Cyber Working Group to progress minimum standards and technical designs for securing interoperability communications.

In addition, the Energy Security Board (ESB) also recognises the need for DER/CER-related cyber-security to be managed, including the design of capabilities and frameworks for security of communications systems being advanced by DEIP, as well as the identification of regulatory levers to implement minimum cyber security capabilities. Beyond these important foundational steps, a range of other cyber-based risk treatments may also need to be considered, including:

+ Advanced monitoring of external threats;
+ Active surveillance for attacks to support rapid response to cyber penetrations; and,
+ Proactive identification of new and emerging technical vulnerabilities.

Non-cyber Structural Considerations Critical for Layered Defenses

The major commonality across all the above important risk mitigation approaches is that they are all cyber-based. As recent history has demonstrated, however, while these steps are essential, they cannot entirely guarantee cyber-security. In all cases, best practice requires that a layered approach, including multiple classes of defenses, should be applied.

One such layer of defense which is often overlooked is the identification of critical weaknesses created by how data flows are routed, and through which entities and internal systems. These structural considerations can result in serious 'non-cyber' vulnerabilities in legacy systems and alternative future arrangements being considered.

In other words, as Ultra-large Scale (ULS) systems consisting of complex webs of entities and interdependencies, non-cyber structural vulnerabilities must be actively evaluated and addressed if overall Power System cyber-security risks are to be significantly reduced. There have been numerous instances where interconnected systems have been attacked through the weakest element (organisation or system), which then becomes a portal into the entire system.

Addressing this critical gap in Australia's cyber-security considerations will require the mapping of cyber-physical relationships and data flows that are embedded in the legacy Power System. This enables identification of non-cyber structural vulnerabilities that currently exist in NEM legacy structures and/or would emerge in alternative configurations of Roles & Responsibilities and related structures and data routings. It provides a foundational step to applying often comparatively low-cost structural treatments that significantly mitigate or entirely avoid the non-cyber vulnerabilities identified.

As noted above, this is an essential element in enabling a layered approach to Power System cyber-security. The application of non-cyber structural treatments provides a powerful additional line of defense, and complements the conventional cyber-based treatments applied, in support of a Power System that is inherently more resistant to cyber-attack.

Solution Requirements

Both Power System digitalisation and the rapid emergence of millions of DER/CERs are expected to continue unabated. In this context, cyber-security best practice requires that a layered approach with multiple classes of defense be applied. Such an approach requires that critical non-cyber structural vulnerabilities be actively identified and treated. This will require the following:

+ Mapping of all cyber-physical relationships and data flows embedded in the legacy Power System;
+ Analysis and documentation of non-cyber structural vulnerabilities that:
    - Are currently present in the existing legacy structures of the NEM;
    - Will plausibly exist or emerge in alternative configurations of Roles & Responsibilities and the enabling structures and data routings; and,
    - In both cases, includes assessment of structural vulnerabilities across the full Transmission-Distribution-Customer (TDC) value chain, including Aggregators and DER/CER devices;
+ Identification of structural treatment options that significantly mitigate or entirely avoid the non-cyber vulnerabilities identified; and,
+ Application of Graph Theory analysis and Resilience Algebra to evaluate alternate structures and treatments to select the most inherently resistant structures for Australia's future needs.

Key Concepts I

Systems Architecture

A formal part of Systems Engineering, which enables objective, collective reasoning about the underpinning Structure or Architecture of a complex System, together with its Components, Interfaces, Feedback Loops and other behaviours.

This is particularly important as the Architecture of a System always has a disproportionate and irreducible influence on what the System can reliably and efficiently perform. As such, a System is not the sum of its parts, but the product of the interactions of those parts as enabled by its underpinning Architecture.

While having a major impact on the performance of any System, Architecture is usually less tangible and harder to discern than the Components of the System. Therefore, the Systems Architecture discipline provides formal tools for examining how all the Components of a system are related together by the underpinning Architecture, the Emergent behaviours that arise through their interactions, and the most robust options for making changes where required.

Systems Architecture disciplines, therefore, help stakeholders visualise and make more informed decisions about the relationships embedded in the legacy System, including how they might best be adapted to ensure the System is ready to meet future needs.

2.8. Multi-party Data Sharing Risks: Comprehensive options analysis and the formal application of Systems Architecture disciplines is required to mitigate non-trivial data sharing risks including Scalability, Extensibility, Cyber-security and Anti-resilience issues.

Cross Cutting Issue

Data exchange between multiple actors is becoming critical with the digitalisation of Power Systems and the emergence of millions of LV-connected Distributed Energy Resources (DER/CER) and Electric Vehicles (EV).

While still a relatively immature area in the power sector, several approaches are being proposed and trialed. Across many sectors there is significant hype about potential enabling technologies such as Distributed Ledger Technologies (DLT) and digital Platform solutions. However, there is currently no single or perfect solution to the data sharing challenges relevant to increasingly decentralised Power Systems.

Further, despite the promise of specific technologies, none can be successfully implemented without a disciplined, comprehensive and multi-stakeholder approach to developing the Systems Architecture that must underpin them. The failure to do so significantly increases the risk of structurally 'brittle' or 'Anti-resilient' solutions that impact interoperability and exacerbate cyber and non-cyber security vulnerabilities.

At present, however, it has been noted that the NEM is currently on a trajectory toward a suboptimal, non-scalable and inherently 'brittle' approach to data exchange.[66]

Contributing Factors

Efficient, secure and scalable data exchange between multiple industry actors and millions of Energy Resources is becoming critical with the digitalisation of Power Systems and the emergence of huge volumes of LV-connected Distributed Energy Resources (DER/CER) and Electric Vehicles (EV).

In what remains a comparatively nascent area in the power sector, three approaches are typically being implemented or proposed for consideration. These include:

1. Point-to-point interfaces between any pair of industry actors or systems that need to exchange data;

2. Centralised data exchange or data sharing Platform that participating industry actors stream or upload data into, with each entity accessing whatever data it requires; and,

3. Decentralised data exchange.

[66] Project EDGE Lessons Learnt Report #2, AEMO, 2022

Each of these approaches have key challenges and are considered below together with a fourth potential area of consideration.

Option 1: Point-to-point Interfaces

The point-to-point interface approach is typically implemented in demonstration projects and individual use cases at a small scale. Examples may include a small number of Aggregators collaborating with a Distribution Network to obtain Dynamic Operating Envelope (DOE) information. However, as the Project EDGE Lessons Learnt Report #2[67] noted:

> *"…the following factors associated with a high DER future mean point-to-point approaches could lead to adverse outcomes for consumers:*
>
> - *Proliferation of aggregators needing to obtain DOEs from all DNSPs across the NEM.*
> - *Proliferation of new use cases, such as:*
>   - *Retailers sending zero export limits to consumer agents/aggregators to manage negative price exposure;*
>   - *DNSPs sending dynamic network prices to EV charge point operators to manage peak charging risks; and,*
>   - *DNSPs seeking to procure DER-based local network support services from aggregators.*

Evaluated using Systems Architecture tools and methodologies, the point-to-point approach is recognised as being inherently 'brittle' structurally or architecturally, which has a direct impact on its Scalability and Extensibility. What may also be referred to as the architectural characteristic of 'Anti-resilience' arises from multiple pair-wise interfaces being required to directly or indirectly connect between various organisational data siloes. Failures and changes in this arrangement easily cascade through the entire system. In addition, the integration of a new application system or organisation is costly and time consuming despite the best efforts at ensuring interoperability between systems.

The Anti-resilience of this approach is compounded by each system typically having its own primary data sources, communication systems, data formats, and protocols. The is further compounded where there are multiple organisations providing functionally equivalent data (e.g. meter data, DER/CER and EV data from Aggregators, DOE data from DNSPs, etc.). A given application system may have to contend with multiple interfaces and representation schema for essentially the same categories of information. The inherently brittle architecture makes the interoperability issue contentious and costly with the result that more than thirty years of experience with this type of arrangement have demonstrated its basic unsuitability.

Despite these significant constraints, it is important to note that the above Project EDGE report also noted the following:

[67] Ibid

"Without mandated communication of DER data transactions through a data hub, the industry is currently on a path of point-to-point data exchange proliferation."[68]

Option 2: Centralised Data Exchange

The centralised data exchange or data sharing Platform approach (also known as 'data warehousing' or a 'data lake', etc.) is also commonly proposed as a solution to data exchange between multiple industry actors and millions of devices. Although quite different to the point-to-point approach, several critical issues arise immediately with this architecture, including:

+ Who owns and maintains the data Platform hardware and software?
+ Who curates and manages the data repository?
+ What standards will be applied to data representation and documentation? Who selects them?
+ How are the multiple time scales and unsynchronized data sampling schedules managed?
+ How often are data refreshed?
+ How much data should be kept online before being archived, and for how long?
+ What contractual (legal and financial) agreements must be put in place to enable data sharing?
+ Who owns the data once it is included in the repository?
+ Who pays for the repository, including its operation and ongoing maintenance?

This approach also suffers from a critical architectural deficiency, namely, in that is creates a single point of failure in terms of both:

+ Reliability/resilience issues; and,
+ Cyber-security issues.

In other words, the central repository is anti-resilient due to its very centrality, which results in the participating organisations and their systems being coupled. It is also weak from a structural cyber-security standpoint as demonstrated by the many instances where interconnected systems have been attacked via the weakest element (organisation or system), which then becomes a portal into the others.

In addition, depending on the number of organisations involved, the central data store approach can raise two types of Scalability challenges: data volume, and number of communication connections. While both can be managed, they are not trivial.

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[68] Ibid

Finally, power sector actors are often reluctant to share operational data before they are able to 'cleanse' it (which can take very long periods of time) and/or may also view it as valuable intellectual property that they do not wish to share. In addition, the data representation issue can become complex since functionally equivalent entities and systems often have different schemes for the representation of the same underlying physical phenomena (meter data for example). The challenge of settling on commonly accepted data representations and exchange protocols is essentially the same as for the point-to-point approach.

Option 3: Decentralised Data Exchange

When subjected to theoretical evaluation, decentralised data exchange approaches using Distributed Ledger Technology (DLT) such as Blockchain appear to have great promise and deliver greater benefits than the centralised approach. On the face of it, this is because decentralised architectures:

+ Have enhanced Scalablity and minimise or avoid Single Point of Failure (SPOF) risks;
+ Are modular, flexible and interoperable;
+ May be more secure[69], trustworthy and auditable; and,
+ Support greater standardisation and fairness though the application of ecosystem wide standards.

It is important to note, however, that DLT-based solutions remain immature in the power sector. Any significant application of promising technologies will require extensive further development, testing and phased deployments.

In addition, the application of DLT or any other enabling technology in no way eliminates, or even minimises, the foundational requirement of formally developing the underpinning Systems Architecture of any decentralised (or centralised) approach. On the contrary, to be successful, its development would require the disciplined, granular and multi-stakeholder consideration of:

+ All structural relationships and interdependencies between all participating entities and application systems;
+ Spanning the full Transmission-Distribution-Customer (TDC) value chain and including Aggregators, DER/CER devices and EVs; and,
+ Include consideration of both requirements for the current state and the most plausible emerging future state configurations.

[69] As a cautionary note, numerous major DLT-based financial systems have been compromised in various ways.

Option 4: Publish-and-subscribe Model

While there is no perfect solution to the data sharing challenge pivotal to an increasingly decentralised Power System, the Publish-and-subscribe model is an alternative, more mature approach that mitigates or overcomes several of the above shortcomings. It does so by enabling the combination of a multi-layer Platform and federated databases which can both manage data in motion and archived data sets.

The model allows organisations and application systems to provide specific data to other authorised recipients, via a service bus or distributed Platform, which is underpinned by a centralised server. The Platform will typically provide valuable additional functionality such as message queuing and persistent delivery, message routing, data transformation, and communication contention management.

To the extent that the Platform stores data briefly while in transit, it may be considered a SPOF and a source of system coupling. The approach also generally involves significant effort to interface via ETL (extract, transform, load) adapters that must be created for all the interconnected systems.

Nevertheless, this approach allows the residual shortcomings to be mitigated by Layering how the underlying electrical infrastructure, sensors, and multi-services IP communication network are structured as a Platform. Each authorised organisation and application system can obtain the required data from the distributed Platform and the source organisation for specific data can control which entities have access to it.

For data that must be persisted, each organisation can maintain a decentralised data store, the set of which can be federated across the communication network to function as a repository, but with no central location. Each organisation both retains ownership of its data and access control.

Solution Requirements

As a relatively immature area in the power sector, while there is significant hype about the potential of technologies such as Distributed Ledger Technologies (DLT) and digital Platform solutions, there is no single or perfect solution to the data sharing needs of an increasingly decentralised Power Systems.

In addition to their comparatively nascent status in the power sector, no single data exchange solution – no matter how promising – can be successfully implemented without a disciplined and comprehensive approach to developing the Systems Architecture that underpin its relationships and interfaces with multiple other systems and subsystems. Where this is applied, the potential for more scalable, structurally resilient and cyber-secure data exchange solutions expands significantly.

2.9. DER/CER Flexible Export Risks: Greater whole-system perspective is required in the further development of DER/CER flexible export solutions to mitigate potential instability issues and non-linear behaviours, ensure capacity allocation equity, and achieve full benefits realisation.

Cross Cutting Issue

Enhancing DER/CER integration through the application of Dynamic Operating Envelope (DOE) solutions has significant potential for supporting Australia's transition to a Power System future. In the context of the NEM's structural separation, DOE solution development first originated in the context of providing flexible export limits to DER/CER to enable more advanced distribution network capacity management. From these origins, Australia's market, regulatory and innovation funding bodies also anticipate an impressive range of contributions that DOE solutions may make to overall Power System optimisation and customer benefits.

As noted throughout this document, the full benefits-realisation of this and other promising technologies originating in one layer or segment of the supply chain will be advanced by applying a Whole-system view in its further development. This is particularly important as Power System operations will increasingly depend on stable, dynamic interoperability between the bulk power / transmission systems and the respective distribution systems.

Conversely, the failure to apply such a holistic development approach heightens the risk of unintended consequences emerging when DOEs are deployed and activated at mass scale (i.e., in the hundreds of thousands or more). This could include significant instability issues which may manifest in the form of unstable oscillation manifesting at the Transmission – Distribution Interface (TDI). Other outcomes may include non-linear behaviours, structural complexity and fragility, and stakeholder concerns over the equity of capacity allocation mechanisms.

Essential Context

A unique feature of Australia's Power System transition is the progressive shift from hundreds to tens of millions of participating Energy Resources due to world leading levels of DER/CER deployment. As such, Dynamic Operating Envelope (DOE) technologies have much promise as a key enabler of this transition.

The genesis of DOE development has been the enabling of flexible – rather than static – export limits to LV-connected solar PV systems in support of local network capacity management. In the context of Australia's vertically disaggregated market structure, this has involved a primary distribution network or electricity 'transport' framing.

In parallel, there is a growing recognition that deeply decarbonized Power Systems will require the bulk energy, transmission and distribution systems – together with millions of demand-side resources – to function much more holistically for reliable and efficient operation. In this context, Australia's market, regulatory and innovation funding bodies are recognising a wider range of contributions that DOE technologies may make in addition to flexible export limits. These include:

- Efficient management of a variety of flexible resources such as residential battery storage systems and other smart technologies, in terms of both exports and imports;
- Expanded electric vehicle charging and faster charging by allowing for higher loads during off-peak times, again including vehicle-to-grid electric vehicle battery discharging;
- Managing fluctuations in solar output that significantly impact on both instantaneous and average voltage and make it harder and more expensive to maintain regulated voltage limits;
- Supporting the instantaneous balance of supply and demand in the bulk Power System, including the management of minimum operational demand; and,
- Reduced curtailment of distributed solar PV and lower wholesale electricity prices due to increased supply.

In summary, market and regulatory bodies note that this will enable business models that provide participating DER/CER owners with greater access to financial returns through the monetization of:

- Bulk power market services including wholesale energy, FCAS, or Reliability and Emergency Reserve Trader (RERT); and,
- Network services, where excess capacity is provided to local networks to defer or avoid the need for network upgrades.

As such, there is a recognition of the wider value of DOEs as a key part of Australia's emerging ecosystem that enables new retailer/aggregator business models that unlock the full system value of millions of DER/CERs.

Contributing Factors

Potential Instability & Latency Issues

A DOE engine is essentially a specialised distribution state estimator that produces finely granular circuit capacity limits, ideally for both power export and import. A pair of values is calculated for each DER/CER or customer connection point. The DOE engine is dependent on several external inputs:

- Sufficient voltage and power flow visibility data to support accurate state estimation of all voltages and flows;
- Topology models for the network circuits, including DER/CER and load location and phase connectivity;
- Distribution network impedance values; and,
- Distribution network constraints (voltage limits, thermal limits, protection settings).

DOE engines are currently envisaged as being centralised, where the above data feeds are required from a variety of sources: GIS or OMS, DMS, AMI head end, substation and line sensors, and DER/CER. These existing systems containing the necessary data are often siloed and can impose their own significant time delay / latency constraints.

Once the DOE envelope is calculated, the information is issued to the DER/CER or customer connection point, possibly via the relevant aggregator. Under different models, the DOE information may also be sent to the DNSP / DSO and System / Market Operator.

From a data flow perspective, this creates a DOE substructure which is a star or hub-and-spoke arrangement, with the DOE engine at the centre of the hub.   From a control system perspective, however, the DOE system operates as a closed loop control circuit where the DOE engine is inside a loop that may contain other entities. Beyond trial scale, when mass deployed the structural configuration may present the following issues:

+ Closed loop control systems are subject to instability issues, namely bi-stable behavior in the envelope limit outputs which may manifest. Where mass deployment and activation of DOEs occurs, this may result in unstable oscillation at the Transmission – Distribution Interface.
+ The mass deployment of DOE will co-exist with other distribution network control systems (Volt/Var regulation, DMS, DERMS, FLISR, and protection systems). Without coordination/integration, unplanned interactions and resultant grid unreliability are significant hazards.
+ Depending on how DOE is structurally integrated with various supply chain entities, massive latencies may be cascaded in the closed loop control circuit, causing performance issues and aggravating instability. This is particularly problematic if DOEs are to be updated in near-real time (≤ 5-min updates) to reflect current and local conditions as is currently asserted.[70]
+ Communication is currently proposed to be via internet, which opens significant reliability, throughput, latency and cybersecurity issues.

Diversity of Structural Alternatives

In addition to the above considerations, given the ongoing development and trialing of DOE models, there is currently a diversity of deployment models under development in Australia. For example:

+ AEMO / AusNet - Project EDGE
+ Western Power - Project Symphony
+ Ausgrid - Project Edith
+ EvoEnergy – Project Converge
+ Energy Queensland Limited – GridQube deployment
+ SAPN – Flexible Exports and VPP projects

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[70] Refer Dynamic Operating Envelopes Working Group – Outcomes Report, ARENA, Mar 2022

While there are similarities across many of these projects, there are also material differences in design priorities functions and customer incentives, the entities involved, and the deployment approach – all of which may impact the above potential instability and/or latency considerations.

This is ultimately because each of these trial / demonstration projects bring their own set of assumptions about the current (and in some cases, the plausible future) structural relationships in which DOEs will exist. As these medium – longer term future structural or architectural configurations remain unresolved, however, these must be considered working hypotheses. Nevertheless, as a DOE engine can only be understood within a wider ecosystem of relationships and critical data sources, these structural questions must ultimately be empirically resolved as a basis for future-ready mass deployment.

Equitable Capacity Allocation

The important issue of Equitable and Scalable models of Capacity Allocation for DOE's currently remains unresolved. For example, two DER/CERs on the same LV feeder may wish to export volumes of power that, together, jointly exceed the feeder capacity. The question of how the available capacity is fairly distributed becomes increasingly complex as the number of DER/CER and EVs connected to a feeder expands.

A range of proposals have been put forward but with a level of uncertainty as to whether they can provide comprehensive solutions. In several cases, 'Black Box' concepts in the form of some type of market/price formation mechanism (to be determined) are proposed. In addition to being contingent on DER/CER and EV owners' intentions being encoded via price bids, such processes would add latency into the closed loop control and more complexity in data management. In support of addressing this issue, there is an opportunity to take advantage of successful architectural approaches that have been applied to wireless communications and cellphone tower bandwidth allocation.

'Whole System' DOE Benefits at Risk

As noted above, market, regulatory and innovation funding bodies are communicating a wide range of aspirational benefits that DOE technologies will support. In a context where customers are said to be at the centre of the system, these aspirations are framed around delivering tangible benefits to customers.

Unlocking this value, and the full multi-functional benefits of DOEs, cannot be achieved with a primary orientation to any one segment of the traditional electricity supply chain (e.g. bulk power, transmission, distribution, energy retailer, etc.). While the genesis of DOE development has been the beneficial enabling of flexible export limits at the Distribution network level, giving full effect to these aspirations will require a new level of 'whole system' intentionality in the further phases of DOE development.[71]

[71] While not limited to the topic of DOEs, Section 2.7 of the DER Market Integration Trials – Summary Report, ARENA, 2022 provides an illustration of the need and difficulty to unlock multiple sources of DER/CER value.

In effect, DOE constitutes either a whole new grid (sub)structure or a modification/extension of existing control and coordination structure. Either way, applying a whole- system approach to DOE is vital to ensuring its success at scale.

While this may be staged to ensure the continued priority on local flexible export limits, the failure to pursue holistic solution development will result in the above aspirations being significantly delayed or unrealised.

Solution Requirements

+ In a context where LV-connected DER/CER and Electric Vehicles (EVs) are projected to continue strong upward growth as a proportion of all NEM Energy Resources, the successful mass deployment, activation and full benefits realisation of DOEs is expected to be key. Achieving this will require holistic, structurally integrated solutions that include:
+ Timely, low latency access to voltage and power flow data, network topology models, relevant DER/CER and EV information; network impedance values and constraint information;
+ Comprehensive integration with distribution network control systems (Volt/Var regulation, DMS, DERMS, FLISR, and protection systems) to avoid unintended interactions and resultant grid unreliability are significant hazards;
+ Avoidance of closed loop control instability issues that may manifest at mass deployment and activation of DOEs and result in unstable oscillation at the TDI;
+ Identification of optimal structural relationships and data flows between DER/CER, EVs, Aggregators, DNSP/DSOs and the System/Market Operators and ensure a range of negative Architectural Issues are avoided;[72]
+ Avoidance of latency cascading closed loop control circuits which would otherwise cause performance issues and aggravating instability; and,
+ Application of Layered Decomposition methods to achieve Scalable and Equitable resolution of capacity allocation optimisation problems.[73]

[72] Refer to Key Concepts H for more information on Architectural Issues.

[73] An approach that has been successfully applied to wireless communications and mobile tower bandwidth allocation and allows formulation in terms resource allocations only or, alternately, hybrid decompositions that incorporate resource allocation and price feedback mechanisms in the one solution. For example: Daniel P. Palomar and Mung Chiang, Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications, IEEE Trans. On Automatic Control, Vol. 52, No. 12, December 2007.

Future-ready Roles & Responsibilities

Future-ready Roles and Responsibilities involves the consideration of how roles, responsibilities and detailed system interfaces may be provisioned to cost-efficiently manage the whole-system operation of decarbonising Power Systems that experience massive increases in volatility, complexity and operational dynamics.

2.10. Roles & Responsibilities Risks: High-resolution analyses of Power System structures, multi-entity relationships and data flows – in the current, future, and transitionary states – are essential to identifying holistic, least-regret and future-ready options for evolving Roles & Responsibilities.

Cross Cutting Issue

As noted throughout this document, legacy Power Systems – already recognised as Ultra Large-scale (ULS) systems – are becoming vastly more dynamic, interdependent, and complex. Therefore, the ability to formally interrogate their underpinning structures is pivotal to identifying least-regret and future-ready options for evolving Roles & Responsibilities, not only at a high-level but also at a granular, Cyber-physical level.

Where the aim is to provision the Power System for the longer-term future, the consideration of future Roles & Responsibilities must be informed by key types of advanced functionality that are widely recognised as being essential to enabling deep decarbonisation. These include the advanced functionality specifically required at the Transmission-Distribution Interface (TDI) and by Distribution System Operators (DSO).

Unfortunately, however, while Australia's Power System transformation has occurred rapidly to become one of the world's fastest, both the application of formal structural analysis and the detailed consideration of TDI and DSO models have lagged international best practice. Given the ultra-complex nature and transformational context of modern Power Systems, however, the risk of unintended consequences compound exponentially where these are either inadequate or functionally absent.

Finally, it is noted that many of the considerations pertaining to the matter of future-ready Roles & Responsibilities are highly relevant to Interoperability across an increasingly interdependent Power System.

Contributing Factors

Detailed Interrogation of Structural Dependencies a Critical Requirement

The scale and sophistication of the structural interdependencies embedded in GW-scale Power Systems are humanly overwhelming. They are not dissimilar to – but more complex than – the multi-structure combination of aerospace systems embedded in advanced passenger aircraft such as a Boeing 787 or Airbus A380.

Properly understood as a 'Network of Structures', modern Power Systems are a web of seven distinct but deeply interdependent structures, several of which dynamically influence each other on a hours-minutes-microseconds basis). Further, many of these structures span the continental electricity supply chain, including Bulk Power, Transmission and Distribution Systems, Energy Retailers, Aggregators and Customers.

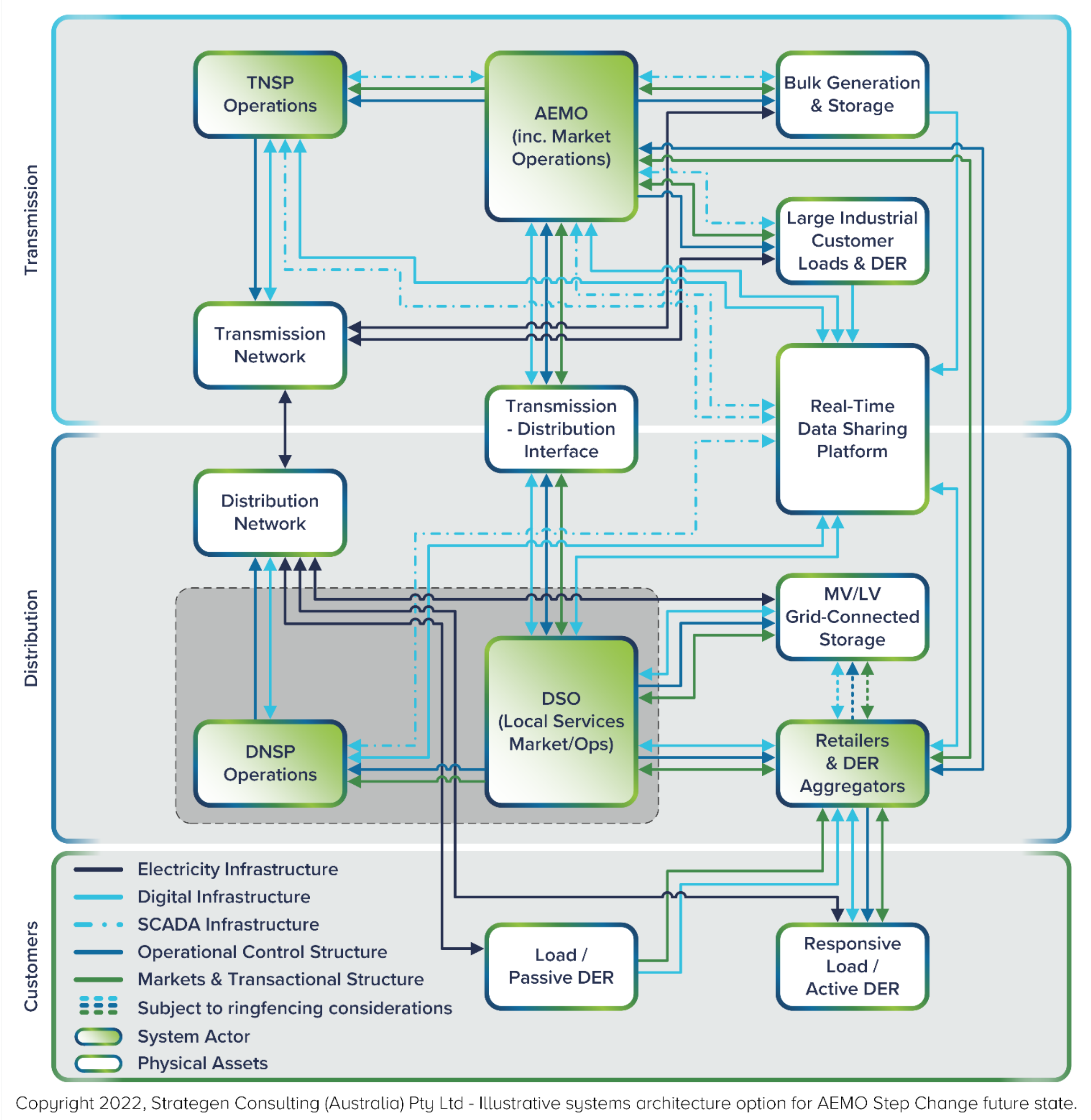

Figure 8: One plausible version of NEM's transition to enable a Step Change type of future[74]

[74] Image: AEMO Operations Technology Roadmap, AEMO, 2022

Recognising the fundamental nature of these highly sophisticated systems, and having the ability to formally interrogate their underpinning structures, is pivotal to any enduring consideration of future Roles & Responsibilities. This is because formal Systems Architecture methodologies are critical to enabling the:

- Granular analysis of the as-built structures, entity relationships and data flows embedded in the legacy Power System; and,
- Interrogation of different options for how they may plausibly need to transform to enable, for example, a future similar to that characterised by AEMO's Step Change scenario.

Each of these are inextricably linked to the identification of least-regret and future-ready recommendations for evolving Roles & Responsibilities, not only at a high-level but also in the Cyber-physical detail.

As an example, Figure 8 (above) highlights the hundreds of interfaces and interdependencies between subsystems and actors that exist in one plausible version of NEM's transition to enable a Step Change type of future. It is simply impossible to navigate this scale of complexity primarily by workshop-based sharing of perspectives and/or the development of individual Use Cases. While useful elements of a wider process, such approaches are incapable of holistically navigating the intricate web of interdependencies of transitioning such a ULS complex system and only elevate the potential for unintended consequences.

Critical Emerging Topics that Require Formal Structural Analysis

There is a wide recognition globally that enabling deep decarbonisation of legacy Power Systems will require the structured development of several new system functions, which will materially impact future Roles & Responsibilities.

For example, the advanced functionality required at the Transmission-Distribution Interface (TDI) and by Distribution System Operators (DSO)[75] is being actively explored internationally, and especially in the United States, the United Kingdom and the European Union.

+ **Transmission-Distribution Interface (TDI):** Power Systems that host growing volumes of Variable Renewable Energy (VRE) and Distributed Energy Resources (DER/CER) experience both significantly greater levels of Volatility and the erosion of the once-dominant Supply-side / Demand-side bifurcation. As a result, simultaneously ensuring system Adequacy, Security, Reliability and Cost-efficiency will require much greater levels of dynamic inter-dependence between the upstream Bulk Power and Transmission System and the downstream Distribution System.

[75] For example: System Operation Collection, International Renewable Energy Agency, 2020; Coordination of Distributed Energy Resources; International System Architecture Insights for Future Market Design, Newport Consortia, 2018; and, Evaluation of Combinations of Coordination Schemes and Products for Grid Services, EU CoordiNet Project, 2022.

This will require many existing and new functions and protocols executed across the TDI to be formalised and automated.

+ **Distribution System Operator (DSO):** In addition, in contexts where a growing proportion of the Energy Resource fleet is LV-connected, the need for formalised functions for the advanced planning, system operation and optimisation of high-DER/CER Distribution Systems, together with their interoperation with the Bulk Power System, also becomes essential. Due to our deeply decentralised Power System transformation, the holistic range of functions required of Australia's future Distribution System Operators will arguably be some of the world's most expansive.[76]

Such matters are fundamentally architectural by nature and must therefore be prominent in the detailed design of future Roles & Responsibilities. For example, in discussing FERC Order 2222[77] (which relates to DER integration in wholesale markets), the expert Electricity Advisory Board to the United States Department of Energy (DOE) recently noted:

> *"…**DOE's work on grid architecture** can help identify pathways for mitigating issues related to transmission-distribution-customer operational coordination processes, **including how to allocate roles and responsibilities between various system actors** based on a jurisdiction's policy objectives, and **define information and data exchange requirements.**"*[78]

As the US DOE Electricity Advisory Board notes, in such ultra-complex systems, there are direct relationships between the underpinning Systems Architecture of the system, the need for high-resolution analysis of the Cyber-physical relationships, and the definition of future Roles & Responsibilities.

Australia Lagging Global Developments

As indicated above, the international consideration of such topics is very significant. It includes both major national and continental-scale demonstration projects and the detailed interrogation of cyber-physical-transactional relationships and the attendant Roles & Responsibilities that will be required.

By contrast, while Australia's Power System transformation has occurred rapidly to become one of the world's fastest, the consideration of such matters has been piecemeal and lags significantly behind. This may be compounded in Australia's vertically disaggregated market structure where traditional models of change have tended to focus on emerging issues within

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[76] Refer Key Concepts J for example TDI and DSO definitions.

[77] FERC Order 2222 - Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators, Federal Energy Regulatory Commission, 2020

[78] FERC Order 2222 – Recommendations for the U.S. Department of Energy, Electricity Advisory Board, 2021 (emphasis added)

the segment of the supply chain most impacted. Unfortunately, this framing has led some to argue that such considerations are unnecessary or lacking practicality.[79]

On the contrary, in transformational periods where complex new system functions are emerging, the due diligence required to ensure system Roles & Responsibilities are provisioned to meet future needs (and avoid unintended consequences) will be compromised. A more holistic approach, therefore, will appreciate the complementarities between the different approaches. For example:

+ Critical near-terms issues may be scoped through multi-stakeholder workshopping and the development of individual Use Cases (a 'present-forward' orientation);
+ High-resolution analysis of the as-built structures, entity relationships and data flows embedded in the Power System provides an objective set of options for how specific functions, and their Roles & Responsibilities, may plausibly need to transform in the longer-term (a 'future-back' orientation); and,
+ All options viewed from both the current and plausible future states, and supported by formal structural analysis, can then be evaluated via multi-stakeholder workshopping to shortlist the preferred transition pathways.

In summary, a more holistic approach provides greater assurance that system Roles & Responsibilities are future-ready due to the Systems Architecture methodology being focused on both the current state and decadal time horizons, supported by the formal analytical tools for identifying credible transition pathways.

Given the ULS nature of modern Power Systems, even where a legacy system is operating in a comparatively stable environment, such changes have significant potential for unintended consequences. In a context where the scale and pace of transformation is world-leading, these risks compound exponentially.

A Related Critical Application

Much of the above discussion has relevance the critical topic of Interoperability across an increasingly interdependent Power System, that includes Bulk Power, Transmission and Distribution Systems, Energy Retailers, Aggregators and Customers.

This is because formal Systems Architecture methodologies enable the:

+ Granular analysis of the as-built structures, entity relationships and data flows embedded in both the legacy Power System and plausible future states; and,
+ Detailed interrogation of all subsystems and components, subsystem boundaries, interfaces and functional interdependencies.

[79] This is misguided as the detailed consideration of essential functionality required to support plausible futures, such as the widely recognised AEMO's Step Change scenario, ultimately cannot safely be avoided.

As a result, some of the world's most authoritative treatments of future-ready approaches to Interoperability in the power sector employ Systems Architecture methodologies for framing alternative futures.[80]

Solution Requirements

Given the magnitude of transformation impacting the NEM, the consideration of future Roles & Responsibilities must be informed by the functionality widely recognised as essential to enabling deep decarbonisation and increasing decentralisation. These include the advanced functionality specifically required at the Transmission-Distribution Interface (TDI), the need for maturing Distribution System Operator (DSO) models, and a significantly more detailed understanding of the complex interfaces between all interdependent grid systems and subsystems.

As indicated earlier, however, many core functions have historically been arranged in 'vertical' structures and siloes. When experiencing significant transformation and a more dynamic operational context, these legacy structural settings lack agility and may exacerbate whole-system coordination issues. Given the nature and scale of transformation impacting GW-scale Power Systems is fundamentally structural in nature, it will not ultimately be possible to provision such systems, or their formal Roles & Responsibilities, for a 'Step Change' type of future solely by the multiplication of issue-specific adjustments.

By contrast, the application of System Architecture disciplines enables a more holistic and stepwise view of the system's transformation and how its key Roles and Responsibilities may need to change over time. Critically, this also enables much higher resolution analyses of changing Power System structures, the multi-entity relationships and necessary data flows – in the current, future, and transitionary states. This provides a far more objective basis for multi-stakeholder consideration and debate of how Roles & Responsibilities may be configured, including key delegations and points of hand-off, to manage end-to-end coordination in an increasingly dynamic and complex system.

[80] For example, Framework and Roadmap for Smart Grid Interoperability Standards 4.0, National Institute of Standards & Technology (NIST), 2021

Key Concepts J

Distribution System Operator (DSO)

An entity responsible for the planning, operation and optimisation of a distribution system with high levels of Distributed Energy Resource (DER/CER), Electric Vehicles (EV) and other Flexible Resources. Depending on the DSO model implemented, this may include the following functions:

1. Implement advanced, scenario-based modelling of DER/CER and EV uptake and operation, bi-directional power flows and distribution system operations;
2. Establish Distribution System State Estimation (DSSE) and near real-time Visibility across the distribution network;
3. Dynamically manage the network within the technical constraints and hosting capacity of distribution assets including computation and issuing of Dynamic Operating Envelopes (DOEs);
4. Advance the transition to more cost and value-reflective pricing in broad-based tariff reform and establish bilateral reserve contracts for short and long-term emergency support of distribution security;
5. Implement Integrated Distribution Planning (IDP) to medium-long term network requirements, incorporating non-network alternatives;
6. Actively identify opportunities for aging distribution feeders to be progressively replaced with Microgrid, individual Stand-alone Power Systems and/or grid-connected Energy Storage solutions;
7. Analysis and evidence-based determination of the temporal and locational value of DER Services to the distribution system;
8. Establish and operate a Flexibility Market or Network Services Market that enables more close coupled 'market-control' alignment at the distribution layer; and,
9. Work collaboratively with the Market/System Operator (MSO) to dynamically manage the Transmission-Distribution Interface relevant to the DSO’s service territory.

In many contexts, the DSO role is likely to emerge through a progressive expansion of the function of Distribution Network Service Providers.

Transmission-Distribution Interface (TDI)

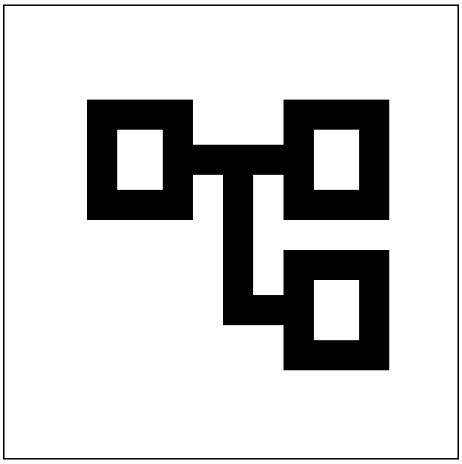
The physical point at which the upstream Bulk Power and Transmission System and the downstream Distribution System interconnect, typically at one or several major substations. In a conventional, highly bifurcated Power System, these were traditionally known as the Supply-side and Demand-side respectively.

Power Systems that host growing volumes of Variable Renewable Energy (VRE) and Distributed Energy Resources (DER/CER) will experience significantly greater levels of Volatility, which can propagate upstream and downstream. Ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require much greater levels of dynamic inter-dependence across the TDI than in the past.

Transmission-Distribution Interoperability Mechanisms (TDIM)

The various existing and expanding number of emerging functions and protocols that need to be executed across the Transmission-Distribution Interface (TDI) in their formalised and automated form. Key areas of priority are expected to include enhanced, low latency data exchange relevant to Frequency control, Voltage control, Congestion management Energy flow, Power-based services and System Balancing.

Underpinned by appropriate decisions about the enabling Cyber-physical Architecture, the TDIM will play a key role in supporting next generation Visibility, Operational Coordination and Resource Adequacy analysis.



Section 4: Evolving System Structures

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1. SECTION 4 INTRODUCTION

1.1. Purpose of Section 4

Over the next decade, the expanding number of participating Energy Resources and the increasing complexity of Operational Coordination will continue to grow by orders of magnitude. Informed by Sections 1 – 3, some characteristics that are already well recognised include:

+ The NEM's transition from hundreds of participating Energy Resources to tens of millions;
+ Increasing Volatility throughout and across all Tiers/Layers of the Power System (including Bulk Power, Transmission and Distribution Systems) with the transition to highly variable generation; and,
+ Power System digitalisation driving the transition from slow data sampling to fast streaming data, vast data volumes and a declining tolerance for latency.

In this context, Interoperability standards, Two-sided Markets and Dynamic Operating Envelopes (DOEs), for example, are all expected to play key roles in supporting Australia's future Power Systems.

However, where the legacy 'as built' Structural settings are not well aligned with the rapidly emerging future needs of the NEM, costly scaling and fragility issues will arise, such as: latency cascading, computational constraints and time wall effects, and cyber-security vulnerabilities. These in turn will progressively erode the Reliability, Resilience and Efficiency of the NEM and exacerbate upward cost pressures.

A range of analytical methods have been successfully applied to evolving individual elements of the NEM over the last several decades. **The magnitude and pace of transformation now unfolding, however, presents a new class of decisions that are architectural in nature and will require architectural interventions to resolve.**

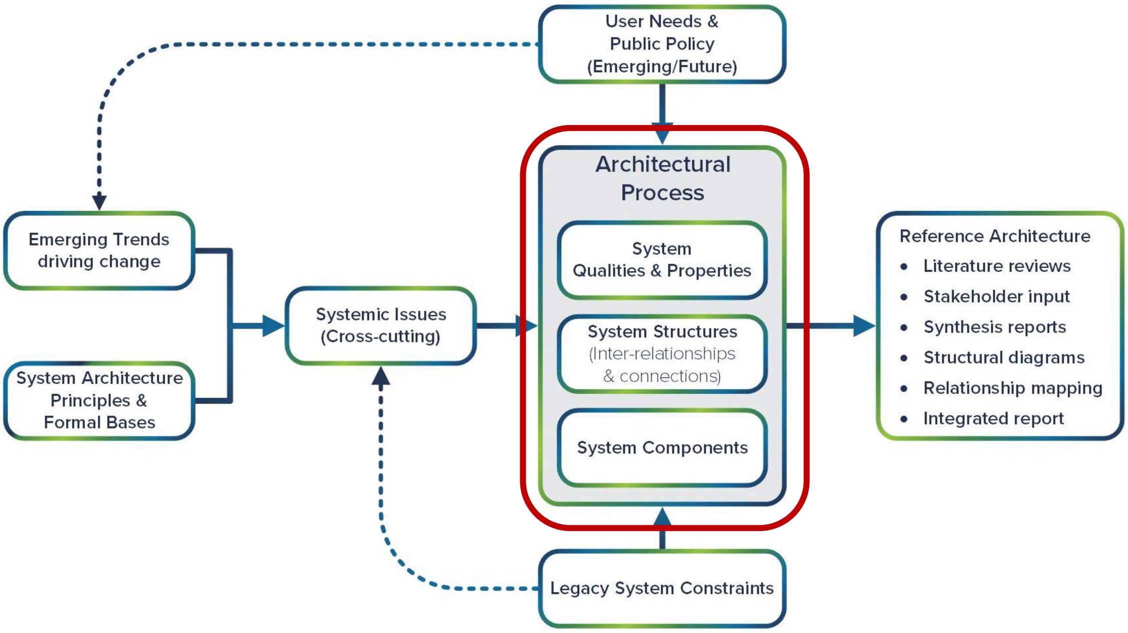


Figure 1: Section Report 4 draws upon a range of inputs developed earlier in the project and particularly focuses on System Structures.[81]

In profound transformation, architectural interventions are unavoidable because the original 'as built' Structure of any complex System always establishes its essential capabilities and limits (i.e. the 'performance envelope' and functionality of the System).

Where any highly complex legacy System like the NEM is required to perform an expanding range of entirely new functions, **the application of Systems Architecture disciplines is pivotal to the timely identification of the minimal structural interventions required to deliver maximal System capability uplift.** Compared with any number of incremental changes, targeted enhancements to the underpinning Architecture will deliver a disproportionate uplift in what a complex System experiencing transformation can reliably and cost-effectively do.

[81] Image: Pacific Northwest National Laboratory (Adapted).

As Figure 1 (above) illustrates, Section 4 draws upon and integrates a range of inputs examined and presented earlier in Section 1 – 3. In the context of a Reference Architecture project, it gives particular attention to the 'as built' and plausible future Structures that are likely to be necessary to underpin NEM operations. It does so by:

+ Providing an overview of the approach taken to interrogating the seven interdependent structure classes that constitute modern GW-scale Power Systems;
+ Examining and illustrating how these seven structure classes are configured in the 'as built' NEM – something not available in any other single set of artefacts;
+ Providing an overview of the approach taken to considering and illustrating the plausible future Architecture(s) of the NEM;
+ Illustrating a Hybrid Architecture of the NEM and considering both strengths and weaknesses; and,
+ Illustrating a Layered Architecture example of the NEM and considering both strengths and weaknesses.

Finally, it is important to reiterate that the development of a preliminary Reference Architecture is somewhat like an initial 'prototype' of a highly complex system. It provides a powerful mechanism for shared learning and collective reasoning about the system but will, by its nature, contain gaps that need to be addressed in subsequent phases of work.

1.2. Report Structure

As noted above, this project is focused on the development of Reference Architecture of the NEM. It is therefore important to note that a Reference Architecture is a prototypical model of an ultra-complex System that examines both its Components and underpinning Structure. As such, it provides a high-level view of the entire System with a focus on how the many parts are related together as an interdependent, functional whole to achieve key purposes.

A key aim of a Reference Architecture is to provide a powerful mechanism for shared learning and collective reasoning about how an ultra-complex System is presently configured. In a transformational context, it also provides a model for multi-stakeholder exploration of how these structural settings may need to change that is more explorative and creative than traditional approaches.

While the development of a Reference Architecture is a first step in the formal Systems Architecture process, it is particularly relevant to the power sector as it seeks additional tools for navigating the next decade of unprecedented transformation. In drawing upon and integrating the key insights provided by Sections 1 – 3, this report is structured to provide mapping and analysis of the current and evolving system structures of the NEM.

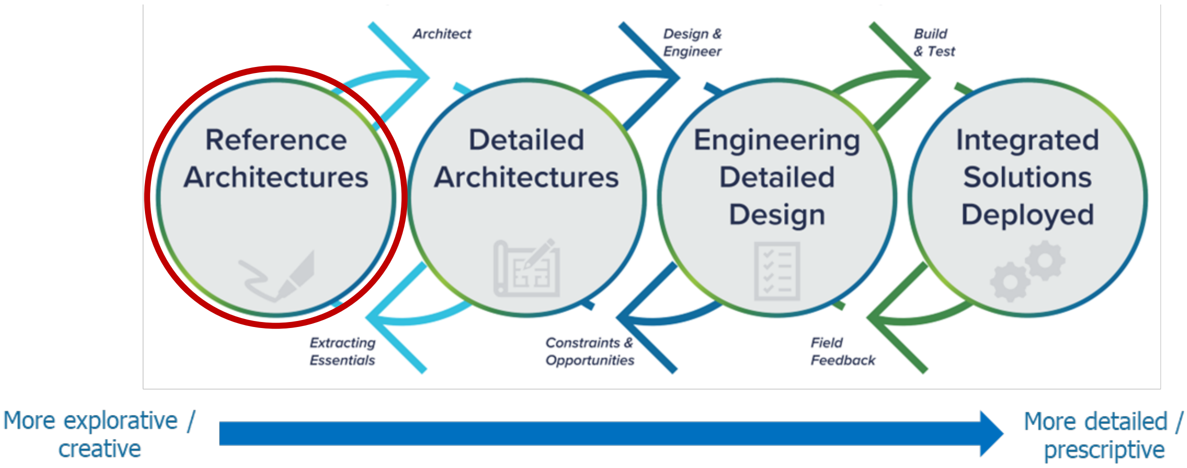


Figure 1: Reference Architecture development is a key first step in the application of Systems Architecture disciplines to an ultra-complex System.

2. MAPPING THE 'AS BUILT' ARCHITECTURE OF THE NEM

2.1. Development Context of the NEM Architecture

Modern power systems are highly complex cyber-physical-economic systems. As some of the largest and most sophisticated 'machines' ever created by humanity, legacy Power Systems are formally defined as Ultra Large-Scale (ULS) complex systems.[82]

Like most GW-scale power systems in the developed world, however, what we now know as the National Electricity Market (NEM) evolved and matured throughout the 20th century. This was a technological, economic, and societal context where:

+ Almost all generation was served by a fleet of centralised, MW-scale merchant resources connected to the HV Transmission System;
+ A wide range of Essential System Services were delivered to the system as bi-products of a generation fleet that was predominantly synchronous, dispatchable and highly predictable;
+ End-users were considered as largely passive 'receiver-consumers' of electricity and distribution networks functioned largely as an extension of the bulk delivery system;
+ Steady load growth was highly correlated with economic growth; and,
+ All market and system functionality were informed by historical arrangements including:
+ a dominant 'Supply-side / Demand-side' bifurcation;
+ an unchallenged 'Load-following' operational paradigm; and,
+ unidirectional supply of electricity.

These essential characteristics have existed largely unchallenged for most of the first 100-years of electric power systems.

2.2. Tools for Interrogating Complex Grid Structures

It was in the above historical context that the underpinning structural, market and system coordination arrangements of the NEM – or its 'Architecture' – evolved over many decades.

Like most GW-scale power systems of the 20th century, however, the somewhat organic development meant that no holistic mapping of all the 'as-built' structures and interfaces embedded in the NEM was comprehensively documented as a single set of artefacts that could be agreed upon by diverse stakeholders.

[82] Feiler et al, Ultra-Large-Scale Systems: The Software Challenge of the Future, Carnegie Mellon, Software Engineering Institute, 2006.

Key Concepts A

Structure

Every functioning System created by humans has an underpinning Structure. The Structure of a System consists of the formal, stable relationships and interdependencies that exist between the numerous Components of the System and enable it to reliably achieve specific purposes.

Architecture

The term Architecture is formally used in Systems Science to refer to holistic conceptual model that details how the many Components of a System are linked or related together by an underpinning Structure. The purpose of the conceptual model is to make explicit how all the physical, informational, operational, and transactional Components function together as a whole. This supports more robust reasoning about System capabilities, behaviours and transformational options.

Simplistically, if the boxes in a Block Diagram represent the Components, the Structure is represented by the lines connecting the boxes. Although the individual Components are often more tangible and easier to see, studying the underpinning Structure of a complex System is critical as it will always have a disproportionate impact on what the System is ultimately capable of.

Where the underpinning Architecture is well aligned with the current and/or emerging purpose of the System, the Components will function effectively together, and the System will exhibit Scalability and Extensibility. Where the Architecture is misaligned with current or future needs, technology integration becomes increasingly costly, investments may be stranded, and full benefits realisation placed at risk.

A non-trivial complication has been the deep complexity of modern Power Systems such as the NEM which spans numerous professional disciplines and operational spheres. This has been further compounded by the lack of agreed, holistic models that enable all stakeholders to comprehend and collectively interrogate the mesh of underpinning structural, market and operational coordination arrangements.

What we know as 'the Power System' is, in practical reality, a web of several distinct but deeply inter-dependent structures. As identified in the G-PST Stage 1 Report which provided a meta-analysis of analytical methodologies deployed globally, however, this deep complexity spanning numerous professional disciplines which makes viewing and interrogating the whole system problematic. This heightens the risk of selecting analytical tools and techniques that are not sufficiently holistic and/or fit-for-purpose, with the result that partial insights are misinterpreted as providing comprehensive and holistic perspectives.[83]

[83] For example, the 'system-of-systems' paradigm from software engineering is somewhat useful, being largely component-focused it does not adequately represent the complex multi-structural properties that constitute a modern power system. SGAM & Enterprise IT Architecture.

In this wider context, the 'Network of Structures' model developed under US Department of Energy funding by the Pacific Northwest National Laboratory (PNNL) was identified as uniquely enabling integrative, whole-system analysis of transforming Power Systems. Supported by the combined application of Systems Architecture, Network Theory, Control Theory, Systems Science and Model-based Systems Engineering (MBSE), this is central to the PSA practice by making tangible the following seven interdependent Structure Classes that make up the Power System:

1. Electricity Infrastructure (Power Flows);
2. Data / Digital Infrastructure;
3. Operational Coordination Structure;
4. Markets / Transactional Structure;
5. Industry / Market Structure;
6. Regulatory Structure; and,
7. Sector Coupling Structures (Gas, Water, Transport, etc).

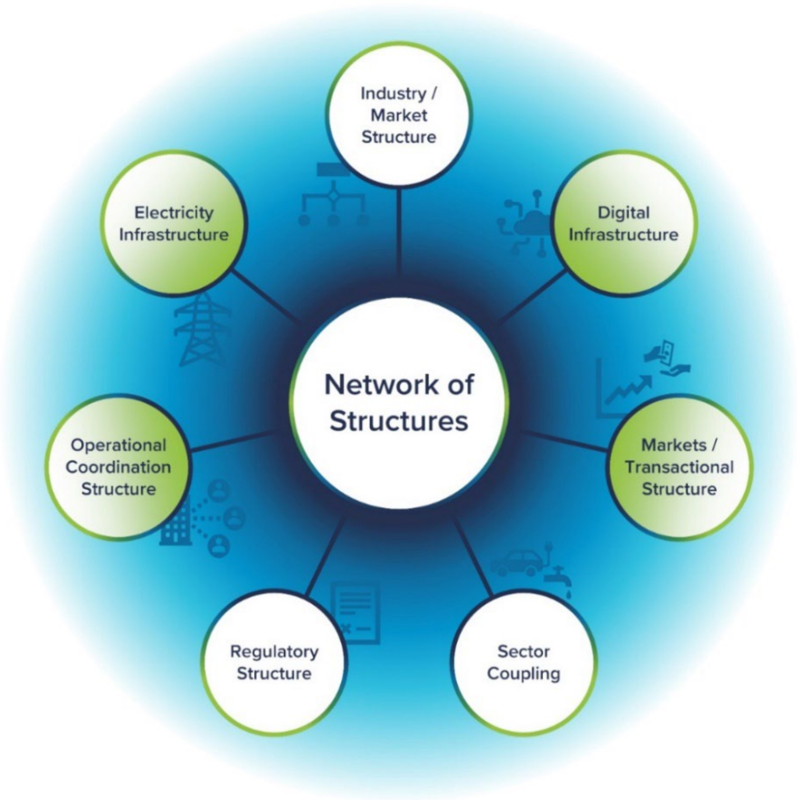


Figure 2: The Network of Structures model provides a whole-system view for the detailed analysis, mapping, and optimisation of current and future requirements.[84]

[84] The Network of Structures concept was originally developed by Pacific Northwest National Laboratory.

It is noteworthy that these seven Structure Classes span and/or influence all vertical Tiers/Layers of the Power System, including the Bulk Power, Transmission, Distribution, Energy Retail and DER/CER Aggregation functions. In addition, the first four of these structure classes (green nodes in Figure 3) are also functionally interdependent with each other on a days–hours–minutes–milliseconds basis.

Finally, it is also particularly important to recognise the 'systemic' character of all seven structure classes: changes to one will typically impact some or all the other structures – in both intended and unintended ways.

2.3. Overview of the Seven Interdependent Structures

Following is an overview of the seven distinct but interdependent Structure Classes that underpin a modern Power System and are key to enabling 'whole system' insight.

2.3.1. Electricity Infrastructure (Power Flows)

Provides for the physical movement of electric power across the end-to-end Power System, including Transmission and Distribution networks, Microgrids, Substations, bulk Energy Storage and end-user customers, etc. While historically this was primarily unidirectional, it now increasingly involves bi-directional flows, especially across the Distribution System. Examples include:

+ Power flows from the Bulk Power System to load centres through the Transmission System.
+ Power flows to and between customers through the local Distribution System.
+ Bulk storage of excess renewable energy output and subsequent injection to the Power System during periods of Peak Demand.
+ Customer generation and storage provides power to customer loads and/or injects power into the local distribution system.

2.3.2. Data / Digital Infrastructure

Provides for all information, control messages and data exchange required to maintain the safe and reliable operation of the Power System and enable its coordinated operation. This includes a diverse range of elements including resource telemetry, system topology changes, resource interoperability, etc. Examples include:

+ Signals and data used for real-time protection and control of the Power System.
+ Energy Resources participating in the Wholesale Market submit telemetry to the Market/System Operator (MSO) to indicate asset performance in real-time.
+ MSO and emerging Distribution System Operators (DSO) exchange system condition information to support the conjoint management of relevant Transmission-Distribution Interfaces.

- Energy Retailers and DER/CER Aggregators participating in the Wholesale Market and DSO Flexibility Markets submit telemetry to the relevant entities to indicate asset performance in real-time.

2.3.3. Operational Coordination Structure

Provides for the holistic orchestration of diverse Energy Resources, including Flexible Resources on the Demand-side, and other Power System facilities, in a manner that supports the Adequacy, Security[85], Reliability and Cost-efficiency of the system. Examples include:

- MSO exerts control over Energy Resources participating in the Bulk Power System by sending Dispatch instructions and basepoints to secure necessary services.
- MSO exerts control over the Transmission System in response to a Constraint or Contingency to preserve system safety and reliability.
- DER/CER Aggregators provide the MSO and DSO resource availability forecasts for Energy Resources;
- MSO and DSO conjointly manage their respective sides of the Transmission-Distribution Interface(s) supported by two-way data flows between the parties.
- DER/CER Aggregators orchestrate contracted DER/CER in response to various calibrated market structures for procuring the Energy Products required by different Tiers/Layers of the system.

2.3.4. Markets / Transaction Structure

Provides for the procurement and sale of Energy, Capacity, and Essential System Services at any Tier/Layer of the Power System through market or other financial arrangements. This may include participation in Wholesale Market, DSO Flexibility Markets, Power Purchase Agreements (PPA), and capacity or service contracts. This also includes market schedules and dispatch instructions.

- Energy Resources participating in the Wholesale Market provide bids/offers to the MSO who subsequently schedules the Dispatch of participating resources.
- Relevant to the Operational Coordination of the Power System (see below), various current and emerging market structures are calibrated to incentivise Energy Resource behaviours and the provision of Energy Products needed by different Tiers/Layers of the system.
- Energy Retailers and DER/CER Aggregators procure and contract services from DER/CER and other Flexible Resources located on the Demand-side and sell them in the Wholesale Market, ESS Market and/or DSO Flexibility or Network Services Markets.

[85] Includes the management of Minimum Operational Demand

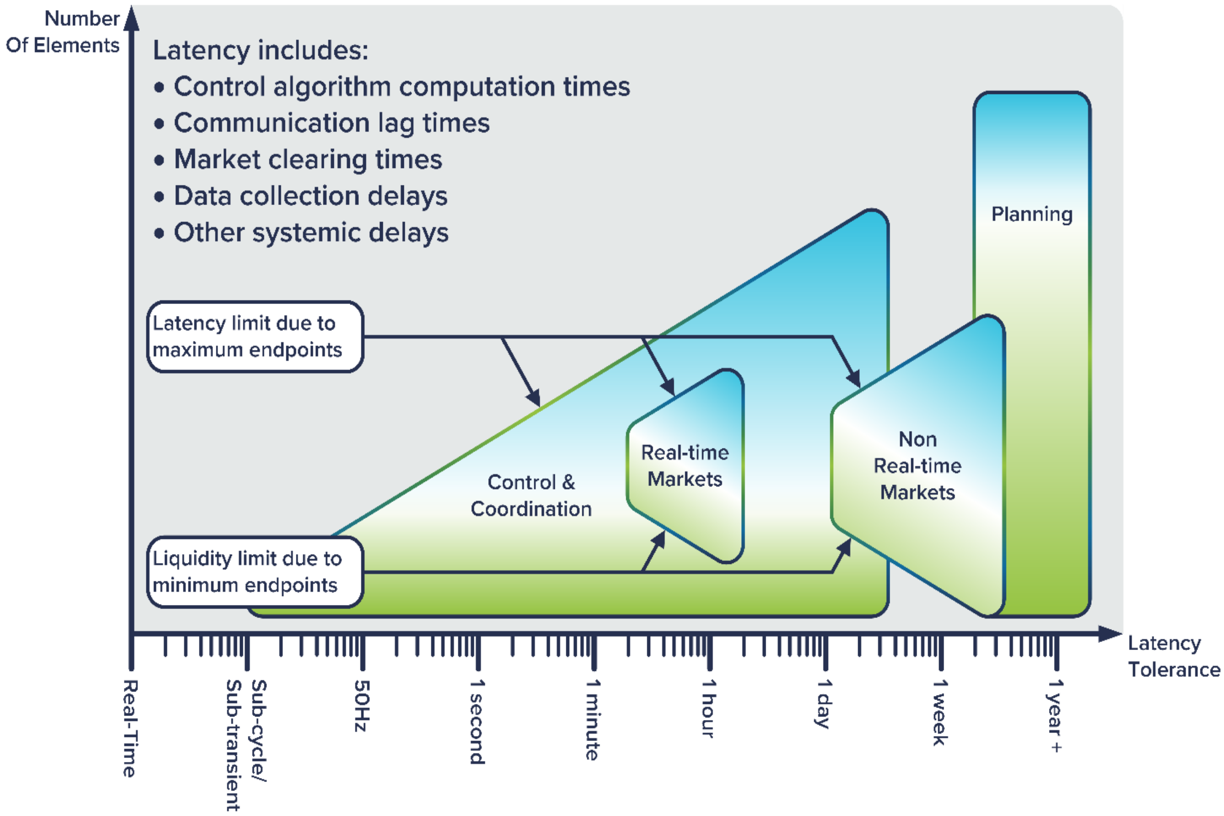


Figure 3: Advanced Operational Coordination mechanisms require 'market-control' alignment and complementarity across key layers of the Power System[86]

2.3.5. Industry / Market Structure

The set of entities involved in operating the physical Power System, across its vertical Tiers/Layers and their related markets, through various relationships and interdependencies, many of which are set out in formal Roles & Responsibilities. Some examples of these entities include:

+ Market/System Operator (MSO)
+ Transmission Network Service Provider (TNSP)
+ Distribution Network Service Provider (DNSP)
+ Distribution System Operator (DSO)
+ Merchant Generators
+ DER/CER Aggregators
+ Participating DER/CER owner-investors

[86] Image: Adapted from Paul De Martini and Dr Jeffrey Taft

2.3.6. Governance / Regulatory Structure

The set of entities involved in the governance and regulation of the Power System and its related markets. It provides a graphical mapping of various regulatory relationships, in particular which entity regulates which industry/market participants and processes (but is not a description of regulatory rules themselves). In the NEM context, some examples include:

+ Commonwealth Government
+ State & Territory Governments
+ Energy Security Board (ESB)
+ Australian Energy Market Commission (AEMC)
+ Australian Energy Regulator (AER)
+ Australian Energy Market Operator (AEMO)

2.3.7. Sector Coupling Structures

Sector Coupling structures determine how adjacent industries may function more interdependently with the Power System as a critical part of enabling a significantly more flexible and adaptive Power System. Examples of various sector couplings include:

+ Electricity and gas sectors
+ Electricity and industrial processes
+ Electricity and transport
+ Electricity and water systems
+ Power system and ICT technologies
+ Electricity and the emerging Green Hydrogen sector

2.4. Structural Mapping of the 'As-built' NEM

2.4.1. The importance and challenge of mapping the 'as-built' Power System

In jurisdictions where the underpinning Architecture of a GW-scale Power System has been evaluated, it has been common to discover that no complete and agreed single set of documents exists that represent how the above seven inter-dependent structure classes are actually configured. While the many thousands of individual system Components are very well understood, this is particularly problematic as the underpinning Structure always has a disproportionate impact on what a complex System is ultimately capable of.

Given the critical societal and economic roles complex Power Systems play in modern economies, this realisation can be at first quite startling. In a context where any Ultra-Large Scale (ULS) complex system must be profoundly transitioned, a most basic pre-requisite of effective change is to possess a comprehensive mapping of the entire system as it currently exists and functions.

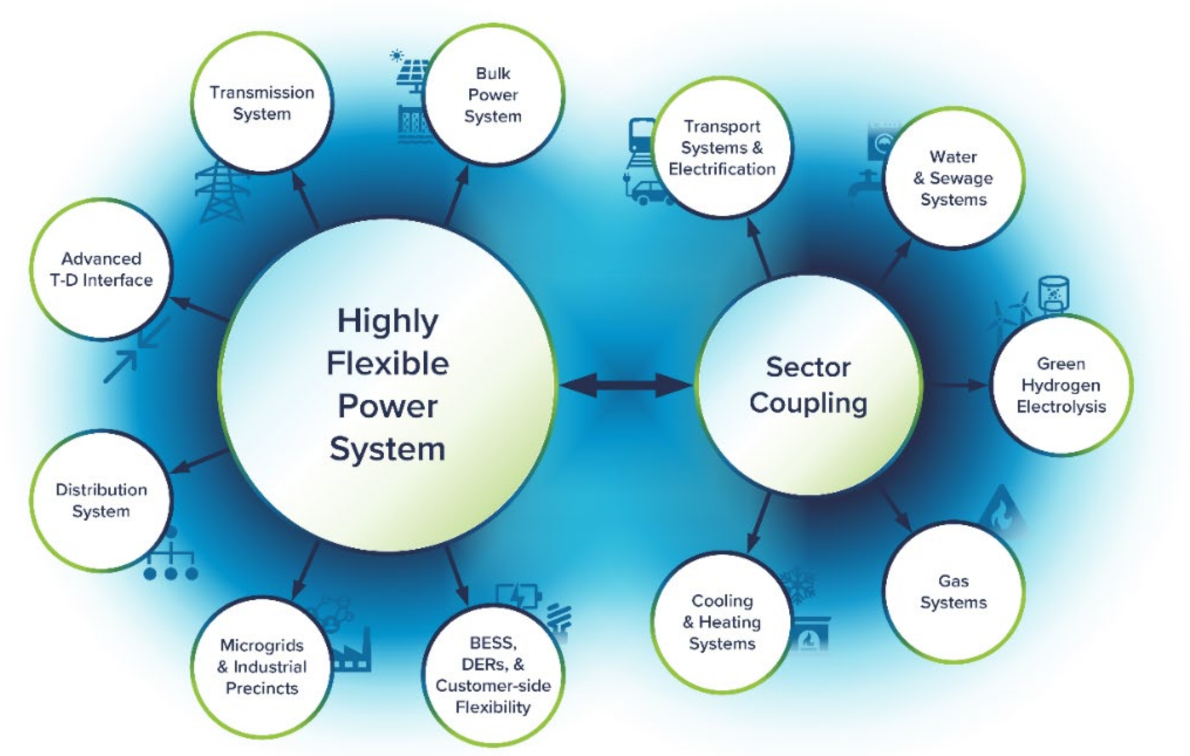


Figure 4: System optimisation benefits emerge through advanced sector couplings[87]

A mitigating factor is that the cyber-physical-economic Architecture of today's Power Systems developed somewhat organically throughout the 20th century around a highly centralised, synchronous, dispatchable and unidirectional paradigm. A further complication of developing such a whole-system mapping, given the multi-structure, multi-stakeholder and multi-disciplinary nature a GW-scale Power System, is that many stakeholders have quite different perceptions of how the system and its many interfaces actually work.

2.4.2. Critical insight for 'taming' complexity and collective reasoning

Therefore, a critical step in identifying and shortlisting the options and trade-offs that may be required to transition a legacy Power System is to ensure the 'as built' Network of Structures is documented, debated and sufficiently agreed upon by diverse stakeholders.

As a formal part of a subsequent Detailed Architecture project, this would result in detailed mapping of how all the physical, informational, operational, and transactional Components and Interfaces of the end-to-end NEM function together and influence each other. As an iterative, multi-stakeholder process, this would support a substantive deepening of the shared understanding of NEM functions and enable more objective and robust collective reasoning about the plausible transition options and trade-offs.

[87] Image: International Renewable Energy Agency (Adapted)

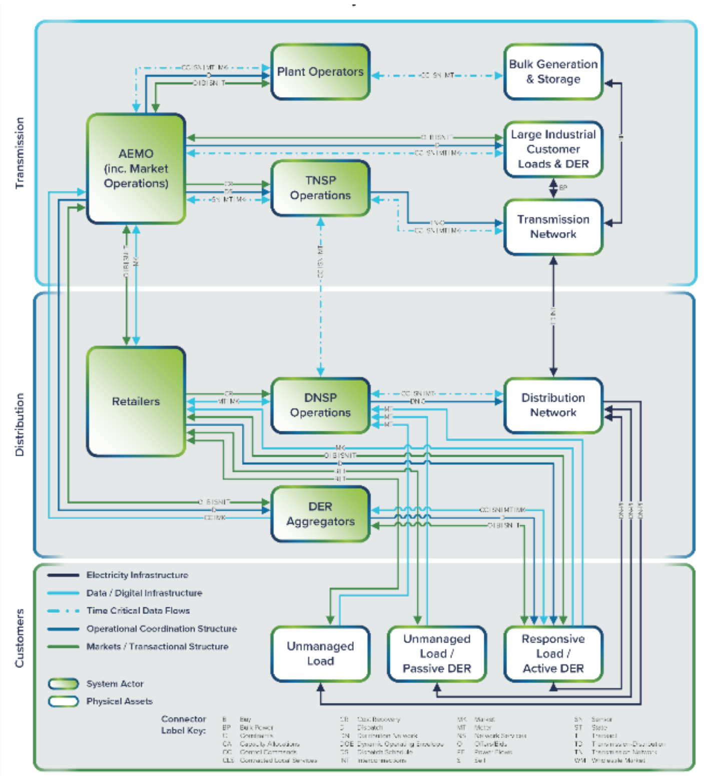
As noted earlier, the development of a Reference Architecture precedes a Detailed Architecture project. This enables the development of an initial blueprint or model of how all the key Components and Structures function together in the System under consideration. In the case of ultra-complex modern Power Systems, this step is critical as it develops an initial prototype or model of the end-to-end system through a more focused sequence of collaborations with representative stakeholders. This fosters a widening understanding of the Systems Architecture discipline and its benefits. It also supports the efficient co-design by diverse stakeholders of any subsequent Detailed Architecture project.

2.4.3. "Everything should be as simple as possible, but no simpler"

Einstein understood the paradox of complexity and simplicity. Indeed, a key benefit of the Systems Architecture discipline is that it provides formal mechanisms for 'decomposing' ultra-complex systems in a manner that helps tame complexity. At the same time, it maintains the integrity of the irreducible complexity that is inherent to the System under consideration.

In other words, a key goal of the Systems Architecture discipline is to provide a representation of the end-to-end System that is as simple as possible but no simpler.

However, herein lies danger. When a Reference Architecture of the as-built Power System is first developed, a visceral human reaction can be that it seems to "make things more complicated". This is compounded by the power sector, historically, being deeply siloed across its vertical Tiers/Layers and diverse participants. In addition, the sector has been accustomed to a highly reductionistic model of problem solving. This enables complex issues to be decomposed into manageable elements, although often at the expense of an inadequate appreciation of how those elements will function as systemic whole, both now and in the future.



A critical point to bear in mind is that an accurate Systems Architecture simply represents the complexity that exists within the System: no more and no less. It is not creating new complexity.

In addition, it is important to note that the structural mapping developed in a Reference Architecture has the status of a prototypical model of how the key Components and Structures function together as a System. In a multi-layered System as complex as the NEM, however, there will necessarily be many details that will benefit from further stakeholder engagement, debate and refinement.[88]

A further key point to note is that, as a work-in-progress, a Reference Architecture provides a uniquely valuable means to substantively deepen and refine the sector's[89] collective appreciation of how the end-to-end System functions within, between and across all functional siloes.

2.4.4. Interpreting Functional Layer mapping

The following content illustrates the Network of Structures that makes up the as-built or 'current state' Architecture of the NEM. Figures 6 – 10 represent the four cyber-physical-transactional structures that are dynamically interdependent on a days–hours–minutes–milliseconds basis. These are the:

1. **Electricity Infrastructure** (Black lines);
2. **Data / Digital Infrastructure** (Light blue lines);
3. **Operational Coordination Structure** (Dark blue lines); and,
4. **Markets / Transactional Structure** (Dark green lines).

These diagrams map how these four functionally interdependent structures span the vertical Tiers/Layers of the Power System. These are laid out as follows:

Top Panel: Bulk Power / Transmission System and HV-connected Customers;

Middle Panel: Distribution System, Energy Retail and DER/CER Aggregation (middle); and,

Foundation Level: Residential and SME Customers.

As noted above, the connectors between all the elements are colour-coded and a key is provided for each identifying the nature of the transactions or relationships.

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[88] For example, in a subsequent Detailed Architecture project, each of the following as-built structure diagrams would be intensively reviewed in multi-stakeholder workshopping. This would illicit input from diverse subject matter experts with a detailed understanding of each of the many sub-system interfaces to enable the detailed functionality specification of each interface, both now and in the future.

[89] A wide diversity of stakeholders – both technical and non-technical – will benefit from '101' level training in the Power Systems Architecture discipline. This in turn enables diverse stakeholders to engage more effectively on key trade-off decisions that require collective input.

2.5. Interpreting Industry Structure mapping

In addition to the mapping of the four Functional Layers, the existing industry structures embedded in the NEM are mapped in Figures 11 - 16. These Entity-Relationship Diagrams illustrate the interdependences and transactions between the various entities involved in NEM governance, operation and market functions. The different entities and their relationships mapped are:

1. **Governance & Regulation relationships** (Dark blue lines);
2. **Energy & Services relationships** (Light green lines);
3. **Control & Coordination relationships** (Bright blue lines);
4. **Wholesale Market Interaction relationships** (Dark green lines); and
5. **Energy Retail relationships** (Light blue lines).

Once again it is noteworthy that these relationships span and/or influence many or all Tiers/Layers of the NEM in its current form. Similar to the Functional Layers (above), the Industry Structure relationships also have a 'systemic' character where changes to one set of relationships will typically impact other relationship – in both intended and unintended ways.

4 x Functional Layers – As Built System

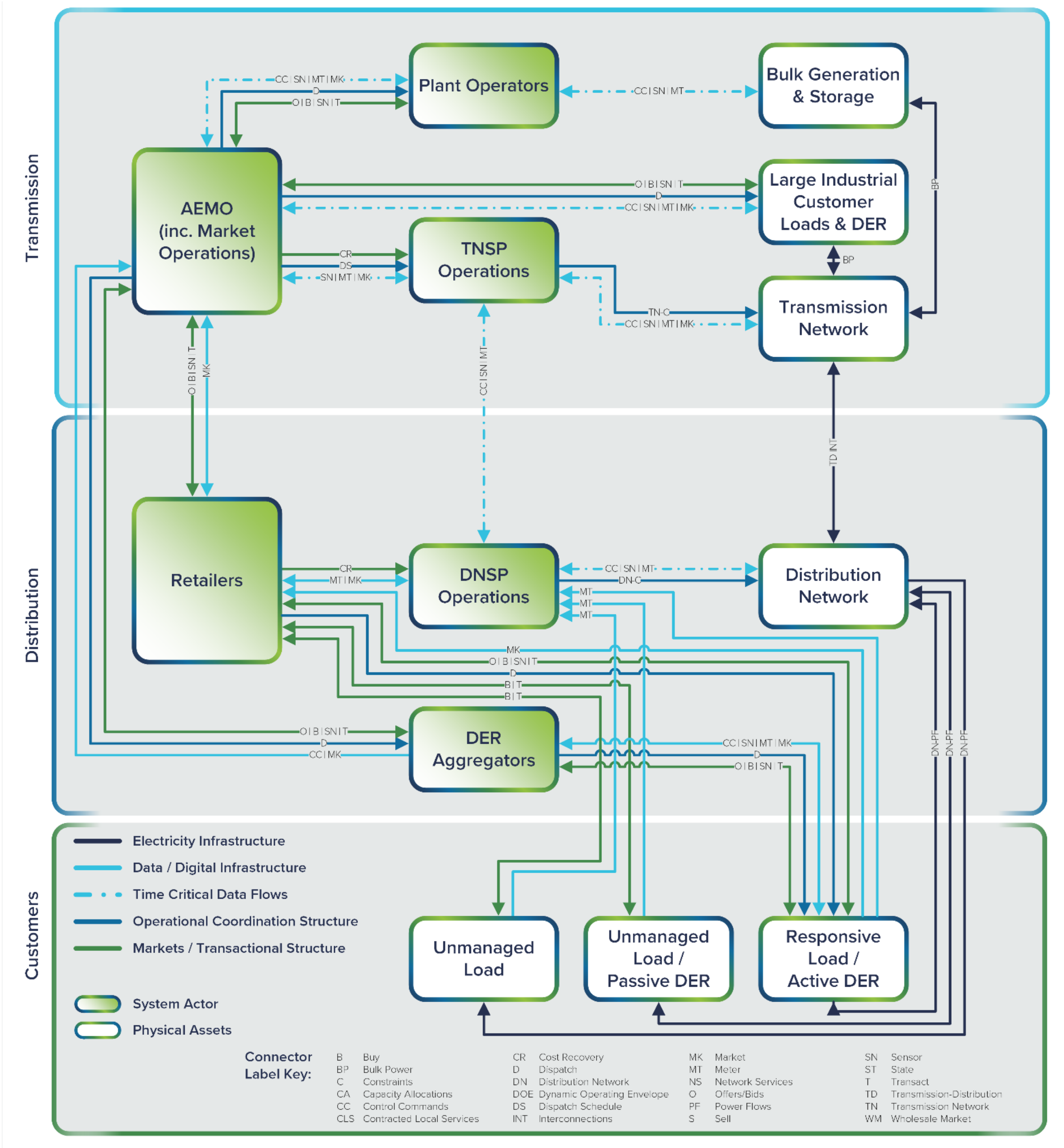

Figure 5: Four Functional Layers – As Built System

Electricity Infrastructure – As Built System

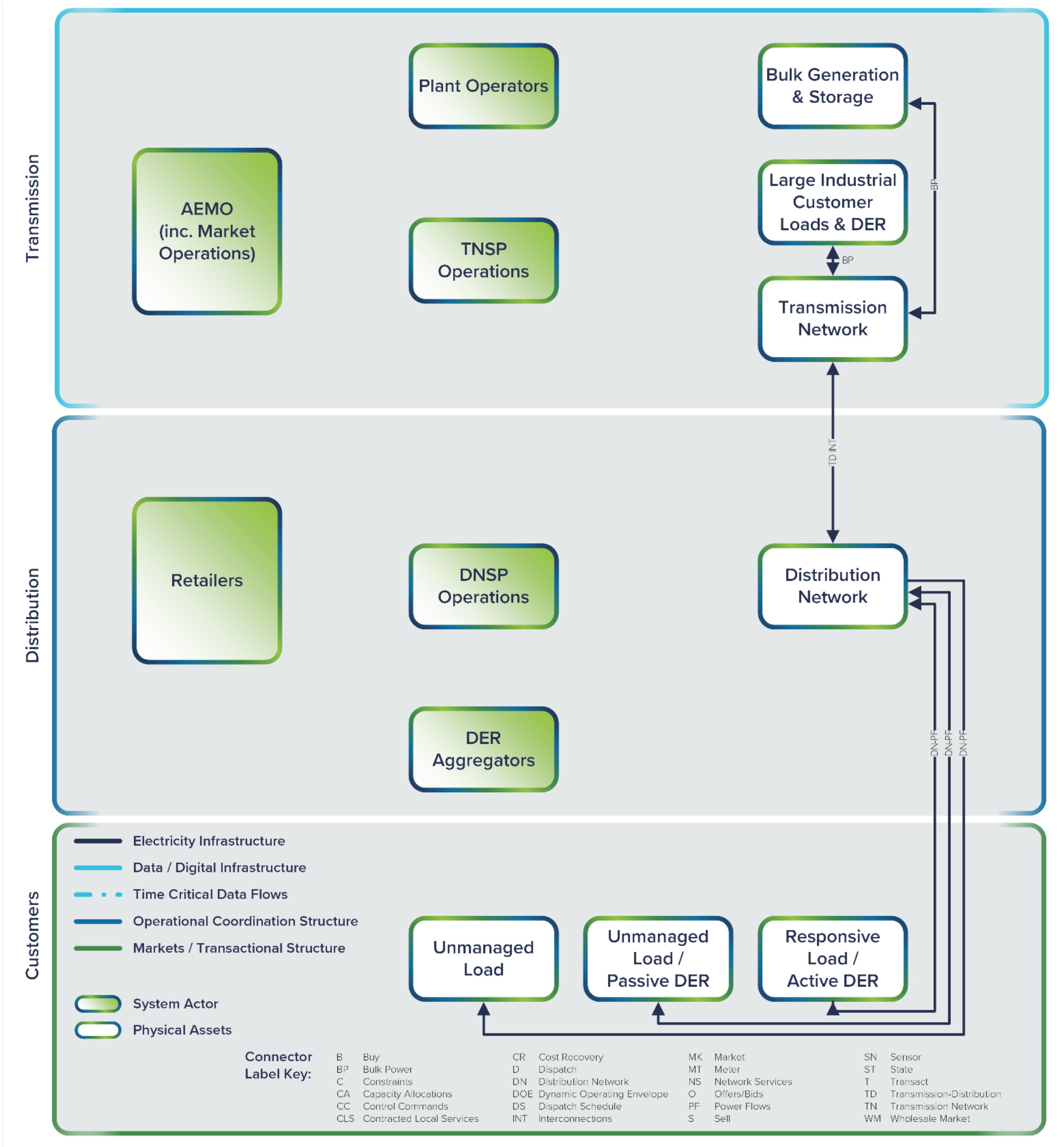

Figure 6: Electricity Infrastructure – As Built System

Data / Digital Infrastructure – As Built System

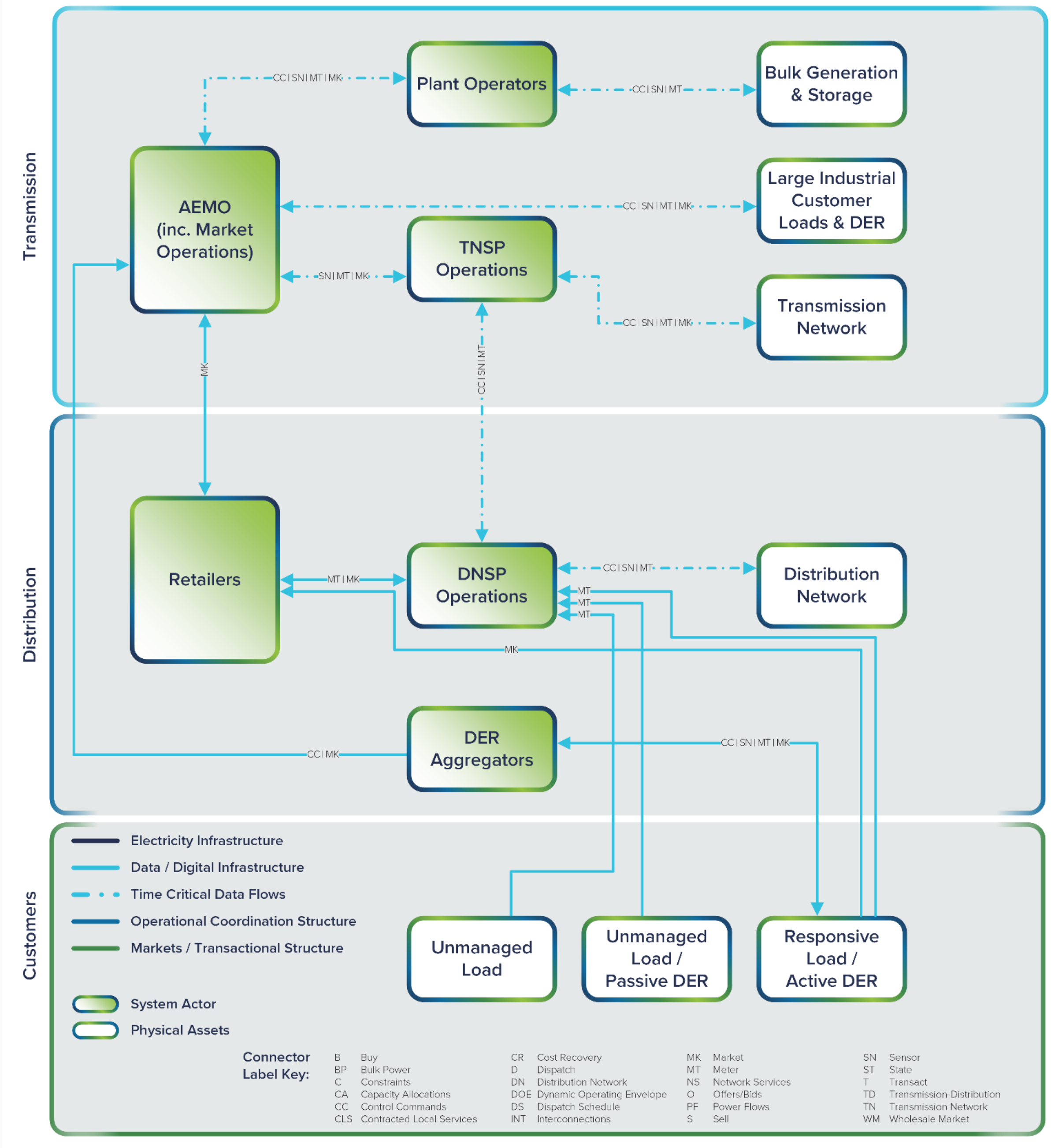

Figure 7: Data / Digital Infrastructure – As Built System

Operational Coordination Structure – As Built System

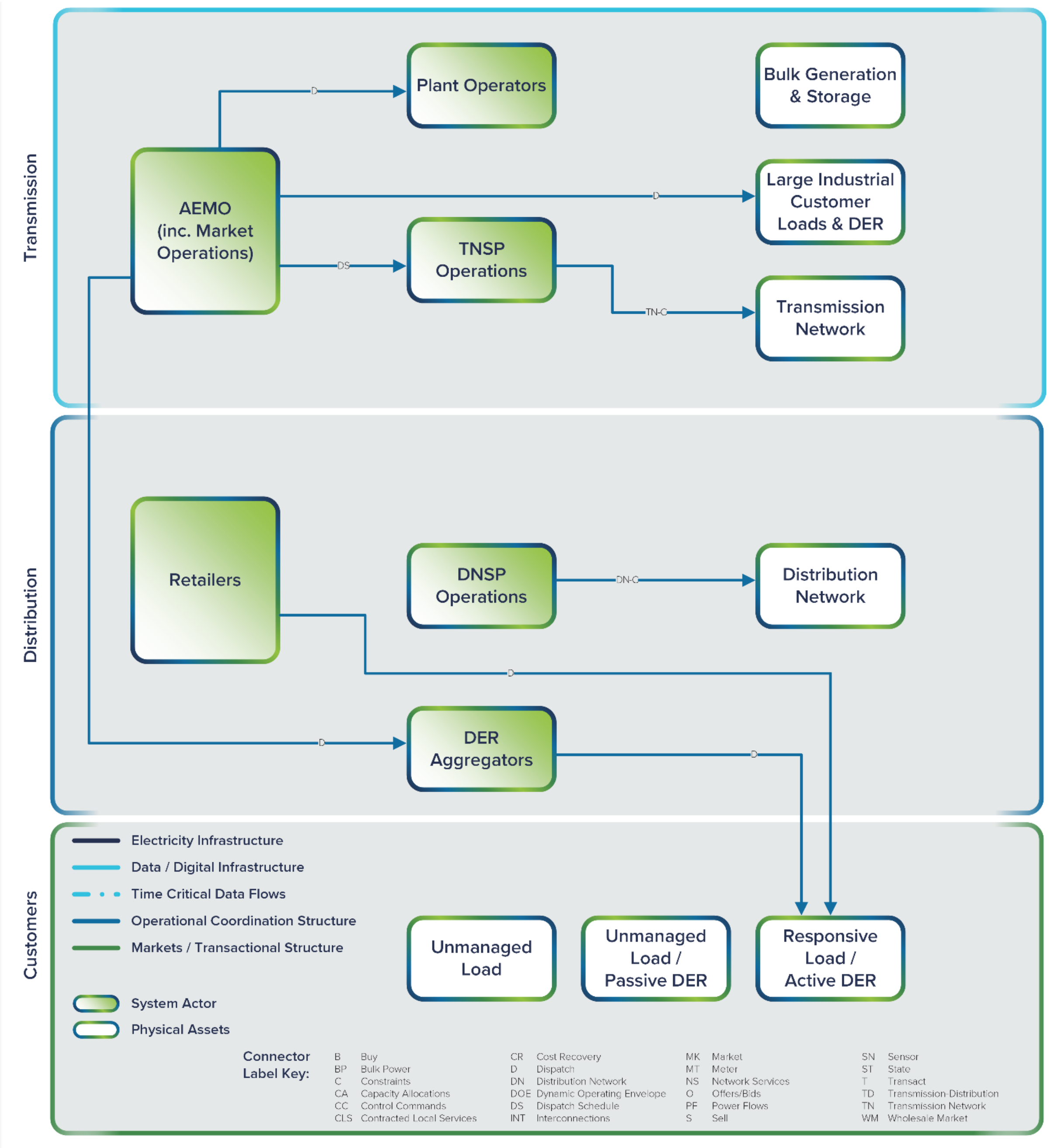

Figure 8: Operational Coordination Structure – As Built System

Markets and Transactional Structure – As Built System

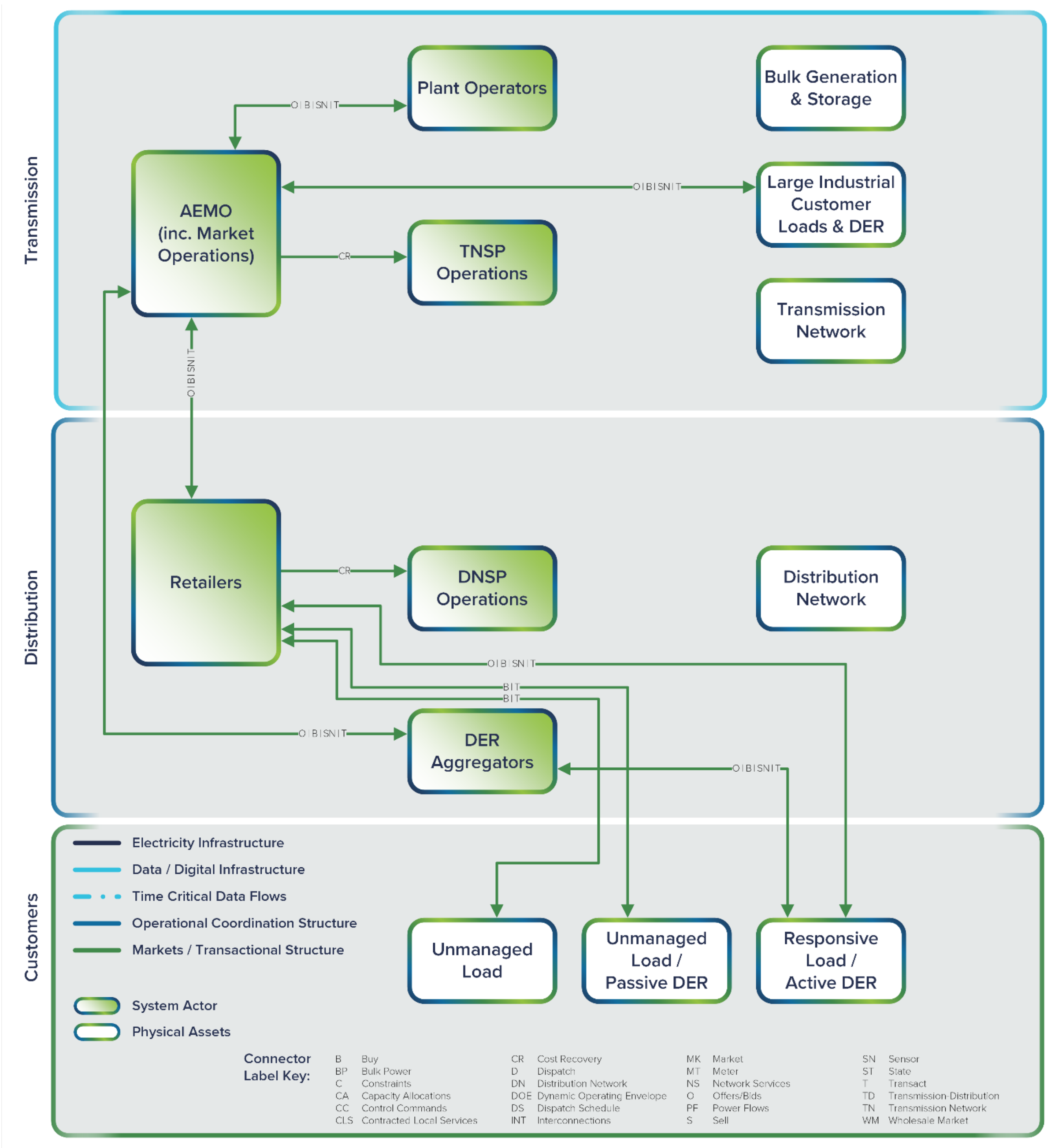

Figure 9: Markets and Transactional Structure – As Built System

Industry Structure Diagram – Current State

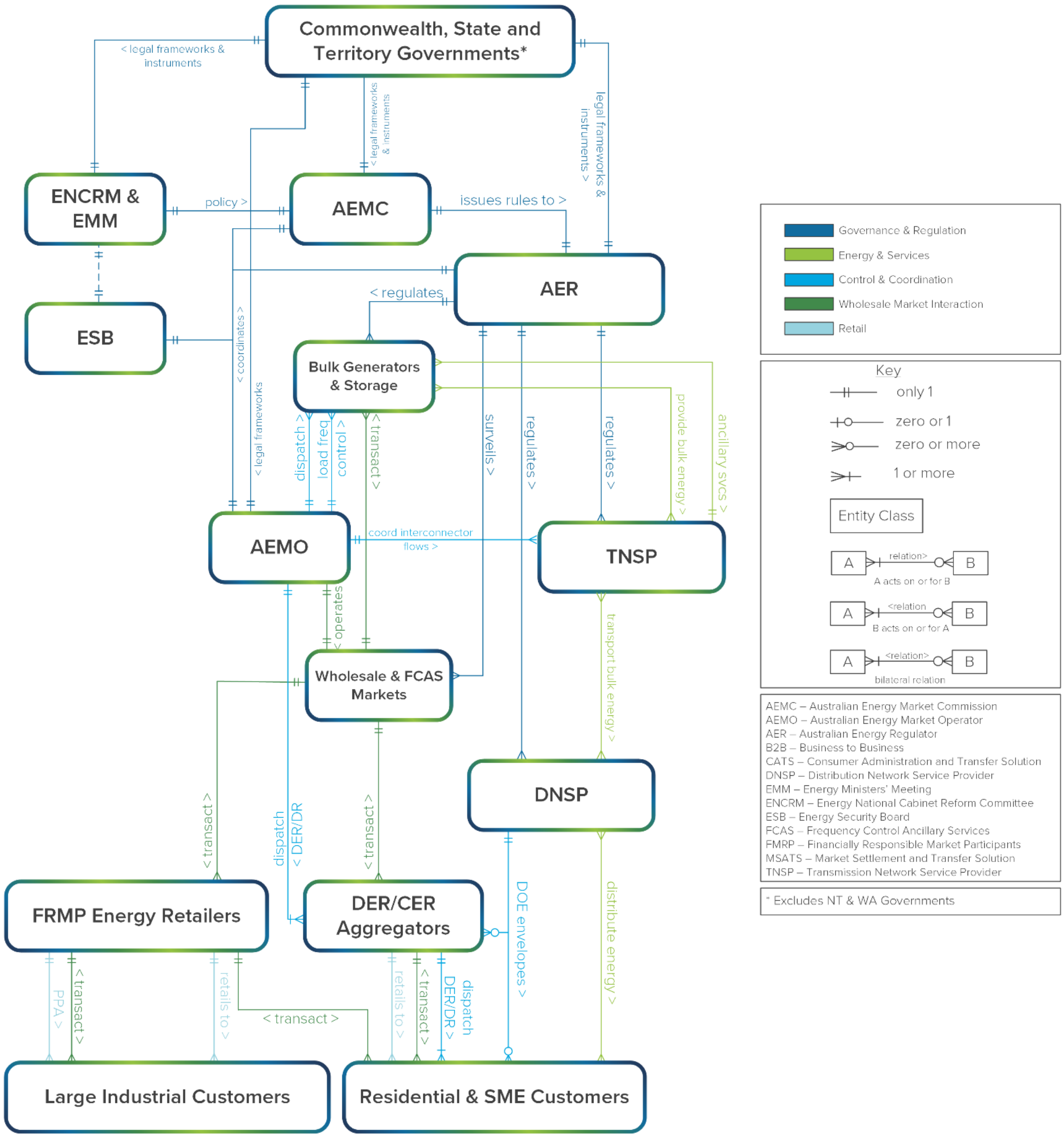

Figure 10: Industry Structure Diagram – Current State

Governance & Regulation Relationships

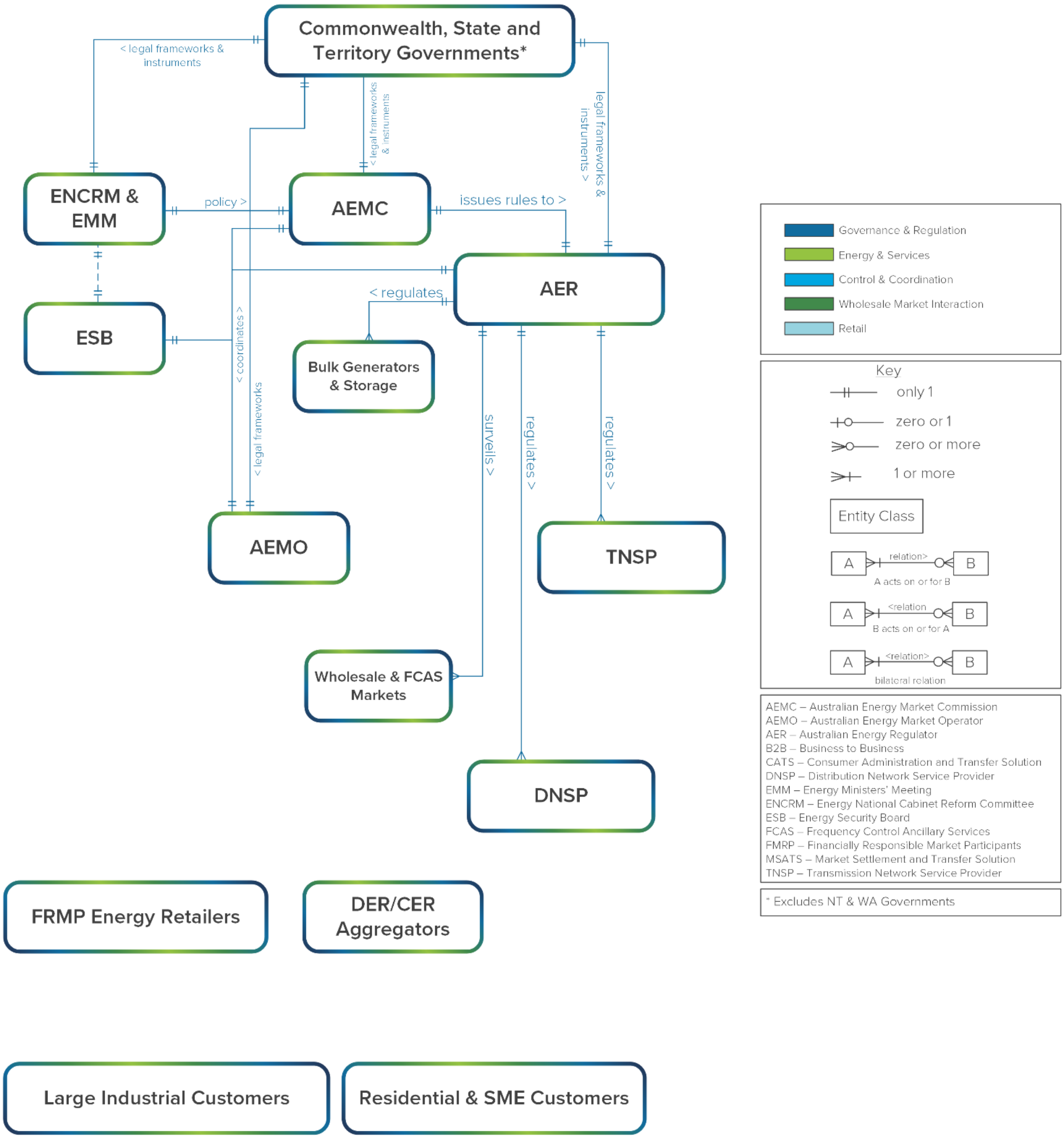

Figure 11: Governance & Regulation Relationships – Current State

Energy & Services Relationships

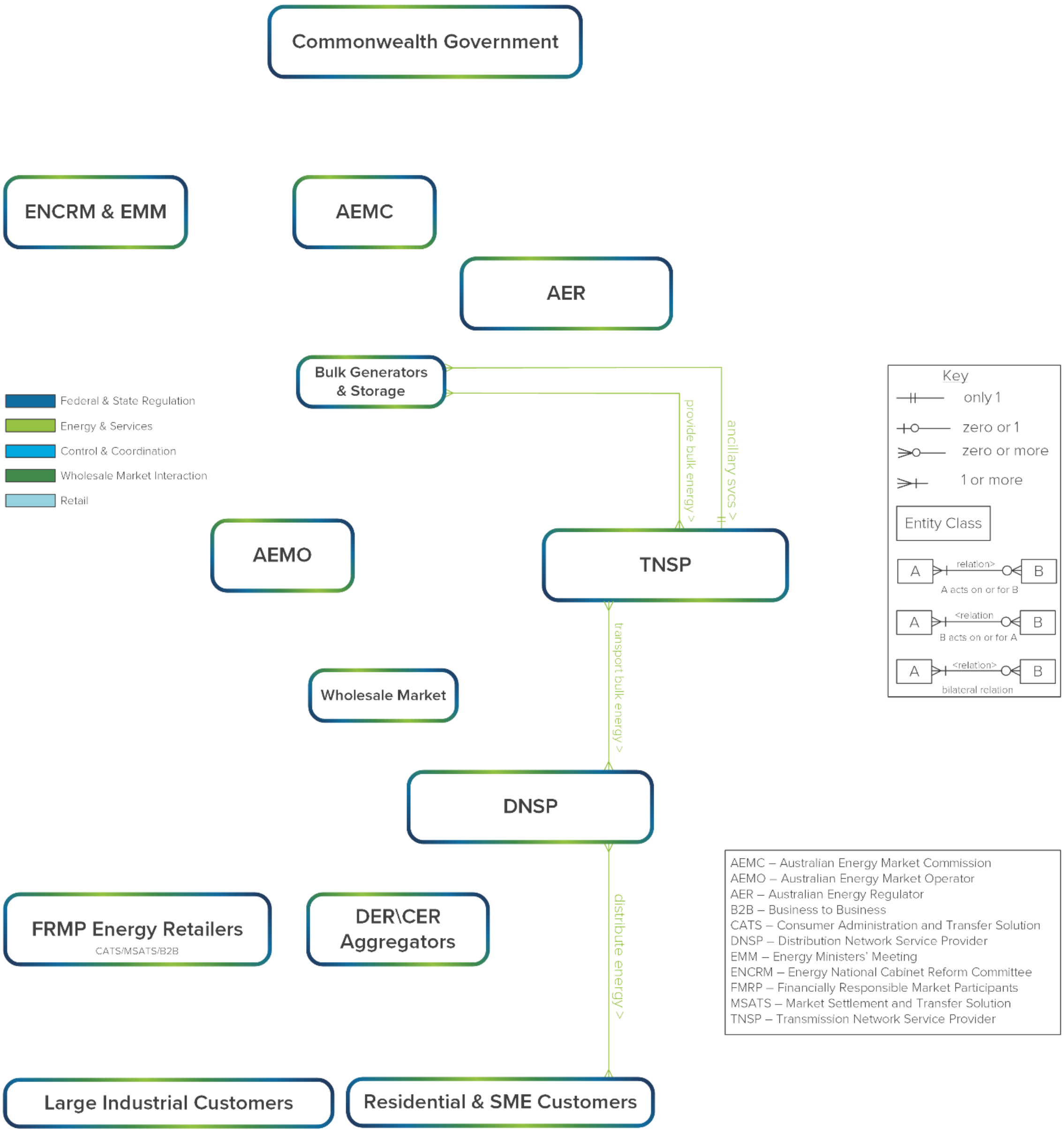

Figure 12: Energy & Services Relationships – Current State

Control & Coordination Relationships

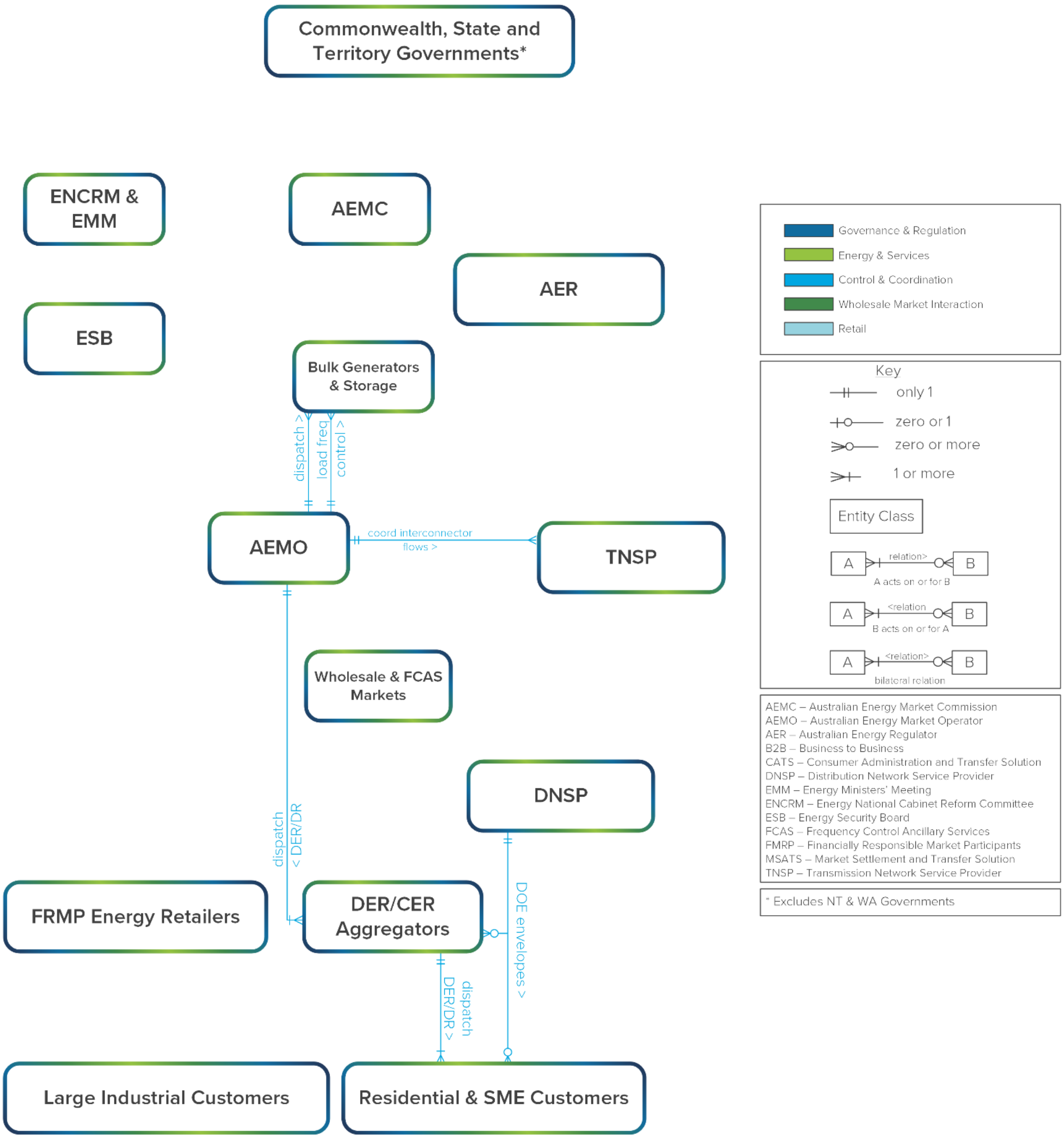

Figure 13: Control & Coordination Relationships – Current State

Wholesale Market Interactions

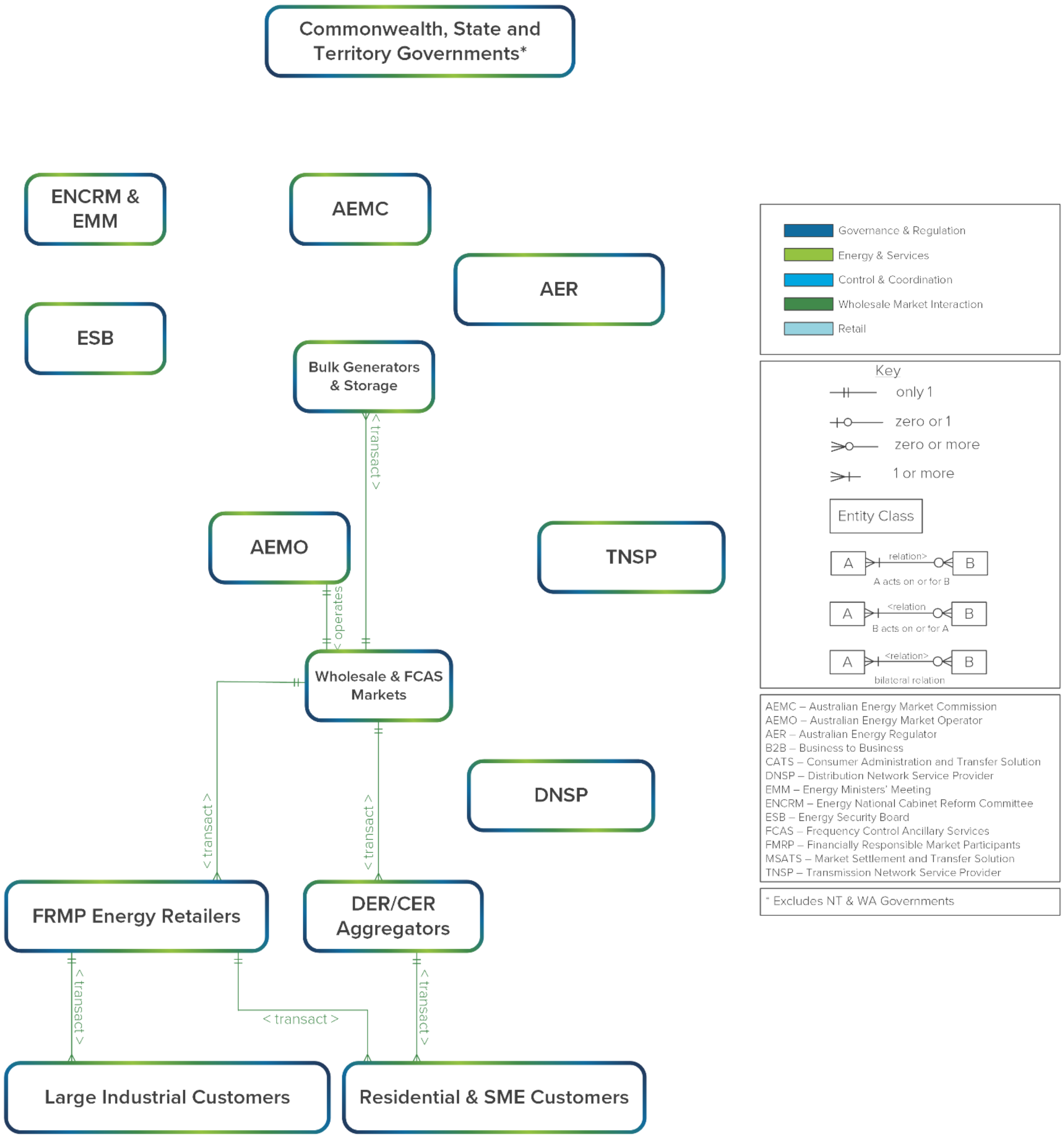

Figure 14: Wholesale Market Interactions – Current State

Retail Relationships

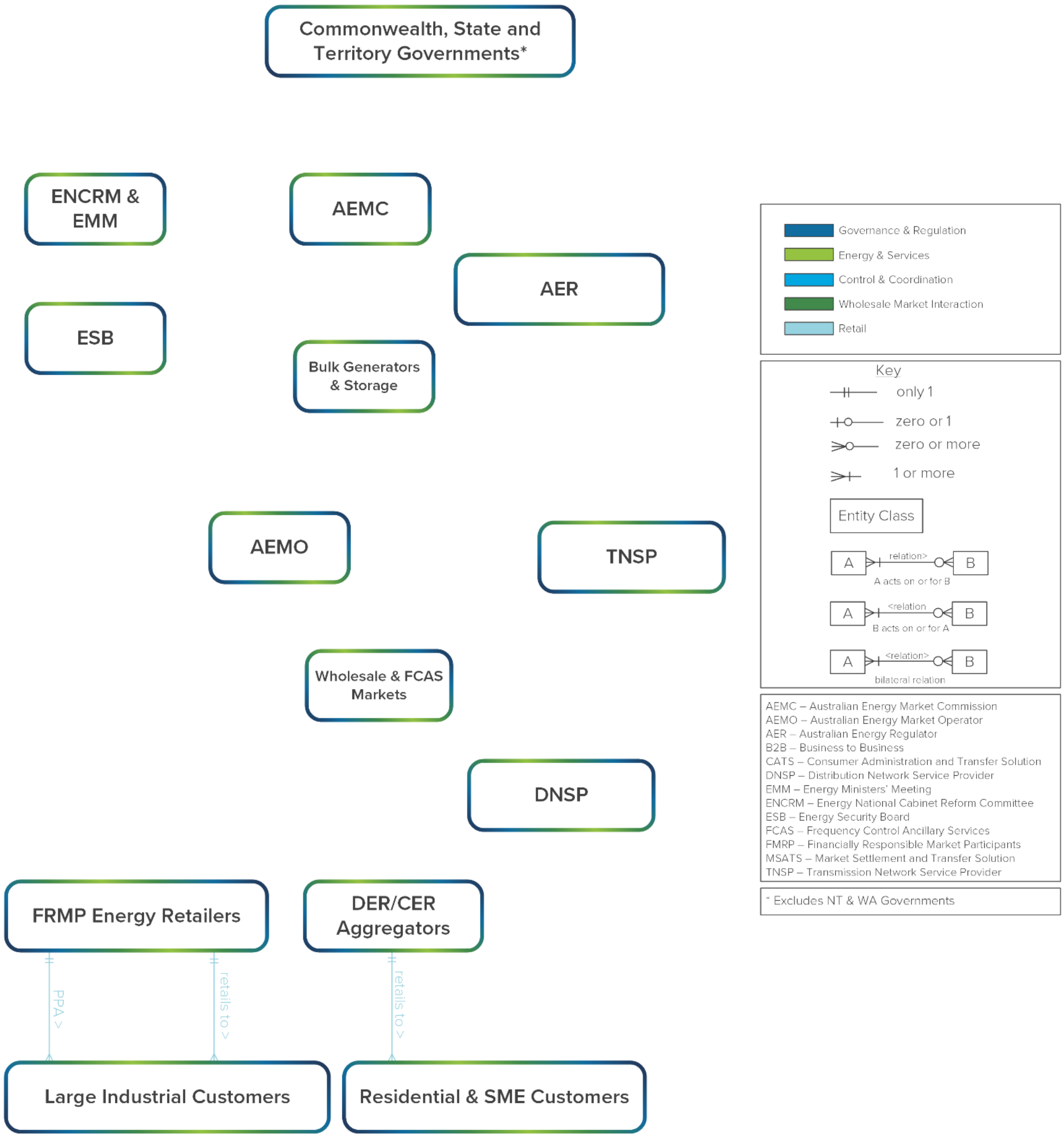

Figure 15: Retail Relationships – Current State

Key Concepts B

Architectural Issues

Following are seven important structural issues that the System Architecture discipline addresses that will otherwise negatively impact the Operability and Resilience of decarbonising Power Systems:

1. **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System's operational hierarchy.
2. **Coordination Gapping**: An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation.
3. **Hidden Coupling:** Two or more control entities with partial views of System State issue simultaneous but conflicting coordination signals to a DER/CER or Component of the Power System.
4. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
5. **Computational Time Walls:** Where excessive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines will hit a computational 'time wall' at some point where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time.
6. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
7. **Back-end Integration Constraints:** Multiple vertical silo structures found in many supply-chain organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others.

2.6. Observations about the current NEM Architecture

Similar to many GW-scale Power Systems in advanced economies, the NEM developed in a somewhat organic manner over the 20th century around a traditional architectural paradigm. Understandably, this was configured around the technology of the time, namely: centralised, synchronous generation and unidirectional supply through 'poles and wires' infrastructure to largely passive consumers.

Since the formation of the NEM with the interconnection of several state-based Power Systems, the NEM is generally recognised as having served Australia well in the centralised context for which it was originally configured. However, as the NEM transitions toward a future even remotely like AEMO's Step Change scenario, Sections 3 highlighted that:

+ As the approximately eighty Emerging Trends studied in Sections 2 materialise, a range of cross-cutting Systemic Issues also emerge in the NEM; and,

+ These Systemic Issues will require architectural interventions to resolve if the Customer & Societal Expectations of the future Power System studied in Sections 1 are to be viable.

The benefit of the structural mapping enabled by the Systems Architecture discipline is that the underlying Architectural Issues that compound these effects can be made explicit and solutions derived. For example, as the level of DER/CER grows exponentially as a proportion of the NEM generation fleet, legacy Hidden Couplings and Tier/Layer Bypassing at both the Operational Coordination and Market/Transaction Functional Layers will increasingly interfere with the Operability and Reliability of the NEM.

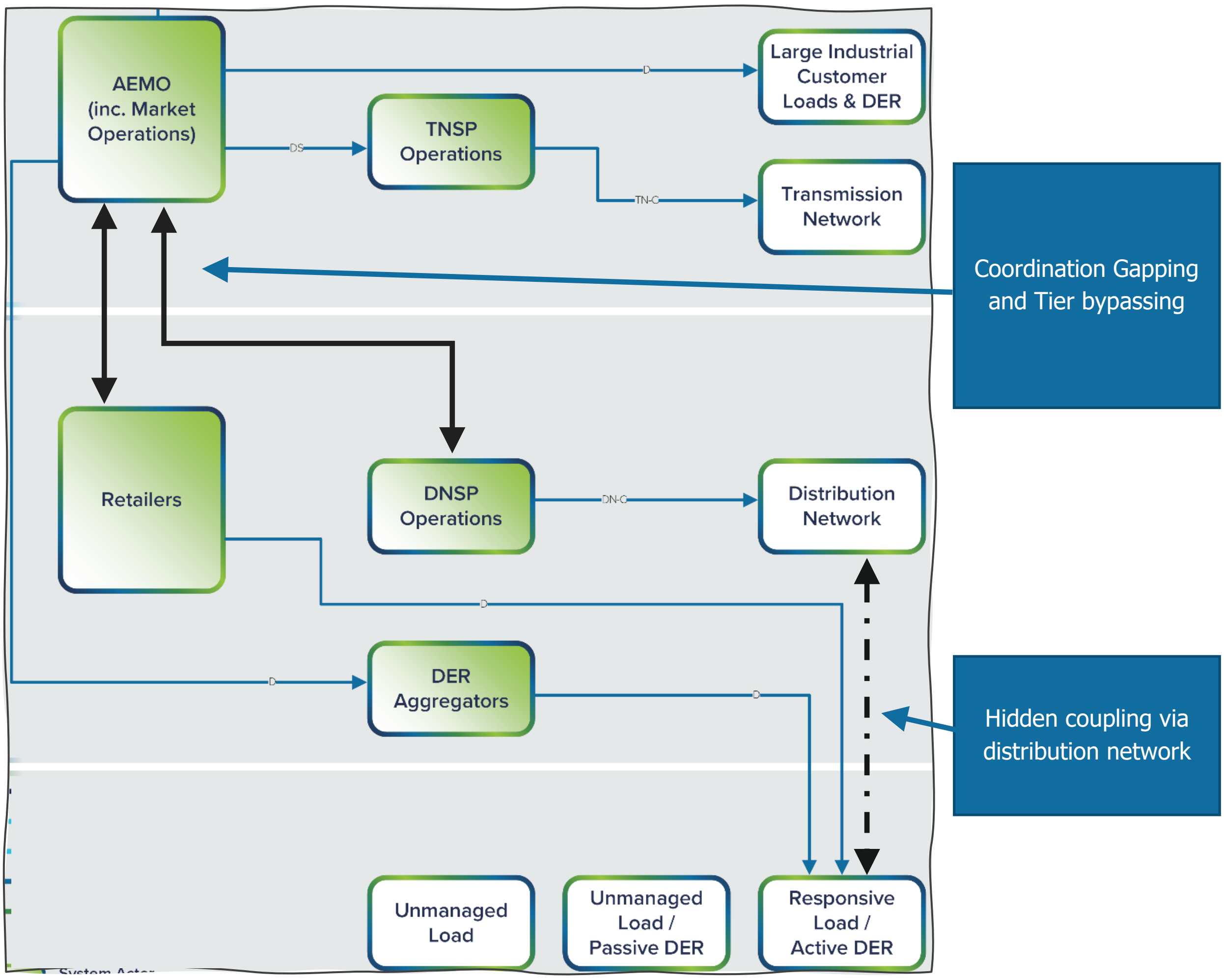

Figure 16: As-built Operational Coordination Annotations

Far from an abstraction, each of the three types of Operational Coordination problems (Tier/Layer Bypassing, Coordination Gapping, and Hidden Coupling) is increasingly occurring in actual Power Systems that host high levels of DER/CER. In addition, Latency Cascading has appeared in various approaches for DER/CER management at scale as have Computational Time Wall and Back-end Integration Constraints.

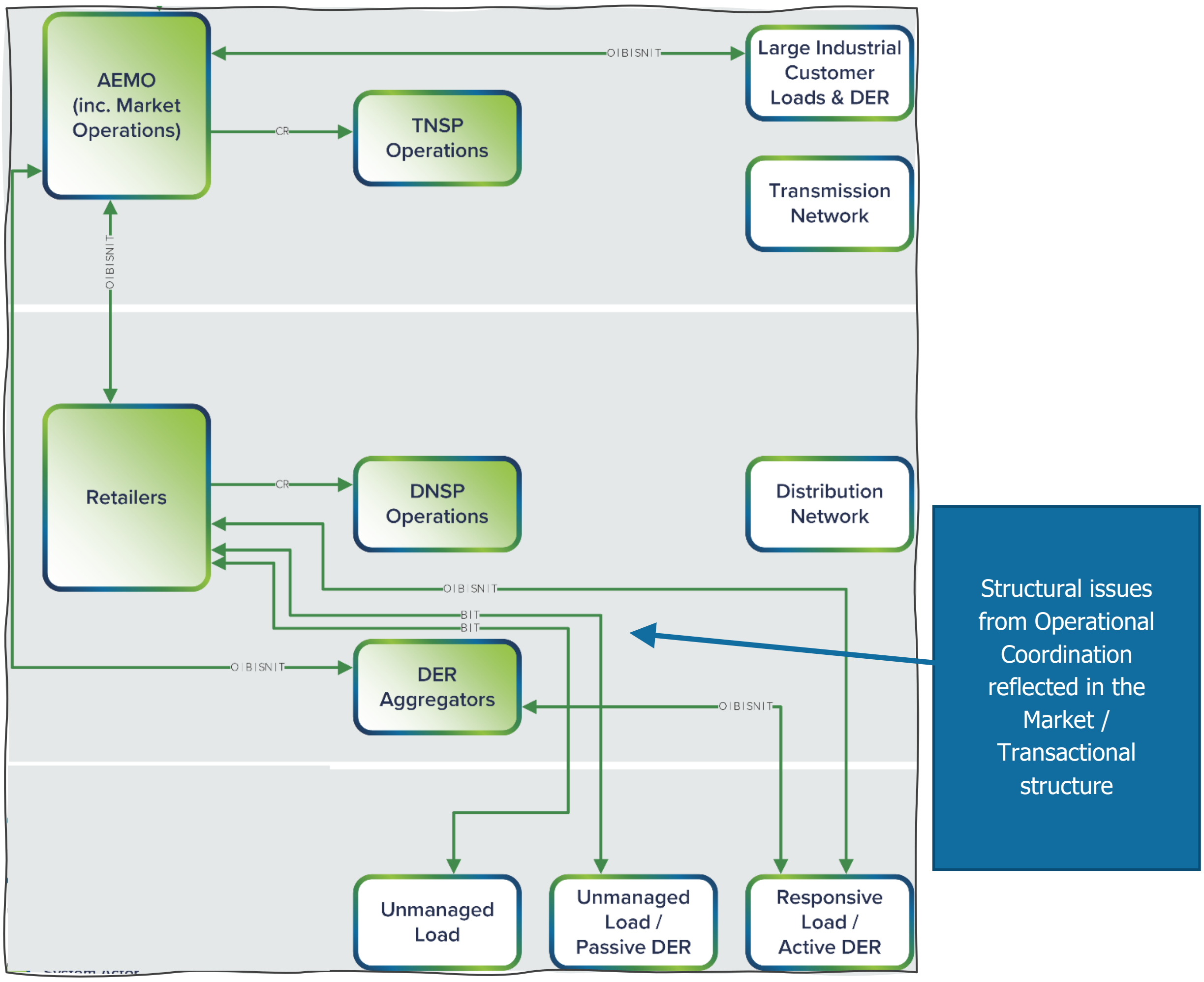

Figure 17: As-built Market / Transactional Structure Annotations

Ultimately, the seven Architectural Issues listed above must be navigated very carefully in a continental scale Power System like the NEM that is undergoing profound transformation. Where appropriate architectural interventions are not applied, they will ultimately drive increasingly misalignment between the operational performance of the Power System and its operational goals.

3. EXPLORING FUTURE ARCHITECTURAL OPTIONS

Power Systems Architecture (PSA) provides a holistic approach to exploring Power System transition options and is supported by the combined application of Systems Architecture, Network Theory, Control Theory, Systems Science and Model-based Systems Engineering (MBSE).

This section provides an overview of the following development considerations employed in the development of future architectural options for the NEM:

+ PSA Guiding Principles & Key Characteristics;
+ Framed by Plausible NEM Future State(s);
+ Informed by Customer & Societal Objectives;
+ Responsive to Emerging Trends & Systemic Issues;
+ Essential Focus on Advanced Operational Coordination;
+ Identification and Mitigation of Key Architectural Issues; and,
+ Supporting Role of Platform-based or Layered Structures.

3.1. PSA Guiding Principles & Key Characteristics

At a high level, the following ten principles and characteristics of the PSA discipline have guided the investigation of all architectural options explored in this Reference Architecture.

1. **Stakeholder / User-centric:** Systems Architecture methodologies are grounded in a detailed knowledge of the current and emerging future expectations of relevant stakeholders, including customers, policy makers and system actors, to ensure the System is able to deliver a balanced scorecard of stakeholder outcomes.
2. **Contextually Informed:** Systems Architecture methodologies give priority to examining the full range of Emerging Trends that are driving significant change together with the resulting Systemic Issues that must be addressed if stakeholder expectations of the future System are to be made achievable.
3. **Principles-based:** System Architecture methodologies are grounded in established principles and formal bases, ensuring conceptual integrity through consistent, traceable and verifiable processes, enhancing multi-stakeholder trust, and minimising the potential for unintended consequences.
4. **Structural Focus:** Systems Architecture methodologies give particular attention to the underpinning structure or 'architecture' of a complex System due to the disproportionate influence it has on what the system can safely, reliably and cost-efficiently do (i.e. the 'performance envelope' of the system).

5. **Whole-system Perspective:** Systems Architecture methodologies provide a holistic view of the entire System as the primary basis for considering the interdependencies between its many Tiers/Layers, Subsystems and Components.

6. **Decadal Time Horizon**: By identifying structural options that enhance (rather than constrain) multi-year optionality, Systems Architecture methodologies ensure the System is Robust, Adaptable, Scalable and Extensible across a range of alternate future scenarios and maximise the 'future-proofing' of investments.

7. **Technology Agnostic:** By focusing on the required outcomes of the current and future System, Systems Architecture actively identifies alternative implementation pathways, supports technology innovation and avoids dependence on any particular proprietary solution.

8. **Complexity Management:** By making explicit the underpinning structures of a legacy system, Systems Architecture enables inherent complexity to be decomposed, legacy structural constraints to be identified, and proposed changes to be accurately targeted and avoid complexity escalation.

9. **Subsystem Analysis:** By providing formal analytical tools, Systems Architecture enables the detailed interrogation of all current Subsystems and Components, their individual Form and Function, Boundaries, Interfaces and Functional Interdependencies to holistically consider potential future enhancements.

10. **Stakeholder Empowerment:** By providing an objective and evidence-based set of tools that can be learned, Systems Architecture empowers diverse stakeholders – both technical and non-technical – to collectively reason about current and future options and better contribute to key trade-off decisions.

3.2. Architecture Framed by Plausible NEM Future State(s)

To ensure the Reference Architecture has a strong future-orientation, it has been framed around AEMO's 'Step Change' 2050 scenario to provide a sense of the scale of transformation that is widely anticipated as impacting the NEM over the coming decades.

In addition to considering the architectural settings that may be required for the NEM to operate securely and cost-effectively in a future like the Step Change scenario, it also recognises that insights gained must provide actionable inputs to near and medium-term decision making. This is particularly critical as by 2025, significant regions of the NEM will need to be capable of operating reliably during periods where 100% of instantaneous demand is met by variable generation sources.

3.3. Informed by Customer & Societal Objectives

The Reference Architecture process recognises that Power Systems are complex techno-economic systems that have a critical societal role. Given the many essential functions they perform in a modern economy – and the growing potential for customer participation – any credible consideration of future architectural options must be informed by what customers and policy makers are expecting of these systems in the future.

Figure 18: Eight themes of Customer & Societal Expectations for future Power Systems

As noted above, the PSA discipline is fundamentally stakeholder and user-centric. Therefore, the consideration of future architectural options is informed by the analysis of the relevant Australian and global sources outlined in Sections 1 – Customer & Societal Objectives. The report outlined eight key objectives for future Power Systems that emerged from the literature and were corroborated by stakeholder interactions.[90]

Based on the analysis, the eight objectives that Australian and global customers and policy makers expect of their future Power Systems are as follows:

[90] In seeking to fairly report the findings, no opinion was offered on the appropriateness or otherwise of the objectives as stated.

1. **Dependable**: Safe, secure, adequate, reliable and resilient;
2. **Affordable**: Efficient and cost-effective;
3. **Sustainable**: Enables 2030 and 2050 decarbonisation goals;
4. **Equitable**: Broad accessibility of benefits and the fair sharing of costs;
5. **Empowering**: Advances customer and community agency, optionality, and customisation;
6. **Expandable**: Enables electrification of transport, building services and industrial processes;
7. **Adaptable**: Flexible and adaptive to change, including technological, regulatory and business model innovation; and,
8. **Beneficial**: Socially trusted, public good/benefits, commercially investable and financeable.

Importantly, it is worth noting that a complex web of relationships exists between these various objectives – several of which directly impact each other. As such, the prioritisation of the various objectives would require a process of broad societal engagement to collectively navigate the various trade-off choices. This would normally be a part of a subsequent Detailed Architecture project.

3.4. Responsive to Emerging Trends & Systemic Issues

The Reference Architecture process recognises that a range of cross-cutting Systemic Issues currently exist in NEM and/or are currently materialising as the approximately eighty Emerging Trends studied in Sections 2 converge. Examined in Sections 3, ten Systemic Issues were organised under three clusters;

1. **Transition Constraints:** Fundamental considerations that influence many aspects of Australia's Power System and may impede our collective ability to navigate its transformation in a timely, efficient and technically robust manner.
2. **Core Structural Issues:** Structural and technological shifts that will become increasingly necessary to underpin Australia's Power System transformation from hundreds of centralised to tens of millions of ubiquitous energy resources.
3. **Future-ready Roles and Responsibilities:** Key considerations about how roles, responsibilities and detailed system interfaces may be provisioned to cost-efficiently manage the whole-system operation of decarbonising Power Systems that experience massive increases in volatility, complexity and operational dynamics.

While not exhaustive, all ten Systemic Issues identified require architectural interventions of various kinds to resolve. Where this is absent, it is questionable whether the Customer & Societal

Expectations of the future Power System identified in Sections 1 will be achievable in a secure and cost-efficient manner.

3.5. Essential Focus on Advanced Operational Coordination

The consideration of advanced Operational Coordination mechanisms is perhaps one of the most critical issues facing global Power Systems that are experiencing deep decarbonisation, expanding decentralisation and unprecedented levels of Volatility. The structural mapping contained in this Reference Architecture is designed to support this critical area of consideration.

The concept of Operational Coordination is closely related to the topic of Operability. In engages with the emerging reality that an ever-growing proportion of the Energy Resource fleet in the NEM is not Dispatchable by traditional, hierarchical means. As a result, Bulk Power, Transmission and Distribution Systems – together with deep Demand-side Flexibility – will need to function far more holistically together to maintain instantaneous supply-demand balance under all circumstances. In addition, as Australia's coal-fired generation fleet is withdrawn, this type of Advanced Operational Coordination will be increasingly critical for ensuring the Adequacy, Security[91], Reliability and Cost-efficiency of the NEM.

This will require closely coupled new market and control mechanisms to incentivise and coordinate the beneficial participation of millions of Energy Resources located at different Tiers/Layers of the Power System. In a context where the proportion of privately owned resources increases, the provision of a sustainable 'quid pro quo' supported by technological automation will be essential to ensuring the necessary system services efficiently procured and precisely delivered when and where needed across each Tier/Layer of the NEM (i.e. targeted and firm response).

Therefore, as illustrated earlier, the need for more closely coupled market and control elements to Operationally Coordinate a fleet of millions of Energy Resources is a key feature of applying Systems Architecture disciplines to a transforming Power System. The basic rationale for doing so is summarised in the following three points:

1. Well-designed markets operate as excellent sensors and optimisation engines; reduce transaction friction and cost; and, enable the System Operator, emerging DSOs, consumers and 'prosumers' to reveal what they need and value at significantly higher levels of resolution.
2. Technological controls are required as markets alone cannot address all power system dynamics and timeframes; and, automation is required to deliver firmness of response and make the day-to-day experience of market participants essentially effortless; and,

[91] Includes the management of Minimum Operational Demand

3. The proximity of a market structure to a fleet of energy resources connected to a particular layer of the power system, together with the approach to the cyber-physical coordination of these resources, is likely to have a significant impact on both the scalability of the approach and the overall system benefits delivered.

Ultimately this is analogous to the Security Constrained Economic Dispatch (SCED) paradigm applied in many traditional bulk power markets, albeit devolved across an operating context involving tens of millions of participating Energy Resources that may function within different Tiers/Layers of the system.

3.6. Identification and Mitigation of Key Architectural Issues

To ensure this Reference Architecture is both future-oriented and supports practical near-term action, it has been framed around the following two questions:

- **Critical Enablers:** What architectural settings might be required if the NEM is to operate securely and cost-effectively in a credible future like AEMO's Step Change[92] scenario?
- **Decision Support:** How might this longer-term perspective help enhance the shortlisting and future-readiness of both near and medium-term transitionary steps?

In this context, seven important structural issues that the System Architecture discipline surfaces are outlined below. Where these common legacy issues remain unaddressed, the Operability and Resilience of the NEM will be increasingly compromised as the system decarbonises.

1. **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System operational hierarchy.
2. **Coordination Gapping:** An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation.
3. **Hidden Coupling:** Two or more control entities with partial views of System State issue simultaneous but conflicting coordination signals to a DER/CER or Component of the Power System.

[92] Compared to today's NEM, AEMO's 'Step Change' scenario plausibly envisages a future involving 9x VRE, 5x DER/CER, 3x Dispatchable Firming Capacity and 99% vehicle electrification in 2050.

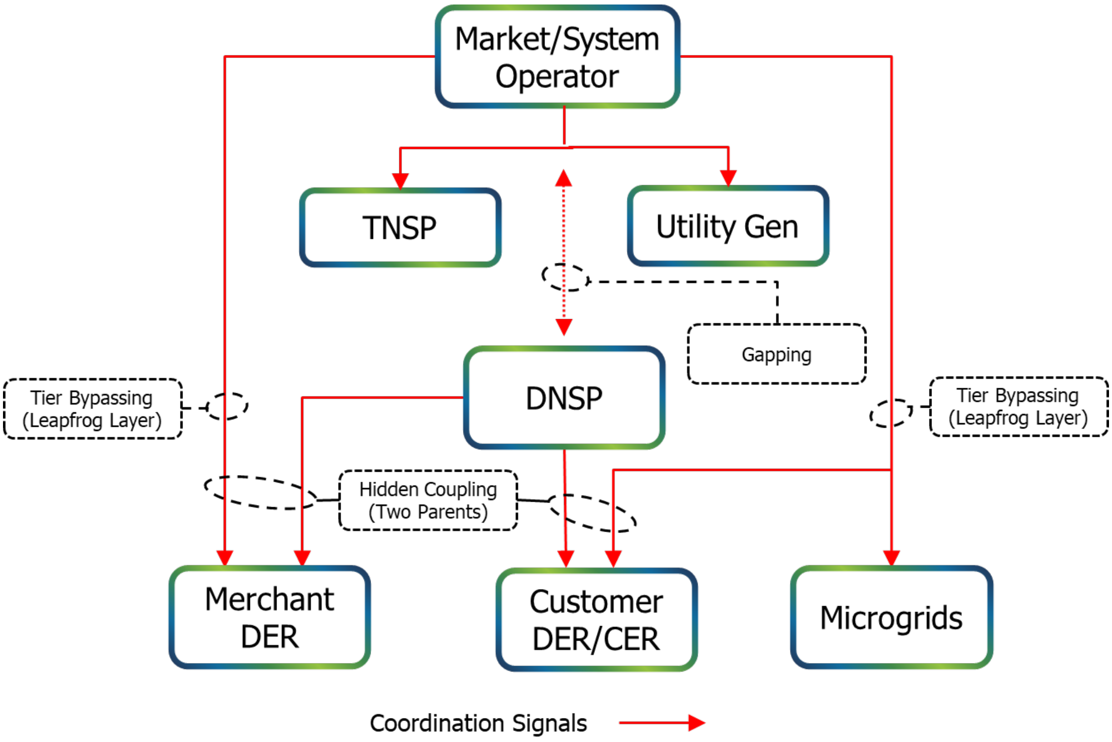

Figure 19: Examples of several Systems Architectural errors that will negatively impact the Operational Coordination of a decarbonising Power System

4. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
5. **Computational Time Walls:** Where massive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines risk hitting a computational 'time wall' where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time (refer Figure 22).
6. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
7. **Back-end Integration Constraints:** Multiple vertical silo structures found in many organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others (refer Figure 23).

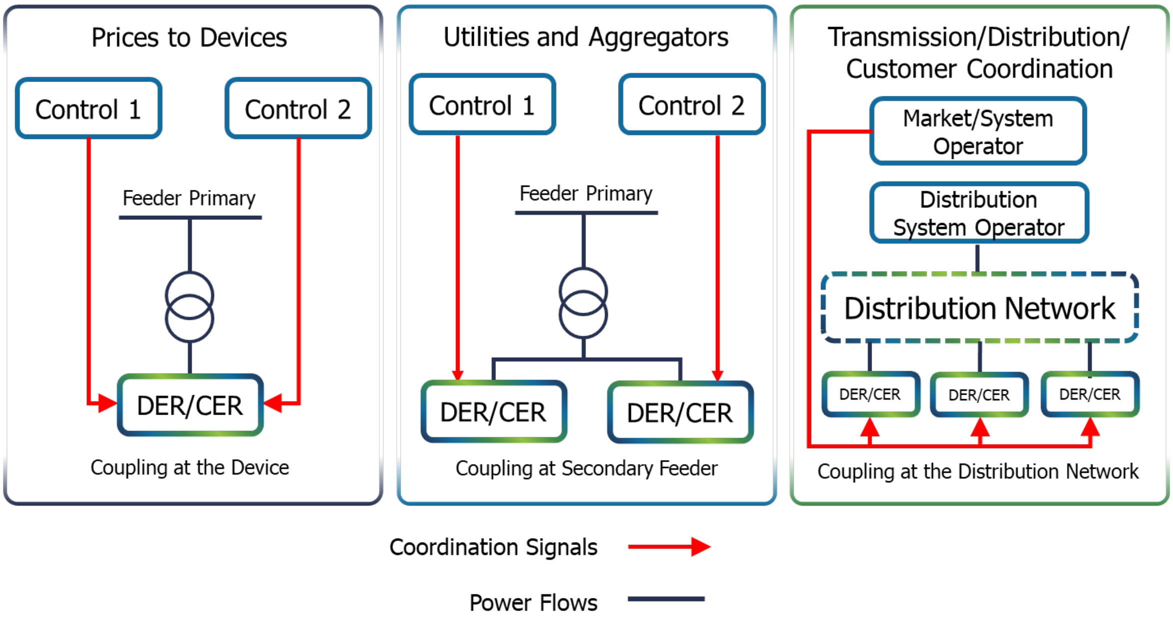

Figure 21: Different ways that Hidden Coupling can occur.

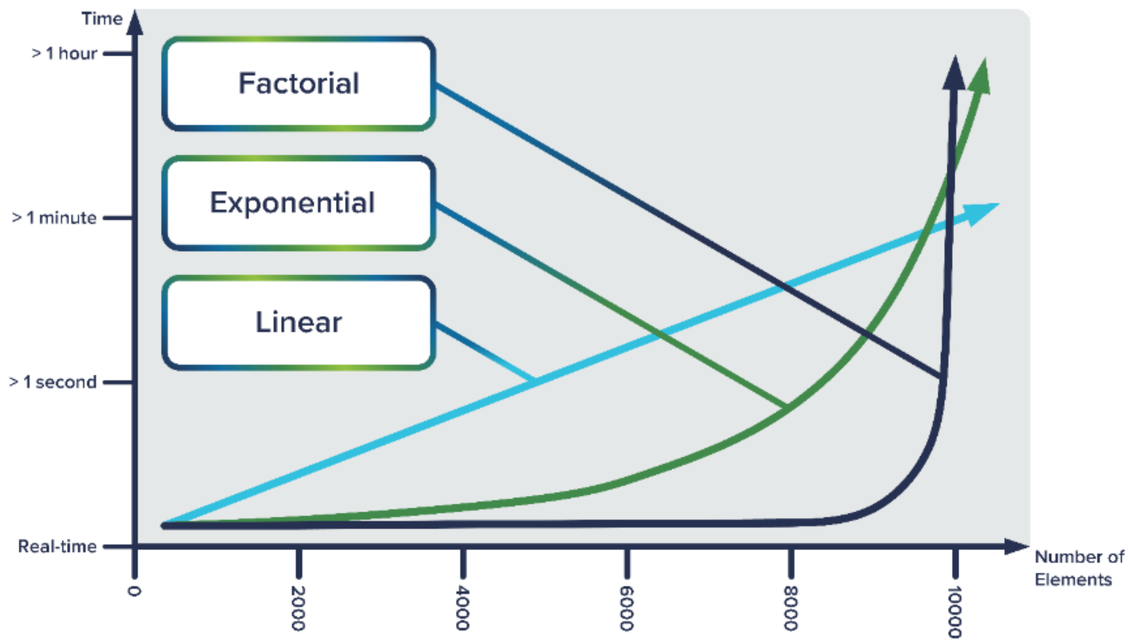

Figure 22: Computational 'time wall' effects can occur quite suddenly. In the case of Factorial curve (black), no amount of computing resources will be adequate to solve the optimisation problems in a reasonable time once the breakpoint has been reached.[93]

[93] Image: Dr Jeffrey Taft

3.7. Supporting Role of Platform-based or Layered Structures

Increasingly complex and dynamic systems experience growing fragility and anti-resilience where their underpinning legacy Architecture remains unduly centralised and based on an outdated, linear 'command and control' model – either explicitly or implicitly.

Layering is a valuable architectural approach that is applied widely in ultra-complex computing and communication systems as it enables the management of exponential complexity. Based on Layered Decomposition mathematics, the core capabilities of an ultra-complex system are configured into interoperable 'horizontal' surfaces or Platforms that enjoy far greater Resilience, Scalability and Extensibility. Given its complex cyber-physical-transactional characteristics, Layering is highly relevant to transforming Power Systems.

By contrast, in highly bifurcated traditional Power Systems core functions were arranged in 'vertical' structures and siloes (often with their own networks, sensors and computational systems). When experiencing significant change, these vertical structures exacerbate integration issues, compromise solution Scalability and Extensibility and result in more brittle, less resilient and higher cost outcomes.

The properties of a layered approach that make it superior for Power Systems that will host millions of participating Energy Resources connected to the LV-system include:

- End-to-end system Visibility, Operational Coordination and Operability outcomes are significantly enhanced;
- The relatively stable core system functions are kept entirely separate from applications, which be changed or upgraded more frequently without impacting the core functions;
- Each Tier/Layer can insulate the one immediately above from changes in the Tier/Layer immediately below, and vice versa - preventing changes at one level being propagated through the entire system;
- Specifying enforceable performance requirements and standards at the Interfaces between Tiers/Layers frees the Market/System Operator of the need for direct Visibility and Controllability in lower levels of the Power System.
- The ability of third parties to create applications that leverage the Platform via open standard interfaces is enhanced; and,
- Changes or upgrades in end-use or third-party applications are decoupled from impacting underlying core functions and capabilities.

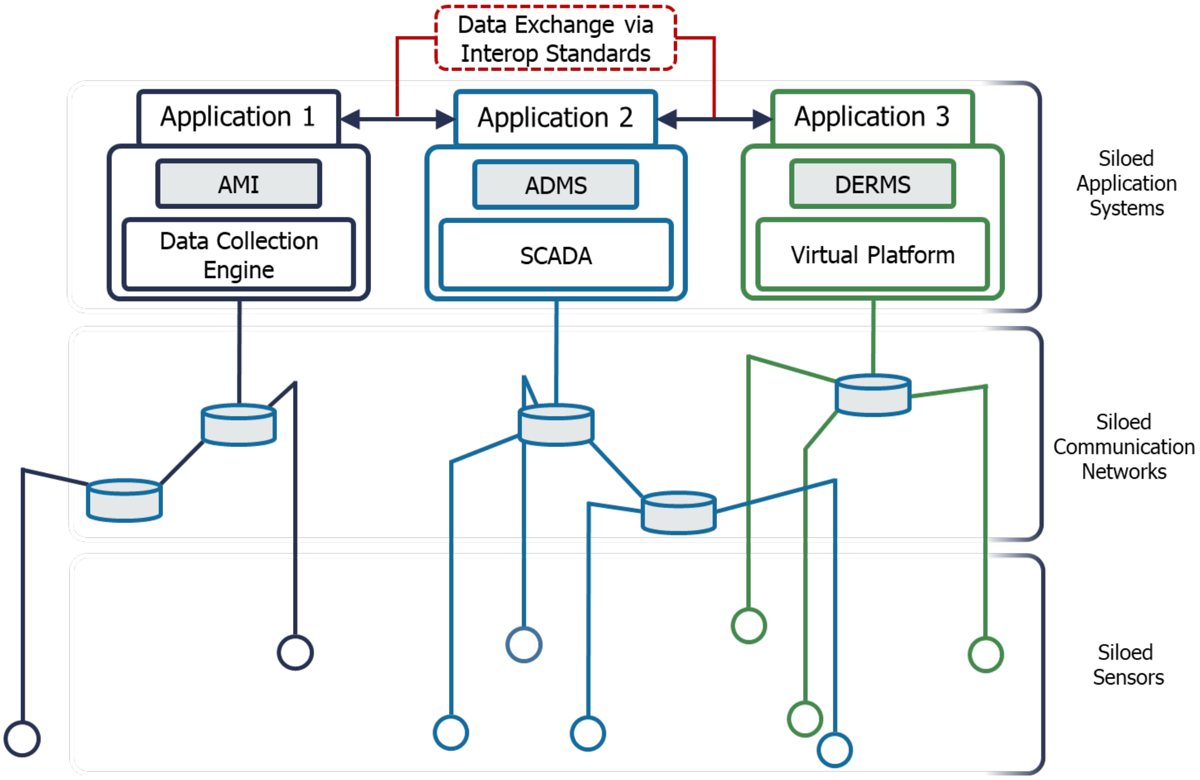

Figure 23: Back-end integration constraints arise due the multiple vertical silo structures found in many supply-chain organisational system.

Key Concepts C

Operational Coordination

The systematic operational alignment of utility and non-utility assets to provide electricity delivery. It can also refer to structured mechanisms by which millions of diverse Energy Resources (merchant and private) operate both to serve individual priorities ('local selfish optimisation') and cooperatively participate to address common Power System issues.

As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, the proportion of synchronous generation declines, and decarbonising Power Systems experience unprecedented levels of Volatility, ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require:

> *Bulk energy, transmission and distribution systems – and the rapidly expanding fleet of distributed resources – to function far more dynamically and holistically across the end-to-end power system.*

Combined with exponential growth in Energy Resource numbers, types and ownership models, and the correlation between the economic value of grid services delivered and the physics-based needs of a Power System (which dynamically vary, both temporally and spatially), more advanced Operational Coordination models become critical to:

- Enhance dynamic Interoperability across the Transmission-Distribution Interface (TDI) due to the Power System's growing dependence on Energy Resources located both up and downstream:
- Support more granular 'market-control' alignment to incentivise and activate targeted provision of grid services in the form of Electric Products when and where most needed;
- Co-optimise the provision of grid services across the vertical Tiers/Layers of the Power System to both enhance operations and maximise the Electric Product Value for participants;
- Mitigate or avoid legacy Architectural Issues[94] that impede the Scalability, Extensibility and Resilience of Operational Coordination models; and,
- Ultimately enable transition to a more holistic Transmission-Distribution-Customer (TDC) model of Operational Coordination customised to local industry structure arrangements.

Co-optimisation

Co-optimisation is a structured approach to ensuring that Energy Resource services dispatched and/or financially incentivised in one vertical Tier/Layer of the Power System (e.g. Bulk Power, Transmission or Distribution System) are not driving unintended negative consequences in other Tiers/Layers of the system.

[94] Refer Key Concepts B

4. EXAMPLE NEM HYBRID ARCHITECTURE

4.1. Background to Hybrid Architectures

A Hybrid Architecture is one in which the functional responsibilities for transacting with, coordinating the operation of, and generally managing the system impacts of DER/CERs are shared between the Market/System Operator (MSO) and the Distribution System Operator (DSO). This sharing of functional responsibilities drives the approach to Operational Coordination and its underpinning architecture described in this section, which is then contrasted with the Layered Architecture alternative in the subsequent section.

When considering the transformation of Power Systems and their attendant Systems Architecture, it is understandable that Hybrid type models will have strong intuitive appeal. On the face of it, this is because they appear to minimise the significance of structural shifts and are more politically achievable. Recognising that these may be necessary goals for transitionary steps in any change process, it is also necessary to consider whether such models are actually capable of scaling to and efficiently supporting a future even broadly similar to AEMO's Step Change scenario.

While Hybrid models initially may appear to be a simpler option, they can ultimately exacerbate operational complexity which will drive significant scalability issues. For example, in a report prepared for AEMO by the Newport Consortium comparing different approaches globally an in Australia, the following was noted:

> *"Several future approaches under discussion internationally are based on the Hybrid DSO model and would seem to be attempts to have it both ways. However, this introduces complexity in structure and roles and responsibilities and therefore coordination processes. This is manageable at lower levels of DER market and network services participation but will face scalability issues as DER participation grows."* [95]

In addition, some initiatives have employed the Smart Grid Architecture Model (SGAM) for conceptual architecture mapping. While SGAM can provide some useful insights, it was developed for the specific purpose of analysing data flows in Smart Grid project use cases. As such, it lacks any comprehensive methodology for performing the detailed analysis of all seven interdependent structures that constitute a modern Power System.

By comparison, Figures 24 – 29 below map one of the various Hybrid model proposals, employing the Network of Structures model to visualise the relationships between the four Functional Layers in such a model. These are followed by some high-level observations about this type of architecture.

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[95] Coordination of Distributed Energy Resources; International System Architecture Insights for Future Market Design, Newport Consortium, 2018

4 x Functional Layers – Example Hybrid Architecture

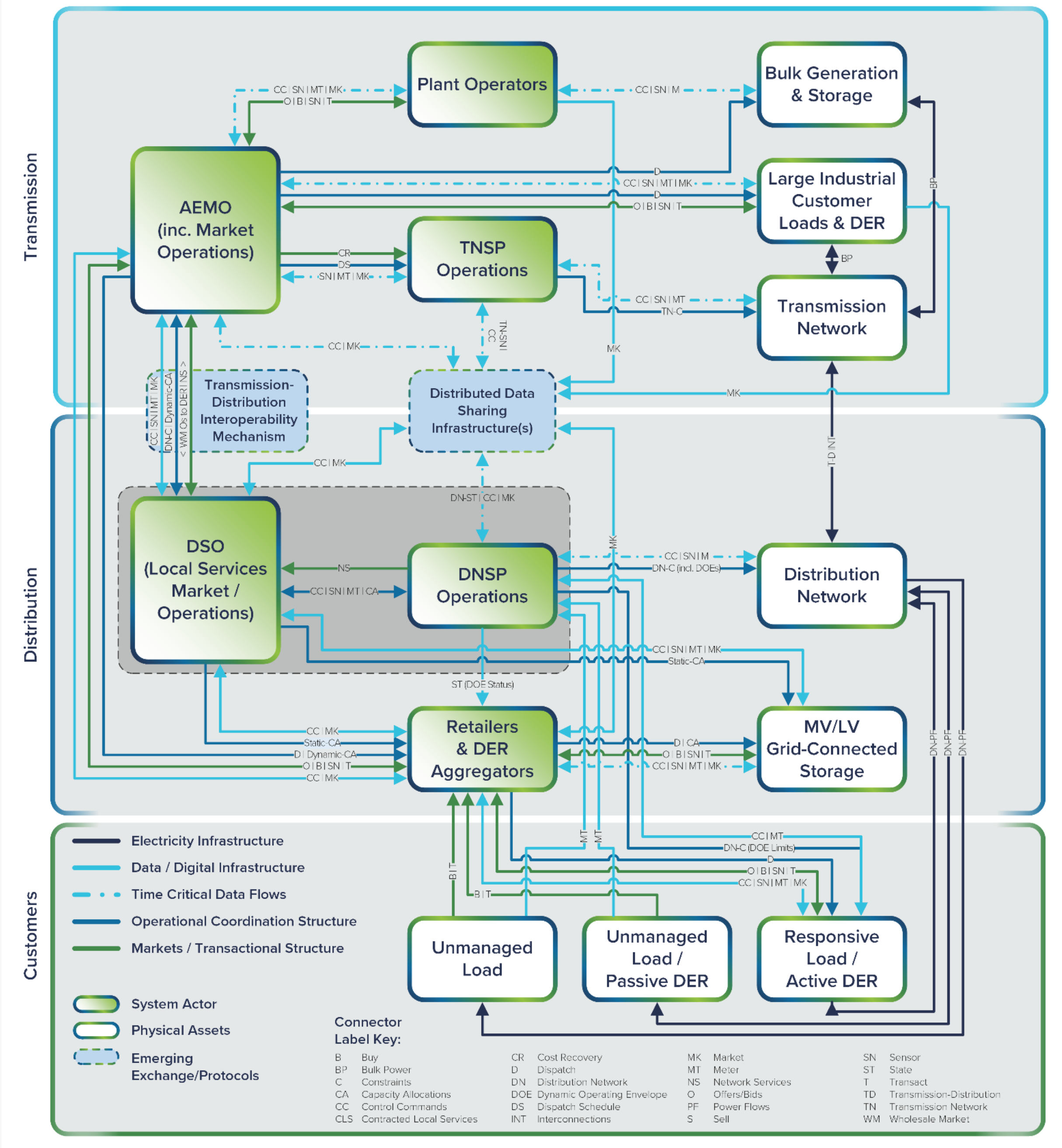

Figure 24: Four Functional Layers – Example Hybrid Architecture

Electricity Infrastructure – Example Hybrid Architecture

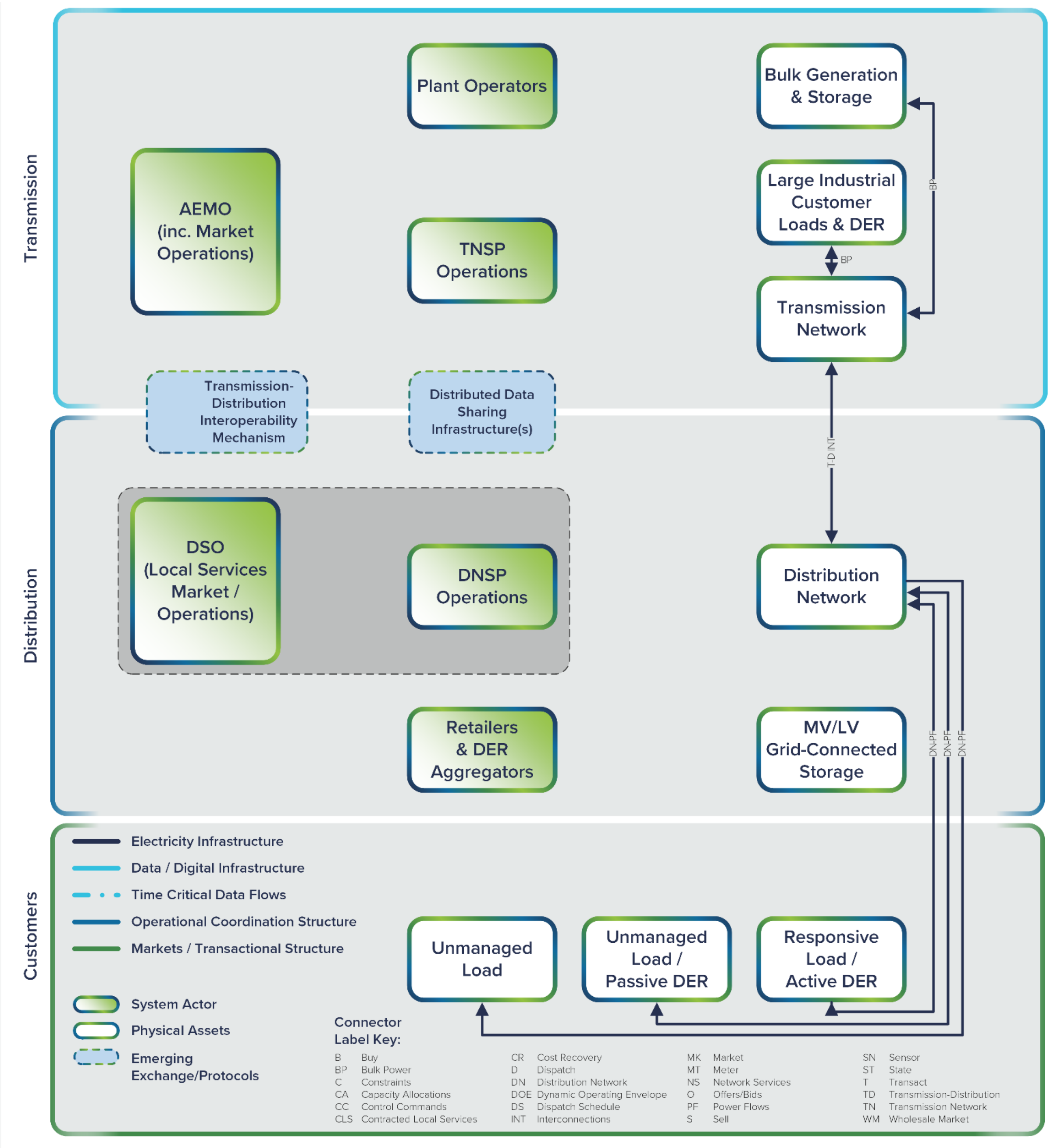

Figure 25: Electricity Infrastructure – Example Hybrid Architecture

Data / Digital Infrastructure – Example Hybrid Architecture

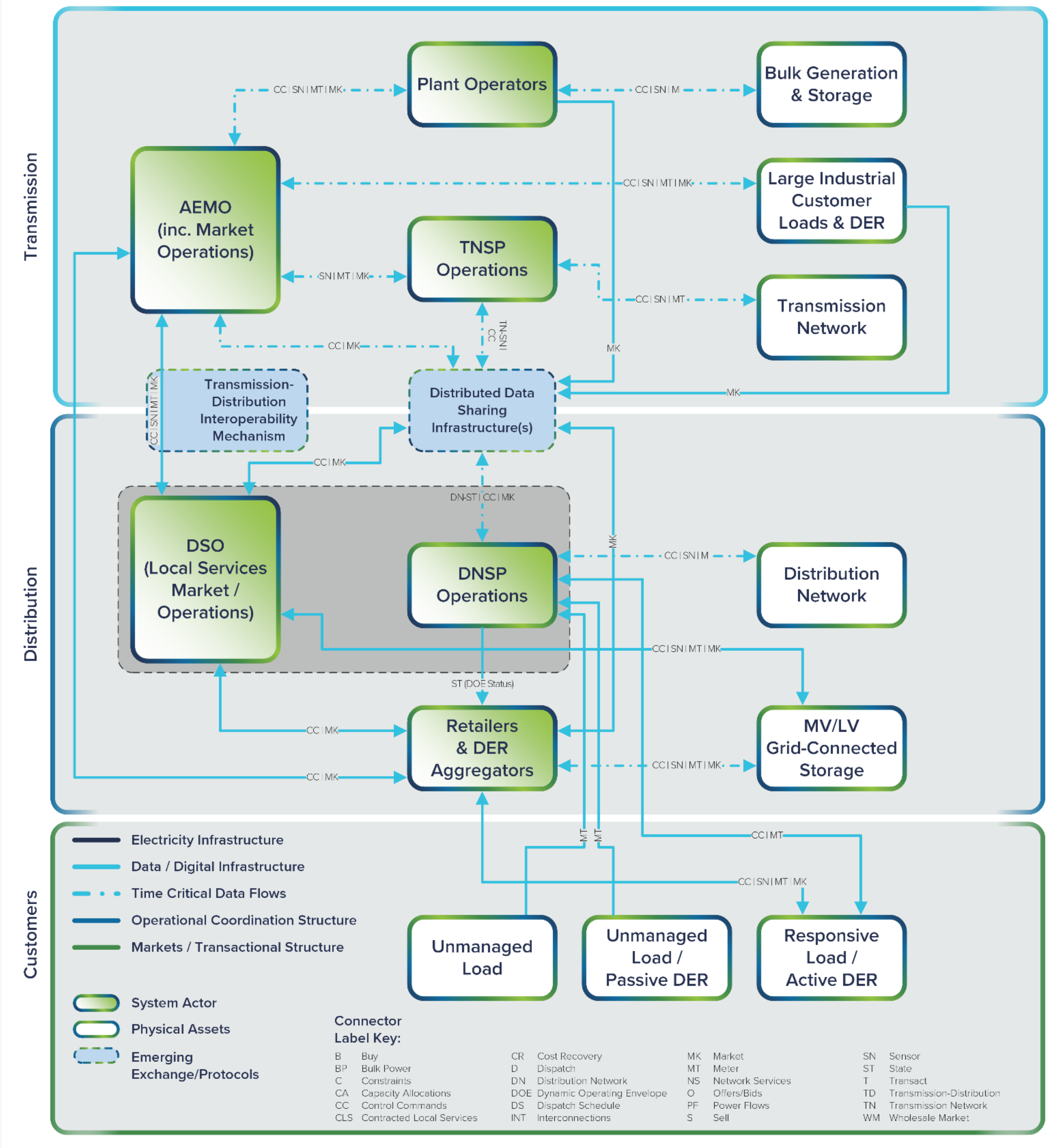

Figure 26: Data / Digital Infrastructure – Example Hybrid Architecture

Operational Coordination Structure – Example Hybrid Architecture

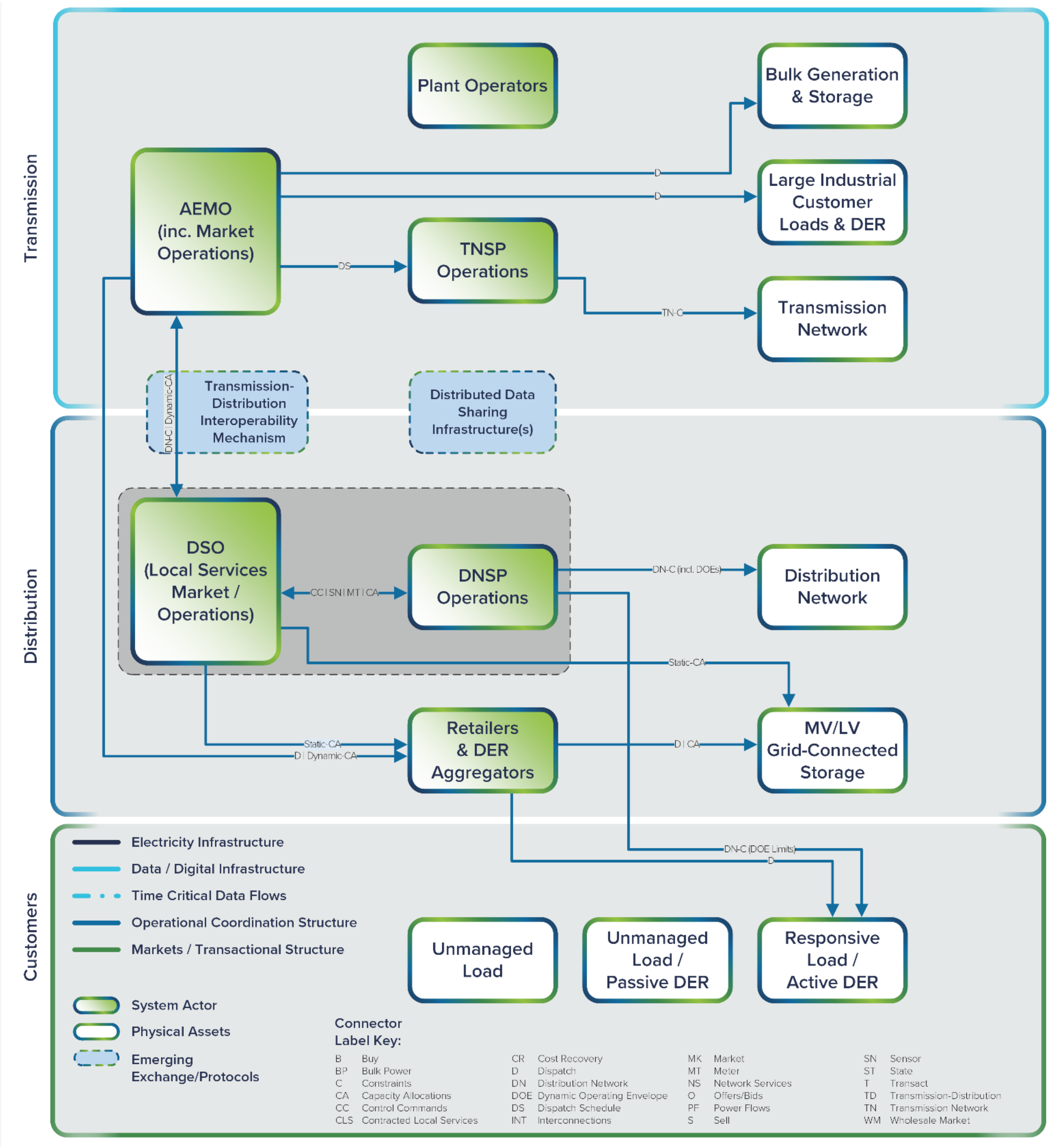

Figure 27: Operational Control Structure – Example Hybrid Architecture

Market and Transactional Structure – Example Hybrid Architecture

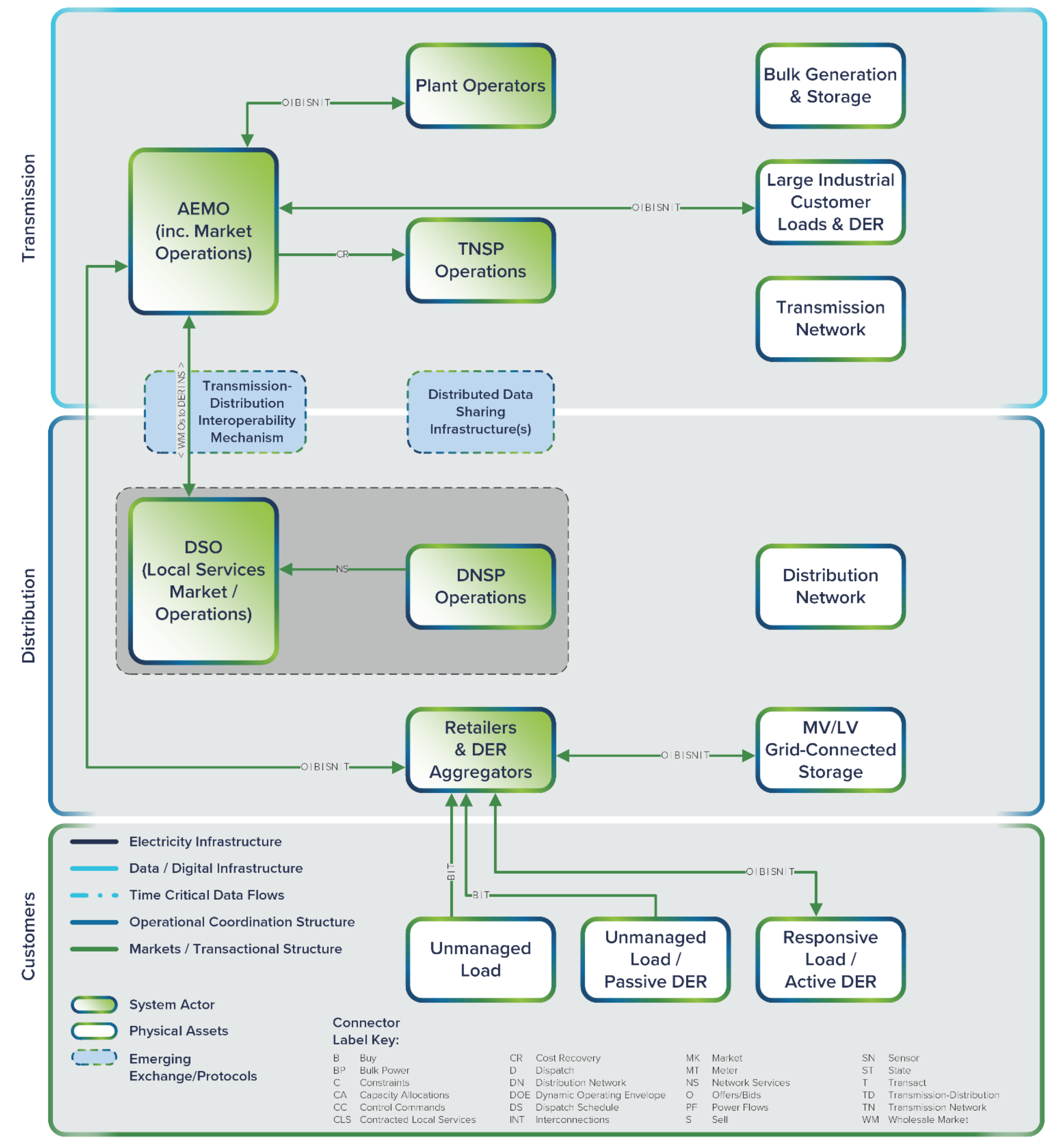

Figure 28: Market and Transactional Structure – Example Hybrid Architecture

4.2. Observations about an Example Hybrid Architecture

The example Hybrid model mapped above introduces the Distribution System Operator (DSO) concept, which has the potential to resolve a number of scaling problems while preventing some Tier/Layer Bypassing and Hidden Coupling issues from arising.

In addition, a potentially well-delineated Data and Coordination interface between Transmission and Distribution Systems is defined to match the Electrical Infrastructure interface, offering the opportunity to more efficiently allocate Roles & Responsibilities to coordinate the Bulk Power and Distribution Systems.

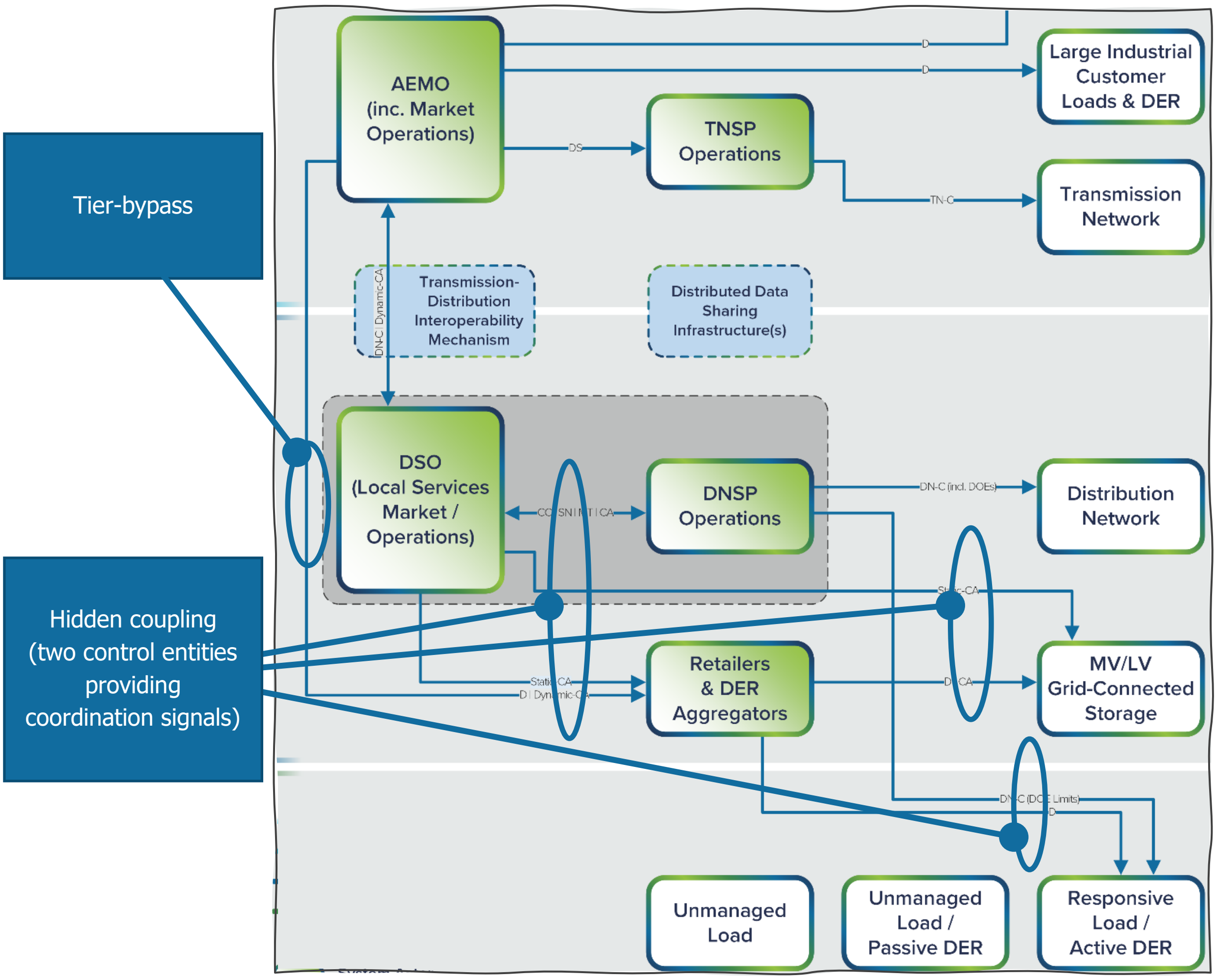

Figure 29: Hybrid Architecture - Operational Coordination Structure Annotations

Unfortunately, however, the Hybrid example has multiple examples of Tier/Layer Bypassing and Hidden Coupling which are structural flaws whose shortcomings have already been mentioned. These are apparent in the Operational Coordination Structure but may not be obvious until it is viewed in combination with the Electrical Infrastructure diagram, which is where the coupling outcomes actually manifest.

In addition, the DSO does not appear to make valuable use of the DER/CER since market functions for them flow through the Retailers/Aggregators to AEMO, so its function is not apparent.

Constraint Allocation is split into two groups that originate with two different sources. Beyond the problematic Hidden Coupling issues, the lack of coordination of DOE values means that there is no structurally supported way to resolve constraint allocation optimisation problems. Assuming there is a desire for such optimisation to maximise use of distribution Feeder capacity, when this becomes apparent, some additional paths involving multiple organisations will likely be created with the result of expanding complexity and latency cascading as data is passed from entity to entity and back to resolve the allocations.

5. EXAMPLE NEM LAYERED ARCHITECTURE

5.1. Background to Layered Architectures

As noted earlier, AEMO recognises that Australia's GW-scale power systems must be capable of operating reliably during periods where 100% of instantaneous demand is served by variable sources. Further, based on extensive consultation, AEMO also notes that the 'Step Change' scenario is overwhelmingly recognised by stakeholders as a highly plausible in the NEM.

The Step Change scenario meets Australia's net zero policy commitments and reflects technology advancements, government ambitions and consumer preferences. Under this scenario, compared with 2021 levels, the NEM will need to accommodate:

- **9x Centralised VRE:** A nine-fold increase in the installed capacity of utility-scale wind and solar VRE generation (from 15GW to 140GW);
- **5x Distributed VRE:** Almost a five-fold increase in the installed capacity of distributed solar VRE / DER generation (from 15GW to 70GW);
- **3x Dispatchable Firming Capacity:** A three-fold increase in installed firming capacity that can respond to a dispatch signal; and,
- **99% Electric Vehicles:** Almost the entire passenger vehicle fleet electrified.

In short, AEMO's Step Change scenario represents profound, transformational shifts for which the NEM must be strategically provisioned. Given this, while Hybrid models may be useful as transitionary steps, significant issues would need considered beforehand. Not least of these are whether such transitionary steps are indeed sufficiently scalable to a future state even broadly similar to the Step Change scenario. In short, there are reasons to question whether they are.

In contrast to Hybrid Architectures, Layered Architectures are demonstrably more scalable. Consistent with the principle of Layered Decomposition[96], as the name suggests such architectures provide for more layered delegations of responsibility. In this case, the Distribution System Operator (DSO) becomes primarily responsible for coordinating the local and wider system impacts of LV-connected DER/CERs. Through the specification of performance requirements at each Transmission-Distribution Interface, the Market/System Operator has assurance of wider system impacts, and is thereby freed of the need for comprehensive Visibility and Controllability into the lower levels of the Power System.

In this context, Figures 30 - 34 below apply the Power Systems Architecture discipline to map a Layered Architecture and visualise the relationships between the four Functional Layers in such a model. These are followed by some high-level observations about this type of architecture.

[96] Refer Key Concepts D

Key Concepts D

Layered Decomposition

A formally established mathematical technique employed in many technology sectors to solve Ultra Large-scale (ULS) optimisation problems characterised by highly coupled constraints.

In the case of Power Systems transitioning from hundreds to tens of millions of participating Energy Resources and experiencing growing levels of operational Volatility, Layered Decomposition provides an empirical basis for solving many critical Architectural Issues, including otherwise intractable Operational Coordination problems.

In contrast with more traditional hierarchical control, it enables highly complex problems to be decomposed multiple times into sub-problems, which then work in combination to solve the original problem in a manner that addresses long-term Scalability, Extensibility, Cyber-security and Resilience issues. Importantly, rather than 'competing' with other Architecture models currently or proposed for use in the power sector, Layered Decomposition provides a universal, canonical structure for unifying alternative models.

Distributed Data Sharing Infrastructure(s)

An arrangement for sharing data among multiple entities wherein each entity owns and controls its data and provides access on an authorised basis to others via a platform that federates or otherwise consolidates data in a logical fashion but not necessarily in a physically centralised data store.

Transmission-Distribution Interface (TDI)

The physical point at which the upstream Bulk Power and Transmission System and the downstream Distribution System interconnect, typically at one or several major substations. In a conventional, highly bifurcated Power System, these were traditionally known as the Supply-side and Demand-side respectively.

Power Systems that host growing volumes of Variable Renewable Energy (VRE) and Distributed Energy Resources (DER/CER) will experience significantly greater levels of Volatility, which can propagate upstream and downstream. Ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require much greater levels of dynamic inter-dependence across the TDI than in the past.

Transmission-Distribution Interoperability Mechanisms (TDIM)

The various existing and expanding number of emerging functions and protocols that need to be executed across the Transmission-Distribution Interface (TDI) in their formalised and automated form. Key areas of priority are expected to include enhanced, low latency data exchange relevant to Frequency control, Voltage control, Congestion management Energy flow, Power-based services and System Balancing.

Underpinned by appropriate decisions about the enabling Cyber-physical Architecture, the TDIM will play a key role in supporting next generation Visibility, Operational Coordination and Resource Adequacy analysis.

4 x Functional Layers – Layered Architecture

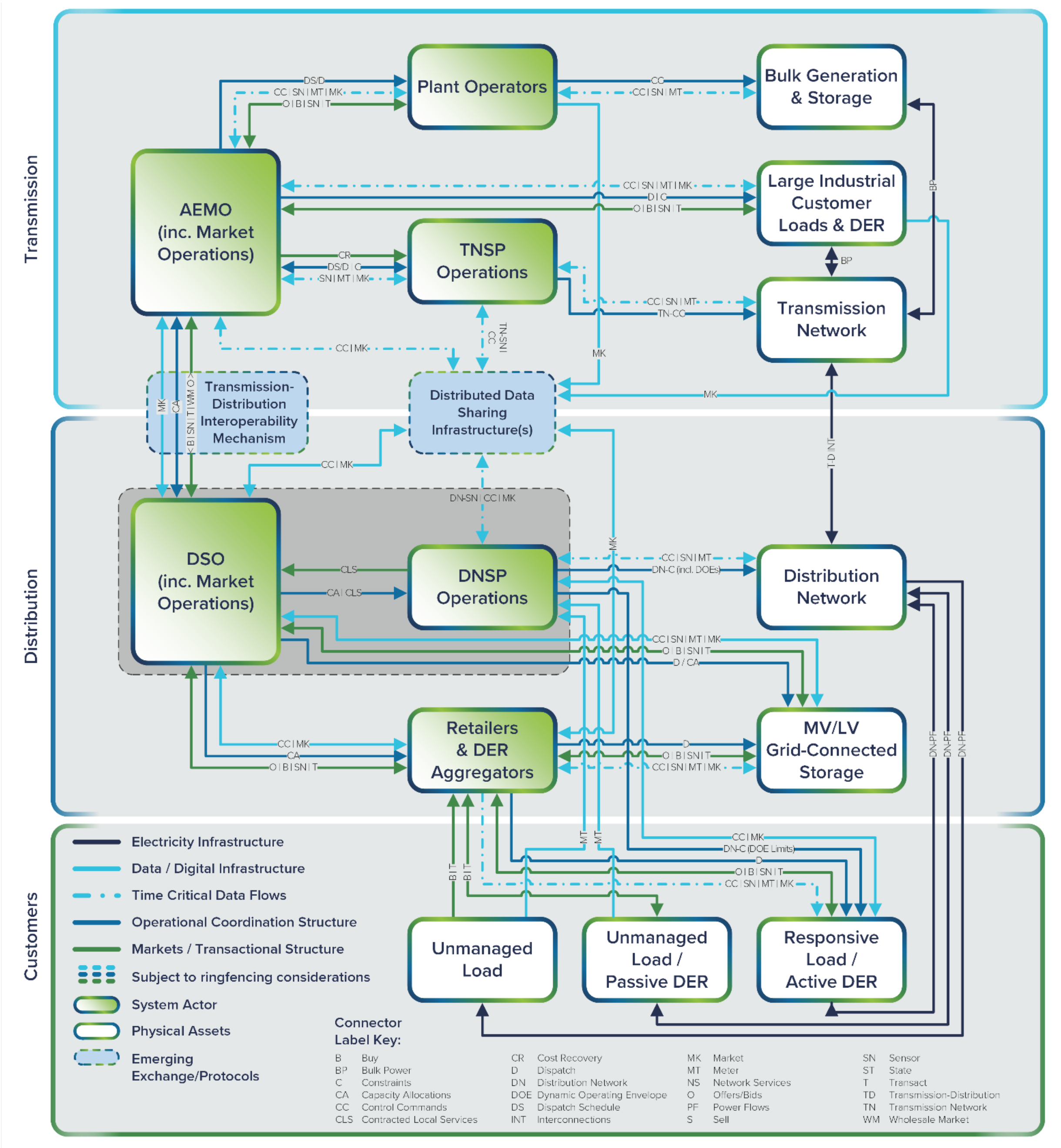

Figure 30: Four Functional Layers – Plausible Step Change Future State

Electrical Infrastructure – Layered Architecture

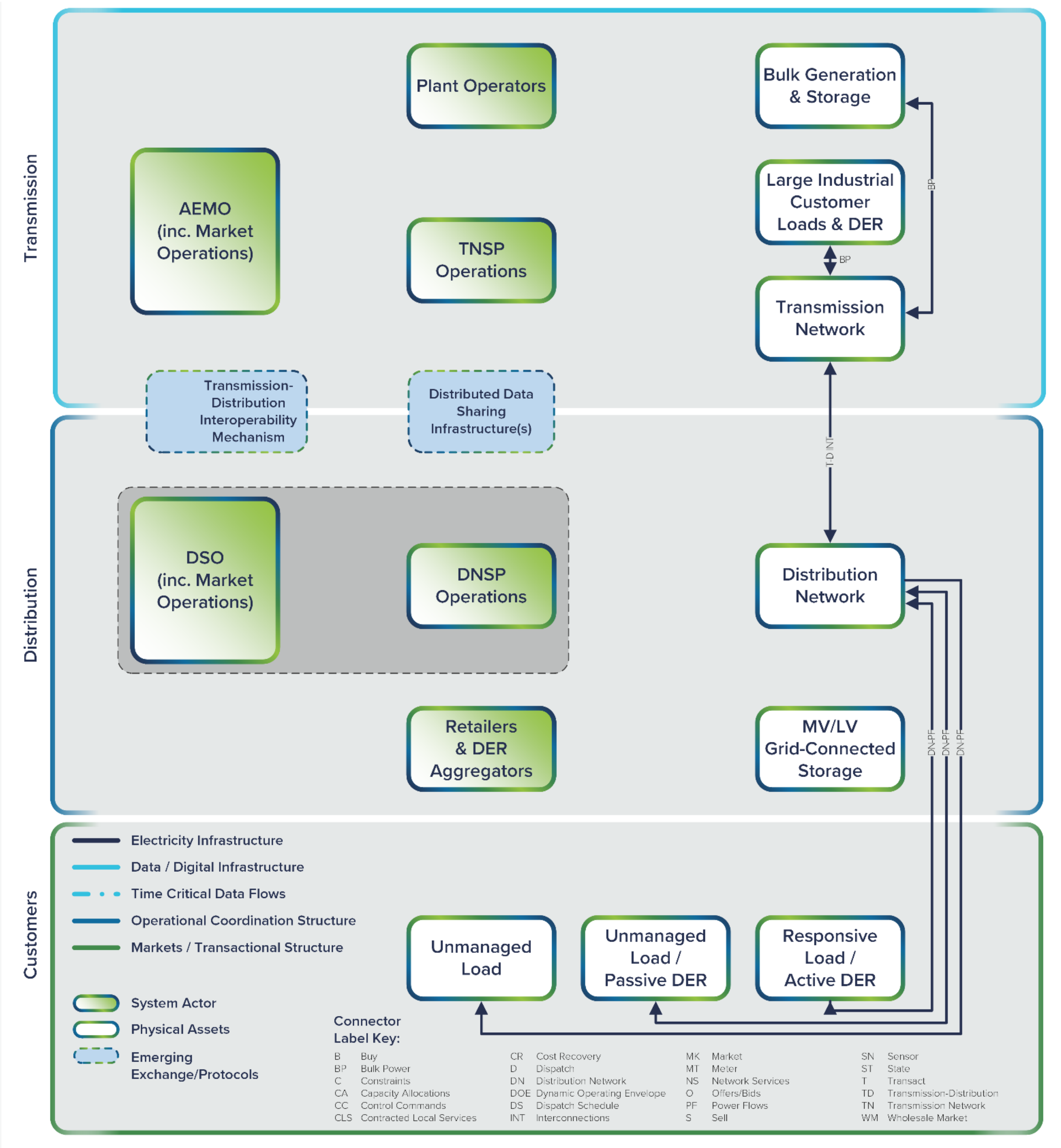

Figure 31: Electrical Infrastructure – Plausible Step Change Future State

Operational Coordination Structure – Layered Architecture

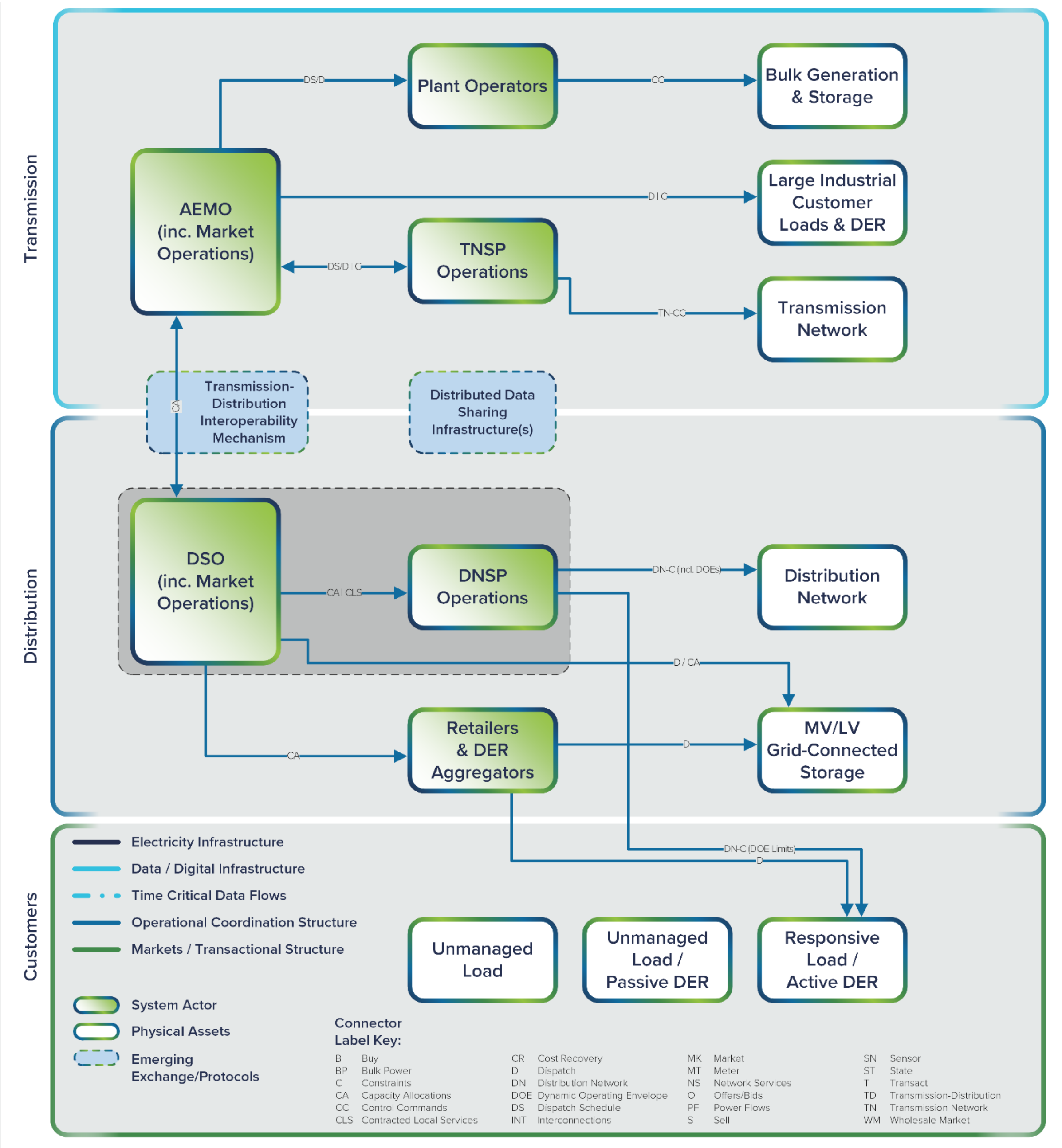

Figure 32: Operational Coordination Structure – Plausible Step Change Future State

Market and Transactional Structure – Layered Architecture

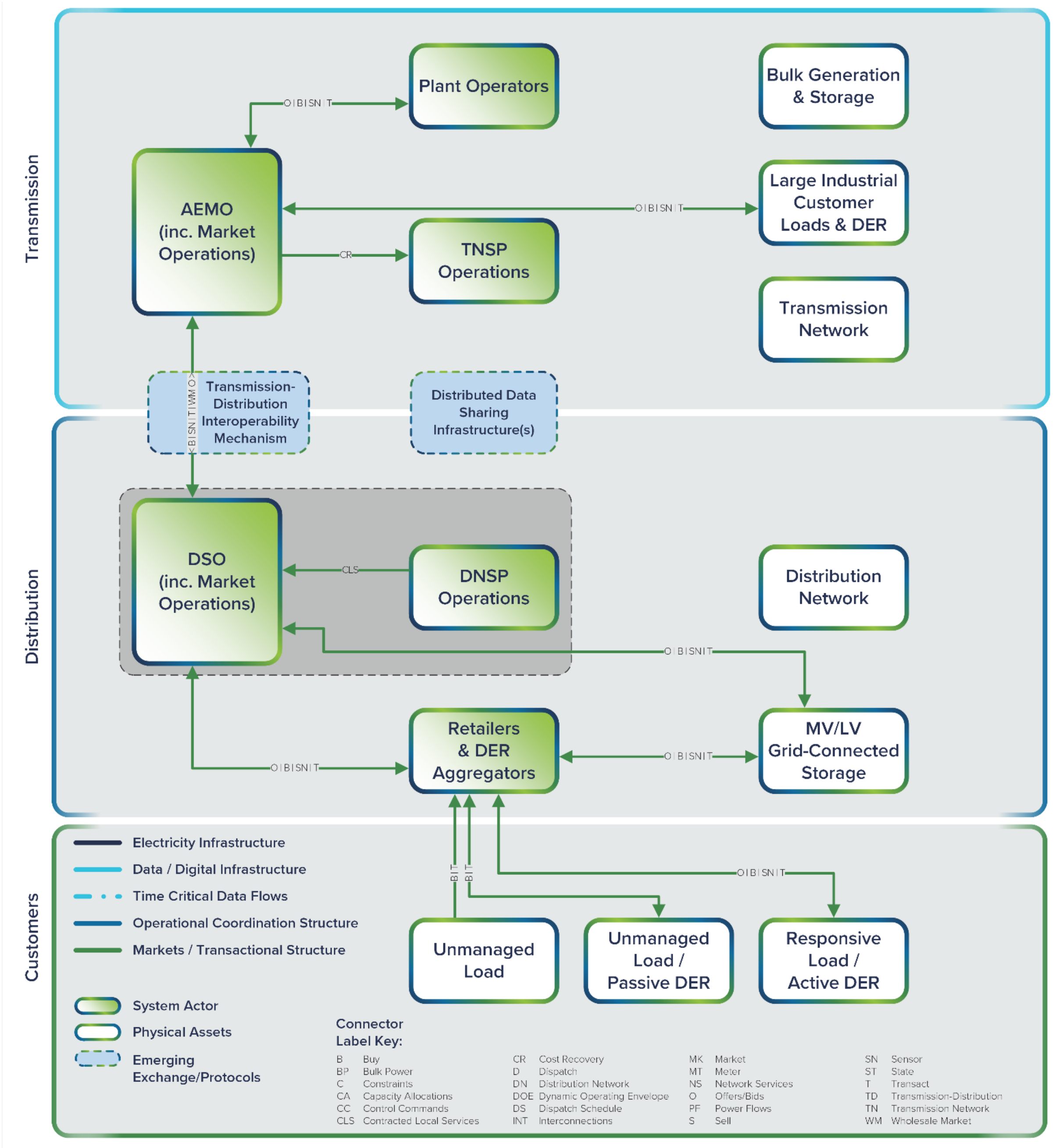

Figure 33: Market and Transactional Structure – Plausible Step Change Future State

Data / Digital Infrastructure – Layered Architecture

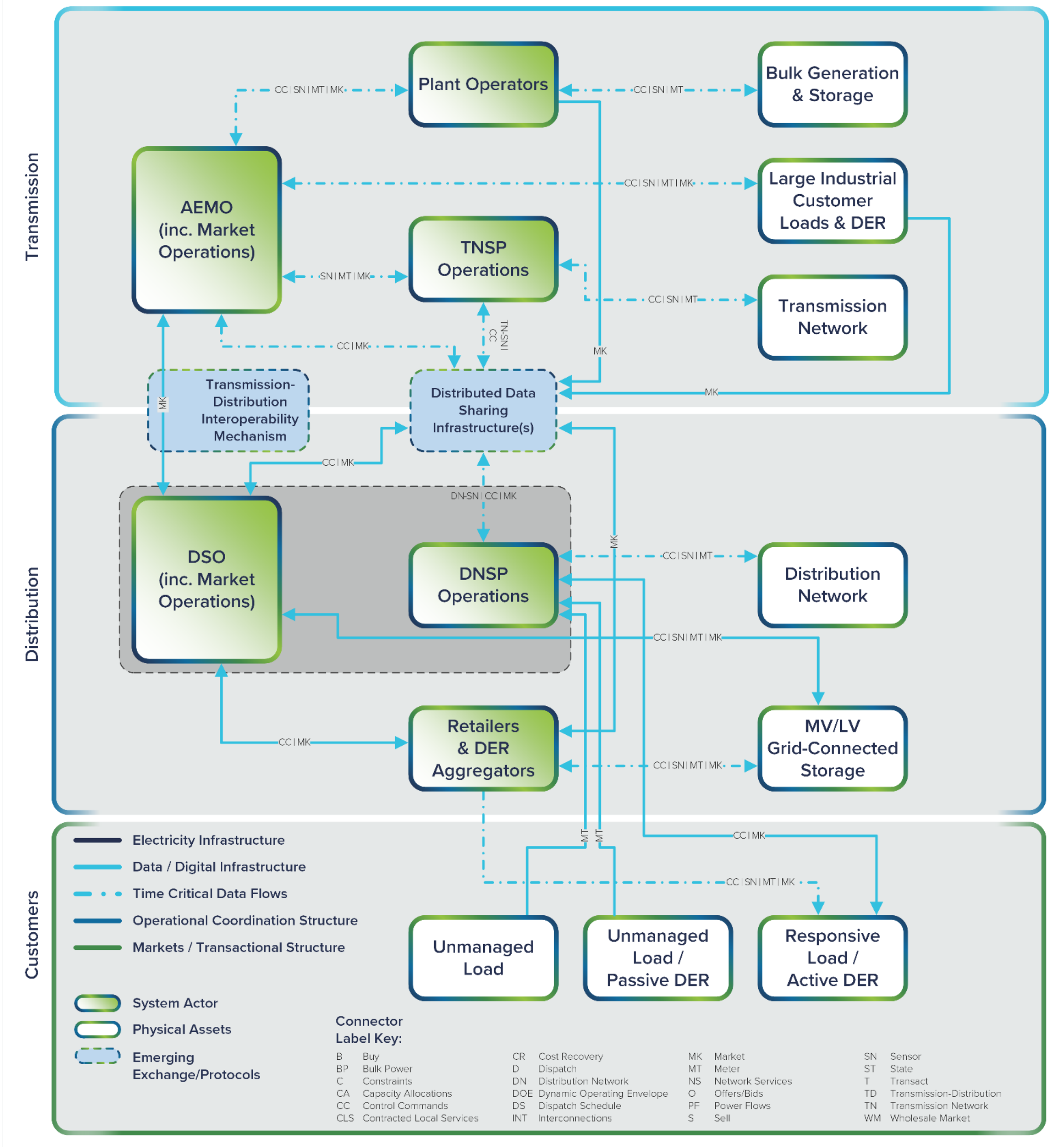

Figure 34: Data / Digital Infrastructure – Plausible Step Change Future State

5.2. Observations about Example Layered Architecture

The Layered Architecture has a very clean interface between Transmission and Distribution Systems, making allocation and implementation of Roles & Responsibilities straightforward and efficient. Tier/Layer Bypassing is eliminated, and Hidden Coupling is minimised, assuming that MV/LV grid-connected storage actually consists of two disjoint sets where one set is operated directly by the DSO and the other is operated indirectly where DSO commands are passed through the Aggregator. In this case, the Retailer/Aggregators must not alter the storage commands.

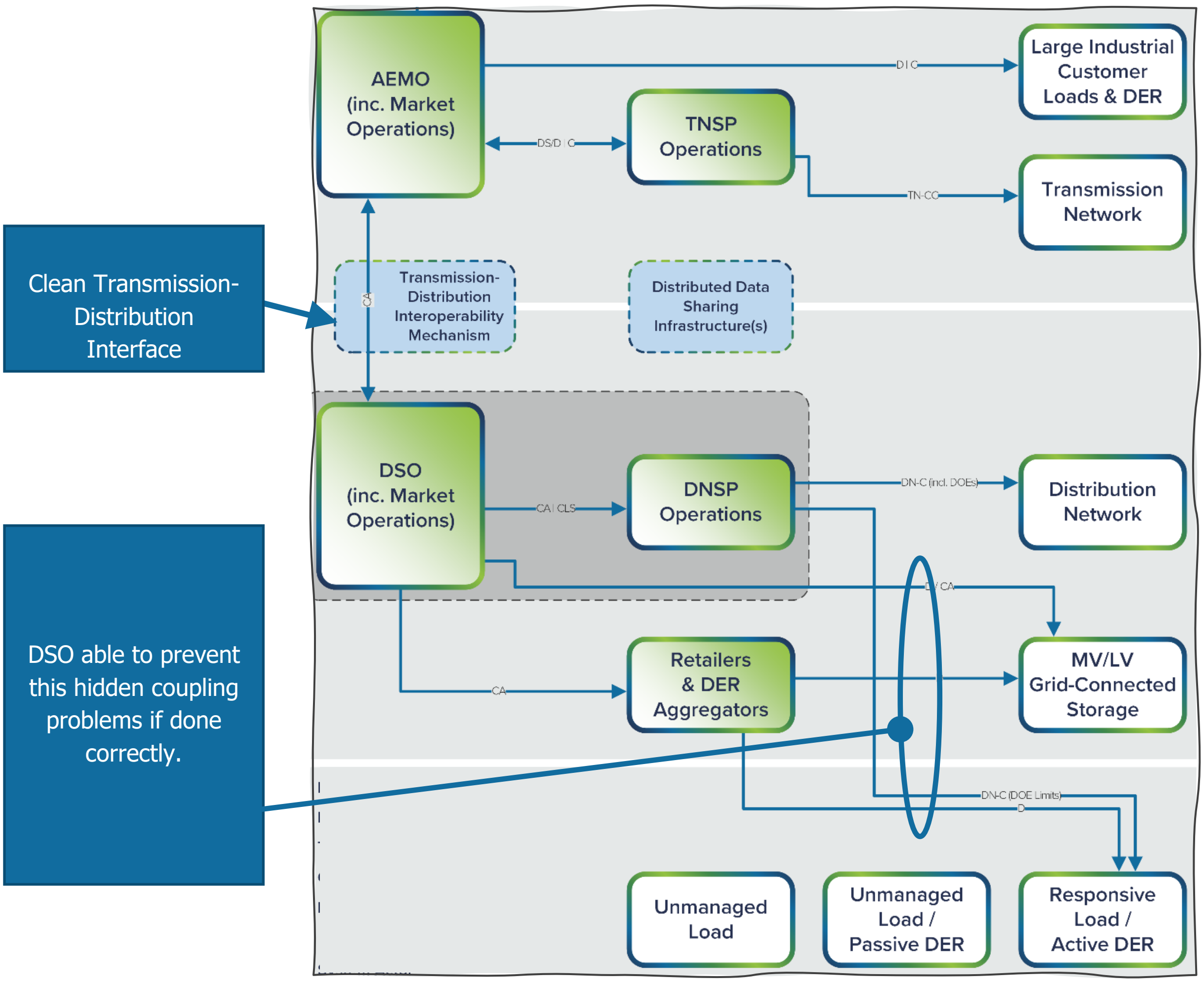

Figure 35: Layered Architecture - Operational Coordination Annotations

The issue of optimal dynamic capacity allocation via Dynamic Operating Envelopes (DOEs) can also be resolved under this structure where the optimisation is carried out by the DSO, which requires that the Retailers and Aggregators provide information to the DSO on each DOE update cycle.

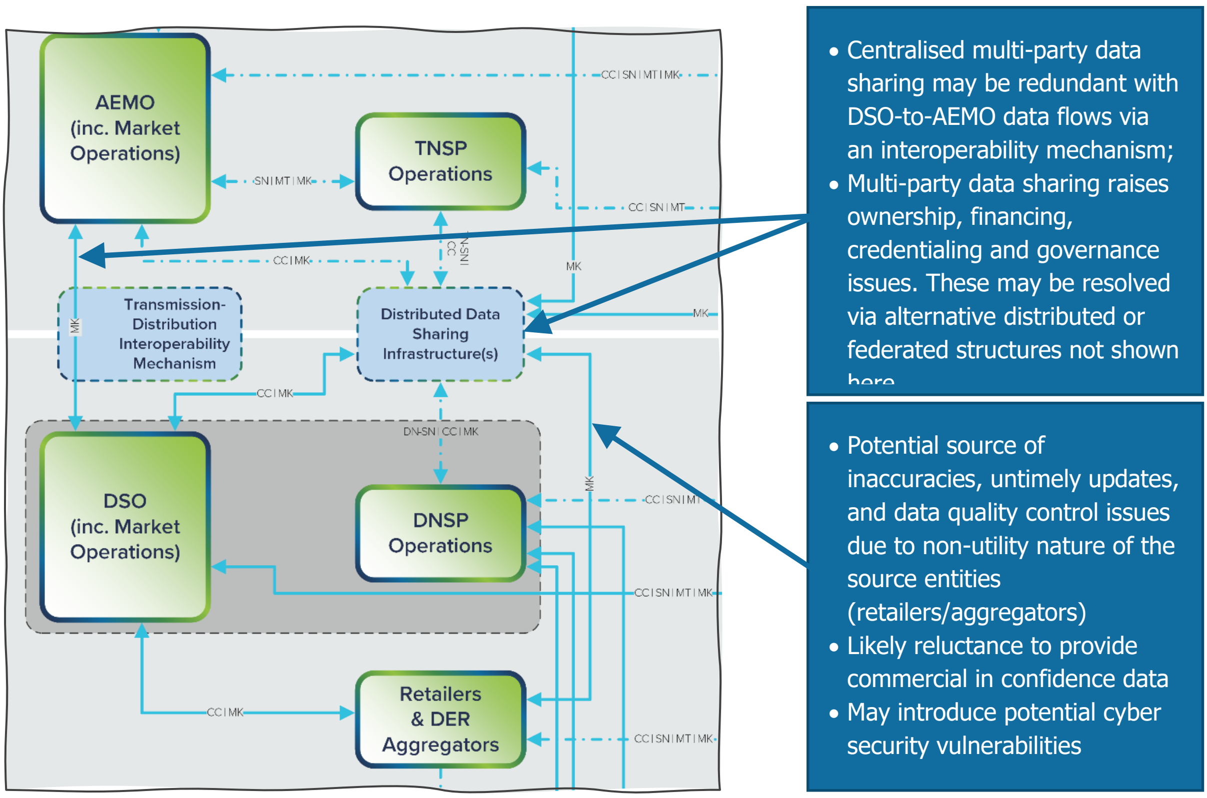

Figure 36 - Layered Architecture - Digital Infrastructure Annotations

Some other matters that may benefit from consideration include whether the Distributed Data Sharing Infrastructure would be redundant with the Transmission-Distribution Interoperability Mechanism.

In addition, the specification of such infrastructure(s) also presents questions about Roles & Responsibilities related to its implementation and operation, the ownership and access control for the data, and cost allocation. It may also pose cyber-security issues due to the related structural data routings.

More broadly, dynamic capacity allocation optimisation may become problematic due to scaling issues and latency stacking as DER/CER volumes continue to expand, a situation that is further complicated by interpenetration of Retailer/Aggregator connections to DER/CER.

Appendices

APPENDIX A: PROJECT TEAM

APPENDIX B: INTERNATIONAL EXPERT PANEL

APPENDIX C: STAKEHOLDER ENGAGEMENT

APPENDIX D: FUTURE POWER SYSTEM GLOSSARY

APPENDIX A: PROJECT TEAM

Mark Paterson

Lead Systems Architect

Mark Paterson is a globally respected energy system transformation leader with over 25-years of experience in power systems, applied science, systems architecture and thermal and fluid systems. He is known for his expertise in leading the collective navigation of complex and contested issues, systems thinking and the co-design of transformation pathways that build social licence and deliver future-resilient outcomes.

Mark's theoretically robust but pragmatic approach is grounded in applied technology origins and Engineering, Business and Master of Enterprise qualifications. He has been formally trained in Systems Architecture & Engineering disciplines at Massachusetts Institute of Technology and the Power Systems Architecture methodologies developed through the US Department of Energy's Grid Modernisation Laboratory Consortia.

Mark is a Fellow of the Pacific Energy Institute, an invited Associate of the GridWise Architecture Council (GWAC), an IEEE Power & Energy Society contributing author and an invited expert contributor to Asia-Pacific Economic Cooperation (APEC) grid resilience activities.

Dr Jeffrey Taft

Key Technical Advisor

Dr Jeffrey Taft was formerly the Chief Architect for Electric Grid Transformation at Pacific Northwest National Laboratory. He has played a seminal role in the development of Grid Architecture methodologies through the US Department of Energy's Grid Modernization Laboratory Consortia. He was also a co-lead for the US DOE's Modern Distribution Grid (DSPx) initiative.

Jeff draws on his unique multi-disciplinary industry experience including electric power systems, software, communications, sensors and signal processing, and control systems, as well as extensive skills and experience as a system architect. Focused on large scale architecture for grid modernization, the Future Power Grid Initiative, advanced computing, and the Control of Complex Systems Initiative

Matthew Bird

Development Team

Matthew Bird is a Systems Engineer and has been a key contributor to both Stage 1 and 2 of architecture work. He co-authored the Customer and Societal Objectives Synthesis Report, and Emerging Trends report, and co-produced the Functional Layer diagrams for current, hybrid and Step Change future state NEM. Previously, Matthew supported the Control Room of the Future work undertaken by EPRI for AEMO, collaboratively iterating diagrammatic architectural representations.

Stephen Wilson

Section 3 - Contributing Author

Stephen Wilson is an engineer and energy economist with 30 years' experience in projects across 30 countries in strategy and policy advice. He has worked in industry, as a consultant, for governments, and in university teaching and research. His experience in energy economics and finance, policy and strategy, project development, new technology research and commercialisation, has variously involved work in or related to markets for electricity, gas, renewable energy, carbon emissions, uranium, oil, coal and steel.

Dr Archie Chapman

Section 3 - Contributing Author

Dr Archie Chapman is a Senior Lecturer in Computer Science at the University of Queensland in the School of IT and Electrical Engineering. Coming from a multi-disciplinary background of economics, mathematics, multi-agent systems and computer science, Archie develops and applies principled artificial intelligence, game theory, optimisation and machine learning methods to solve large-scale and dynamic allocation, scheduling and queuing problems. His applied research focuses on applications of these techniques to problems in future power systems, such as the integration of very large numbers of distributed energy resources and flexible loads and harnessing them to provide power network and system services, while making best use of legacy network and generation infrastructure.

APPENDIX B: INTERNATIONAL EXPERT PANEL

The following experts have provided invaluable input to this body of work.

Prof. Jose Pablo Chaves Avila

Deputy Director at Instituto de Investigación Tecnológica (EU/Spain)

Prof. Jose Pablo Chaves Avila is a researcher at the Institute for Research in Technology (IIT) and professor at the Engineering School (ICAI) of the Comillas Pontifical University.

Jose is engaged with several of the EU's Horizon 2020-funded projects including OneNet and CoordiNet which are establishing future system architecture and coordination schemes between transmission system operators (TSOs), distribution system operators (DSOs) and consumers to contribute to the development of a smart, secure and more resilient energy system. He is also a member of the Expert Group on Demand Side Flexibility of the European Union Agency for the Cooperation of Energy Regulators.

Paul De Martini

Executive Director, Pacific Energy Institute (USA)

Paul De Martini is a globally recognised expert on the business, policy and technology dimensions of a more distributed power system. He works with utility, regulatory and government clients on the practical application of architecture for industry transformation, including DER market integration, integrated system planning, and grid modernisation.

Over the past decade, Paul has supported 12 of the largest US electric utilities, over 20 US state regulatory commissions, market operators in Australia, Canada and the US in their transformation efforts. Paul is the lead for the US Department of Energy's Transmission-Distribution-Edge Operational Coordination initiative and is a principal contributor to distribution resilience planning and grid modernization.

Dr Jeffrey Hardy

Senior Research Fellow at Imperial College London (UK)

Dr Jeffrey Hardy has over 20-years of academic, policy and business experience in sustainable energy. He has helped clients around the world understand, and plan for the implications of zero-carbon futures on business models and strategy, consumers, customers and citizens, policy and regulatory frameworks and energy systems.

As a Senior Research Fellow at Imperial College London, Jeff led a UK Energy Revolution Research Consortium team examining the policy and regulation of smart local energy systems. Previously he was Head of Sustainable Energy Futures at Ofgem and Head of Science for Work Group III of the Intergovernmental Panel on Climate Change.

Prof. Amro M. Farid

Alexander Crombie Humphreys Chair Professor of Economics in Engineering, Stevens Institute of Technology

Prof. Farid Amro has extensive electric power, automotive, semiconductor, defense, chemical, and manufacturing sector experience. In 2010, he began his academic career as a visiting scholar at the MIT Technology Development Program and the Masdar Institute of Science and Technology (UAE). In 2014, he founded Engineering Systems Analytics LLC as a startup engineering software and consulting company to provide techno-economic insight to energy and infrastructure operators. In 2021, he became a Fulbright Future Scholar to investigate the energy-water-hydrogen nexus in Australia.

Amro has made active contributions to the MIT Future of the Electricity Grid Study, the IEEE Vision for Smart Grid Controls, and the Council of Engineering Systems Universities. He currently serves as Chair of IEEE Smart Cities R&D Technical Activities Committee, and Co-Chair of the IEEE Systems, Man & Cybernetics (SMC) Technical Committee on Intelligent Industrial Systems. He is a senior member of the IEEE and a member of the ASME and INCOSE.

Prof. Lynne Kiesling

Co-Director, Institute for Regulatory Law & Economics, University of Colorado (USA)

Prof. Lynne Kiesling is an international thought-leader focused on advanced electricity pricing models that use transaction cost economics to examine regulation, market design, and technology in the development of retail markets, products and services and the economics of smart grid technologies in the electricity industry.

Lynne has served as a member of the GridWise Architecture Council (GWAC) which seeks to articulate the guiding principles for an intelligent, transactive, energy system of the future, and to guide and promote measures to transform electricity systems into a more reliable, affordable, secure network in which users collaborate with suppliers in an information and value-rich market environment.

Dr Lorenzo Kristov

Power Markets & System Architecture Expert (USA)

Dr Lorenzo Kristov is a globally recognised expert focusing on reforming the electric power system to integrate high levels of renewable generation and distribution-connected energy resources (DER). Lorenzo is currently advising the EPRI TSO-DSO Interface Project and engaging across numerous FERC 2222 matters relating to system-level integration of DER.

Based on 18 years as a Principal in market design and infrastructure policy at the California Independent System Operator (CAISO), his expertise includes: wholesale power market design; DER participation in wholesale markets; coordination of transmission & distribution operations, markets and planning; distribution system operator (DSO) models; distribution-level markets; energy resilience strategies and microgrids; and whole-system grid architecture.

Phil Lawton

Energy Systems Catapult (UK)

Phil Lawton has over 40 years of experience of the energy sector, covering transmission and distribution, electricity and gas, project and line management roles, and work with both industry and government. This experience has included both the UK and international engagement.

Phil has been involved in Future Power Systems Architecture programme from the start of the project and led a great deal of project engagement with industry. Previously, Phil worked at National Grid as a Future System Operation Manager and was seconded to the Department of Energy and Climate Change.

Dr Ron Melton

Director, Pacific Northwest National Labs Smart Grid Demonstration Project (USA)

Dr Ron Melton is a Senior Technical Advisor in the Electricity Infrastructure and Buildings Division at Pacific Northwest National Laboratory (PNNL). He is a member of the core team for the DOE Grid Architecture project, and Administrator of the GridWise® Architecture Council.

Previously Ron was the Group Leader of the Distributed Systems Group. He was the original Principal Investigator for the DOE Advanced Grid Research project for an ADMS Open-Source Platform. He was the Project Director of the Pacific Northwest Smart Grid Demonstration that concluded in June 2015.

Francis Mosley

Senior Innovation and Systems Engineer at Ofgem

Francis Mosley works with Ofgem strategy teams to develop thinking on the longer-term issues associated with the UK's transition to a decarbonised, fair and efficient future energy system, with a particular focus on flexibility, storage, data and digitalisation. He has supported the development and delivery of energy company innovation through initiatives such as the Strategic Innovation Fund, the Network Innovation Competition and Network Innovation Allowance. Francis also assists with the development of key areas of transmission and distribution policy.

Dr Seemita Pal

Senior Research Engineer, Pacific Northwest National Labs

Dr. Seemita Pal is a Senior Research Engineer and the Team Leader of the Systems Engineering Team in the Distributed Systems Group at Pacific Northwest National Laboratory (PNNL). She is leading research projects funded by the Department of Energy, and her areas of focus include grid architecture, grid cybersecurity, synchrophasor technologies and power systems. Dr. Pal is a member of PNNL's Grid Architecture core team, and a member of both SEPA Grid Architecture and Cybersecurity Working Groups. She was recognized with the IEEE Member and Geographic Activities (MGA) Achievement Award in 2019.

APPENDIX C: STAKEHOLDER ENGAGEMENT

This body of work was informed by extensive engagement with expert stakeholders and also afforded the opportunity to disseminate key insights broadly. As project sponsors, Strategen also worked closely and collaboratively with nominated AEMO and CSIRO staff in delivering this phase of work. The following table provides a high-level view of stakeholder engagement activities.

Stakeholder Group	Meetings/Workshop Convened
Project Design, Execution & Review	
AEMO, CSIRO & GHD – Project Steering Group (PSG) Communication and collaboration meetings to: a) monitor progress; b) align and calibrate Topic 7 activities with G-PST and Engineering Framework activities; and, c) review progressive deliverables.	Meetings held fortnightly throughout project execution, alternating between check-ins and extended detailed document review, workshopping and discussion.
International Expert Panel (IEP) Periodic meetings to: a) review key content and seek a diversity of expert feedback; b) seek guidance on specific unchartered and/or contested matters; and, c) provide an opportunity for AEMO and CSIRO to seek wider input on G-PST and Engineering Framework activities.	23 August 2022 – Project Orientation 16 November 2022 – Customer and Stakeholder Objectives Review 23 February 2023 – Emerging Trends Review 15 March 2023 – Systemic Issues Review
Customer & Industry Stakeholder Groups (CISG) Periodic meetings to: a) selectively share and test content of relevance to stakeholders; b) progressively upskill a the CISG as an initial 'community of advocates' and early-stage PSA practitioners; and, c) seek process guidance on engaging with specific target groups and/or general stakeholder outreach.	21 September 2022 – Project Overview (Option 1) 29 September 2022 – Project Overview (Option 2) 10 November 2022 – Initial Findings (Option 1) 17 November 2022 – Initial Findings (Option 2) 24 March 2023 – Industry Briefing 24 March 2023 – Regulatory and Market Bodies Briefing 24 March 2023 – Customer Representatives Briefing

APPENDIX D: FUTURE POWER SYSTEMS GLOSSARY

Future Power Systems Glossary

A shared resource to support global and multi-stakeholder collaboration on the transformation of the electric power systems.

BETA VERSION

1. Background & Status

1.1. Glossary Background

Around the world, GW-scale Power Systems are experiencing profound transformation. Central to this transformation is the shift from a supply-side dominant system to one that is increasingly hybridised. This is an operating context where:

- Generation is increasingly provided by diverse sources including centralised and decentralised, fossil fuel and variable renewable, dispatchable and non-dispatchable sources;
- Customer participation in producing, storing and trading electricity is increasing, and this is reshaping load profiles and wider system requirements; and,
- At the same time, concerns about social equity and the ability of all to participate in all aspects of the future energy system are increasing.

In practice, however, the whole-system integration of Variable Renewable Energy (VRE) and Distributed Energy Resources (DER) at scale across technological, market and regulatory structures is non-trivial. It is an inherently complex undertaking that spans numerous professional disciplines and long-standing industry siloes.

In addition, while the application of critical Systems Architecture disciplines to navigate otherwise intractable complexity is becoming more important, the understanding of related key concepts and terminology remains limited.

In this context, diverse stakeholder segments must now collaborate far more effectively in the development of whole-system solutions. Where significant gaps in shared concepts and terminology exist, however, timely collaboration on complex challenges becomes even more difficult.

1.2. BETA Status

This document has been developed as a collaboration between Strategen Consulting, Energy Catalyst and the Pacific Energy Institute. It provides an initial step toward providing a shared repository of 200 key concepts and general definitions that may support more effective stakeholder navigation of energy transformation.

The content is informed by a range of relevant international sources and, where possible, several sources have been compared and contrasted to inform definitions. However, as the topic of future power systems is evolving rapidly, all content should be considered BETA version status and subject to update.

1.3. Disclaimer

The Future Power System Glossary – BETA Version should be considered a 'living document' that will undergo continuous refinement and enhancement. The document provides general information only. Strategen Consulting, Energy Catalyst and the Pacific Energy Institute do not offer any warranty, express or implied, or assume any legal liability or responsibility for, the accuracy, completeness, or usefulness of the content.

2. Glossary & Concepts

2.1. Power Systems 101

2.1.1. Adaptability

The ease with which a System or Energy Resource can be modified for use in environments other than those for which it was specifically designed.

2.1.2. Adequacy

The ability of the Power System to supply the aggregate electrical Demand of customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

2.1.3. Behind the Meter (BTM)

Any technology located on the customer's side of the customer-network meter.

2.1.4. Bulk Power System

The large-scale generation resources, long distance transmission lines and associated equipment and interconnections upstream of customers and generally operated at voltages of 100kV or higher.

2.1.5. Controllability

The ability for the operation of a System or Energy Resource to be remotely altered in real-time and/or near real-time by an authorised third party.

2.1.6. Current

A flow of electrons in an electrical conductor. The strength or rate of movement of the electricity is measured in Amps.

2.1.7. Demand

The total amount of electricity required by one, many or all customers at a point of time. Measured in kW or MW.

2.1.8. Demand-side

The downstream end of traditional Power Systems where consumers have been located.

2.1.9. Embedded Network

A localised distribution system connected via a parent connection point to the wider Power System, and which is owned, controlled or operated by an entity other than a Network Service Provider.

2.1.10. Energy Consumption

The volume of Energy used by a customer over a period of time, normally monthly, quarterly or annually. Measured in kWh or MWh.

2.1.11. Feeder

An electrical line or circuit that extends radially from a distribution substation to supply electrical energy within an electric area or sub-area.

2.1.12. Firming

Maintaining the output from a variable, intermittent power source, such as wind or solar generation, for a committed period of time.

2.1.13. Firming Capacity

A specific volume of flexible energy supply that is available to top-up supply when there is a decline in output from variable, intermittent power sources and/or a sudden increase in demand which exceeds their available capacity.

2.1.14. Flexibility

The ability of the Power System to respond to expected and unexpected changes in the supply-demand position, including generation failures, changes in VRE output and variations in Demand, over all necessary timeframes.

The Flexibility of an individual Energy Resource is the extent to which its output can be adjusted or committed in or out of service. This includes:

a) The speed of response to start up and shut down;

b) The rate of ramping; and,

c) Whether it can operate in the full range of capability, or has restrictions such as a minimum generation requirement, or a limitation on the amount of bulk energy that can be produced.

2.1.15. Frequency

The number of cycles occurring in each second in an Alternating Current (AC) electric system, which is measured in Hertz (Hz). The maintenance of Frequency requires electricity Supply to be instantaneously balanced against customer Demand.

2.1.16. Front of the Meter (FTM)

Any infrastructure located on the distribution network side of the customer meter (i.e. not behind a customer meter, or BTM). FTM infrastructure is still metered, but it is not part of a customer site.

2.1.17. Grid Formation

The ability of the Power System to set and maintain Frequency.

2.1.18. High Voltage (HV)

Electrical installations typically within the range of 100kV to 345 kV.

2.1.19. Hosting Capacity

The amount of DER/CER that can be accommodated within a distribution network, or a specific segment of the distribution network, without adversely affecting security, reliability and/or power quality.

2.1.20. Inertia

The ability of the Power System to resist changes in Frequency before cascading instability results in widespread blackouts.

Inertia has traditionally been provided as a by-product of the operation of Synchronous Generators, electric motors and other devices that are synchronised to the Frequency of the system.

2.1.21. Interconnector

A transmission line or group of transmission lines that connect transmission networks in adjacent regions.

2.1.22. Intermittent

A description of a generating unit whose output is not readily predictable, including solar generators, wind turbine generators and hydro-generators without any material storage capability.

2.1.23. Inverter

An electrical device which uses semiconductors to transfer Power between a DC source and an AC source or load.

2.1.24. Load

The term Load is used in the following ways, subject its context:

a) A connection point, or defined set of connection points, at which electrical power is delivered (to a customer or to another network);

b) The amount of electrical power delivered at a defined instant to either a single connection point or aggregated over a defined set of connection points; or,

c) Customer devices that draw electrical energy from the network and convert it to some other useful form.

2.1.25. Load Shifting

An automated 'turn-up' process that enables essential customer loads to better align their consumption with periods where there is an oversupply of renewable energy, low Demand on the system, or both.

2.1.26. Loss Factor

A multiplier used to describe the electrical energy loss for electricity used or transmitted.

2.1.27. Low Voltage (LV)

Electrical installations typically within the range of 100V to 260V.

2.1.28. Maximum Demand

The highest amount of electrical power delivered, or forecast to be delivered, over a defined period (day, week, month, season, or year), either at a connection point or simultaneously at a defined set of connection points. Measured in kW or MW.

2.1.29. Medium Voltage (MV)

Electrical installations typically within the range of 1kV to 100 kV.

2.1.30. Peak Demand

The highest level of instantaneous electricity Demand at a specific network location or customer site. Measured in kW or MW.

2.1.31. Power

The rate at which Energy is transferred through an electrical system. Power is comprised of two components: Real Power and Reactive Power.

2.1.32. Power Factor

The ratio of the Real Power to the Apparent Power at a metering point

2.1.33. Power System

A highly complex cyber-physical and transactional System that, in the case of GW-scale Power Systems, exists to provide safe, reliable, and efficient electricity services to millions of customers.

The supply chain of a typical legacy Power System incorporates several Tiers/Layers including Bulk Power, Transmission and Distribution, together with the related Energy Retail functions. As a complex web of inter-dependent structures, Power Systems are best understood as an integrated Network of Structures which, due to their unparalleled scale and complexity, are formally defined as Ultra-Large-Scale (ULS) Systems.

2.1.34. Protection System

A System designed to protect equipment, facilities and infrastructure from damage due to an electrical or mechanical fault, or due to certain conditions of the Power System.

2.1.35. Ramp Rate

The rate of change of Real Power required for Dispatch. Expressed as MW/minute.

2.1.36. Rate of Change of Frequency (ROCOF)

The amount of time that is available to arrest a change in Frequency before it moves outside permitted operating limits.

2.1.37. Real Power (Active Power)

Measured in MW, Real Power is the instantaneous rate at which electrical energy is generated, transmitted or consumed.

2.1.38. Reactive Power

Measured in MVAR, Reactive Power sustains the electrical field in alternating-current systems while maintaining Voltage within the limits specified for safe operation.

2.1.39. Reclosers

Electro-mechanical devices that can react to a short circuit by interrupting electrical flow and automatically reconnecting it a short time later. Reclosers function as circuit breakers on the feeder circuit and are located throughout the distribution system to prevent a temporary fault from causing an outage.

2.1.40. Reliability

The ability of the Power System to satisfy consumer Demand, allowing for credible generation and transmission network contingencies.

2.1.41. Resilience

The ability of the Power System to avoid or withstand stress events without suffering operational compromise, or to adapt to and compensate for the strain in a manner that minimises functional compromise via graceful degradation.

2.1.42. Robustness

The ability of the grid to tolerate perturbations and uncertainty. It includes extensibility, flexibility, agility, resilience, and reliability, all of which are distinct potential capabilities or intrinsic characteristics of a grid.

2.1.43. Smart Inverter

An Inverter with a digital architecture, bidirectional communications capability and the ability to provide Reactive Power services. Smart inverters provide functionality including voltage support, frequency regulation, fault-ride-through capabilities. Large numbers of smart inverters can be operated autonomously, either statically or dynamically reacting to changes on the Power System, or in the future remotely controlled through active and reactive power management.

2.1.44. Spinning Reserve

An additional margin of generation capacity that is made available by increasing the power output of generators which are already generating electricity into the Power System.

2.1.45. Stability

The ability of a Power System to maintain a state of equilibrium during normal and abnormal conditions or disturbances.

2.1.46. Supply-side

The upstream end of traditional Power Systems where generation has been located, which includes the transmission and distribution networks through which electricity is transported to customers located on the Demand-side.

2.1.47. Synchronisation

To electrically connect a generating unit or a scheduled network service to the Power System.

2.1.48. System Security

The physical stability of the Power System arising from key technical parameters, such as Voltage and Frequency, being maintained within defined limits.

2.1.49. System Strength

The ability of the Power System to maintain and control the Voltage waveform at any given location, both during steady state operation and following a disturbance. System Strength can be related to the available fault current at a specified location in the Power System, with higher fault current indicating higher System Strength with greater ability to maintain the Voltage waveform.

2.1.50. Transformer

Equipment used to increase or decrease the voltage of an electric current.

2.1.51. Topology

The interconnection pattern of nodes in a network. With respect to the Power System, it is the interconnection pattern of entities that facilitate power generation, transmission, distribution and consumption.

2.1.52. Volatility

The propensity of rapid and/or unpredictable change, especially in a manner that is unfavourable and more difficult to manage.

2.1.53. Voltage

The electrical force or electric potential between two points that gives rise to the flow of electricity.

2.1.54. Voltage Management

Control mechanisms that maintain Voltages at different points in the Power System within acceptable ranges during normal operation, and to enable recovery to acceptable levels following a disturbance.

Voltage control is managed through balancing the production or absorption of Reactive Power. As Reactive Power does not 'travel' far, it is generally more effective to address reactive power imbalances locally, close to where it is required.

2.1.55. Volt-VAR Response

A response mode of an Inverter that smooths the network voltages by absorbing Reactive Power when voltage levels rise. Alternatively, when network voltages fall below 220V, the Volt-VAR mode causes the Inverter to generate Reactive Power to support the network voltage.

2.1.56. Volt-Watt Response

A response mode of an Inverter that reduces its power output when needed to avoid exceeding the voltage limits. If this mode is not enabled, the Inverter may experience frequent nuisance tripping when the network is lightly loaded.

2.2. Energy Resources

2.2.1. Active DER/CER

Distributed Energy Resources (DER/CER) that are capable of automatically altering their operating behaviour in response to the needs of the wider Power System. This may be in response to changes in the energy price, the local condition of the grid and/or upon receipt of instructions, control inputs or data feeds from authorised external entities.

Active DER/CER are significantly more valuable to the electricity system than Passive DER/CER as they as they can provide specific physics-based services that are strongly correlated with the time and nature of a wider system need.

2.2.2. Demand-side Flexibility

The dynamic Orchestration of large volumes of Distributed Energy Resources (DER/CER) and Flexible Resources in a manner capable of supporting supply/Demand balance over timescales from days to milliseconds.

Flexibility in a high-VRE / high-DER Power System is closely related to the topic of Operational Coordination.

2.2.3. Distributed Energy Resources (DER/CER)

A diverse range of small to medium scale Energy Resources that are either connected directly to the Distribution System (known as DER) or located behind the meter at residential, commercial and industrial customer premises. In some jurisdictions, the latter may be referred to as Customer Energy Resources or CER.

Active DER/CER are a multi-application resource capable of providing valuable Electric Products to the Power System. It includes the following types of technologies:

a) Distributed Generation (DG): including Distributed Photovoltaics (DPV) and Embedded Generators;

b) Energy Storage Systems (ESS): including small and medium-scale batteries;

c) Electric Vehicles (EV);

d) Smart Inverters; and,

e) Flexible Resources: including various loads that are responsive, such as air conditioning, electric hot water storage, water pumping, industrial loads and EV charging.

2.2.4. Distributed Generation

A generic term for all forms of electricity generation that are connected to the distribution network. It includes both fossil-fuel and renewable forms of generation.

2.2.5. Distributed Photovoltaics (DPV)

Solar photovoltaic panel installations connected to the Low Voltage network. In many cases, these resources are located behind-the-meter at residential and commercial sites.

2.2.6. Energy Resource

A universal term for all technologies that provide one or several of the Electric Products required by the Power System. It includes conventional Synchronous Generation, utility-scale Variable Renewable Energy (VRE), Distributed Energy Resources (DER/CER) and various forms of Energy Storage and Firming Resources.

2.2.7. Energy Storage (ES)

A means of storing electrical energy, either directly or indirectly and either at centralised locations or widely distributed across a Power System. The numerous types of Energy Storage can provide system services across different time horizons. These include:

a) Shallow storage / Provision of Essential System Services (< 4-hours);

b) Medium storage / Intraday shifting (4 – 12-hours); and,

c) Deep storage / Renewable energy drought (> 12-hours).

Direct forms of Energy Storage such as chemical batteries and power capacitors are those where energy enters the storage device as electrical energy and is retrieved as electrical energy.

Indirect forms of Energy Storage convert electric energy into thermal, rotational or potential energy and may include pumped hydro (pumping of water to elevated storage), the pre-heating or pre-chilling of bulk water or glycol and/or the pre-cooling of a building envelope.

2.2.8. Firming Resources

A flexible supply of energy that can be called upon instantaneously or over long periods as the output of intermittent power sources varies and/or there is sudden increase in demand which exceeds their available capacity. Examples of firming resources include:

a) Energy Storage such as utility-scale batteries, pumped hydro and flywheels;

b) Gas-fired generation; and,

c) Virtual Power Plants (VPP) to aggregate the capacity and capabilities DER/CER.

2.2.9. Flexible Resources (Distributed)

Distribution-connected assets that can, in a reliable and firm manner that minimises or avoids real-time human involvement, modify their operational behaviour in response to specific needs of the bulk power system and/or local distribution network.

Four forms of flexible demand have emerged as follows:

a) Shape – Moving Demand routinely according to a standard long-term pattern;

b) Shift – Moving demand sporadically in response to an external signal;

c) Shimmy – Moving demand over very short timescales in response to an external signal; and,

d) Shed – Switching off equipment.

Commonly (but not exclusively) owned by customers, these flexible assets can automatically increase or decrease their electricity consumption and/or production in response to changes in the energy price, financial incentives, the condition of the local grid and/or upon receipt of a control signal from a third party.

Flexible Resources include the concepts of Demand Management, Demand Response and Controllable Load.

2.2.10. Inverter-based Resources (IBR)

IBR include wind farms, solar PV generators, and batteries that export power to the grid. They do not have moving parts rotating in synchronism with the grid frequency, but instead are interfaced to the Power System via power electronic converters which electronically replicate grid frequency.

2.2.11. Microgrid

A group of interconnected loads, generation sources and diverse Distributed Energy Resources (DER/CER), within clearly defined electrical boundaries, that is supported by its own internal management systems and presents to the wider Power System as a single entity.

Microgrids may connect and disconnect from the Power System, operating in both grid-connected or islanded mode. Alternatively, they may serve a geographically remote customer base, be entirely autonomous and have no interconnection with a larger Power System.

2.2.12. Passive DER/CER

Distributed Energy Resources (DER/CER) that operate only under the direction of their own internal control algorithms and cannot be remotely orchestrated by a third party (such as an Aggregator).

Passive DER are significantly less valuable to the Power System than Active DER/CER due to the negligible capacity to alter their behaviour in response to changes in the condition of the system. This means they cannot reliably provide services that are correlated with Power System needs and may impose additional system inefficiencies on the system.

2.2.13. Static VAR Compensator

A device that has the ability to generate and absorb Reactive Power and to respond automatically and rapidly to Voltage fluctuations or instability arising from a disturbance or disruption on the network.

2.2.14. Synchronous Condenser

Synchronous machines that are specially built to supply only Reactive Power. The rotating mass of a Synchronous Condenser will contribute to the total Inertia of the Power System from its stored kinetic energy.

2.2.15. Synchronous Generator

A generator which is directly connected to the Power System and rotates in synchronism with grid Frequency.

2.2.16. Variable Renewable Energy (VRE)

A generic term for intermittent forms of generation powered by renewable energy resources that are inherently variable, such as wind and solar energy.

While some forms of Distributed Energy Resources (DER/CER) are considered VRE, the term is most commonly used to describe large, utility-scale applications of solar and wind generation.

In the absence of Firming Resources, large volumes of VRE can impact the stability of the Power System and exacerbate periods of misalignment between Demand and Supply.

2.2.17. Vehicle to Grid (V2G)

A system that allows an Electric Vehicle (EV) to send power (i.e. discharge its battery) to the grid or to manage charging of its battery in response to changing grid conditions.

2.2.18. Virtual Power Plant (VPP)

A software and communications-based capability that enables the Orchestration of a fleet of DER/CER in a manner that both meets end-user needs and provides beneficial Electric Products to one or more Tiers/Layers of the Power System.

2.3. Subsystems

2.3.1. Advanced Distribution Management Systems (ADMS)

Software platforms that integrate numerous operational systems, provide automated outage restoration, and optimize distribution grid performance. ADMS components and functions can include Distribution Management System (DMS); Demand Response Management System (DRMS); automated Fault Location, Isolation, and Service Restoration (FLISR); Conservation Voltage Reduction (CVR); and Volt-VAR Optimization (VVO).

2.3.2. Advanced Metering Infrastructure (AMI)

Typically refers to the full measurement and collection system that includes meters at the customer site, communication networks between the customer and a service provider, such as an electric, gas, or water utility, and data reception and management systems that make the information available to the service provider. It is also referred to as a smart meter system. AMI communications networks may also provide connectivity to other types of end devices such as Distributed Energy Resources (DER/CER).

2.3.3. Distribution Management System (DMS)

An operational system capable of collecting, organizing, displaying, and analyzing real-time or near real-time electric distribution system information. A DMS can also allow operators to plan and execute complex distribution system operations to increase system efficiency, optimize power flows, and prevent overloads. A DMS can interface with other operations applications, such as geographic information systems (GIS), outage management systems (OMS), and CIS to create an integrated view of distribution operations.

2.3.4. Dynamic Operating Envelope (DOE)

Distinct from Static Operating Envelopes, DOE's allow customer import and export limits to vary over time and location according to dynamic changes in network Hosting Capacity. Dynamic export limits could enable higher levels of energy exports from customer solar and battery systems by allowing higher levels of export when the distribution network has the capacity to accommodate it.

2.3.5. Emergency Frequency Control Scheme

Facilities for initiating automatic load shedding or automatic generation shedding to prevent or arrest uncontrolled increases or decreases in Frequency (alone or in combination) leading to cascading outages or major supply disruptions.

2.3.6. Energy Management System (EMS)

A system to monitor, control, and optimize the performance of the transmission system and in some cases primary distribution substations. The EMS is the transmission system's analog to the DMS.

2.3.7. Fast Frequency Response (FFR)

A very rapid response to re-balance megawatts on the Power System. May be automatic in response to frequency, or a centrally controlled response (that is, a control scheme to shed load).

2.3.8. Fast Lower Service

The service of providing, in accordance with the requirements of the market ancillary service specification, the capability of rapidly controlling the level of generation or load associated with a particular facility in response to the locally sensed frequency of the Power System in order to arrest a rise in that frequency.

2.3.9. Fast Raise Service

The service of providing, in accordance with the requirements of the market ancillary service specification, the capability of rapidly controlling the level of generation or load associated with a particular facility in response to the locally sensed frequency of the Power System in order to arrest a fall in that frequency.

2.3.10. Fast Response Voltage Control

Fast response voltage control provides rapid adjustments in Reactive Power to support voltage stability during and after system disturbances. Adequate reactive reserves also need to be maintained to ensure the security of the transmission system. Equipment that provides fast dynamic voltage control includes:

a) Automatic voltage regulation from Synchronous Generators

b) Active compensation – fast acting equipment using power electronics

c) IBR, such as wind turbines and solar inverters.

2.3.11. Fault location, Isolation, and Service Restoration (FLISR)

The automatic sectionalising, restoration and reconfiguration of circuits. These applications accomplish distribution automation operations by coordinating operation of field devices, software, and dedicated communications networks to automatically determine the location of a fault, and rapidly reconfigure the flow of electricity so that some or all customers can avoid experiencing outages. FLISR may also be known as Fault Detection, Isolation and Restoration (FDIR).

2.3.12. Frequency Response Mode

The mode of operation of a generating unit which allows automatic changes to the generated power when the Frequency of the Power System changes.

2.3.13. Geographic Information System (GIS)

A software system that maintains a database of grid assets, including transmission and distribution equipment, and their geographic locations to enable presentation of the electric power system or portions of it on a map. GIS may also serve as the system of record for electrical connectivity of the assets.

2.3.14. Inertial Response

Inertial responses provide a rapid and automatic injection of energy to suppress rapid Frequency deviations, slowing the rate of change of frequency (RoCoF) This response has predominantly been provided in the NEM by the inherent electromechanical inertial response of large Synchronous Generators, as a by-product of energy production. It arises because the rotating parts of synchronous generating units (such as the turbine and rotor) connected to an AC power system spin in lock step with the system frequency. The response is provided by the physical properties of the machine, and does not require control system interaction.

This inertial response was historically abundant in many parts of the network. This is, however, no longer the case in certain parts of the network that have high levels of inverter-based resources (IBR). A lack of inertial response can present risks to system security in the event that these regions become separated from the rest of the NEM.

2.3.15. Information Technology (IT)

A discrete set of electronic information resources organised for the collection, processing, maintenance, use, sharing and dissemination of information. This includes interconnected or dependent business systems and the environment in which they operate.

2.3.16. Operations Technology (OT)

Programmable systems or devices that interact with the physical environment and/or manage devices that interact with the physical environment. Examples may include industrial control systems, building management systems, fire control systems, and physical access control mechanisms.

2.3.17. Outage Management System (OMS)

A computer-aided system used to better manage the response to power outages or other planned or unplanned power quality events. It can serve as the system of record for the as-operated distribution connectivity model, as can the DMS.

2.3.18. Primary Frequency Response (PFR)

The first stage of Frequency control in a Power System. It is the response of generating systems and loads to arrest and correct locally detected changes in Frequency by providing a proportionate change in their active power output or consumption.

PFR is automatic; it is not driven by a centralised system of control and begins immediately after a frequency change beyond a specified level is detected.

2.3.19. Slow Response Voltage Control

Managing small adjustments to Reactive Power during normal operation as Demand and Supply varies, in timescales within seconds or minutes. This can be enacted by a range of means, including:

a) Voltage regulators that control voltages farther from the substation and installed at substations and along distribution system feeders;

b) Transformer load tap changes; and,

c) Passive Reactive Power compensation from capacitors and reactors within substations.

2.3.20. Static Operating Envelope

The technical limits that Distributed Energy Resources (DER/CER) must operate within to maintain the security, reliability and power quality of the distribution network and broader electricity system.

Static operating envelopes account for ‘worst case scenario’ conditions and are often fixed at conservative levels regardless of the capacity of the distribution network.

2.3.21. Supervisory Control and Data Acquisition (SCADA)

A system of remote control and telemetry used to monitor and control the transmission system.

2.4. Markets & System Operations

2.4.1. Black Start Capability

A capability that allows a generating unit, following its disconnection from the Power System, to be able to deliver electricity to either:

a) its connection point; or

b) a suitable point in the network from which supply can be made available to other generating units, without taking supply from any part of the power system following disconnection.

2.4.2. Capacity Allocation

The determination of how much of the available power flow capacity should be assigned to individual resources or devices.

2.4.3. Capacity Market

A market in which Energy Resources receive a payment for having capacity available, even if it is not used. An additional payment (spot price) is also made for actual amounts of electricity sold.

2.4.4. Capacity Reserve

At any time, the amount of surplus or unused generating capacity indicated by the relevant Generators as being available in the relevant timeframe minus the capacity requirement to meet the current forecast load Demand, taking into account the known or historical levels of demand management.

2.4.5. Capacity Outage

The occurrence of an uncontrollable succession of outages, each of which is initiated by conditions (e.g. instability or overloading) arising or made worse as a result of the event preceding it.

2.4.6. Central Dispatch Process

The processes managed by the Market/System Operator to maintain energy balance in the Power System via the centrally-coordinated matching of Supply and Demand through the Dispatch of scheduled generating units, semi-scheduled generating units, scheduled loads, scheduled network services and market ancillary services.

2.4.7. Commitment

The commencement of the process of starting up and synchronising a generating unit to the Power System.

2.4.8. Constraint

A physical system limitation or requirement that must be considered by the central dispatch algorithm when determining the optimum economic dispatch outcome, or when performing circuit configuration and operation

2.4.9. Contingency Capacity Reserve

Actual active and reactive energy capacity, interruptible load arrangements and other arrangements organised to be available to be utilised on the actual occurrence of one or more contingency events to allow the restoration and maintenance of power system security.

2.4.10. Control Command

A control command is a directive, usually in the form of a signal or a message, that instructs an entity, system, or device to carry out a specific action, assume a specific state, or cause a specific condition to be reached or maintained.

2.4.11. Day Ahead Market

A market in which electricity is bought and sold for delivery on the day after the trade takes place.

2.4.12. DER/CER Services Beneficiaries

Beyond the direct benefits that accrue to DER/CER owner/investors, these resources may also provide services that benefit the following Tiers/Layers of the Power System:

a) Distribution networks;
b) Transmission networks;
c) Wholesale energy markets;
d) Essential System Services markets; and,
e) Other customers (via peer-to-peer trading).

All services and energy provided by DER/CER to any of the above layers are derivatives of the Electric Products summarised as the ‘3Rs’: Real Power, Reactive Power and Reserves.

2.4.13. Dispatch

Instructions issued by the Market/System Operator (MSO), Distribution System Operator (DSO) and/or Aggregator that either provide directives or targets for participating Energy Resources and Active DER/CER to alter their operating behaviour. This generally means ordering a dispatchable Energy Resource to produce a set amount of output power for a set period of time. The setpoint (power level) may be adjusted periodically either via a predetermined schedule or as the result of shorter-term factors such as to maintain system frequency and/or power balance. This can include setting ramp rates for ramp-capable resources and storing (withdrawing grid power) for bulk energy storage devices. Dispatch may adjust setpoints up or down in general. In addition to bulk generation, DER/CER and ESS devices may also be dispatched.

For resources that are not dispatchable (such as wind generation and solar PV) devices may under some circumstances be curtailed. While curtailment is usually considered as a separate topic, it fits into a larger view about dispatch for the grid.

Which parties have the authority to Dispatch particular resources will largely depend on the System Architecture decisions made in each jurisdiction.

2.4.14. Dispatch Schedule

A dispatch schedule is a list of generator power generation settings as a function of time, in order of execution. A generation dispatch schedule may be determined day ahead or intra-day on an hourly basis, for example.

2.4.15. Dispatchability

The concept of the dispatchability of an energy resource can be considered as the extent to which its output can be relied on to 'follow a target'.

Extent to which the output of an energy resource or portfolio of resources can be relied on to 'follow a target' and adhere to a dispatch schedule at some time in the future.

2.4.16. Distribution-level Markets

Markets for the provision of electricity services in distribution networks, for example the competitive procurement of services enabled by Distributed Energy Resources (DER/CER) for the purposes of managing network congestion or facilitate peer to peer trading.

2.4.17. Electric Product Value

The sustainable economic value of Electric Products provided by merchant or private Energy Resources to support system operations, as an alternative to Power System augmentation.

The value of Energy Products is not static. In general, their value can be expected to increase where provision is highly correlated with the needs of the Power System at a given time and geographic segment or vertical Tier/Layer, which will vary dynamically.

As decarbonising Power Systems experience increasing Volatility, advanced forms of Operational Coordination will be necessary to help increase the strength of this correlation to enhance the dynamic provision of:

a) Energy Products: The required '3Rs' physics-based service(s): Real Power, Reactive Power, Reserves;

b) Timing: At the right time: days, hours, minutes, seconds, microseconds; and,

c) Location: At the right geographic segment or vertical Tier/Layer of the Power System.

2.4.18. Electric Products

The physics-based services that may be provided by Energy Resources to the Power System, and which can be summarised as the '3Rs':

a) Real Power: measured in MW, is the instantaneous rate at which electrical energy is generated, transmitted or consumed;

b) Reactive Power: measured in MVAR, sustains the electrical field in alternating-current systems while maintaining voltage within the limits specified for safe operation (source or sink); and,

c) Reserves: measured in MW, represent contracted commitments to deliver or reduce Real Power (MW) or Energy (MWh) at a point of time in the future.

All beneficial products and services provided by Energy Resources to any Tier/Layer of the Power System are derivatives of the 3Rs.

2.4.19. Firmness

System operators need to have some level of confidence that resources are available. The firmness of a resource relates to the resource's ability to confirm its energy availability. For example, how long can the source provide a requested amount of energy once dispatched, and how far in advance can the energy be guaranteed by the source? This could be a probabilistic quantification for wind and solar. Firmness also relates to whether a resource is dependable or prone to technical failures.

2.4.20. Flexibility Market

A market that provides the means to monitor flows of Energy and dynamically create value-based signals that incentivise changes in supply and Demand.

2.4.21. Forward Market

A market in which electricity is bought and sold for delivery at a future date, such as a month, season or year ahead.

2.4.22. Integrated Resource Planning (IRP)

A holistic approach to Power System design that recognises a growing volume of Energy Resources will be LV-connected and must be considered as an integrated part of any future system design.

It actively incorporates public participation in the co-development of plans to ensure both centralised and decentralised Energy Resources will interoperate in a manner that optimises cost and reliability and maximises societal and environmental outcomes.

2.4.23. Load-following Paradigm

The traditional operational paradigm of Power Systems where large-scale centralised generation is dispatched to match electrical Demand as it varies across periods of time (hours, days, seasons, etc.).

This paradigm was premised on a historical context where the major source of uncontrolled variability impacting a Power System was changing customer Demand over time.

2.4.24. Market Platform

A digitised commercial environment that enables value-creating interactions between stakeholders including consumers, producers, producer-consumers and infrastructure managers.

In a Power System context, a Market Platform provides an open, participative and dynamic infrastructure for these interactions and sets governance conditions for them. Its key purpose is to consummate matches among users and enable the monetisation and low-friction exchange of Electric Products, thus enabling value creation for all participants.

2.4.25. Network Services Market

A market established and operated by the entity responsible for the Operational Coordination of the Distribution System for the purpose of efficiently procuring Electric Products from Distributed Energy Resources (DER/CER) to support local network stability, power quality and economic efficiency.

2.4.26. Operability

Critical pre-requisites for secure and reliable operation of the Power System, which include a key focus on its Predictability and Dispatchability.

The Predictability of the Power System is the ability to:

- Measure or derive accurate data on energy demand, power system flows, and generation output across numerous time frames as key inputs into planning and operational decision-making; and,
- Forecast upcoming Power System conditions and have confidence in how the system will perform.

The Dispatchability of the Power System is the ability to configure system services, sourced from a diverse range of Energy Resources, in a manner that consistently maintains system security and reliability.

Related to the above, the Dispatchability of a particular Energy Resource is the extent to which its output can be relied upon to 'follow a target' issued by the Market/System Operator (MSO) and adhere to a pre-agreed dispatch schedule at some time in the future.

2.4.27. Orchestration

The coordination of dispatchable Energy Resources, including but not limited to Distributed Energy Resources (DER/CER), in a manner that moderates negative system impacts and may include facilitating the provision of Electric Products to various Tiers/Layers of the Power System under a commercial arrangement.

2.4.28. Power System Model

A set of mathematical equations, typically a combination of algebraic and differential equations, which can be used to emulate the response, over time, of a real physical system. Power system operators require adequate models and tools to simulate system performance under future conditions, to have confidence in how the overall system will perform.

2.4.29. Self-commitment

Commitment, where the decision to commit a generating unit was made by the relevant Generator without instruction or direction from Market/System Operator.

2.4.30. Single Point of Failure (SPOF)

An environment/system where one failure can result in the failure of the entire system. For critical system such as GW-scale Power Systems, a key design goal is to reduce the number of single points of failure.

2.4.31. Situational Awareness

A sufficiently accurate and up-to-date understanding of the past, current, and projected future state of a system, including its cybersecurity safeguards. It involves the collection of data via sensor networks, data fusion, and data analysis, which may include modelling, simulation, data visualisation and alarms. This supports both automated and/or human decision-making concerning power system functions.

2.4.32. Spot Price

The price for electricity in a trading interval at a regional reference node or a connection point.

2.4.33. Strategic Reserves

Strategic reserve refers to reserve capacity that sits outside the market to procure additional bulk energy services as insurance against unexpected Demand growth and/or reductions in supply.

2.4.34. Supply-following Paradigm

A proposed operating paradigm for electric systems where a very significant proportion of generation is served by Variable Renewable Energy (VRE) and Distributed Energy Resources (DER/CER).

The paradigm is premised on a context where the major source of Volatility impacting the Power System is the output of highly variable wind and solar generation, exacerbated by declining levels of dispatchable Synchronous Generation. In this case, large volumes of LV-connected flexible loads and resources are dynamically orchestrated to follow the output of variable generation sources across a range of time windows (seconds, hours and days).

In the context of global Power System transformations, the international literature evidences increasing consideration of operational paradigms that incorporate Supply-following features.

2.4.35. Supply Chain Risk

Supply chain risk is measured by the likelihood and severity of damage if an Information Technology (IT) or Operational Technology (OT) system is compromised by a supply chain attack. Supply chain attacks may involve manipulating computing system hardware, software, or services at any point during the electricity production and transport life cycle.

2.4.36. Value Stacking

The process of providing Electric Products to several vertical Tiers/Layers of the Power System (e.g. wholesale market, transmission, distribution system) for the purpose of maximising participant remuneration.

Value Stacking and Co-optimisation are closely related.

2.4.37. Visibility

The degree to which information on Energy Resource characteristics and operational information is available to the Market/System Operator (MSO), Distribution System Operator (DSO), and other authorised third parties.

Examples including real-time or near real-time information on electrical demand, generation output, state of charge for Energy Storage, availability of Demand Response, system voltages and system frequency, and power flows on major network elements.

2.5. Emerging Roles

2.5.1. Aggregator

An entity that orchestrates a fleet of energy resources, including Distributed Energy Resources (DER/CER), for the purpose of providing one or more Electric Products to different Tiers/Layers of the Power System. Key functions and goals are to:

a) Agree with customers/owner-investors the commercial terms and conditions of orchestrating their DER/CER;

b) Maximise the value of the Electric Products by providing them to the vertical Tier/Layer(s) of the Power System with the most urgent need and/or where they attract a premium price;

c) Compute optimal dispatch configurations across their DER/CER portfolio consistent with: a) customer contract provisions; b) instructions issues by the Market/System Operator (MSO) and/or Distribution System Operator (DSO); and, c) the Dynamic Operating Envelope (DOE) information pertaining to each customer;

d) Mitigate or avoid the uncertainties of non-delivery from a single customer so that the services provided to the relevant markets are reliable;

e) Prevent customers from being unduly exposed to the risks involved in participating in the above markets; and,

f) Administer payments and invoicing associated with the delivery and receipt of services.

2.5.2. Distribution Market Operator (DMO)

Distinct from the role of managing a Network Services Market (normally the role of the Distribution System Operator), the DMO is the entity responsible for operating a distribution-level energy market in a system that has very high levels of DER.

While this type of market may be required in vertically disaggregated markets in the longer term, the full DMO concept may emerge first in vertically integrated market structures.

2.5.3. Distribution System Operator (DSO)

An entity responsible for the planning, operation and optimisation of a Distribution System with high levels of Distributed Energy Resource (DER/CER), Electric Vehicles (EV) and other Flexible Resources. Depending on the DSO model implemented, this may include the following functions:

a) Implement advanced, scenario-based modelling of DER/CER and EV uptake and operation, bi-directional power flows and Distribution System operations;

b) Establish Distribution System State Estimation (DSSE) and near real-time Visibility across the network;

c) Dynamically manage the network within the technical constraints and hosting capacity of distribution assets, including computation and issuing of Dynamic Operating Envelopes (DOEs);

d) Advance the transition to more cost and value-reflective pricing in broad-based tariff reform and establish bilateral reserve contracts for short and long-term emergency support of distribution security;

e) Implement Integrated Distribution Planning (IDP) to medium-long term network requirements, incorporating non-network alternatives;

f) Actively identify opportunities for aging network assets to be progressively replaced with Microgrid, individual Stand-alone Power Systems and/or grid-connected Energy Storage solutions;

g) Analysis and evidence-based determination of the temporal and locational value of Electric Products provided by DER/CER to the Distribution System;

h) Establish and operate a Flexibility Market or Network Services Market that enables more close-coupled 'market-control' alignment at the distribution Tier/Layer;

i) Provide real and near real-time data flows to relevant Distributed Data Sharing Infrastructure(s); and,

j) Work collaboratively with the Market/System Operator (MSO) across the Transmission-Distribution Interoperability Mechanism (TDIM) relevant to the DSO's service territory.

In many contexts, the DSO role is likely to emerge through a progressive expansion of the function of Distribution Network Service Providers (DNSP).

2.6. Systems Architecture

2.6.1. Architect

In the context of the Systems Architecture discipline, the Architect is a professional specialising in the management of systemic Complexity. Cognisant of the entire System, the Architect works closely with the full range of key stakeholders and diverse subject matter experts relevant to a complex System.

Importantly, the Architect complements and does not replace the many diverse functions that require specific discipline expertise in a complex System.

2.6.2. Architecture

Every functioning System created by humans, including legacy Power Systems, have an underpinning Structure or 'Architecture' that is configured to achieve certain purposes.

The term Architecture is formally used in Systems Science of a holistic conceptual model that describes how the many Components of a System are linked or related together by its underpinning Structure. The purpose of the conceptual model is to make explicit how all the physical, informational, operational, and transactional Components function together as whole, and support more robust reasoning about how the System may be enhanced and/or transformed.

Architectural disciplines have a primary focus on the underpinning Structure of a System. Simplistically, if the boxes in a Block Diagram represent the Components, the Architecture is represented by the lines connecting the boxes. Although the individual Components are often far more tangible and easier to see, studying the underpinning Structure of a complex System is critical as it will always have a disproportionate impact on what the System is ultimately capable of.

Where the Architecture is well aligned with the current and/or emerging future purpose of the System, the Components will function effectively together, and the System will exhibit greater Scalability and Extensibility. Where the Architecture is misaligned with current or future needs, technology integration becomes increasingly costly, investments may be stranded, and full benefits realisation is placed at risk.

2.6.3. Architecture Issues

Following are seven important structural issues that the System Architecture discipline addresses that will otherwise negatively impact the Operability and Resilience of decarbonising Power Systems:

1. Tier/Layer Bypassing: The creation of information flows or coordination signals that 'leapfrog' a vertical Tier/Layer of the Power System's operational hierarchy.
2. Coordination Gapping: An element of the Power System does not receive an explicit flow of coordination signals from any higher Tier/Layer of the system and therefore operates in isolation.

3. Hidden Coupling: Two or more control entities with partial views of System State issue simultaneous but conflicting coordination signals to a DER/CER or Component of the Power System.
4. Latency Cascading: Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
5. Computational Time Walls: Where excessive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines will hit a computational 'time wall' at some point where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time.
6. Cybersecurity Structural Vulnerabilities: Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
7. Back-end Integration Constraints: Multiple vertical silo structures found in many supply-chain organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others.

2.6.4. Block Diagram

A diagram showing in schematic form the general arrangement of the Components of complex System together with the Structures that link them together to achieve desired outcomes.

2.6.5. Bottom-up

An approach to problem solving and/or the design of a System that starts from the most basic or primitive Components and moves incrementally to higher level Components and Structures.

2.6.6. Centralised Future Architecture

A vision of a future Power System that aspires to whole-of-system optimisation being directly managed by the Market/System Operator (MSO). In this model, the MSO needs detailed Visibility into all Tiers/Layers of the Power System including the Distribution System. This model is a logical extension of historical Power System operational paradigms but with much greater diversity and volumes of Energy Resources.

2.6.7. Centralised Legacy Architecture

A traditional Power System structure that is characterised by unidirectional supply through 'poles and wires' infrastructure to largely passive consumers. Historically, this type of Architecture was almost entirely served by centralised generation.

2.6.8. Complexity

A System is complex if it has many interrelated, interconnected, or interdependent entities and relationships. A high-level indicator of the complexity of any System is the amount of information required to describe its full range of functions and behaviours (i.e. words, formulae, lines of code, etc.).

It is important to note that additional Complexity is driven into a legacy System by 'asking more' of it: more functions, more interdependencies, more robustness, more flexibility, etc. This expansion of Complexity is always exacerbated by the addition of new Components and may ultimately require targeted modifications to the Structure through the application of Systems Architecture disciplines.

See also Ultra-Large-Scale (ULS) Systems

2.6.9. Component

A generic term for the uniquely identifiable elements, building blocks, organisations, devices and applications which are related together by a Structure to enable the purposes of the System to be achieved. The term also includes mechanisms intrinsic to the functioning of the System that are both tangible and intangible, such as policy instruments, regulatory mechanisms, rate or tariff structures, etc.

2.6.10. Co-optimisation

Co-optimisation is a structured approach to ensuring that Energy Resource services dispatched and/or financially incentivised in one vertical Tier/Layer of the Power System (e.g. Bulk Power, Transmission or Distribution System) are not driving unintended negative consequences in other Tiers/Layers of the Power System.

2.6.11. Conceptual Integrity

A property of a System Architecture that denotes being intellectually clean of unnecessary complexities or 'exceptions', solving similar problems in similar ways, and having a basis in formal principles which are applied in a consistent manner .

2.6.12. Connectivity

The state of being linked or joined together to enable some form of exchange. Connectivity is a basic form of Structure.

2.6.13. Control Loop

An arrangement of control system components (for example, sensors, actuators, and control algorithms) with the intent of regulating a controlled variable at a set point. Control loops can be open or closed. An open-loop system is one whose output is a function of only the inputs to the system; a closed-loop system is one in which the output is fed back and compared to the input to generate an error signal, which is then used to generate a new output signal.

2.6.14. Control Theory

A branch of engineering and mathematics that deals with the analysis and design of systems. It involves developing models that describe the behaviour of systems and using these models to design controllers that can adjust the inputs to the system in order to achieve a desired output. The goal is to make the system perform optimally, despite uncertainties and disturbances in the system.

2.6.15. Decentralised System

Multiple separate Components and Energy Resources operating independently and in a manner that is solely focused on local or 'selfish' optimisation, with either very limited or no Orchestration or Operational Coordination.

2.6.16. Distributed Data Sharing Infrastructure(s)

An arrangement for sharing data among multiple entities wherein each entity owns and controls its data and provides access on an authorised basis to others via a platform that federates or otherwise consolidates data in a logical fashion but not necessarily in a physically centralised data store.

2.6.17. Emergence

The desired outcome of a System which arises from the interactions between the Components that are enabled by the linkages, relationships and interdependencies embodied by the Architecture. Rather than being the sum of the behaviours of individual Components, Emergence is the product of all interactions as a systemic whole.

'Emergency' is also a related systems concept. It is an undesirable outcome that 'emerges' from a System as the product of dysfunctional interactions between the Components due to structural relationships that are not fit-for-purpose.

2.6.18. Emerging Trends

An element of the PSA methodology that involves the mapping of the drivers of change that may significantly influence the transformation of GW-scale Power Systems over the next decade and beyond.

These drivers present both challenges and impediments and/or new opportunities that are either probable or plausible (but not simply possible).

While some may be endogenous to the Power System, they are typically exogenous and will include the impacts of evolving Customer & Societal expectations of future Power Systems.

2.6.19. Enterprise Architecture

The design and description of an enterprise's entire set of Information Technology (IT) and Operational Technology (OT). This includes how both IT and OT are configured and integrated, and how they interface to the external environment at the enterprise's boundary. It also includes protocols for how they are operated to support the enterprise strategic mission, and how they contribute to the enterprise's overall security posture.

It is important to note that Enterprise Architecture and Power Systems Architecture are complementary but different. As the names suggest, the former is focused on the IT and OT environment within an enterprise while the latter focuses on the overlaid Network of Structures which constitute the end-to-end Power System.

2.6.20. Entity

A specific institution, company or natural person that can be distinctly identified within a System.

2.6.21. Entity-Relationship Diagram

A diagram that illustrates the interdependences and exchanges between a range of Entities in a particular System.

2.6.22. Extensibility

An architectural characteristic that takes the future extension of System functions and capabilities into consideration. It is a systemic measure of the Architecture's ability to extend System functions and capabilities, and the level of effort needed to implement the extension.

In the context of a Power System experiencing significant transformation, Extensible architectural and technology choices aim to be:

- Cognisant of the plausible future developments that the solution will need to enable or migrate toward;
- Capable of accommodating future requirements without impairing core, critical functionality; and,
- Capable of enabling cost-effective migration to longer-terms solution when required.

2.6.23. Feedback Loops

A process whereby a portion of the output of a system is fed back as an input, which then affects subsequent outputs. The output of the system is compared to a desired set point, and any difference between the output and the set point is used to adjust the system's inputs in order to reduce the difference. They are commonly used in control systems and can be either positive (reinforcing) or negative (dampening) depending on whether the output and input have the same or opposite effects on each other.

2.6.24. Industry Structure Diagram

An Entity-Relationship Diagram that illustrates the interdependences and transactions between Entities involved in the governance, operation and market functions of a Power System.

2.6.25. Interaction

A class of behaviours that comprise a set of mutual or reciprocal influences among a set of objects within a particular context to accomplish a purpose. Influences may take the form of conversation, transaction, or closed-loop (feedback) control.

2.6.26. Interface

A boundary-level connection between entities or systems, which provides a set of mechanisms and rules for interaction of the two entities or systems, independent of the content of the interactions.

2.6.27. Interoperability

The capability of two or more Systems, Components or Applications to share, transfer, and readily use information, energy, power and services securely and effectively with little or no inconvenience to the user.

2.6.28. Laminar Coordination Framework

A coordination framework for Distributed Systems that keeps the individual elements aligned on solving a common problem. The Laminar approach uses structure derived from the layered decomposition/network utility maximization approach to provide a formal basis for network architectures. See also Whole Grid Coordination.

2.6.29. Laminar Network

A communication structure that can be viewed as a combination of multi-layer hub-and-spoke and peer-to-peer forms arranged in a hierarchical, self-similar structure.

2.6.30. Layered Future Architecture

A vision of the future Power System that involves optimisation to be managed at each Tier/Layer of the System, based on the mechanism of Layered Decomposition. For example, in this model the distribution layer of the system would be wholly managed by the Distribution System Operator (DSO).

In its most mature future state, the Market/System Operator (MSO) would see each Transmission-Distribution Interface as a single virtual resource. In turn, the DSO would also see a Microgrid within its distribution system as a single virtual resource. In other words, each tier/layer of the Power System would interface most directly only with the Tiers/Layers immediately above and below.

2.6.31. Layered Decomposition

A formally established mathematical technique employed in many technology sectors to solve Ultra Large-scale (ULS) optimisation problems characterised by highly coupled constraints.

In the case of Power Systems transitioning from hundreds to tens of millions of participating Energy Resources, and experiencing growing levels of operational Volatility, Layered Decomposition provides an empirical basis for solving a range of critical Architectural Issues, including otherwise intractable Operational Coordination problems.

In contrast with more traditional hierarchical control, it enables highly complex problems to be decomposed multiple times into sub-problems, which then work in combination to solve the original problem in a manner that addresses long-term Scalability, Extensibility, Cyber-security and Resilience issues. Importantly, rather than 'competing' with other Architecture models currently or proposed for use in the power sector, Layered Decomposition provides a universal, canonical structure for unifying alternative models.

2.6.32. Layering

A valuable architectural approach that is applied widely in computing and communication systems and is key to managing exponential complexity in transforming Power Systems.

By contrast, in highly bifurcated traditional Power Systems, core functions were arranged in 'vertical' structures and siloes (often with their own networks, sensors and computational systems). When experiencing significant change, these vertical structures exacerbate integration issues, compromise solution Scalability and Extensibility and result in more brittle, less resilient and higher cost outcomes.

The properties of a layered approach that make it superior for Power Systems that will host millions of participating Energy Resources include:

- End-to-end system Visibility, Operational Coordination and Operability outcomes are significantly enhanced;
- The relatively stable core system functions are kept entirely separate from applications, which be changed or upgraded more frequently without impacting the core functions;
- Each Tier/Layer can insulate the Tier/Layer immediately above from changes in the Tier/Layer immediately below, and vice versa (i.e. preventing changes at one level from being propagated through the entire system);
- The ability of third parties to create applications that leverage the Platform via open standard interfaces is enhanced; and,
- Changes or upgrades in end-use or third-party applications are decoupled from impacting underlying core functions and capabilities.

2.6.33. Local Selfish Optimisation

The means to enable devices to operate using local optimisation goals and constraints within the global coordination framework.

2.6.34. Model-Based Systems Engineering (MBSE)

While many engineering disciplines are oriented toward individual Component technologies or sub-systems, Systems Engineering brings a transdisciplinary and 'whole-system' approach to designing and operating ultra-complex Systems.

MBSE provides for the formalised application of modelling to support System requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.

2.6.35. Network of Structures

A modern Power System consists of an ultra-complex web of seven distinct, interdependent structures. Viewed from a whole-system perspective, the Power System is a Network of Structures that consists of:

1. Electricity Infrastructure (Power Flows);
2. Digital Infrastructure (Information/Data Exchange);
3. Operational Coordination Structure;
4. Markets / Transactional Structure;
5. Industry / Market Structure;
6. Regulatory Structure; and,
7. Sector Coupling Structures (Gas, Water, Transport, etc).

Many of these Structures have evolved progressively over decades in the context of a highly centralised, unidirectional Power System. These legacy systems are subject to hidden and overt interactions, cross-couplings, constraints and dependencies which impede change. While the 'system-of-systems' paradigm from software engineering is somewhat useful, being largely focused on Components, it does not adequately represent the complex multi-structural properties evident in a modern Power System.

The Network of Structures paradigm provides invaluable perspective for the detailed analysis, mapping, and optimisation of current and future Systems Architecture requirements. This is critically important as the underlying Structure of any complex System establishes its essential capabilities and limits and has a disproportionate impact on what it can reliably and cost-effectively perform.

2.6.36. Network Theory

A branch of mathematics and computer science that studies the properties and behaviour of complex systems that can be represented as networks of interconnected nodes. It involves analysing the relationships and interactions between the nodes of a network to understand how information, resources, or influence flow through the network. The goal is to develop mathematical models and algorithms that can be used to optimize network performance, predict network behaviour, and identify vulnerabilities or bottlenecks in the network.

2.6.37. Operational Coordination

Operational Coordination is the systematic operational alignment of utility and non-utility assets to provide electricity delivery. It can also refer to structured mechanisms by which millions of diverse Energy Resources (merchant and private) operate both to serve individual priorities ('local selfish optimisation') and cooperatively participate to address common Power System issues.

As the historically dominant 'Supply-side / Demand-side' bifurcation erodes, the proportion of synchronous generation declines, and decarbonising Power Systems experience unprecedented levels of Volatility, ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require:

Bulk Power, Transmission and Distribution Systems – together with deep Demand-side Flexibility – to function far more holistically together, regardless of industry structure.

Due to the exponential growth in Energy Resource numbers, types and ownership models, more advanced Operational Coordination models become critical to:

- Enhance dynamic Interoperability across the Transmission-Distribution Interface (TDI) due to the Power System's growing dependence on Energy Resources located both up and downstream:
- Support more granular 'market-control' alignment to incentivise and activate targeted provision of grid services in the form of Electric Products when and where most needed;
- Co-optimise the provision of grid services across the vertical Tiers/Layers of the Power System to both enhance operations and maximise the Electric Product Value for participants;
- Mitigate or avoid legacy Architectural Issues that impede the Scalability, Extensibility and Resilience of Operational Coordination models; and,
- Ultimately enable transition to a more holistic Transmission-Distribution-Customer (TDC) model of Operational Coordination customised to local industry structure arrangements. Also refer Markets vs Control Fallacy.

2.6.38. Operational Coordination Framework

A formalised model for determining how a diverse range of Power System assets and Distributed Energy Resources (DER/CER) will cooperate to solve common problems. This requires the delineation all participant roles and responsibilities together with their needs and/or capabilities regarding business objectives, market responsibilities, device or system performance constraints, and data requirements.

2.6.39. Power System Architecture (PSA)

Power Systems Architecture is a generic term for an integrated set of disciplines that support the structural transformation of legacy ('brownfield') power systems to meet future policy and customer expectations, by:

- Providing formal tools that enable the decomposition and 'taming' of massive complexity that is inherent in transforming Power Systems;
- Empowering more informed, multi-stakeholder participation by making critical content explicit and tractable which would otherwise remain opaque and intractable; and,
- Increasing decision quality, timeliness and traceability to increase the potential for full benefits-realisation and avoiding the propagation of unintended consequences.

By recognising each Power System as an ultra-complex 'Network of Structures', the PSA methodologies are uniquely designed to provide:

- **Whole-system insight** over 5, 10 and 20-year time horizons, enabling the interrogation and mapping of current, emerging and future power system priorities, objectives, functions and enabling structures that may emerge under a range plausible future scenarios;
- **Evidence-based tools** to identify, analyse and shortlist key transformational options through the combination of Systems Architecture, Network Theory, Control Theory, Systems Science and Model-based Systems Engineering (MBSE) supported by Strategic Foresight, Behavioural Science and Energy Economics; and;
- **Future-resilient decision making** by surfacing hidden structural constraints early which may otherwise drive future issues such as computational constraints, latency cascading and cyber-security vulnerabilities, providing greater assurance that new investments will be scalable and extensible under all plausible futures.

Importantly, PSA expands rather than limits optionality. It enables architectural decision making based on key principles, formal methodologies and rigorous structural analysis. It gives priority to extensive collaboration with diverse stakeholders so as to enhance trust, ensure high levels of alignment and support social license for change.

2.6.40. Reference Architecture

An initial integrated set of documents and structural diagrams that capture the essence of the relationships, linkages and interdependencies embodied in a complex System.

The development of a Reference Architecture functions as the first major loop of architectural development and 'community of practice'. It is foundational to subsequent Detailed Architecture and Engineering Detailed Design phases.

2.6.41. Scalability

An architectural characteristic that takes the future scale growth of a System into consideration. It is a systemic measure of the underpinning Structure's ability to accommodate significant increases in the number of Components and Endpoints without degrading System functions and/or requiring major modifications.

2.6.42. Systemic Issues

Cross-cutting conditions and/or structural settings that:

- Currently exist in a specific GW-scale Power System and/or will arise from the convergence of various Emerging Trends; and,
- Will require architectural interventions if the emerging Customer & Societal Expectations for the future Power System are to be enabled in a secure, cost-efficient, timely and scalable manner.

2.6.43. Structure

The stable relationships, linkages and interdependencies that are established between the Components of the System to enable the reliable achievement of the System purposes.

Refer also to Architecture.

2.6.44. System

A set of Components that are formally related together by a shared Structure to achieve outcomes that exceed the sum of the individual Components. As such, a System is not the sum of its parts, but the product of the interactions of those parts – a concept referred to as Emergence.

Simplistically, if the boxes in a block diagram are the Components, then the Structure or Architecture is represented by the lines that connect the boxes.

Importantly, the underpinning Architecture always has a disproportionate and irreducible influence on the essential limits of what a System can reliably and efficiently perform. Given this decisive impact on System performance, changing or enhancing any number of Components cannot ultimately compensate for a failure to address an underpinning Architecture that is no longer fit-for-purpose.

2.6.45. System Engineering

An established engineering discipline applied in numerous sectors focused on the development and operation of ultra-complex Systems including aerospace, military, manufacturing, energy and electronics sectors.

While many engineering disciplines are oriented toward individual Component technologies or sub-systems, Systems Engineering is a transdisciplinary approach that brings a holistic or 'whole-system' approach to the realisation of successful Systems which consistently satisfy the needs of their customers, users and other stakeholders.

In the application of PSA disciplines, the System Functions emerge as the product of decisions made about both Architecture and then Components. These decisions are in turn informed by those made about System Qualities and System Properties (see below).

2.6.46. System Science

A multi-domain, integrative discipline that brings together research into all aspects of complex Systems with a focus on identifying, exploring and understanding the universal patterns and behaviours of Complexity and Emergence.

2.6.47. Systems Architecture

A formal element of Systems Engineering, which enables objective, collective reasoning about the underpinning Structure or Architecture of a complex System, together with its Components, Interfaces, Feedback Loops and other behaviours.

This is particularly important as the Architecture of a System always has a disproportionate and irreducible influence on what the System can reliably and efficiently perform. As such, a System is not the sum of its parts, but the product of the interactions of those parts as enabled by its underpinning Architecture.

While having a major impact on the performance of any System, Architecture is usually less tangible and harder to discern than the Components of the System. Therefore, the Systems Architecture discipline provides formal tools for examining how all the Components of a system are related together by the underpinning Architecture, the Emergent behaviours that arise through their interactions, and the most robust options for making changes where required.

Systems Architecture disciplines, therefore, help stakeholders visualise and make more informed decisions about the relationships embedded in the legacy System, including how they might best be adapted to ensure the System is ready to meet future needs.

2.6.48. Tiers / Layers

In the mathematical method known as layered decomposition, optimisation problems are decomposed from a master problem into a sub-problem and the sub-subproblems in a recursive manner. Each level of decomposition is a Tier or Layer.

In Power Systems Architecture, this decomposition is often applied to the consideration of advanced Operational Coordination mechanisms in which the vertical Tiers/Layers include the Bulk Power System, Transmission System and the Distribution System.

2.6.49. Top-down

An approach to problem solving and/or the design of a System that derives a hierarchical structure by successive subdivisions from the top. This is also known as stepwise refinement.

2.6.50. Transactive Energy (TE)

A system of economic and control mechanisms the dynamically enable Operational Coordination by using value as a key operational parameter.

2.6.51. Transmission-Distribution Interface (TDI)

The physical point at which the upstream Bulk Power and Transmission System and the downstream Distribution System interconnect, typically at one or several major substations. In a conventional, highly bifurcated Power System, these were traditionally known as the Supply-side and Demand-side respectively.

Power Systems that host growing volumes of Variable Renewable Energy (VRE) and Distributed Energy Resources (DER/CER) will experience significantly greater levels of Volatility, which can propagate upstream and downstream. Ensuring system Adequacy, Security, Reliability and Cost-efficiency simultaneously will require much greater levels of dynamic inter-dependence across the TDI than in the past.

2.6.52. Transmission-Distribution Interoperability Mechanisms (TDIM)

The various existing and expanding number of emerging functions and protocols that need to be executed across the Transmission-Distribution Interface (TDI) in their formalised and automated form. Key areas of priority are expected to include enhanced, low latency data exchange relevant to Frequency control, Voltage control, Congestion management Energy flow, Power-based services and System Balancing.

Underpinned by appropriate decisions about the enabling Cyber-physical Architecture, the TDIM will play a key role in supporting next generation Visibility, Operational Coordination and Resource Adequacy analysis.

2.6.53. Ultra-Large-Scale (ULS) System

Extremely large, ultra-complex Systems that consist of unparalleled volumes of: hardware and software; data storage and exchange; computational elements and lines of code; participants, stakeholders and end-users; and, multiple complicated Structures interconnected in complicated ways.

A ULS System also typically exhibits the following characteristics:

- Wide geographic scales (continental to precinct);
- Wide-time scales (years to microseconds);
- Long-term evolution and near continual deployments;

- Centralised and decentralised data, control, and development;
- Wide diversity of perspectives on the purpose(s) and priorities of the System;
- Inherently conflicting diverse requirements and trade-offs;
- Heterogeneous, inconsistent, and changing elements; and,
- Locational failures and response occur as a matter of normal operations.

The Power System is a prime example of an ULS system, and arguably one of the world's most complex.

2.6.54. Whole Grid Coordination

The means by which distributed grid elements are made to cooperate to solve a common problem—in this case, grid control. See also Laminar Coordination Framework.

2.7. Power System Structures

2.7.1. Electricity Infrastructure (Power Flows)

Provides for the physical movement of electric power across the end-to-end Power System, including Transmission and Distribution networks, Microgrids, Substations and Switching Stations, embedded bulk Energy Storage, etc. While historically this was primarily unidirectional, it now increasingly involves bi-directional flows, especially across the Distribution System. Examples include:

- Power flows from the Bulk Power System to T/D interface substations through the Transmission System.
- Power flows to and among customers through the local Distribution System.
- Bulk storage of excess renewable energy output and subsequent injection to the Power System during periods of Peak Demand.
- Customer generation and storage that provides power to customer loads and/or injects power into the local distribution system.

2.7.2. Digital Infrastructure (Information/Data Exchange, Storage, and Processing)

Provides for all information and data exchange required to maintain the safe and reliable operation of the Power System and enable its coordinated operation. This includes a diverse range of elements including resource telemetry, system topology changes, resource interoperability, etc. Examples include:

- Signals and data used for real-time protection and control of the Power System, including grid state measurement and estimation, real time balance and system frequency telemetry, switch states and grid topology.
- Energy Resources participating in the Wholesale Market submit telemetry to the Market/System Operator (MSO) to indicate asset performance in real-time.
- MSO and emerging Distribution System Operators (DSO) exchange system condition information to support the conjoint management of relevant Transmission-Distribution Interfaces.
- Energy Retailers and DER/CER Aggregators participating in the Wholesale Market and DSO Flexibility Markets submit telemetry to the relevant entities to indicate asset performance in real-time.

2.7.3. Markets / Transaction Structure

Provides for the procurement and sale of Energy, Capacity, and Essential System Services at any Tier/Layer of the Power System through market or other financial arrangements. This may include participation in Wholesale Market, DSO Flexibility Markets, Power Purchase Agreements (PPA), and capacity or service contracts. This also includes market schedules and dispatch instructions.

- Energy Resources participating in the Wholesale Market provide bids/offers to the MSO who subsequently schedules the Dispatch of participating resources.
- Relevant to the Operational Coordination of the Power System (see below), various current and emerging market structures are calibrated to incentivise Energy Resource behaviours and the provision of Energy Products needed by different Tiers/Layers of the system.
- Energy Retailers and DER/CER Aggregators procure and contract services from DER/CER and other Flexible Resources located on the Demand-side and sell them in the Wholesale Market, ESS Market and/or DSO Flexibility or Network Services Markets.

2.7.4. Operational Coordination Structure

Operational coordination is the systematic operational alignment of utility and non-utility assets to provide electricity delivery. Coordination structure provide the framework for the holistic orchestration of diverse Energy Resources, including Flexible Resources on the Demand-side, and other Power System facilities, in a manner that supports the Adequacy, Security[1], Reliability and Cost-efficiency of the system.   Examples include:

- MSO exerts control over Energy Resources participating in the Bulk Power System by sending Dispatch instructions and basepoints to secure necessary services.
- MSO exerts control over the Transmission System in response to a Constraint or Contingency to preserve system safety and reliability.
- DER/CER Aggregators provide the MSO and DSO resource availability forecasts for Energy Resources;
- MSO and DSO conjointly manage their respective sides of the Transmission-Distribution Interface(s) supported by two-way data flows between the parties.
- DER/CER Aggregators orchestrate contracted DER/CER in response to the various calibrated market structures for procuring the Energy Products required by different Tiers/Layers of the system.

2.7.5. Industry / Market Structure

The set of entities involved in operating the physical Power System, across its vertical Tiers/Layers and their related markets, including their formal Roles and Responsibilities, as well the various interconnections, relationships and interdependencies of these entities. Some examples of these entities include:

- Market/System Operator (MSO)
- Transmission Network Service Provider (TNSP)
- Distribution Network Service Provider (DNSP)
- Distribution System Operator (DSO)
- Merchant Generators
- DER/CER Aggregators

[1] Includes the management of Minimum Operational Demand

- Participating DER/CER owner-investors

2.7.6. Governance / Regulatory Structure

The set of entities involved in the governance and regulation of the Power System and its related markets, and their relationships to the regulated entities and the nature of what is regulated. It provides a graphical mapping of various regulatory relationships, in particular which entity regulates which industry/market participants and processes (but is not a description of regulatory rules themselves). In the NEM context, some examples include:

- Commonwealth Government
- State Governments
- Australian Energy Market Commission (AEMC)
- Australian Energy Regulator (AER)
- Australian Energy Market Operator (AEMO)

2.7.7. Sector Coupling Structures

Sector Coupling structures determine how adjacent industries are presently related and how they may function more interdependently with the Power System as a critical part of enabling a significantly more flexible and adaptive Power System. Examples of various sector couplings include:

- Electricity and gas sectors
- Electricity and industrial processes
- Electricity and transport
- Electricity and building services
- Electricity and water systems
- Power system and ICT technologies
- Electricity and the emerging Green Hydrogen sector

2.8. Other

2.8.1. 'Centralised vs Decentralised' Fallacy

A position that asserts that the Systems Architecture of an electricity system that hosts high levels of DER must be either entirely centralised or entirely decentralised. In practice, both approaches have strengths and weaknesses that must be carefully balanced in a given context.

For example: wholly centralised schemes may have scalability, computational and security challenges whereas wholly decentralised schemes may have deployment, diagnostic, functional limitation and Co-optimisation challenges.

Where a significant transformation is underway, it is imperative to undertake a holistic examination of the most appropriate System Architecture to achieve sustained least-cost outcomes. However, rather than a 'big bang' architectural shift, this will always require a progressive transition in which elements of both schemes may co-exist as a legacy Architecture is progressively transitioned over time toward the required future Architecture.

2.8.2. 'Market vs Control' Fallacy

Polarised positions that assert the coordination or Orchestration of DER must be largely or entirely achieved via technological control or economic incentives. For example, a market economics view may assert that establishing the right market rules and prices will be sufficient. By contrast, a control engineering perspective may assert that establishing the right standards, protocols and optimisation equations will be sufficient.

This is a false dichotomy as elements of both markets and controls are necessary for a holistic approach to Operational Coordination where a Power System is increasingly decentralised. For example:

a) Well-designed markets operate as excellent sensors (of market participant capabilities and intentions) and optimisation engines;

b) Technical controls are required as markets alone cannot address all Power System dynamics; and,

c) Beyond basic connection requirements compliance, economic incentives will be required to induce millions of privately-owned DERs to provide beneficial services to the Power System.

2.8.3. 'Tariffs vs Markets' Fallacy

A position that asserts or implies that tariff reforms and the emergence of DER Market Platforms are in competition or even dichotomous. This is a false dichotomy as:

a) Both tariffs and Market Platforms will co-exist for an indefinite period of time;

b) The reform of tariffs and the emergence of new DER markets will need to be strategically aligned for maximum complementarity; and,

c) Tariffs and tariff reform will be critical to the large number of customers who do not currently and may never own DE

2.8.4. Power System Architecture & Enterprise Architecture Comparison

Area of Comparison	**Power System Architecture**	**Enterprise Architecture**
Focus	Industry / Sector	Enterprise IT systems
Complexity	• Industry Level: Ultra-Large-Scale Complexity • Help manage complexity and risk within industry	• Enterprise Level: Large Scale Complexity • Helps manage complexity and risk within the enterprise
Stakeholders	Diverse stakeholders including policy makers, regulators, industry, customer groups, environmental groups, etc.	Internal enterprise stakeholders. Generally reports to CIO and reflects interests of IT primarily
Motivation	Power System Architecture is focused on clearly identifying key industry problems and opportunities (issues) that architecture is focused on resolving. Define essential industry limits/constraints.	• More narrowly focused on the various challenges the enterprise faces. • Less focused on resolving key issues facing the industry as a whole.
Requirements	Defines qualities and properties of the future power system based on a broad range of societal and stakeholder perspectives.	Defines business requirements primarily from the perspective of enterprise stakeholders only.
Current State	• Defines current state of essential power system structures and the relationships between these structures: • Electricity Infrastructure (Power Flows); • Digital Infrastructure (Information/Data Exchange); • Operational Coordination Structure;	Defines the current state of the enterprise: • Strategic enterprise objectives mapped to capabilities • Enterprise principles • Business Architecture • Information System Architecture • Technology Architecture

	• Markets / Transactional Structure; • Industry / Market Structure; • Regulatory Structure; and, • Sector Coupling Structures (Gas, Water, Transport, etc).	
Gap Analysis	Identify gaps in theory, technology, organisation, regulation	Identify gaps in business, information systems, and technology.
Target Future State	Identify and remove barriers and define essential limits Assist in developing a future vision for the power system and communicating among stakeholders around a shared vision of the future grid: • Electricity Infrastructure (Power Flows); • Digital Infrastructure (Information/Data Exchange); • Operational Coordination Structure; • Markets / Transactional Structure; • Industry / Market Structure; • Regulatory Structure; and, • Sector Coupling Structures (Gas, Water, Transport, etc).	Defines target state of the enterprise: • Strategic enterprise objectives mapped to capabilities • Enterprise principles • Business Architecture • Information System Architecture • Technology Architecture
Transition Planning	Provides a framework for complex power system transformation and related development activities	Develop enterprise roadmap to move from current state to target future state

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