AUSTRALIAN RESEARCH IN POWER SYSTEMS TRANSITION (STAGE 4)

Energy Catalyst

REPORT 3 OF 5

Systemic Issues & Transformation Risks

AUGUST 2025

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Navigating to 2035 en route to 2050

Consistent with Systems Engineering practice, this report distils a finite set of cross-cutting issues derived from the almost one hundred trends impacting global power systems and mapped in Report 2. The resulting fifteen Systemic Issues provide key points of leverage for preparing the NEM for an increasingly decarbonised and distributed future. This enables stakeholders to move from interrogating dozens of individual trends and large use case libraries, which rapidly become unwieldy, to a more focused set target issues that provide compounding benefits if addressed and directly inform Distribution System Operator (DSO) and T-D Coordination (TDC) design.

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Executive Summary

Australia's electric power sector finds itself on the global frontier of large-scale grid transformation. The nation's power systems are transforming from a past of hundreds of large, upstream generation plant to a future with tens of millions of diverse energy resources participating across all vertical tiers/layers of the grid.

This is in a context where the combined impact of increasingly volatile and bidirectional operations is driving world-first challenges for managing a grid originally designed for comparatively stable, unidirectional operation. In such a context where the operational requirements of a legacy system are changing quite fundamentally from their original design philosophy, while targeted treatments may assist for a time, enduring scalable solutions ultimately require structural interventions.[1] As a result, in more recent years, the expanding complexity of navigating large-scale grid transformation has forced an increased focus on the critical role of structural analysis.

Consistent with Systems Engineering practice, this analyses and distils a finite set of Systemic Issues that must be addressed to enable increasingly decarbonised and distributed grids like the NEM to transform in a secure and affordable manner. This enables stakeholders to move from interrogating dozens of individual trends and large use case libraries, which rapidly become unwieldy, to distil a more focused set of cross-cutting issues that require targeted structural resolutions.

As part of an integrated reference set of five reports, Chapter 1 and Chapter 2 provide an overview of the set and the development approach applied with this report. Informed by Design Thinking and underpinned by Systems Engineering, Systems Architecture and a range of related disciplines, the reference set is designed to enable a subsequent Detailed Architecture process for Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models.

Chapter 3 then presents an analytical framework that groups the identified Systemic Issues into four categories: strategic transformation risks, core structural and operability issues, digitalisation and scalability constraints, and participation and alignment risks. Chapter 4 then provides a detailed analysis of each of the fifteen issues showing how they span technical, operational, and institutional boundaries and provide guidance on the characteristics of potential solutions.

Functioning as a key input to Report 4 and Report 5 in the series [33] [34], this report concludes in Chapter 5 by providing a summary of observations about the relevance and veracity of focusing on a finite number of cross-cutting Systemic Issues rather than scores of issues in isolation. The findings of this report are widely employed in the development of the two subsequent reports.

[1] A necessary material change to the structural and functional arrangements of a system. It requires a significant departure from the original structural and functional design of the system. Refer also to Key Concepts A.

Table of Contents

Table of Figures

List of Acronyms

AR-PST	Australian Research in Power System Transition
ACER	Agency for the Cooperation of Energy Regulators (EU)
AEMO	Australian Energy Market Operator
ADMS	Advanced Distribution Management System
AI	Artificial Intelligence
ANM	Active Network Management
API	Application Programming Interface
BESS	Battery Energy Storage System
BPS	Bulk Power System
BTM	Behind-the-meter
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CER	Consumer Energy Resources
CIM	Common Information Model
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DER	Distributed Energy Resources
DERMS	Distributed Energy Resources Management System
DLT	Distributed Ledger Technology
DMO	Distribution Market Operator
DMS	Distribution Management System
DNSP	Distribution Network Service Provider
DNO	Distribution Network Operator
DOE	Dynamic Operating Envelopes
DPV	Distributed Photovoltaics
DSMO	Distributed System Market Operator
DSO	Distribution System Operator
DSR	Demand Side Response
E.DSO	European Distribution System Operators
EE-ISAC	European Energy – Information Sharing & Analysis Centre
ENA	Energy Network Association (UK)
ENCS	European Network for Cyber Security (EU)
ENISA	European Network and Information Security Agency

ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute (
ESO	Electricity System Operator
EV	Electric Vehicle
FCAS	Frequency Control Ancillary Services
FERC	Federal Energy Regulatory Commission (US)
FLISR	Faul Location, Isolation, and Service Restoration
FTM	Front of the Meter
GW	Gigawatt
GWh	Gigawatt Hour
HP	Heat Pump
HV	High Voltage
HVAC	Heating, Ventilation, and Air Conditioning
IBR	Invertor-Based Resources
ISO	Independent System Operator
ISP	Integrated System Plan
KW	Kilowatt
LV	Low Voltage
MBSE	Model-Based Systems Engineering
MV	Medium Voltage
MVAr	Megavolt-ampere Reactive
MW	Megawatt
MWh	Megawatt Hour
NCERR	National Consumer Energy Resources Roadmap
NEM	National Electricity Market
NESO	National Energy System Operator
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OFGEM	Office of Gas and Electricity Markets (UK)
OMS	Outage Management System
OPEX	Operational Expenditure
OPF	Optimal Power Flow
OT	Operational Technology
PNNL	Pacific Northwest National Laboratory (US)
PV	Photovoltaic
RIIO	Revenue = Incentives + Innovation + Outputs (UK)
SCADA	Supervisory Control and Data Acquisition

SO	System Operator
SPOF	Single Point of Failure
TDC	Transmission–Distribution Coordination
TDI	Transmission–Distribution Interface
TNSP	Transmission Network Service Provider
TOTEX	Total Expenditure
TSO	Transmission System Operator
TW	Terawatt
TWh	Terawatt Hour
UKPN	UK Power Networks
ULS	Ultra Large Scale
USEF	Universal Smart Energy Framework
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
WEM	Wholesale Energy Market

1 Report Purpose, Context & Rationale

1.1 Purpose

As Australia's power systems continue to decarbonise, they are becoming orders of magnitude more volatile and bidirectional. The combined impacts of decarbonisation, democratisation and decentralisation are driving an unprecedented scale and pace of transformation. Notably, these three drivers are themselves underpinned by a complex range of societal, technological, economic and commercial shifts, many of which fall outside the direct control of traditional regulatory and governance mechanisms.

The following seven selective examples illustrate the scale of transformational change now reshaping Australia's power systems:

1. An escalating ***locational and operational diversity*** of energy resources as the system moves from a past of hundreds of large, upstream merchant resources to a future involving ***tens of millions of diverse technologies*** participating across all tiers/layers of the system.

2. Increasing ***whole-system dynamics*** as dispatchable, synchronous generation is progressively withdrawn and an ever-increasing proportion of net generation capacity is provided by ***variable, inverter-based resources.***

3. Structural shifts in ***customer demand, variability and predictability*** are being driven by the mass deployment of distribution-connected CER/DER and compounded by the electrification of transport, industrial processes and data centres.

4. The ***erosion of once-dominant operational paradigms***, such as a strict 'supply-side/demand-side bifurcation' and the universal 'load-following operational paradigm', both inherent to the functioning of a unidirectional power system.

5. With the progressive withdrawal of dispatchable, synchronous generation, ***coordinated new sources of system flexibility, buffering and ancillary services*** located on both sides of Transmission-Distribution Interface (TDI) are increasingly required.

6. An ***expanding set of operational responsibilities*** must be coordinated ***across several different entities***, including AEMO, TNSPs, DSOs and large third-parties that are increasingly capable of influencing system stability, either directly or indirectly.

7. An increasing need for ***whole-system digitalisation of power system*** to enable alignment across multiple upstream and downstream entities, enable advanced operational visibility and coordination, and reduce traditional infrastructure overbuild risks.

After many decades of relatively slow change, what is now occurring in Australia involves transformative shifts of a scale impossible for the original architects of the system to anticipate. This is a scale of transformation that challenges the structural underpinnings of the system itself.

The study of emerging trends and development of use case libraries is useful at such times. However, being inherently focused on specific elements of the wider transformation, they struggle to encapsulate the overarching currents of transformative change impacting such a large, complex system. By themselves, they tend to inform more 'issue-in-isolation' problem solving.

Consistent with Systems Engineering practice, however, an additional step of identifying a limited set of *Systemic Issues* provides a powerful and holistic approach to problem definition in a complex, transforming system. It enables stakeholders to move from dozens of individual drivers of change, which fast become unwieldy and impractical, to a more finite set of cross-cutting issues requiring attention.

By highlighting key points of leverage, the Systemic Issues enable targeted structural interventions that can deliver transformative, whole-system benefits any number of individual changes never can. As such, they provide the next critical step in answering the question:

> ***After mapping dozens of emerging trends (Report 2), how do we shortlist the priority issues that, if addressed effectively, will accelerate transformative change and underpin many of the new whole-system capabilities that decarbonising power systems require?***

It is expected that the topics of Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models in this series will receive particular attention (Reports 4 & 5 respectively). Whether fully appreciated or not, however, all DSO and TDC models are ultimately structural interventions seeking to address the impacts of many Systemic Issues analysed here.

1.2 National Context

Electricity systems are some of the largest and most complex systems ever created by humans. Following decades of comparatively slow change, these critical societal systems are now experiencing a scale of structural transformation not seen since the dawn of electrification.

On numerous metrics Australia's NEM is leading the way in navigating this complex and multi-faceted transformation. In this context, several formal initiatives[2] are currently reviewing key elements of the 'as built' NEM and each of these processes are expected to add value within their respective remits in the near to medium-term. It is likely that the recommendations of each of these initiatives will also have near, medium and long-term structural or 'architectural' implications that may benefit from a common set of reference materials.

[2] For example, the National Consumer Energy Resources Roadmap, the Review of Market Settings in the National Electricity Market and the recently completed CER Data Exchange Industry Co-Design.

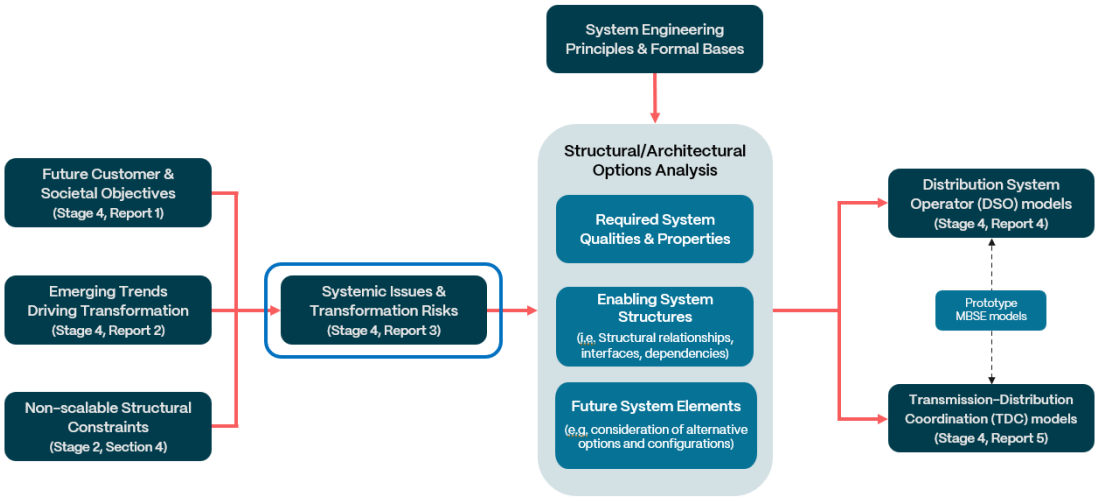


Figure 1: This report is one of five which, as a reference set, are designed to support an integrative approach to Australia's power system transformation

To help support such a foundation, this document is part of an integrated set of five reports developed under the Australian Research – Power System Transformation (AR-PST) initiative sponsored by Australia's national science agency CSIRO and in collaboration with the Australian Energy Market Operator (AEMO). This reference set consists of the following reports:

- **Report 1:** Future Customer & Societal Objectives
- **Report 2:** Emerging Trends Driving Transformation
- **Report 3:** Systemic Issues & Transformation Risks
- **Report 4:** Distribution System Operator (DSO) Models
- **Report 5:** Transmission–Distribution Coordination (TDC)

1.3 Practical Rationale

In the formal Systems Engineering and Systems Architecture[3] disciplines, a cross-cutting problem that stems from the fundamental structure of a complex system and/or impedes efforts to holistically transform the system is referred to as a Systemic Issue. These issues emerge from the way the entire system is structured, rather than from isolated component failures or random anomalies.

In the context of system transformation, Systemic Issues typically surface when the cumulative impact of diverse Emerging Trends (refer Report 2) intersects with the systems legacy structural arrangements and constraints. In the case of electricity systems, Systemic Issues often simultaneously impact several of the seven interdependent technological, market, and regulatory structures that make up a modern grid.

[3] Refer to Key Concepts A.

Identifying, analysing, and documenting Systemic Issues is a powerful, holistic means of problem definition for complex, evolving systems. Focusing on Systemic Issues enables collaborating stakeholders to distil a finite set of cross-cutting problems that are strategic points of leverage. In an ultra-complex system, this uniquely enables targeted structural interventions capable of delivering enduring system-wide benefits at least cost.

Table 1: An illustrative comparison of the scale of change impacting many GW-scale power systems globally

Aspect	Fossil Fuel, Unidirectional Grids	Decarbonised, Bidirectional Grids
Customers	Largely passive receivers/consumers of energy.	Wide diversity of customer types and preferences spanning active prosumers through traditional consumers.
Power Flows	Unidirectional, comparatively predictable.	Bidirectional, increasingly volatile.
System & Market Operation	Top-down, hierarchical, unicentric (primarily AEMO).	Layered, collaborative, polycentric (AEMO, TNSPs, DSOs, etc.)
Generation	Hundreds of large-scale, centralised generation plant located upstream (largely merchant resources)	Tens of millions of diverse energy resources located both upstream and downstream (merchant, private and third party)
Balancing Paradigm	Load-following.	Conventional load-following paradigm progressively integrating supply-following flexibility during low load periods.
Flexibility Sources	System flexibility primarily provided by large-scale dispatchable generation.	Hybridised combination of dispatchable generation, flexible demand and energy storage/buffering across all system tiers/layers.
System Services	Synchronous generation providing rotational inertia and FCAS.	New sources of rotational and synthetic inertia and FCAS required.
Digitalisation	Centralised data processing. Fragmented digital landscape.	Ubiquitous and mission-critical. Expanding dependance on decentralised and edge data processing.

2 Report Development Approach

As illustrated in Figure 1 (above), the analysis of Systemic Issues & Transformation Risks is a critical input to holistic transformation design model provided Systems Architecture disciplines. The approach to developing this report is outlined below.

2.1 Philosophy

The set of reports has been developed through the lens of Design Thinking and underpinned by Systems Engineering, Systems Architecture and related disciplines. In doing so, it attempts to take a longer view of whole-system transformation relevant to the NEM and the increasingly critical role of DSO models for achieving the key objective of the federal National CER Roadmap initiative [1].

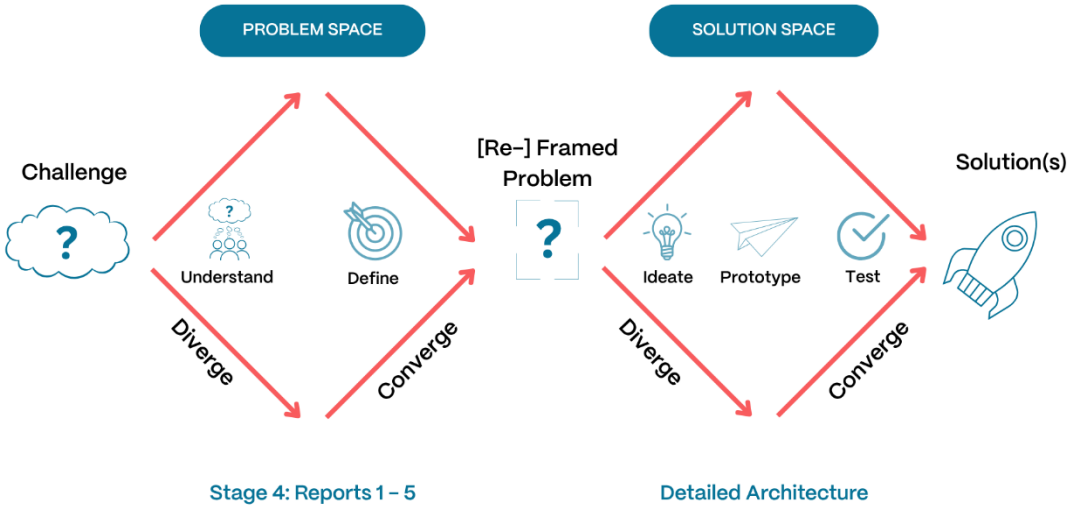


Figure 2: The reference set of five reports applies a Design Thinking approach to whole-system transformation underpinned by Systems Engineering and related disciplines

As noted previously, the reference set is designed to underpin a subsequent Detailed Architecture process that provides an integrated approach for navigating Australia's timely and efficient deployment of DSO and TDC models (i.e. 'solution space'). As illustrated in Figure 2 **Error! Reference source not found.**, the five reports developed in AR-PST Stage 4 evaluate the divergent global and Australian content relevant to each of the topics covered (i.e. 'problem space'). This enables a rigorous, objective and traceable means for reporting and converging on the most critical issues that must be addressed to develop future-ready solutions enabled by constructive multi-stakeholder collaboration.

2.1 Working Definition

Identifying, analysing, and documenting Systemic Issues provides a powerful, holistic means of problem definition in a complex, transforming system. In developing this report, the following definition of a Systemic Issue was formulated informed by Systems Engineering practice:

> ***A cross-cutting problem that stems from the fundamental structure of a complex system and/or impedes efforts to holistically transform the system.***
>
> ***Systemic Issues are uniquely distinguished as follows:***
>
> - ***Multiple Systems/disciplines:*** *Systemic Issues are cross-cutting in that they span multiple subsystems and/or disciplines, making them challenging to isolate and address through traditional, topic-specific approaches.*
> - ***Emergent Behaviours:*** *Systemic Issues often lead to system behaviours that are not predictable by analysing individual components alone, as their emergent behaviours result from complex interactions within and across the system.*
> - ***Structural Root Causes:*** *Systemic Issues are commonly embedded in the architecture of the system – such as its topology, control mechanisms, information flows, governance models – rather than individual constraints, elements or mechanisms.*
> - ***Resistant to Local Fixes:*** *Addressing Systemic Issues will typically require targeted structural interventions – localised treatments alone are incapable of resolving the underlying problem and can sometimes exacerbate it.*

2.2 Development Approach

As noted above, identifying and shortlisting Systemic Issues in a complex system is a cornerstone of Systems Engineering and Systems Architecture disciplines and underpins robust problem definition and solution ideation. Guided by the principles and methodologies outlined in Appendix A, the process moved through the following steps:

Review and Synthesise Key Inputs

Review the range of inputs required to inform the architectural methodology, including:

- The range and diversity of future customer and societal objectives that inform the capabilities needed by future power systems (Report 1).
- The extensive range of emerging trends that are driving the transformation of existing power systems (Report 2).
- Interrogation of the underpinning legacy structure or 'architecture'[4] of the NEM to identify embedded constraints that present future scalability risks (Stage 2, Section 4).

[4] Refer Key Concept F.

- Continued reference to the scale of medium and long-term change anticipated by AEMO's Integrated System Plan (ISP) scenarios.
- Evaluation of the architecturally informed inputs needed to inform examination of Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models (Reports 4 & 5).

a. Identification of Potential Systemic Issues

Recognising the diverse, wide-ranging nature of the above topics, progressively evolve a concise set of potential Systemic Issues identified by key indicators, including:

- New and/or changing system behaviours which present growing operational challenges for the power system as a whole.
- Structural constraints embedded in the legacy architectural arrangements of the end-to-end NEM that impact future scalability and extensibility.
- Cross-cutting issues that span multiple subsystems and drive complex interactions within and across the system.
- Key issues that are resistant to localised treatments and will require targeted structural interventions to resolve.

b. Refinement of Priority Systemic Issues

Refine the final set of Systemic Issues through several loops of iterative review to identify those most directly relevant to the consideration of future DSO and TDC models. This has included:

- Ongoing calibration with the above range of inputs needed to inform the architectural methodology that underpins DSO and TDC evaluation.
- Identification of the specific issues most likely to require targeted structural interventions to address which Systems Architecture methodologies and tools are most suitable to help resolve.
- Examination of each of the shortlisted Systemic Issues to provide analysis of relevant cross-cutting issue, contributing factor and solution requirements.

2.4 Inherent Limitations & Constraints

Given the wide-ranging nature of the reference set, the following points highlight limitations that are inherent to any such analysis. They should therefore be noted in the interpretation and application of this report subject to the formal disclaimers provided above.

- The five reports have been developed as an integrated reference set which, by definition, covers an extremely wide range of complex topics. This necessarily means that none of these topics have been treated exhaustively.
- As a reference set, it is anticipated that most readers will refer to particular content on an 'as needs' basis. Therefore, each of the five reports is designed to stand alone which has required some repetition of key unifying themes and concepts.

- While a modern GW-scale power system involves a complex overlay of technological, market, regulatory, economic and policy dimensions, the key principles and disciplinary perspectives applied in developing this series are outlined in Appendix A.
- Many of the topics covered by the reference set are inherently complex and some are hotly contested. This is necessary and appropriate in an evolving sector but can often be less productive than it may otherwise be due to a lack of shared concepts and language. Therefore, the development team has firstly attempted to maintain an objective and evidence-based approach. Further, to support the most informed debate, a glossary of key terms is provided in Appendix B and many report sections contain Key Concept breakouts designed to support clarity of communication.
- The reference set focuses on several emerging areas of consideration and is designed to assist navigation of the 'emerging future' over the next decade and beyond. It is therefore a consolidation of the development team's understanding at the time of publishing and will likely benefit from a comprehensive update on at least a bi-annual basis.
- While a range of tools and models are employed as a basis for reasoning about how the power system and its wider societal context may evolve, it is recognised that reality is far more complex than any model or archetype can ultimately represent.
- Recognising the inherent complexity of the topics explored, the diversity of perspectives and terminology, and the many thousands of pages of global content that is more or less relevant, the following points should be noted:
    - The reference set is inherently explorative and spans numerous overlapping topics and developments, many of which are yet to mature to a point of industry consensus, either in Australia or globally.
    - Therefore, it is inevitable, expected and healthy that different readers will draw different conclusions on some or several of the topics addressed.
    - Particular content will mean more to some system actors and/or those with particular discipline expertise than others. The standpoint of the reader and the time horizon they are primarily focused on will likely influence how the desirability or otherwise of particular content is evaluated.
    - Accurately predicting the future and/or foreseeing all eventualities is impossible. Therefore, it is anticipated that some of the content contained in this reference set will prove to be incorrect. For that reason, stakeholder feedback is strongly encouraged and a formal mechanism to do so is provided below.
    - In summary, the information contained in the reference set comprises general statements based on research. No claim to represent the official policy of CSIRO, AEMO or any other third party is made.

- Finally, while each of the five reports are designed to stand alone, they are best employed as an integrated set of reference material. Reports 3, 4 & 5 in particular should be read with reference to each other.

2.5 Accessing the Reference Set & Providing Feedback

The Energy Catalyst team deeply values excellence and humility. We believe that true leaders in times of transformational change do not overestimate their own knowledge. On the contrary, they foster and contribute to an ecosystem of diverse perspectives which enables shared understanding and mutual progress – even where differences remain.

This reference set is developed from a perspective that values exploration, discovery and convergence based on shared learning. Others will have important insights that the development team has not considered, and we would like to hear them. As noted earlier, as realists we also anticipate that some of the content contained will ultimately prove to be incorrect.

The full reference set of reports is available free for download at energycatalyst.au/futuregrid or by scanning the following QR code.

Constructive stakeholder feedback is also strongly encouraged, and a formal mechanism is also provided for each report at the same location. Thank you in advance for your collaboration.

Key Concepts A

Structural Analysis

In the context of electricity system transformation, structural analysis refers to the systematic evaluation of the physical, operational, and organisational structures of the power system to determine the changes necessary to transition from a conventional, fossil-fuel-based, unidirectional grid to a decarbonised, distributed, and bidirectional grid.

This process involves assessing how new technologies (such as distributed energy resources, storage, and electric vehicles), market mechanisms, and control strategies will alter the system's topology, power flows, stability characteristics, and resilience requirements. The goal is to ensure that the restructured grid can accommodate variable renewable energy sources, enable two-way energy and information flows, and maintain security, reliability, and affordability under future scenarios. Key components of structural analysis include:

- Physical Structure: Reconfiguration of transmission and distribution networks for bidirectional flows.
- Operational Structure: Adaptation of protection systems, frequency control, and flexibility measures.
- Institutional/Market Structure: Integration of distributed generation, demand-side participation, and new pricing models.
- Resilience and Stability: Ensuring robust system performance under uncertainty and high penetration of renewables.

Structural Intervention

In the context of power system transformation, a structural intervention refers to the deliberate modification or redesign of the physical, operational, and institutional components of the system to enable, for example, the transition from a centralised, fossil-fuel-based, unidirectional grid to a decarbonised, distributed, and bidirectional grid.

Structural interventions go beyond incremental operational adjustments; they involve fundamental changes to the system's architecture and governance to ensure it can support developments such as:

- High penetration of renewable energy sources.
- Two-way energy and information flows.
- Distributed generation, storage, and flexible demand.
- New market structures and regulatory frameworks.

These interventions may include network reinforcement and reconfiguration, deployment of advanced digital infrastructure, implementation of new control and protection schemes, and policy and market redesign to maintain reliability, resilience, and economic efficiency in the evolving energy ecosystem.

3 Report Structure

In this report, fifteen Systemic Issues are identified and grouped under the following four categories for further consideration.

Systemic Issue Categories & Definitions	
Category	**Definition**
1. Strategic Transformation Risks	Overarching considerations that impact many aspects of Australia's GW-scale power systems and risk impeding the timely, cost-efficient and technically robust navigation of whole-system transformation.
2. Core Structural & Operability Issues	Critical structural matters that will require holistic consideration and targeted interventions as Australia's power systems transform from a unidirectional past to an increasingly dynamic and bidirectional future.
3. Digitalisation & Scalability Issues	Key challenges that arise from the increasing need for more dynamically interdependent and digitalised end-to-end power systems, including cyber-security, data sharing and the scalability of cyber-physical elements and solutions.
4. Sectoral Alignment & Participation Risks	Considerations relevant to the future scalable assignment of roles and responsibilities and new mechanisms for supporting the seamless engagement and beneficial participation of millions of Consumer Energy Resources (CER/DER). Note that 'CER' and 'DER' recognises that distributed resources may be located either behind-the-meter or front-of-meter.

The fifteen Systemic Issues & Transformation Risks identified have been clustered under four categories and are summarised as follows.

Systemic Issues by Category	
Systemic Issue	**Summary**
1. Strategic Transformation Risks	
a. Limited Shared Future Vision	Beyond high-level emission reduction targets and long-term scenarios, no positive, shared and whole-system vision of Australia's future power systems currently exists to enable sectoral alignment on an integrated suite of medium and long-term transformative action.
b. Inadequate Complexity Management	As an ultra-complex 'system of systems' undergoing profound structural and functional shifts, reliability, cost-efficiency and scaling risks escalate by orders of magnitude where formal systems-based tools and methodologies designed to manage large-scale complexity are not actively employed.
c. Benefits Realisation Risks	Conventionally siloed, issue-in-isolation approaches to change, and the absence of formal models for holistic system transformation, place the realisation of $-billions of optimisation benefits for customers, society and the system at significant risk.
2. Core Structural & Operability Issues	
a. Foundational Structural Shifts	A range of inherent constraints are embedded in the legacy grid structures developed for unidirectional power flows and passive consumers. These constraints become increasingly problematic as decarbonisation advances and power flows become more bidirectional and volatile. Impacting the various segments of the grid, their impact is compounded where no single entity is responsible to ensure the system architecture of the end-to-end system is both scalable and future ready.
b. Operational Visibility Risks	As profound structural and operational shifts increase, the lack of a layered, end-to-end approach for providing operational visibility, especially of the growing fleet of millions of CER/DER, risks compromising the operability, reliability and cost-efficiency of the bulk power, transmission and distribution systems serving the NEM and WEM.

c. System Coordination & Balancing Risks	Bidirectional power flows and operational volatility are increasing as dispatchable, synchronous generation is being progressively withdrawn. As the NEM and WEM transition from hundreds to many millions of participating resources, the absence of layered, end-to-end models for operational coordination will place instantaneous system balancing and overall economic efficiency at growing risk.
d. Whole-system Buffering Needs	As a growing proportion of renewable generation is deployed, unprecedented levels of power flow volatility are propagated across the end-to-end system. While most complex systems and supply chains have internal buffering mechanisms (e.g. warehouses, storage tanks), these have not been widely available in conventional power systems. Given the scale of Variable Renewable Energy (VRE) and CER/DER deployment underway, a targeted and whole-system approach to deploying energy storage for system buffering will be required to augment system balancing and operational coordination.
e. Multiple Aggregator / VPP Risks	The involvement of multiple CER/DER aggregators and Virtual Power Plants (VPP) introduces an additional level of structural and functional complexity across several layers of a GW-scale power system. In the absence of a holistic structurally based approach to their integration, system and market operations will face increasing conflicts and inefficiencies where aggregators and VPPs are present at significant scale.
f. Single Point of Failure Risks	Electricity underpins every part of Australia's digitalised economy. Major disruptions rapidly cascade through numerous other societal systems. Given the highly centralised origins of our power systems, driving toward economy-wide electrification also requires a transition to more modular grid structures designed for resilience and redundancy. Failing to do so will significantly escalate major single-point-of-failure risks and national security vulnerabilities.
g. Modelling & Forecasting Risks	As power systems experience fundamental change in customer participation, technology mix, operational dynamics and enabling structures, the usefulness of existing modelling and forecasting tools is increasingly challenged. Given their key role in governance, investment and operational decision making, they must be constantly evaluated to ensure their continued adequacy as power system design and operations moves further away from the many legacy assumptions that informed the development of these tools.

3. Digitalisation & Scalability Issues	
a. Structural Cyber-security Vulnerabilities	Critical energy infrastructure faces a growing volume of cyber-security threats which can have catastrophic societal and economic impacts. Best practice approaches to cyber-security require a multi-layered approach that address different attack vectors. By contrast, a limiting factor across many risk mitigations in the power sector is a primary focus on cyber-based defences, with limited if any focus on 'non-cyber' structural vulnerabilities that are rapidly expanding.
b. Data Sharing Risks	Data sharing in increasingly distributed power systems involves complex functional relationships and hidden constraints that are embedded in legacy system structures. While promising digital technologies are promoted by different entities no single, comprehensive solution to grid data sharing needs exists. All data exchange options require the application of formal architectural analysis to make visible issues that directly impact the scalability, extensibility, resilience, cyber-security and interface design of proposed solutions.
c. Solution Scalability Risks	Greater focus on the whole-system functionality, scalability and potential unintended impacts of new technology and solution innovations, including but not limited to Dynamic Operating Envelope (DOE) solutions, to identify and pre-emptively address cyber-physical issues that will otherwise only manifest during mass-deployment of solutions post-trial phase.

4. Sectoral Alignment & Participation Risks	
a. Roles & Responsibilities Assignment Risks	The secure and efficient operation of GW-scale power systems depends on an intricate web of relationships across numerous functions, entities, structures, system boundaries, interfaces and hand-off points. As decarbonising power systems become increasingly volatile and bidirectional, this inherent complexity grows and new capabilities such as Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models are required. Given their deeply interconnected role in future system operations, the assignment of related DSO and TDC roles and responsibilities must be underpinned by formal structural and behavioural analyses to avoid unintended consequences, sub-optimal outcomes, cost escalation and the need for substantial rework and role reallocations.
b. CER/DER Scale Participation Risks	Future scenarios highlight the important role millions of orchestrated CER/DER, BESS and EVs could play in supporting more secure and efficient future power systems. Without a holistic strategy for scaling mass adoption and sustained participation, current trends suggest that achieving the scale of participation required will continue to prove challenging if not infeasible.

Key Concepts B

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), Consumer Energy Resources (CER/DER) and various forms of energy storage and firming resources.

Variable Renewable Energy (VRE)

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

While some forms of CER/DER are considered VRE, the term is mostly 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.

Consumer Energy Resources (CER/DER)

A diverse range of small to medium scale energy resources that are located behind-the-meter at residential, commercial and industrial premises and are owned and operated by the customer. CER/DER are a multi-application resource that include the following types of technologies:

- Distributed Photovoltaics (DPV) and embedded generators
- Battery Energy Storage Systems (BESS), including small and medium-scale batteries
- Electric Vehicles (EV)
- Smart Inverters
- Flexible Resources (Distributed)

The term Distributed Energy Resources (DER) is commonly used of these technologies where they connected directly to the distribution system (i.e. front-of-meter).

Active CER/DER

Consumer Energy Resources (CER/DER) capable of automatically altering their operating behaviour in response the needs of the wider power system. This may be in response to changes in the price of energy, the operating conditions of the local distribution network and/or upon receipt of instructions, control inputs or data feeds from authorised external entities.

4 Systemic Issues & Transformation Risks

Four Categories of Systemic Issues & Transformation Risks
1. Strategic Transformation Risks
2. Core Structural & Operability Issues
3. Digitalisation & Scalability Issues
4. Sectoral Alignment & Participation Risks

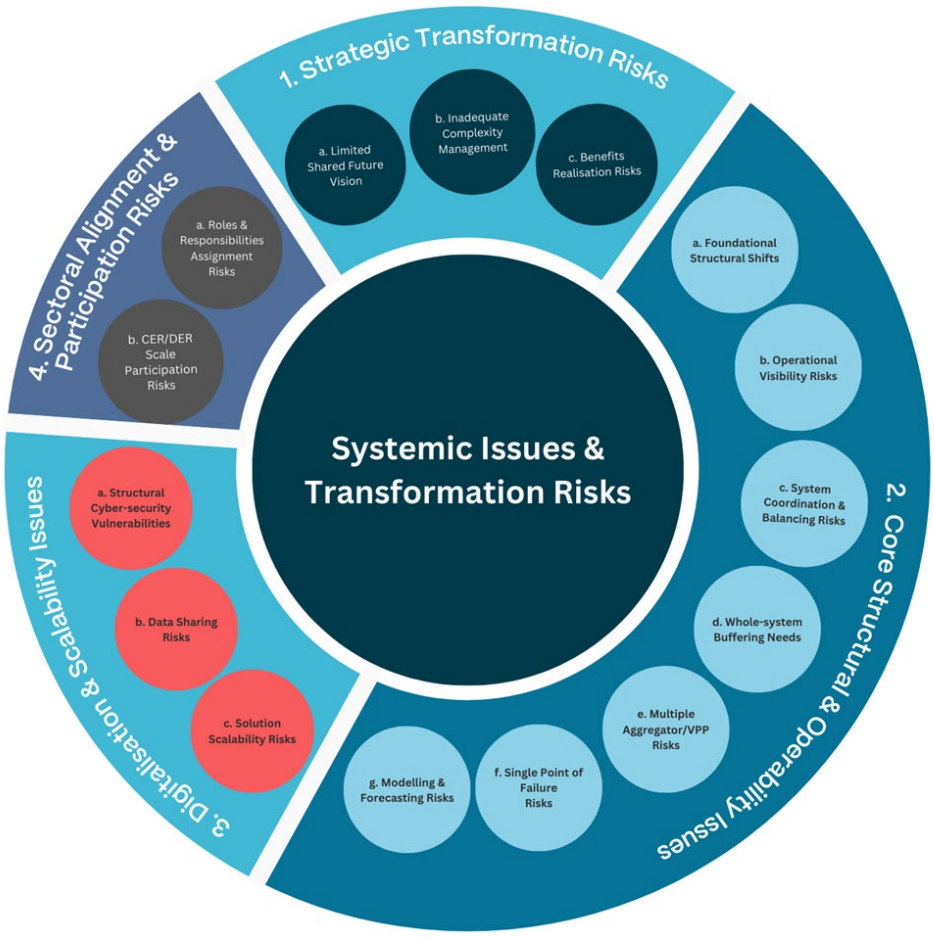


Figure 3: The structural analysis undertaken identified fifteen Systemic Issues & Transformation Risks clustered under four categories.

4.1 Strategic Transformation Risks

The following section examines three overarching considerations that impact many aspects of Australia's GW-scale power systems and risk impeding the timely, cost-efficient and technically robust navigation of whole-system transformation.

4.1.1 Limited Shared Future Vision

Beyond high-level emission reduction targets and long-term scenarios, no positive, shared and whole-system vision of Australia's future power systems currently exists to enable sectoral alignment on an integrated suite of medium and long-term transformative action.

a. Cross Cutting Issue

Australia is experiencing one of the world's fastest, large scale power system transformations. The nation provides a window on the energy future for many global jurisdictions.

The combined impacts of the '4 x Ds' – Decarbonisation, Digitalisation, Democratisation and Decentralisation – are driving Australia's unparalleled transformation. These, in turn, are accelerated by a complex range of societal, technological, economic and commercial shifts, many of which are outside the direct control of traditional power sector regulatory and governance mechanisms.

Under AEMO's 2024 Integrated System Plan 'Step Change' scenario, rooftop solar capacity is forecast to quadruple to 72GW of installed capacity, and distributed storage is forecast to account for 66% of the NEM's storage capacity by the year 2050[1]. CER/DER already provides more than 100% of instantaneous generation in South Australia at times[2]. Beyond kilowatt hours, CER/DER is also expected to provide a range of other services both locally, and into the wholesale market via customer agents. Distribution-connected FTM DER, such as community batteries and generation assets, are anticipated to provide 'downward' services to consumers and local network services, and 'upward' services to wholesale markets.

It is important to recognise that such futures represent a materially – indeed radically – different operational environment for the NEM than its original architects envisaged. For example, as the proportion of upstream thermal generation declines as both centralised and distributed renewable energy increases, the system becomes more volatile, and its legacy structures, balancing and operational coordination[5] mechanisms experience expanding risks.

[5] Refer to Key Concepts H.

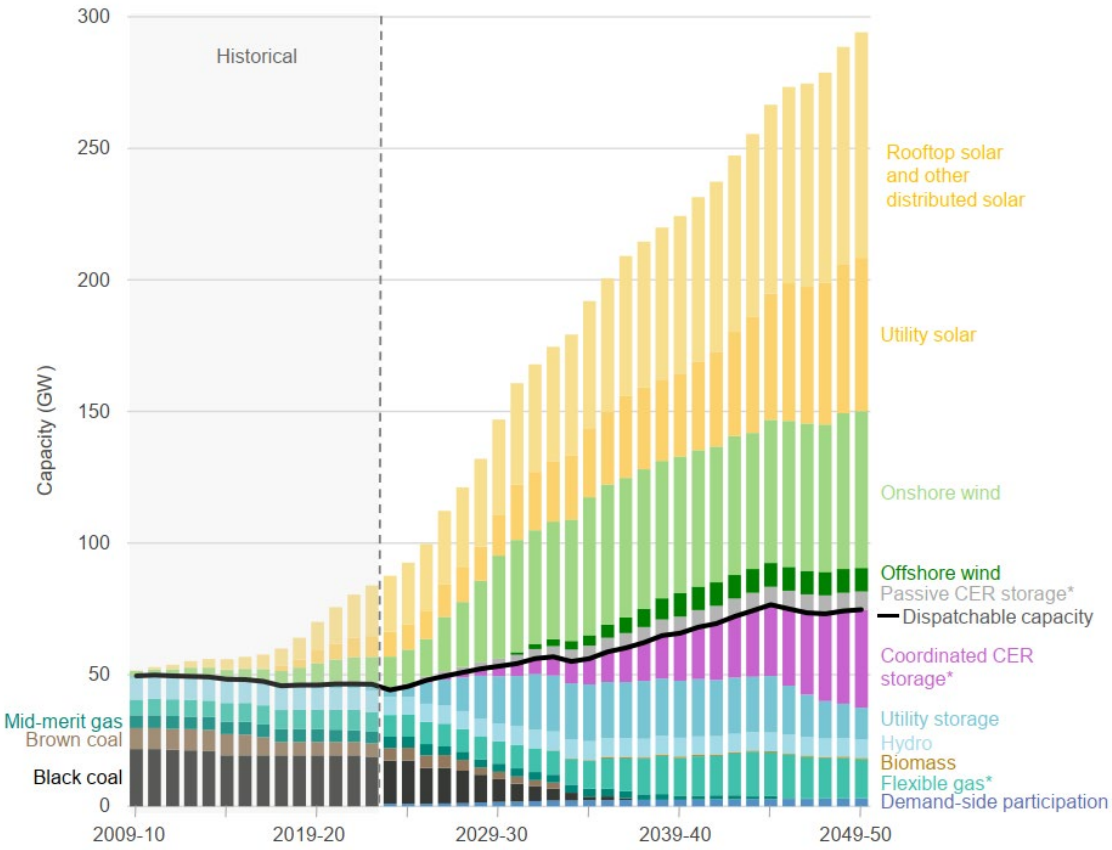


Figure 4: AEMO 2024 Step Change Scenario[1].

Beyond high-level emission reduction targets and a range of 2050 scenarios, Australia has not developed a positive vision of the future end-to-end NEM even in 'broadbrush' terms. As one example, given the context of Australia's significant adoption of distributed resources, this could include the development of a vision for the role of millions of CER/DER as an integral part of a dynamic, integrated and self-balancing power system. Without attempting to 'predict the future', the purpose of such a directional vision would be to enable convergence on an integrated set of whole-system matters that must be advanced to enable each and all the most plausible future scenarios.

In the absence of a process or mechanism for developing a greater level of whole-system coherence and shared vision, most activity continues to occur inside legacy supply chain 'siloes' (e.g. bulk power, transmission, distribution, retail, etc.), often with limited focus on the upstream and downstream interdependencies. This conventional approach to change often applies limited attention to the whole-system impacts of each individual initiative, and all initiatives together.

Ultimately, the Laws of Physics are blind to legacy structural separations and interact with the NEM as one integrated system. To avoid 'competing with physics' in futures even remotely similar to AEMO's Step Change scenario[1], the bulk power, transmission and distribution systems – and the rapidly expanding fleet of CER/DER – must be made capable of functioning far more dynamic, end-to-end was that enable secure, cost-efficient operation.

b. Contributing Factors

Despite widespread agreement on the directional imperative of decarbonisation, Australia has not yet developed even 'rough consensus'[6] on a positive, whole-system vision for the future NEM, nor what steps must be taken to holistically achieve it.

Diverse stakeholders typically operate with varying assumptions, priorities, and terminologies, often extrapolating into the future from legacy paradigms which are increasingly misaligned with future needs. This absence of a unifying reference architecture further exacerbates the potential for misalignment in objectives, disconnects between planning horizons, and inconsistency in interface design across domains.

Limited shared vision is further entrenched by institutional fragmentation. Current governance models tend to prioritise short-term compliance and risk containment at the expense of long-term structural coherence and integration. No single entity is ultimately responsible for facilitating convergence on an envisioned future for the NEM nor the enabling architecture required to achieve it. In practice, this is opaquely diffused across regulatory bodies, system operators, market participants, policymakers and incumbent actors.

Finally, the lack of shared conceptual frameworks and terminology also tends to exacerbate misalignment, often unnecessarily, making timely convergence difficult if not impossible.

c. Solution Requirements

A more secure, efficient and dynamically inter-dependent grid will not be achieved without an integrative program of transformative action focused across the full length of the power system.

In a highly politicised sector, this must ultimately be informed by processes that enable the collaborative development of a mature, positive vision (or visions) of the future power systems Australia needs. This should be informed by a strong focus on the future customer and societal objectives for the grid, cognisant of the wide range of Emerging Trends that are driving change to the legacy system (refer Reports 1 & 2).

Addressing this gap will also benefit from the co-development of a set of future-state reference architectures that examine and iterate the most credible pathways to realise the shared vision(s). The collaborative development process should be facilitated by an independent entity with relevant specialist expertise, unincumbered by individual organisational interests and capable negotiating pathways that maximise alignment and structural coherence.

Critical to overall success is the debate, convergence and articulation of system-level functional goals. These must then be expressed through interface definitions, operational templates, and transformation pathways. The architecture must be linked to policy and investment mechanisms, embedding structural coherence into decision-making criteria for both public and private actors.

Ultimately, however, without a unifying vision to inform structural alignment, transition efforts will remain fragmented, investments will underperform, friction between stakeholders perpetuates unnecessarily, and the power system's ability to meet societal expectations will be materially compromised.

[6] Refer to Key Concepts D.

Key Concepts C

System

An interconnected set of components that are formally linked together by a set of structural and functional relationships to achieve specific purpose(s).

A system always involves three things:

- **Components or elements**, which may be many or few, tangible or intangible.
- **Structural and functional relationships**, which link or relate all the components together in a manner that enables interdependent operation.
- **One or more purpose(s)**, which provide the ultimate reason for the system's existence, and toward which the collective functions of all the components are directed, enabled by the architectural structures.

While the components of a system are often the most visible/tangible, the underpinning structure or architecture always has a disproportionate influence on the essential limits of what the system can reliably and efficiently perform.

Systems Architecture

A formal discipline within Systems Engineering that supports objective and collective reasoning about the foundational structure and organisation of a complex system. This includes its components, interfaces, feedback loops, and other critical behaviours.

The architecture of a system exerts a disproportionate influence on what the system can reliably and efficiently accomplish. Accordingly, a system should not be viewed merely as the sum of its parts, but rather as the product of the interactions among those parts—interactions that are enabled and constrained by the underlying architectural design.

Although architecture plays a pivotal role in shaping system performance, it is often less tangible and more difficult to discern than the system's individual components. The discipline of systems architecture, therefore, provides formal methods and tools to analyse how system components are interconnected, to identify emergent behaviours that arise from these interactions, and to explore robust options for modification and improvement.

By enabling a deeper understanding of how legacy systems function and how their structures can evolve, systems architecture empowers stakeholders to visualise relationships, evaluate trade-offs, and make informed decisions that enhance the system's capacity to meet current and future demands.

4.1.2 Inadequate Complexity Management

As an ultra-complex 'system of systems' undergoing profound structural and functional shifts, reliability, cost-efficiency and scaling risks escalate by orders of magnitude where formal systems-based tools and methodologies designed to manage large-scale complexity are not actively employed.

a. Cross Cutting Issue

The GW-scale power systems developed throughout the twentieth century are some of the largest and most sophisticated 'machines' created by humanity. They are formally defined as Ultra Large Scale (ULS)[7] complex systems.

While we commonly refer to the power system (singular), it is illuminating to realise that a modern grid is a 'super-system' of seven structures which must be holistically transformed if VRE and CER/DER are to be systemically integrated at massive scale. They consist of a complex web of the following inter-dependent structures:

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

In the case of power systems such as the NEM and WEM, these seven structures variously span the vertical tiers/layers of the power system, impact multiple system actors (e.g. bulk power, transmission, distribution, energy retailers, aggregators, customers, etc.) and must be transitioned holistically. As noted earlier, the Laws of Physics interact with such systems blind to legacy structural separations, which highlights the need for an aligned set of transformative action.

It is within these constraints that Australia must, for example, transform its power systems to operate at 100% or more instantaneous renewable generation connected to both the transmission and distribution systems. This is an undertaking that AEMO recognises as globally unparalleled for a GW-scale system. It will require vastly more functionality, interoperability, dynamic balancing, participating entities and sector-couplings than the legacy NEM presently has.

[7] Refer to Key Concepts D.

As Crawley et al [3] note, however, additional complexity is unavoidably driven into an existing system where more functionality and interoperability are required of it, especially where legacy structural constraints are not specifically examined and updated as necessary. This point bears repeating. Where a largely 'issue-in-isolation' approach to change is applied to a complex system, while each change may address the specific issue in focus, individually and in combination they will ultimately add complexity to both the structures and functions of the legacy system.

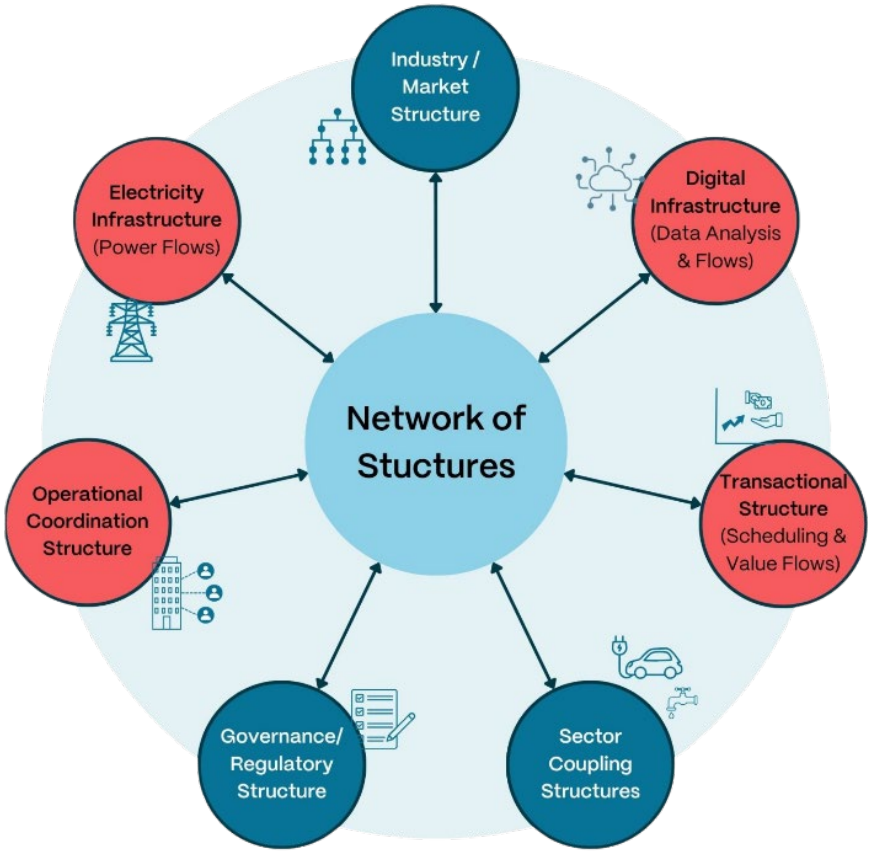


Figure 5: Modern power systems are a 'super-system' of seven structures, four of which are functionally interdependent on a days-to-sub second timescale (coral nodes)[8]

Interestingly, as most legacy power systems have emerged and evolved over decades, it is also common to find that no complete and generally agreed set of documents exists that represent how all seven structures are currently configured and dynamically interact. In addition, it is common to find that no entity is responsible for ensuring these critical underpinning structures (or ''architecture') remain fit-for-purpose in a transformational environment.

[8] Refer to Key Concepts E.

This is an extremely significant gap. Systems science highlights that the underpinning architecture of any complex 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. 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.

Given the unparalleled cyber-physical interdependencies critical to increasingly digitalised power systems, the capability to undertake formal, whole-system structural analysis of significant initiatives becomes critical while still 'on paper'. The failure to do so elevates the potential, under wide-spread deployment, for:

- Unintended consequences
- Long-term scaling issues
- Non-linear behaviours
- Runaway complexity
- The propagation of structural fragility
- Stakeholder friction
- Cost escalations

In summary, an already ultra-complex system undergoing transformation will become intractably more complex where the underpinning structural arrangements do not keep pace with the expanding expectations of the system[4]. In addition, the absence of a shared 'view of the whole' exacerbates 'issue-in-isolation' research and solution development. Despite being ahead globally on several metrics, in this area Australia significantly lags the United States, the United Kingdom and the European Union in the application of more advanced Systems Engineering-based tools for managing and 'taming' the related escalation of complexity.

b. Contributing Factors

Operating Australia's GW-scale s 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."*[5]

In the context of provisioning our power systems to operate at 100% instantaneous renewable generation, AEMO highlighted the following three broad themes as pivotal[5]:

1. **Power system security** – maintaining the secure technical operating envelope of the power system under increasing renewable penetrations.

2. **System operability** – 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[6] that are simultaneously converging and escalating whole-system complexity. These include:

- A rapidly escalating number and technical diversity of energy resources
- The highly variable nature of many renewable energy resources
- Structural shifts in customer demand and the volatility of apparent 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
- Faster system dynamics, bi-directional energy flows and multi-lateral logical relationships
- Mobility of load with the electrification of transport
- Deeper interdependencies with other industry sectors (gas, hydrogen, transport, water, etc)

As noted above, these drivers of change are impacting the mesh of seven inter-dependent structures that map across the power system. Successfully transitioning such a critical and complex system requires additional tools for whole-system structural analysis that were not needed in a more steady-state operating environment. As noted above, the failure to apply structural analysis and enhancements will expand the potential for unintended consequences, non-linear behaviours, runaway complexity, and the propagation of non-scalable characteristics.

c. Solution Requirements

The significant escalation of complexity in Ultra Large Scale (ULS) must be formally managed in a manner commensurate with the scale and pace of change impacting the system.

What is not always well understood is that a well-designed system structure both enables complexity to be 'tamed' and downstream decisions simplified. It frees up engineers and other specialists working on individual components or sub-systems to innovate with assurance that unintended consequences will not crop up to hamper or even invalidate their work.

Consistent with complexity management in other advanced sectors such as aerospace, defence, mining, etc., formally managing the expanding complexity intrinsic to grid transformation requires a programmatic approach underpinned by established disciplines and capabilities. At a most basic level, this will include:

- 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.
- 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.

Key Concepts D

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
- Locational failures and response occur as a matter of normal operations.

Rough Consensus

A collaborative model developed by the Internet Engineering Task Force (IETF)[7], the premier standards development organisation for the Internet, for effective multi-stakeholder problem solving in an ultra-complex systems environment. It provides a collaborative approach to achieving general agreement among multiple participants, rather than strict unanimity or a formal majority. It emphasises general alignment of the direction while allowing for areas of dissent. Points of disagreement are weighed and collectively explored rather than ignored. Decision making largely based on voting outcomes, without understanding and addressing meaningful technical concerns, is avoided.

4.1.3 Benefits Realisation Risks

Conventionally siloed, issue-in-isolation approaches to change, and the absence of formal models for holistic system transformation, place the realisation of $-billions of optimisation benefits for customers, society and the system at significant risk.

a. Cross Cutting Issue

In contrast the unidirectional bulk delivery system of the 20th century, rapidly decarbonising power systems require much greater levels of dynamic inter-dependence between both ends of the system [8], [9], [10]. This will require the bulk power, transmission and distribution systems – and Australia's rapidly expanding fleet of CER/DER – to be made capable of functioning together in a significantly more coordinated, end-to-end manner.

Despite a general recognition of the magnitude of transformation now unfolding, however, Australia currently lacks a holistic approach to transformation design in the electric power sector. Its absence means Australia's strategic context for integrated, collective action is limited, further compounded by the absence of an emerging whole-system vision and the limited application of systems-based tools (as outlined in Sections 4.1.1 and 4.1.2 above).

In a sector often focused on tangible solutions, there may be a temptation to dismiss the need for formal transformation design, underpinned by a well-considered 'theory of change', as overly academic. However, this overlooks that the sector already has a long-standing, albeit tacit, theory and practice of change. Informed by decades of comparatively slow, incremental change in a highly regulated context, the sector has tended to apply a quite linear and reductionistic approach to addressing issues in relative isolation.

As noted earlier, however, are some of humanity's largest and complex systems, electricity systems are now transforming in unprecedented ways. In such a context, the need to address urgent targeted initiatives will remain constant. However, full benefits realisation of a secure, future-ready grid capable of delivering $-billions in customer savings demands holistic transformation design in such a complex, multi-faceted context [11], [12], [13], [14].

Conversely, the lack of formal transition methodologies and supporting tools will significantly elevate benefits realisation risks through the misalignment of stakeholders, solutions and structural relationships, all directly impacting the potential for whole-system optimisation.

b. Contributing Factors

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. For example, Enterprise Architecture's focus is primarily on the IT/OT system architecture within a particular enterprise, the Smart Grid Architecture Model was developed to analyse discrete smart grid project use cases, and subjective workshopping often oversimplifies issues to facilitate indicative statistics at the cost of thorough root cause analysis. None of these provide the necessary empirical rigour required to map in detail the interfaces between all sub-systems.
- 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[15] needed to support a future similar to AEMO's 'Step Change' scenario[1].
- 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 an unprecedented challenge.

c. 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 Sections 4.1.1 and 4.1.2 above, 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.
- 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[1].

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. In this context, a brittle system is a system characterised by a sudden and steep decline in performance as the system state changes, often due to input parameters that exceed a specified input, or environmental conditions that exceed specified operating boundaries. In practice, this means that such a system can suddenly fail to operate in a reasonable way when operating conditions depart significantly from nominal.

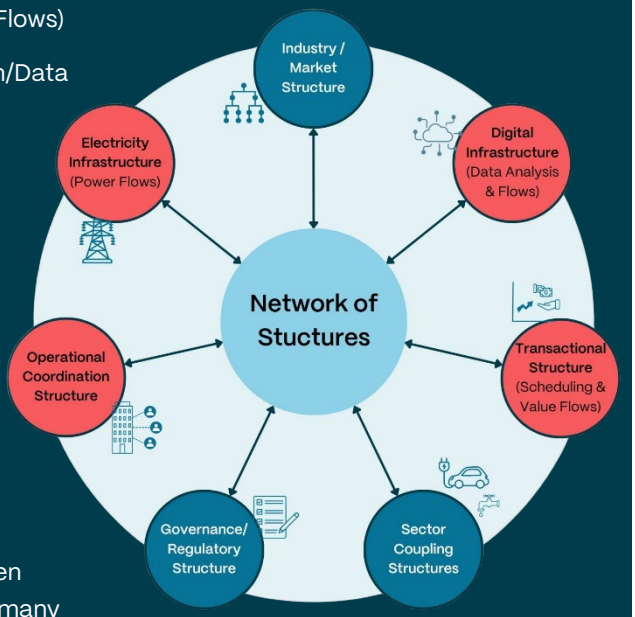
Key Concepts E

Network of Structures

While it is customary to refer to the power system in the singular, a modern electricity system is in reality a 'super-system' of seven structures, four of which are functionally interdependent on a days-to-sub second timescale (coral nodes).

Formally categorised as Ultra Large Scale (ULS) complex systems **[16]**, GW-scale power systems like the NEM and WEM consist of an intricate web of the following seven inter-dependent structures that must ultimately be transformed holistically:

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



The legacy configuration of these seven structures progressively evolved over many decades for the purpose of enabling a highly centralised, unidirectional power system. In their current form, they are subject to many hidden interactions, cross-couplings, constraints and dependencies that make change difficult – many of which are largely invisible without structural analysis.

As power systems are transformed to enable far more dynamic, bidirectional and whole-system operation, provisioning these underlying structures to meet future needs becomes critical. While much effort is necessarily focused on the many new system elements needed (e.g. transmission links, energy storage systems, tariff reforms, etc.), the underlying structure of a complex system establishes its essential capabilities and has a disproportionate impact on what it can reliably and cost-effectively do.

The Network of Structures paradigm provides an essential framework for the holistic analysis, mapping, and optimisation of current and future system structures [17].

4.2 Core Structural & Operability Issues

The following section explores seven critical structural matters that will require holistic consideration and targeted interventions as Australia's power systems transform from a unidirectional past to an increasingly dynamic and bidirectional future.

4.2.1 Foundational Structural Shifts

A range of inherent constraints are embedded in the legacy grid structures developed for unidirectional power flows and passive consumers. These constraints become increasingly problematic as decarbonisation advances and power flows become more bidirectional and volatile. Impacting the various segments of the grid, their impact is compounded where no single entity is responsible to ensure the system architecture of the end-to-end system is both scalable and future ready.

a. Cross Cutting Issue

Australia's 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 connected across the system. With the progressive withdrawal of conventional generation, a wide range of energy and system services will need to be provided from new sources, including energy resources located on the demand-side of the system. In this context, it is worth noting that the term 'demand-side' is becoming increasingly imprecise, as Australia's distribution systems are becoming an increasingly hybridised location of demand, consumption, supply, storage, flexibility and essential system services.

Historically, GW-scale power systems developed around a dominant 'supply-side/demand-side' bifurcation. This acted as one of the most dominant paradigms of the global electric sector and, although now eroding, continues to shape much of the thinking of the sector. In parallel, as this paradigm erodes, two new bifurcations of energy resources is occurring as locational and functional/investment categories emerge.

Given the increasing volatility and bi-directionality of a decarbonising power system, and the emergence of near ubiquitous energy resources, a more holistic approach to system operability and Transmission-Distribution Coordination (TDC) becomes critical.

Importantly, it cannot be assumed that the existing structures, designed for a unidirectional past, 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 process for ensuring the adequacy of the systems end-to-end underpinning architecture.

b. Contributing Factors

Erosion of a Defining Paradigm

Australia's GW-scale power systems developed over the last century around an entrenched 'supply-side/demand-side' bifurcation. This acted as one of the most dominant organising paradigms of the sector based on the following assumptions:

- An upstream 'supply-side' of the system which consisted of a fleet of centralised MW-scale generators connected to the HV transmission system.
- A downstream 'demand-side' of the system where customers were connected to the LV distribution system and only consumed energy (i.e. they did not produce or store energy).
- Unidirectional bulk real power flow from the supply-side to the demand-side.
- Almost all essential system services were provided by the fleet of upstream synchronous, generators.
- Customer demand was considered the primary independent variable and therefore system operation was based on a demand-following model.
- Supply-demand balancing was largely managed top-down with the majority of system flexibility provided by dispatchable coal-fired generation.

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..."*[18]

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 CER/DER 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[9] are experiencing increasing stress as this defining paradigm erodes, and system dynamics fundamentally change.

It is noteworthy that mass adoption of DPV in Australia is largely customer-driven and agnostic to traditional bulk power, transmission, and distribution system boundaries and planning conventions. In the process, energy resources are now bifurcating into two new locational and functional/investment categories as discussed below.

[9] Refer to Key Concepts C.

Energy resources are bifurcating into two locational classes

Australia's fleet of energy resources is bifurcating into two major locational classes: centralised and distributed. 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 located across two opposite extremities of the power system. Under AEMO's widely noted 2050 Step Change scenario[1], this will involve:
    - A progressive narrowing of the differential between HV-connected generation capacity in comparison to the proportion 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 renewable sources, both HV-connected and LV-connected.
    - Whole regions experiencing increasing time windows periods where 100% of instantaneous demand is met by LV-connected DPV, especially at solar zenith on days with low levels of demand.
    - Power system operations becoming increasingly 'tidal' as these regions are increasingly supplied by local generation during daylight hours and then largely dependent upon utility-scale wind generation and other centralised resources overnight.
    - Over time, the entire NEM must be provisioned to operate reliably for increasing frequency and duration of time windows where 100% of instantaneous demand is served by IBR, whether centralised, decentralised or a combination of both.

Such changes are structural in nature, not peripheral. They fundamentally change the physics-based operability of any GW-scale power system.

Energy resources are Bifurcating into Two Functional/Investment Classes

Australia's fleet of energy resources is also 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 CER and EVs have under-utilised capacity and capabilities that would be of value for providing beneficial services to the wider power system in exchange for a share of the resulting value. 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 capacity will involve:

- Significantly different motivational dynamics and engagement models
- Advanced forms of visibility and operational coordination to ensure the right physics-based services are dynamically sourced when and where required most
- New procurement and remuneration models that are:
    - Capable of reflecting the dynamically changing temporal and spatial value of different grid services 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.

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 inter-dependent.

The range of functions performed across the Transmission-Distribution Interface (TDI), therefore, must be expanded, formalised and automated. This will involve enhanced data exchange and formalised roles and protocols for the integrated management of system operations. It includes a focus on matters such as system balance, frequency control, congestion management, voltage control and involves appropriate levels of real-time or near real-time CER/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 supports the need for consideration of paradigm variants that include supply-following features. In this context, large volumes of LV-connected flexible loads and resources are orchestrated to dynamically follow the output of high VRE.

Finally, as the Laws of Physics interact with the entire power system blind to its historic demarcations and delegations of roles and 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.

c. Solution Requirements

Given the once-in-a-century magnitude of transformation impacting GW-scale power systems such as the NEM and WEM, it is simply no longer tenable to advance transformational solutions that assume (either 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 confront the full implications of this profound structural shift for the future operability of decarbonised power systems. The vast increase in both volatility and bidirectionality experienced by Australia's power systems, and the emerging new bifurcations of energy resources into distinct locational and functional/investment categories, will require a fundamentally more holistic and structural approach to system coordination. Additionally, this bifurcation may require a similarly bifurcated market structure, where millions of CER/DER participate in distribution-level markets which then must be co-optimised with the bulk power markets across the TDI.

In summary, the fundamental nature of the unfolding transformation means that it is not possible to provision large-scale power systems for a 'Step Change' type of future solely 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 fit-for-purpose.

Key Concepts F

Structure

Every functioning system created by humans has an underpinning structure. The structure of a system consists of the formal, stable connections, interactions, relationships and interdependencies that exist between the numerous components of the system and enable it to reliably achieve specific purposes.

Architecture

A holistic conceptual framework that defines how diverse components within a system—spanning physical, informational, operational, and transactional domains—are interconnected through foundational structural relationships. This architecture enables the entire system to operate cohesively in pursuit of specific, often complex, objectives.

At its core, a systems architecture articulates the structural linkages, interdependencies, and interactions among components, capturing the essential logic that binds them into an integrated whole. In simplified terms, while the boxes of a block diagram represent the system's constituent elements, it is the connecting lines—the architecture—that illustrate how these elements cooperate to achieve functionality.

A primary function of systems architecture is to expose and support collective reasoning about how all components interact to deliver intended capabilities. This includes identifying non-scalable legacy structures that may hinder future performance. While individual components are often more visible, it is the underlying architecture—those hidden yet critical relationships—that exerts disproportionate influence over system-wide capabilities, resilience, and limitations.

In times of rapid change or transformation, ensuring that legacy structural relationships can adapt and scale is vital. This adaptability is crucial to maintaining secure, reliable, and cost-efficient operation in the face of evolving requirements and technological disruption.

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.

4.2.2 Operational Visibility Risks

As profound structural and operational shifts increase, the lack of a layered, end-to-end approach for providing operational visibility, especially of the growing fleet of millions of CER/DER, risks compromising the operability, reliability and cost-efficiency of the bulk power, transmission and distribution systems serving the NEM and WEM.

a. Cross Cutting Issue

Two critical aspects of power system operability are its predictability and dispatchability[19]. In a decarbonising system that is also experiencing significant growth in LV-connected CER/DER 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 distinct 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 TDI, from millions of CER/DER 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 drive 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.

b. Contributing Factors

Relevance of Visibility to System 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
- 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. Further, it enables AEMO to develop and validate forecasting models to reflect a diversity of emerging operational and planning scenarios more accurately.

In the context of resource adequacy, an important note is that 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.

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 AEMO has limited visibility of the LV systems.

Operational Impediments

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 CER/DERs 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 CER/DER 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.
- Have certainty in the effectiveness of emergency control schemes to manage frequency, if CER/DER affected, and more accurately quantify and target the volume of load available to be shed.
- 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 CER/DER 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. Further, it enables the development and validation of forecasting models that more accurately reflect the effects of CER/DER 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 CER/DER and EVs, system operators will increasingly require the following:

- Standing data on the location, capacity, and technical characteristics of CER/DER and EV charging, in particular the inverters interfaced to the network.
- Near real-time data with resolution of at least 5-minutes for operational forecasts, to 30-minutes for longer-term forecasts, are required from CER/DER and EVs, aggregated at the TDI[10].
- 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

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.

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

[10] Both temporal resolution and lead time need to be considered. The data that is input to forecasting or dispatch plans is needed far enough in advance to be able to use it. Data used for feedback control must have sufficiently bounded latency for loop stability.

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.

c. Solution Requirements

In a context where LV-connected CER/DER 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
    - More accurately inform the volume of load available to be shed to manage frequency 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 G

Visibility

The degree to which information on energy resource characteristics and operational information is available to the System Operator, Distribution System Operator (DSO), and other authorised third parties.

Examples include 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. Statistical data filtering methods also allow establishing trustworthiness of the obtained data enabling the visibility, and reconcile them amongst each other, and with respect to network models, to identify bad and / or malicious data.

Observability

The ability to infer the complete internal state (e.g., voltages, power flows, system frequency, and phase angles at all buses) of the system based on available measurements (e.g., SCADA, PMUs, smart meters) and the network model.

A power system is said to be observable if it is possible to uniquely determine the system's state from available data.

Operability

The capability to plan and operate the power system reliably, securely and efficiently under all expected conditions. Core prerequisites for operability include predictability, which is the ability to forecast system behaviour accurately, and dispatchability, which is the ability to control and adjust generation or demand in response to system needs.

Operability is a multidimensional system attribute, not a single metric, and encompasses the ability of system operators and control mechanisms to:

- Maintain supply–demand balance at all times
- Keep voltage and frequency within allowable limits
- Ensure thermal loading of equipment remains within capacity
- Respond to contingencies, such as generator or network outages
- Manage ramping, variability, and uncertainty (especially from renewable sources)
- Coordinate resources and orchestrate flexibility (from generation, demand, or storage), and
- Respect operational and market constraints and interfaces (e.g., congestion, availability, ramp rates, dispatchability).

4.2.3 System Coordination & Balancing Risks

Bidirectional power flows and operational volatility are increasing as dispatchable, synchronous generation is being progressively withdrawn. As the NEM and WEM transition from hundreds to many millions of participating resources, the absence of layered, end-to-end models for operational coordination will place instantaneous system balancing and overall economic efficiency at growing risk.

a. Cross Cutting Issue

The consideration of advanced operational coordination and system balancing mechanisms is perhaps one of the most critical issues facing decarbonising power systems, growing levels of operational volatility and increasingly bi-directional power flows.

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 means. At the same time, however, ensuring the adequacy, security relating to minimum operational demand, 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 a context where the NEM is also moving toward a future involving tens of millions of participating energy resources connected across the system, advanced operational coordination and balancing models will be required:

- In the near-term, to operate reliably during periods where 100% of instantaneous demand is met by variable sources; and,
- In the longer-term, to be capable of enabling futures even broadly like AEMO's Step Change scenario [1].

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 grid services when and where most needed by the different tiers/layers of the power system.

It is important to note that both market and control elements are essential to advanced operational coordination. This is because well-designed market mechanisms operate as excellent sensors and optimisation engines, as well as a means of incentivising participation. At the same time, technological controls are essential to provide the specific grid services at the time required by the system in a manner that is effortless for participating customers.

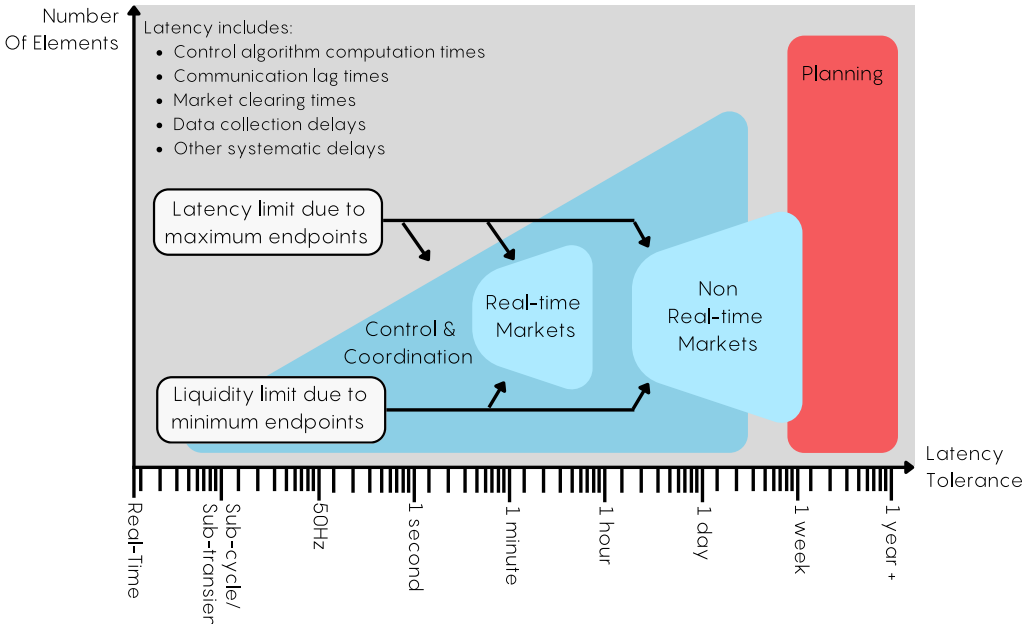


Figure 6: Advanced operational coordination and balancing mechanisms require 'market–control' alignment and complementarity across key tiers/layers of the power system [20].

Given the scale of change this involves, it is not rational to assume the legacy coordination and balancing mechanisms developed last century in a very different operational context will be future-ready. This is further compounded in the NEM by the clear structural separations that, over recent decades, has involved only limited inter-dependence, interoperability and coordination across the supply chain. Where architectural considerations are not formally addressed in developing advanced coordination and balancing mechanisms, costly scaling issues and structural brittleness will emerge that risk impacting system reliability and economic efficiency.

b. 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. 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 and AEMO's Engineering Roadmap to 100% Renewables[5] includes approximately twenty references to system coordination or derivatives thereof [8], [9], [10]. Further, in commenting on critical priorities relevant to FERC Order 2222, the US Department of Energy's Electricity Advisory Board noted the following[21]:

> *"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."*

Elsewhere, the same document nominates advanced operational coordination as one of the most critical issues raised by initiatives such as FERC Order 2222[21] 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."*

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 dependence on LV–connected energy resources.
- 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.

Whole-system Approaches Increasingly Required

Australia's power systems are moving toward a future where of millions of participating energy resources will be located on either side of the Transmission-Distribution Interface (TDI). Ensuring a scalable approach to operational coordination and balancing will require what may be referred to as a Transmission-Distribution-Customer model of coordination.

In other words, due to the wide locational spread of energy resources, the erosion of the supply-side / demand-side bifurcation, and the increasingly 'tidal' bi-directional power flows experienced by high-CER/DER power systems, advanced coordination models must be designed to function in a whole-system manner, including across the TDI.

Key Concepts H

Operational Coordination

The management and coordination of decisions, actions, and information flows across multiple actors, assets and system tiers/layers to ensure the secure, efficient, and stable operation of the power system.

It includes the systematic operational alignment, across timescales from day-ahead to real-time operation, of the following:

- Market/System Operators (MSO) and Distribution System Operators (DSOs);
- Generators, Energy Storage, Consumer Energy Resources (CER/DER), etc.;
- Transmission and Distribution network assets;
- Market participants, CER/DER Aggregators, etc.; and,
- Adjacent sector couplings (e.g. gas, transport, water, sewerage, etc).

Supply-Demand Balancing is a critical outcome of successful Operational Coordination as it enables the right resources to be activated or curtailed in the right locations in the right timescales to maintain this balance. The goals of Operational Coordination also include network constraint management, voltage support, frequency regulation, outage management, and system restoration.

While both Operational Coordination and Supply-Demand Balancing were traditionally the sole or primary responsibility of the MSO, multi-level Operational Coordination will be increasingly required as power systems become more decentralised and volatile as the scale deployment of VRE and CER/DER continues.

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 [22]:

> *"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..."*

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)
- 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 will fundamentally depend on the holistic application of sound systems architecture practice. Following are seven important structural issues which must be avoided in the design of advanced operational coordination and balancing mechanisms to ensure scalability and extensibility:

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 system does not receive an explicit flow of coordination signals from a 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 CER/DER or component of the power system If multiple VPPs exist in a competitive framework, then the coordination problem becomes significantly more complex (refer Figures 7 & 8).

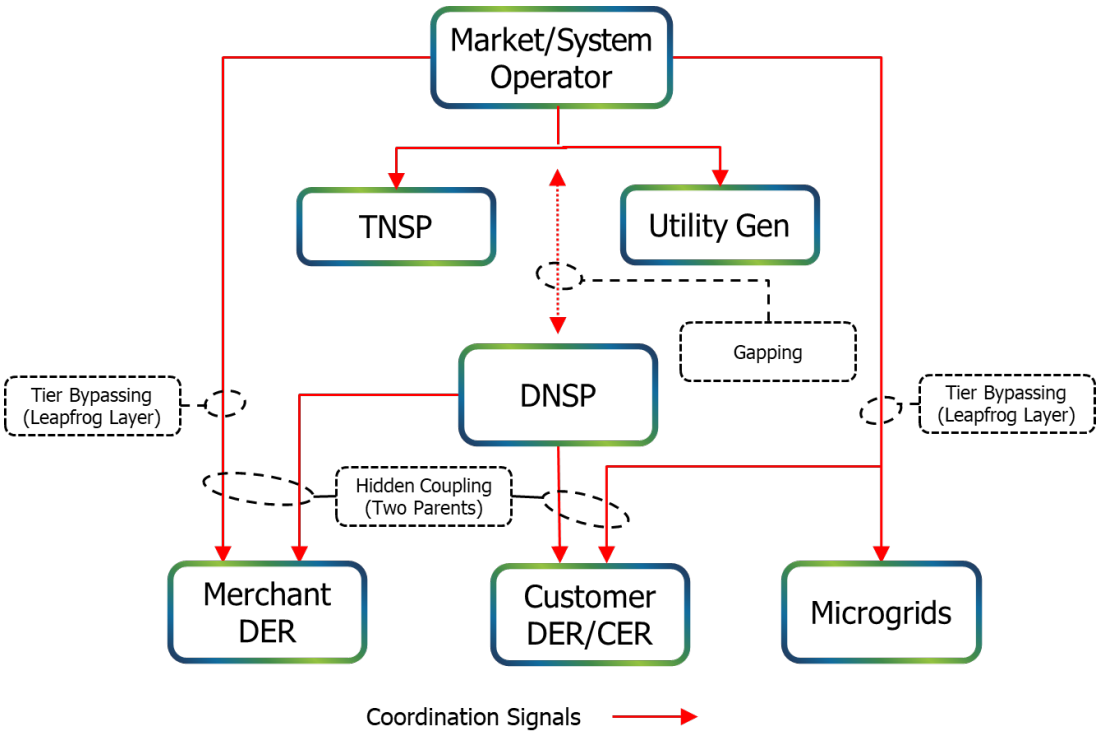


Figure 7: Examples of Architectural Issues that will impact operational coordination.

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 & Cost Excursions**: Where massive data volumes, latencies and processing 'bottlenecks' occur, compounded by unresolved structural issues, optimisation engines risk hitting a computational 'time wall' (refer Figure 9) where no amount of computing resource will be adequate to solve the optimisation problems in an acceptable time and at an efficient cost.[11]
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 10).

[11] It is important to note that in this context, computation resources grow exponentially or even faster (factorially) relative to the amount of data required to be processed. This results in a self-perpetuating pattern of rising computation cost and computation power for less return on investment. As a GW-scale power system is a highly complex cyber-physical system (not only a digital system) deployed over a wide area and involving many separate entities, these effects are compounded where there is a failure to address the underlying structural root causes.

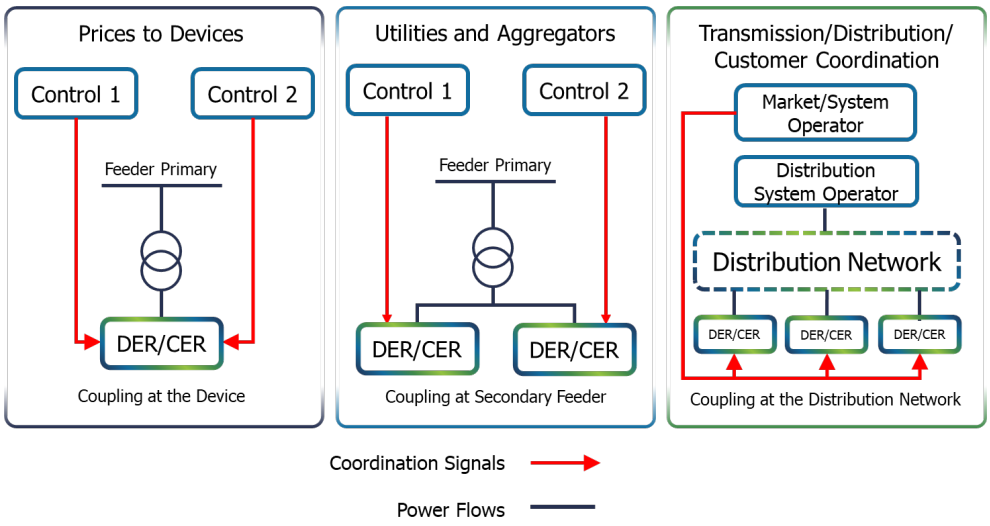


Figure 8: Different examples of how hidden coupling can manifest.

The Importance of Layered Structures

Increasingly complex, dynamic and distributed power systems experience increased fragility and declining resilience where their underpinning legacy architecture is unduly centralised and, explicitly or implicitly, based on an outdated, linear 'command and control' model.

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[12] 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.

[12] Refer Key Concepts G.

- 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.
- Changes or upgrades in end-use or third-party applications are decoupled from impacting underlying core functions and capabilities.

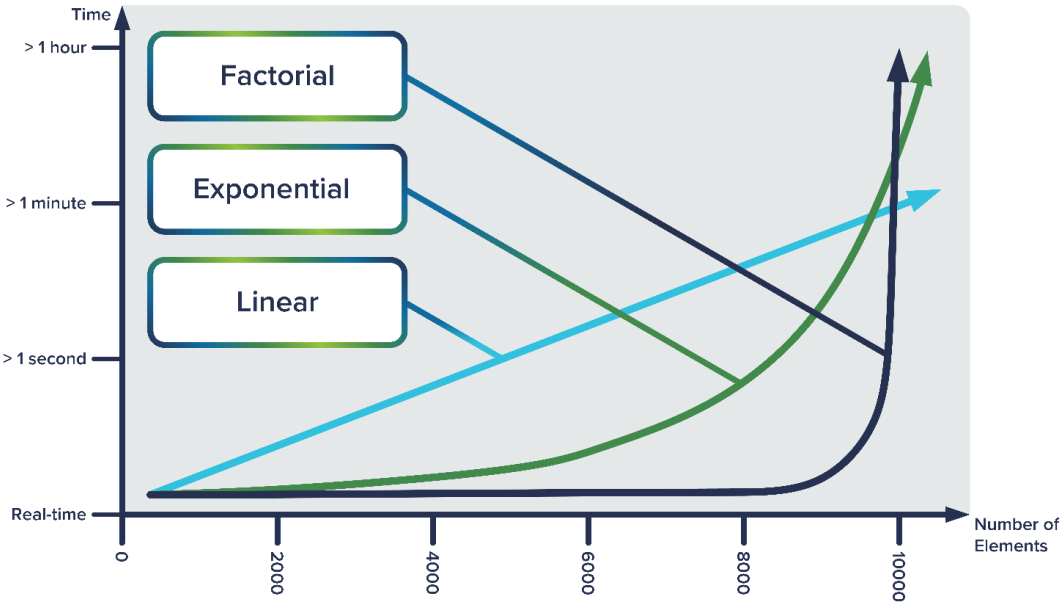


Figure 9: Computational 'time wall' effects can occur quite suddenly. In the case of the factorial curve (black), no amount of computing resources will be adequate to solve the optimisation problems in a reasonable time once the breakpoint has been reached.

c. Solution Requirements

More advanced, future-ready approaches operational coordination and balancing must enable must greater whole-system alignment across the TDI. Given that supply and demand must be maintained in instantaneous balance, this will require the bulk power, transmission and distribution systems – together with demand-side flexibility – to be capable of functioning in a far more holistic manner.

Some key considerations for developing future-ready operational coordination and balancing models include:

- Bi-directional interoperability across the TDI to enable the system to leverage the millions of energy resources connected to both the HV transmission and LV distribution systems, often to different degrees during different time windows.

- More granular market-control alignment models that both incentivise and activate the targeted provision of electric products in the form of grid services when and where they are most needed by the system.
- Co-optimised provision of grid services across the vertical tiers/layers of the power system to enhance operations and maximise value-stacking benefits for participants.
- Design processes that give priority to avoiding the seven common architectural issues that impede the scalability, extensibility and resilience of operational coordination models; and,
- Leveraging decentralised or layered control architecture to progressively expand bottom-up balancing capabilities managed by the relevant DSO which are co-optimised with the more conventional top-down balancing managed by the system operator.

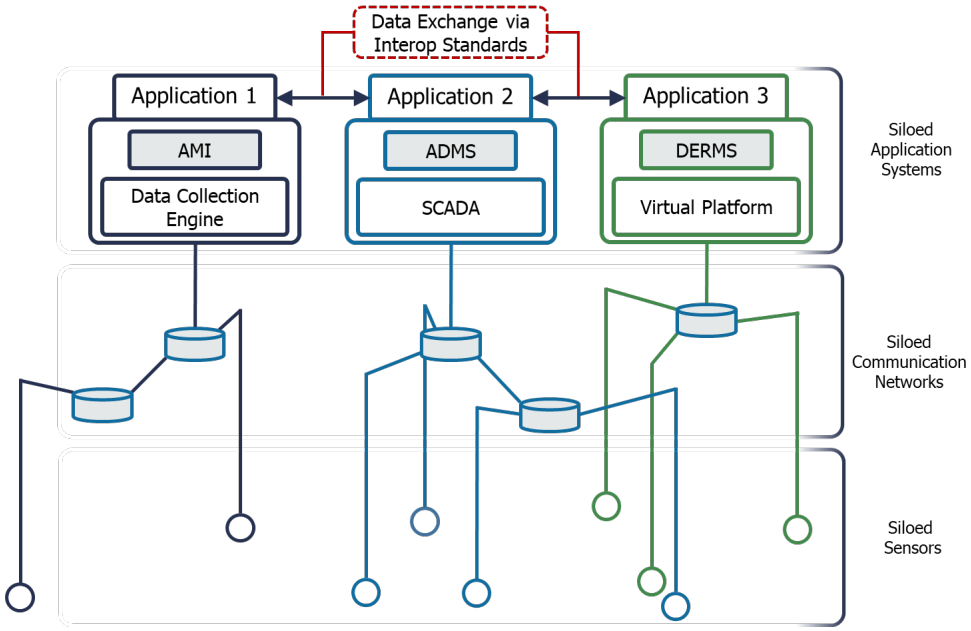


Figure 10: Back-end integration constraints arise due the multiple vertical silo structures found in many supply-chain organisational system.

Key Concepts I

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.

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.

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 include 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. Statistical data filtering methods also allow establishing trustworthiness of the obtained data enabling the visibility, and reconcile them amongst each other, and with respect to network models, to identify bad and / or malicious data.

4.2.4 Whole-system Buffering Needs

As a growing proportion of renewable generation is deployed, unprecedented levels of power flow volatility are propagated across the end-to-end system. While most complex systems and supply chains have internal buffering mechanisms (e.g. warehouses, storage tanks), these have not been widely available in conventional power systems. Given the scale of Variable Renewable Energy (VRE) and CER/DER deployment underway, a targeted and whole-system approach to deploying energy storage for system buffering will be required to augment system balancing and operational coordination.

a. Cross Cutting Issue

Electricity systems were originally designed with generation being provided almost exclusively by large rotating machine generators which provided system inertia as a by-product of their operation. Power system controls made use of this along with various active control measures to keep the system operating in a smooth and stable manner resilient to load variations.

As power system decarbonisation proceeds, rotating machines are being replaced with Invertor Based Resources (IBR), particularly in the form of solar and wind generation. These resources are stochastic in nature and so inject power flow volatility into the grid, without contributing to system inertia to help smooth out the volatility effects. Consequently, legacy power system controls alone are no longer sufficient for the task to ensuring the smooth and stable delivery of electricity, which is placing strains on every aspect of power system operations.

b. Contributing Factors

From a power system perspective, several factors drive the need for significant system buffering, particularly as conventional synchronous generation is withdrawn and the proportion of IBR increases. These include:

- As synchronous generation is replaced by IBR, electromechanical system inertia declines.
- Legacy grid controls depend upon system inertia to smooth out variations in power flow, manage generator load sharing, and help maintain stability.
- Without alternate measures, increasing power flow volatility will propagate throughout the end-to-end system.
- Power flow volatility does not just arise from the bulk power system but also from CER/DER deployed at scale, meaning that volatility propagation will be multi-directional.
- Power flow volatility will affect every other aspect of power system operation, including regulation, stabilisation, synchronisation, protection, power quality, and market operations.
- System services will be increasingly needed to deal with the volatility but will themselves be subject to volatility when derived from IBR.
- As deep decarbonisation is achieved, absent other measures the grid will have very low or even no inertia and so will present significant control challenges.

Several factors intrinsic to IBR also drive the need for significant system buffering as follows:

- IBR resources are stochastic rather than dispatchable, which is itself a source of power flow volatility.
- IBR resources have little or no inherent rotational momentum and so contribute little or nothing to system inertia.
- Power flow volatility injection takes place on slow (daily) and fast (sub-minute to sub-second) time scales.
- The use of IBR in place of traditional generation has a dual impact on the power system: injection of power flow volatility and simultaneous reduction of stabilising system inertia.

c. Solution Requirements

As conventional generation is withdrawn, the integration of IBR at scale into the NEM will require structural changes to the system, particularly with regard to the strategic deployment of buffering throughout the system.

The buffering of power flow volatility requires fast bilateral (two-way) energy storage connected to the power system via bilateral power electronics. New forms of control will also be needed to operate these storage devices in the context of an IBR-based power system. This storage-based buffering arrangement will likely need to be structured in a four-tier architecture:

1. Bulk Power System storage: large utility-scale, transmission-connected storage units intended to supply grid services, stochastic balancing, and wide-area blackout ride-through; these are bid into electricity markets and coordinated by the system operator.
2. Embedded storage networks: storage devices located at Bulk Supply Point (BSP) substations which employ power electronics and advanced sub-second cycle time controls (to function as buffers or 'shock absorbers' for managing power flow volatility rather than participating in markets).
3. Distribution point-connected storage units: standalone units connected to distribution network infrastructure, located and sized via resilience and engineering considerations for ad hoc purposes such as balancing large, distribution-connected solar arrays, supporting specific facility outage ride-through, and enabling microgrids.
4. Behind-the-meter storage: autonomous units located in customer premises for usage optimisation, bill management, and personal resilience, with unutilised capacity potentially leveraged through remunerated coordination.

Ultimately control of the embedded storage network must be dedicated and fast, based on real time grid state, and not operated via market mechanisms[23].

4.2.5 Multiple Aggregator/VPP Risks

The involvement of multiple CER/DER aggregators and Virtual Power Plants (VPP) introduces an additional level of structural and functional complexity across several layers of a GW-scale power system. In the absence of a holistic structurally based approach to their integration, system and market operations will face increasing conflicts and inefficiencies where aggregators and VPPs are present at significant scale.

a. Cross Cutting Issue

Modern power systems such as the NEM and WEM developed over decades based on a set of inherent assumptions which informed their legacy structures. These assumptions include unidirectional flow of real power, dispatchable bulk power generation connected upstream at the transmission level, and largely passive loads. A complex set of processes, protection and controls, sensing and measurement, data management, and industry structures evolved in response to these assumptions.

The adoption of CER/DER at scale fundamentally challenges these assumptions in ways that impact the adequacy of these legacy structures. One of the most significant changes is the rise of the CER/DER aggregator or Virtual Power Plant (VPP) capability. Not only does this new capability imply new functionality, but it is also likely to result in an entirely new class of entity involved in power system operations, and a new layer or structure that has not previously existed in the evolution of grid to date.

The introduction of VPPs, particularly where active at scale, creates new complications in the operation of both the bulk power system and distribution systems. This is due to the reality that VPPs will be performing functions that affect grid operations both at the LV feeder level and at the bulk power level.

b. Contributing Factors

Careful Allocation of New Roles/Responsibilities

The participation of CER/DER aggregators or VPPs in grid operations will require the definition of new capabilities, and therefore the new functionalities needed to support them. Not all the required functionalities or capabilities can necessarily be provided by these entities, however. Therefore, the new roles and responsibilities will need to be defined and allocated to relevant entities in a rigorous, systemic manner that ensures efficient, secure, and conflict-free operation (refer also to Section 4.4.1). Some related considerations also include:

- The rigorous definition of the necessary capabilities and functionalities is critical to determining the data/information requirements, flows and enabling architectures
- Some capabilities and/functions likely already exist but may not be in a form usable by CER/DER aggregators or VPPs, and
- Consolidation and grouping of functions, assignment of function groups to roles, and mapping of roles to entities (AEMO, DNSPs, DSOs, VPPs) must avoid duplication and coupling conflicts.

Key Concepts J

Interface

A point of interaction or boundary where different subsystems, components, or modules communicate and exchange information or energy. It defines the protocols, standards, and methods through which these interactions occur, ensuring compatibility and coordination among the interconnected parts of the system. Interfaces are crucial for the integration and functionality of complex systems, allowing diverse elements to work together effectively.

Interoperability

The capability of two or more systems, components or applications to share, transfer, and readily use energy, power, information and services securely and effectively with little or no inconvenience to the user.

Future-ready approaches to Interoperability recognise that is has an intrinsic relationship to the underpinning Structure and Roles & Responsibilities of the wider system, both in their current state form and as they will plausibly need to evolve to enable an increasingly decarbonised future system.

Hidden Coupling and Tier/Layer Bypassing

The use of CER/DER aggregators or VPPs can result in hidden coupling, meaning that resources connected to the distribution system can end up being controlled or directly influenced by more than one entity, process or control mechanism.

For example, if numerous VPPs directly control large volumes of CER/DER, then dispatch from AEMO through these entities may conflict with management of the distribution grid by the relevant DNSP. This is problematic for several reasons, including that DNSPs have the responsibility maintain distribution system reliability. More directly, the control of distribution elements and individual feeders may be compromised by the conflicting objectives being pursued by various independent entities directly influencing the operation of CER/DER which are connected to them at scale.

In this case, tier/layer bypassing, where CER/DER dispatch from AEMO via the various VPPs effectively bypasses the relevant DNSP/DSO, is a primary structural cause of hidden coupling.

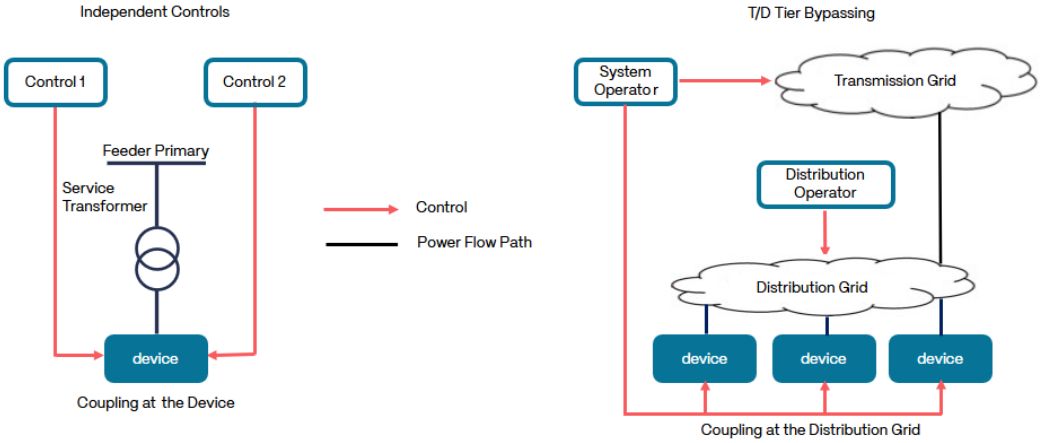


Figure 11: Examples of how hidden coupling can manifest.

It is notable that some jurisdictions have gone down the path of mandating Multi-entity ('Hybrid') CER/DER coordination solutions, notably in the United States with FERC Order 2222 [21]. Such arrangements are compromises that allow CER/DER aggregators or VPPs to participate in both distribution level and bulk system operator electricity markets, and then to handle CER/DER dispatches. While this may function acceptably at lower levels of CER/DER, it is problematic for the longer-term as it creates a tier-bypassing structure which results in hidden coupling. This is different from the examples shown above but creates the very same issues. Structural choices that result in tier/layer bypassing and hidden coupling should be rigorously avoided.

Aggregator/VPP Service Area Interpenetration

A further hidden coupling issue can arise of there are multiple competitive CER/DER aggregators or VPPs who seek CER/DER subscribers without territorial limitations. In this case individual CER/DER will be managed different entities even if they are physically or electrically adjacent.

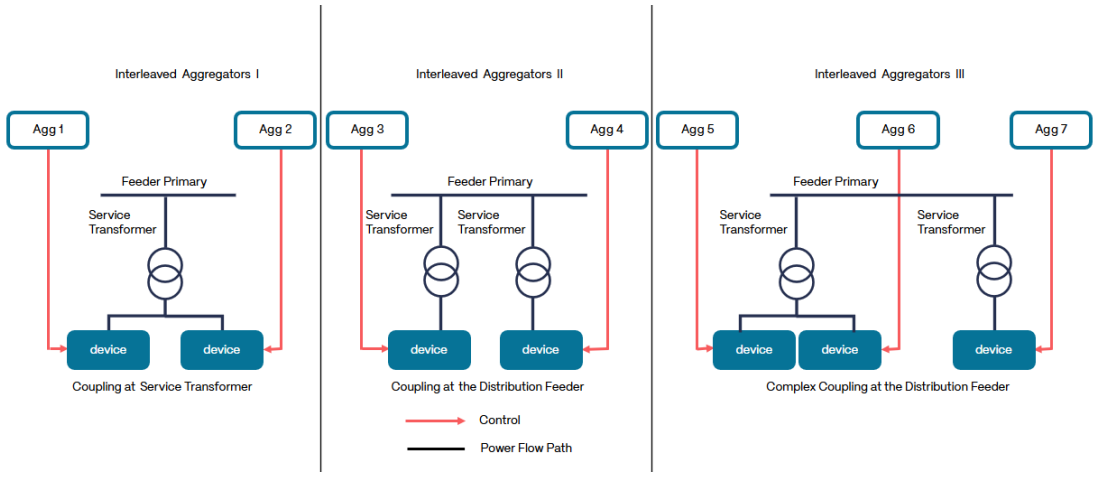


Figure 12: Examples of how multi-VPP hidden coupling can manifest.

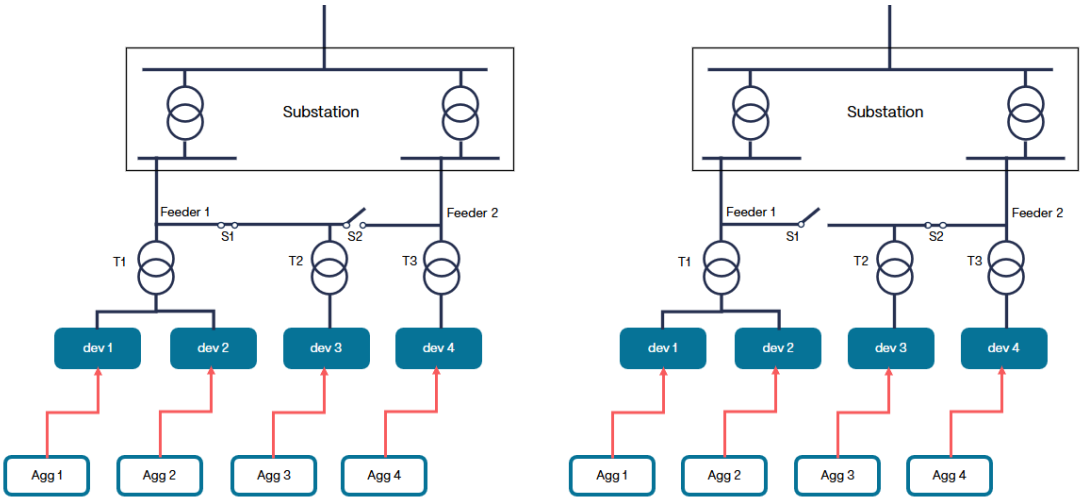


Figure 13: Circuit switching can instantly change VPP–Grid Network Configurations.

Key points of note under this scenario include:

- Switching of CER/DER from one aggregator or VPP to another may occur, causing an issue of keeping track of how and by whom specific resources are being managed.
- If separate entities manage CER/DER on the same LV feeder, inter–VPP coordination is needed to ensure that adjacent CER/DER do not interfere with each other and/or cause local feeder issues (e.g. voltage regulation, thermal, or protection limits).
- Avoiding negative impacts from influencing CER/DER connected at scale to a particular LV feeder will require knowledge of distribution grid state. However, it is unclear whether real time distribution grid state is available at all and whether it should be shared with the VPPs (given the questions of security and market fairness that it raises).
- If a form of hybrid coordination structure allows for VPPs to participate simultaneously in both bulk power markets and distribution-level market mechanisms, this creates a structural hidden coupling, with its well-recognised problems and disadvantages.
- The introduction of CER/DER aggregators or VPPs as an additional layer of entities involved in grid management can cause new latencies, which at scale can cause control loop instability or break operational cycle times.
- If dynamic invocation of CER/DER on a real time (sub-minutes, for example) basis is to be employed, and some form of fairness is appropriate, a new type of coordination across aggregators/VPPs will be needed.

- Cluster coupling occurs when edge devices are addressed in groups that do not allow for separation of edge device commands by specific criterion: location, device type, device service provision, etc. This causes an inability to control resources by functional type or intended use or purpose. Its causes include use of edge devices that do not have individual addresses but only respond to command codes, or applications that do not disaggregate device commands, or control systems that can only issue commands to blocks of devices rather than to individual devices, or device databases that do not have sufficient information to distinguish devices by type, geolocation, electrical location, or other criteria.
- Note that the use of Dynamic Operating Envelopes (DOEs) does not resolve the potential hidden coupling problems or the CER/DER dispatch problems. In fact, the existence of interpenetrated VPPs complicates the operation of the DOEs, since it becomes necessary to create an extra layer of complexity in DOE dispatch to deal with the mappings of circuits to CERs to VPPs. In effect, the DOEs can become coupled through the ad hoc VPP–to–CER/DER mappings.

Key Concepts K

Architectural Issues

Following are eight important structural issues that the Power Systems Architecture disciplines address 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 CER/DER or component of the power system.
4. **Cluster Coupling:** Where CER/DER are addressed in groups that do not allow for separation of edge device commands by specific criterion: location, device type, device service provision, etc.
5. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
6. **Computational Time & Cost Excursions:** Where massive data volumes, latencies and processing 'bottlenecks' occur, compounded by unresolved structural issues, optimisation engines risk hitting a computational 'time wall' where no amount of computing resource will be adequate to solve the optimisation problems in an acceptable time and at an efficient cost.[13]
7. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
8. **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.

[13] It is important to note that in this context, computation resources grow exponentially or even faster (factorially) relative to the amount of data required to be processed. This results in a self-perpetuating pattern of rising computation cost and computation power for less return on investment. As a GW-scale power system is a highly complex cyber-physical system (not only a digital system) deployed over a wide area and involving many separate entities, these effects are compounded where there is a failure to address the underlying structural root causes.

Multi-level Market Co-Optimisation

For power systems with both bulk power markets and distribution-level market mechanisms for CER/DER, it is important to recognise that markets function as elements of the CER/DER coordination system which ultimately contributes to system balancing. It is therefore important that the structure and operation of market mechanisms, individually and together, be informed by sound architectural principles and the application of layered decomposition.

In addition to avoiding tier/layer bypassing, the markets themselves require coordination, which is often called co-optimisation. This can be accomplished simply and efficiently by applying layered decomposition principles. Doing so also avoids the significant disadvantages of needing to create a further entity to somehow accomplish the co-optimisation, which include further escalation of complexity, latency, and risk (operational, resilience, and cyber) to the system.

As to the issue of ensuring market fairness and trustworthiness, this can be established using methods well-known in other jurisdictions, namely market operation regulatory rules and market surveillance (to ensure compliance). This is done, for example in the United States for the regions that have vertically integrated electric utilities and no independent system operator, and for that matter, are also applied to the independent system operators' markets.

Grid Visibility and Observability Issues

Finally, as noted above, optimised management of CER/DER in a manner that both avoids negative impacts on LV and MV network elements and enhances the value of network services, may require detailed distribution grid state determination (estimation) in real time. State estimation in distribution networks is challenging, due to a variety of reasons. A first is the diversity of measurement devices, e.g. SCADA RTUs, smart meters, transformer monitors, as well as issues with limited sensor coverage. Secondly, for physics-based state estimation techniques, network models need to be built, calibrated, and kept in sync with the switching configuration of the network in real time, which is not common practice today. State estimation in distribution networks helps with identifying network congestion and can fill in the gaps in sensor coverage using statistical techniques.

This implies a detailed level of distribution feeder instrumentation and will require a capability at the DNSP level to perform state estimation. Detailed VPP-to-CER/DER-to-LV Network mapping will also need to be maintained and updated in near real time so that effects of CER/DER activation can be assessed during real time operations.

c. Solution Requirements

Moving beyond demonstration volumes, the integration of CER/DER aggregators and VPPs into the NEM and WEM at significant scale will require advanced forms of coordination, increased distribution level observability, careful definition and aggregation of functions and the rigorous assignment of functions to roles, and roles to specific entities capable of performing them.

The following observations outline key further matters that must be considered:

- Enhanced observability will require both distribution electrical grid state and real time feeder topological state (given the dynamic nature of switching).

- Coordination between AEMO, DSOs, DNSPs and VPPs must be structured to ensure no hidden coupling to enable scalable approaches to:
    - The operational coordination of CER/DER dispatch at scale (i.e. ensuring aligned functions between DNSPs and VPPs)
    - Market participation by VPPs, which must not allow for tier/layer bypassing
    - Interleaved VPP coordination to avoid LV feeder level coupling problems, and support fairness outcomes in real time, and
    - VPP-to-CER/DER-to-LV Network mappings must be kept accurate and current.
- Market co-optimisation should be accomplished by application of layered decomposition principles, avoiding the need to create further 'co-optimisation agent' entities.
- Issues of market fairness and trust are best solved using market regulation and surveillance to ensure compliance, as is done in other jurisdictions.
- Though observability can often be established and relied upon, special attention must be given to fallback strategies for network management when for example communication or even the software platform itself is unavailable.
- VPP data management must be handled as a national security issue. This is because the data is being handled by third parties who are not subject to the same kind of oversight as regulated utilities. The personnel, the locations where the data is stored and processed, the internal technical measures and procedures used to protect data, are all potential vulnerabilities. In cases where the VPPs may be able to affect grid operation directly, this raises additional security concerns.
- Processes for handling aggregator/VPP operational failure and business merger or exit must exist.
- Distribution state estimation comes with cyber-physical security concerns, strategic physical interference with the sensors may lead to incorrect assessment of congestion.
- The capability definition, functional decomposition, functional grouping, role definition, and role assignment processes must be rigorously structured to avoid internal hidden coupling and external conflict inter-entity conflict.

4.2.6 Single Point of Failure Risks

Electricity underpins every part of Australia's digitalised economy. Major disruptions rapidly cascade through numerous other societal systems. Given the highly centralised origins of our power systems, driving toward economy-wide electrification also requires a transition to more modular grid structures designed for resilience and redundancy. Failing to do so will significantly escalate major single-point-of-failure risks and national security vulnerabilities.

a. Cross Cutting Issue

The development of our existing power systems occurred in a historical context, naturally being informed by perspectives about how energy, in all its varied sources, would be used in society. This was also a context where electricity was one of several energy vectors that included gas and petroleum, which were also becoming key to the functioning of a modern society. While lightly coupled, these distinct energy systems intrinsically provided a level of redundancy for society should one system fail at a given time. At that time, the societal transition to deep dependence on advanced communications and cyber-physical systems was decades away.

By contrast, the highly digitalised economies of today are critically dependent on a reliable and resilient electricity system. Indeed, electricity is now a foundational enabler of all digital and communications infrastructure. Disruptions to the grid can rapidly cascade through numerous other societal systems, including water, sewerage, food/cold chain, transport, etc. Extended grid outages, today, have a profound impact of the functioning of society – and full electrification is still a long way off.

While full electrification offers major environmental and economic benefits, it introduces significant societal and national security risks if redundancy is lacking. The interdependence of almost all societal systems on electricity demands proactive risk mitigation. This may include, for example, a combination of modularised system architecture, resilience planning techniques and the enabling of localised clusters of distributed generation and energy storage to function autonomously for an extended period should wider grid outages occur.

b. Contributing Factors

While great emphasis has been placed on reliability in the development of today's grid, it was ultimately structured as a highly centralised, bulk delivery system. Its design and structural arrangements were not developed with full societal electrification in mind, nor with the level of holistic resilience and redundancy planning commensurate to such a potentially high-risk undertaking for society. Some contributing factors include:

- The topic of power system resilience is multi-faceted, but still evolving and maturing; it has not generally been defined in a way that holistically responds to the opportunity and challenge of full societal electrification.
- The usual methods of quantifying resilience for power systems are not particularly helpful in comparing design alternatives; partly due to inadequate problem definition and partly the relatively immature evaluation methods employed.

- A lack of methods to understand structural grid resilience and to determine how to make the targeted changes required to significantly enhance resilience.

As noted above, however, electricity underpins every layer of the modern digitalised economy. Numerous examples of the critical interdependence and consequences of a prolonged power system failures are provided below.

- **Telecommunications and Internet:** Mobile towers, fibreoptic node points, and broadband infrastructure lose power. While some systems have battery or generator backups, these are limited (often only a few hours to days).
- **Digital Infrastructure**: Data centres, cloud computing platforms, and AI systems require uninterrupted power. Even momentary outages can lead to data loss, service downtime, and financial losses.
- **Finance and Banking**: Online banking, ATMs, digital transactions, and trading platforms cease to function without power to servers and networks.
- **Industry Automation**: Smart manufacturing, logistics, and supply chain systems operate on real-time data and automated machinery — all of which are power-dependent.
- **Water Supply Systems**: Pumps, purification plants, and distribution systems rely on electricity. Extended outages halt water treatment, leading to unsafe or unavailable drinking water.
- **Wastewater Management**: Sewerage systems often include powered lift stations and treatment plants. Failures can result in raw sewage overflow, causing public health emergencies.
- **Urban Transit**: Electric trains, subways, and trams are immobilised. Traffic lights and signalling systems fail, leading to gridlock and increased accident risk.
- **Fuel Supply Chains**: Petrol stations rely on electric pumps and point-of-sale systems. If these go offline, fuel distribution stops, which in turn hampers logistics and emergency response vehicles.
- **Air Traffic**: Airports rely on power for navigation systems, communication, and air traffic control. Loss of electricity can ground flights and close terminals.
- **Hospitals and Clinics**: Emergency generators may support critical care, but surgical, diagnostic, and administrative systems often degrade rapidly without full grid support.
- **Cold Storage**: Perishable goods spoil without refrigeration.
- **Retail Systems**: Digital point-of-sale systems and inventory tracking fail. Cashless transactions become impossible.

c. Solution Requirements

Full electrification leads to ever greater reliance on not just the generation sources but also the electricity delivery and sharing systems.

Given their highly centralised origins, existing electricity delivery structures present major single-point-of-failure risks where full electrification advances without a comprehensive effort to enhance system resilience and redundancy. Solution requirements would include:

- Adoption of a structurally based approach to defining resilience for power systems[24]
- Identification of resilience and redundancy vulnerabilities that would need to be addressed to enable a significant proportion of electricity service to continue where major natural disasters, domestic terrorist or foreign actor attacks occur
- Consideration of evolving distribution systems to structures that are significantly more variable and modular, including the use of modularity and coupling principles for system re-design[25], and
- Use of advanced analytical techniques for evaluating resilience, modularity, and coupling in grid physical structures[26].

4.2.7 Modelling & Forecasting Risks

As power systems experience fundamental change in customer participation, technology mix, operational dynamics and enabling structures, the usefulness of existing modelling and forecasting tools is increasingly challenged. Given their key role in governance, investment and operational decision making, they must be constantly evaluated to ensure their continued adequacy as power system design and operations moves further away from the many legacy assumptions that informed the development of these tools.

a. Cross Cutting Issue

Advanced models are essential for power system planning and operations, including the ability to forecast upcoming power system conditions and have confidence in how the system will perform in an increasingly varied and dynamic environment.

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

b. Contributing Factors

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.

The development of existing models has typically been based on the extant historical structural and operational paradigms. For example, models based on steady-state power flow conditions are commonly 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 activity may be formulated in many 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 can 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 and voltage/current/power envelopes, it does not and cannot consider stability constraints; this is the task of time domain simulations.

c. Solution Requirements

To ensure the accuracy, trustworthiness and future fitness of power system models, it is essential that data and other inputs, and their underpinning assumptions about system structures and dynamics, are transparent so they can be verified and validated by all stakeholders.

As power systems such as the NEM and WEM 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. Examples of topics where key assumptions may need to be reevaluated are illustrated by several of the Systemic Issues discussed above, including:

- Foundational structural shifts (Section 4.2.1)
- Alternative system coordination and balancing models (Section 4.2.3)
- Whole-system buffering needs (Section 4.2.4)
- CER/DER aggregator/VPP participation assumptions (Section 4.2.5), and
- Structural changes required to mitigate single-point-of-failure risks (Section 4.2.6)

A high level of transparency is also critical for eliminating anti-competitive practices that may arise due to modelling tool vendor lock-in.

4.3 Digitalisation & Scalability Issues

The following section examines three key challenges that arise from the increasing need for more dynamically interdependent and digitalised end-to-end power systems, including cyber-security, data sharing and the scalability of cyber-physical elements and solutions.

4.3.1 Cyber-security Vulnerabilities

Critical energy infrastructure faces a growing volume of cyber-security threats which can have catastrophic societal and economic impacts. Best practice approaches to cyber-security require a multi-layered approach that address different attack vectors. By contrast, a limiting factor across many risk mitigations in the power sector is a primary focus on cyber-based defences, with limited if any focus on 'non-cyber' structural vulnerabilities that are rapidly expanding.

a. Cross Cutting Issue

Around the world, critical energy infrastructure is facing a growing set of cyber-security threats from state actors, terrorists, organised crime and amateur hackers. Two recent examples include:

- Ukraine's power systems were cyberattacked in 2015 and 2016 using malware to control and shut down substations, disrupting power to hundreds of thousands, and
- The 2021 cyberattack on the Colonial Pipeline in the United States exposed how interconnected energy systems the cascading economic impacts of major disruptions.

In Australia, the progressive digitalisation of power systems and the rapid emergence of millions of CER/DER presents major cyber-security challenges for the sector. Increasingly inter-dependent power systems that involve an expanding range of participating entities, data volumes and communication systems is significantly more vulnerable to malicious cyber-attack.

b. Contributing Factors

Expanding Range of Cyber-attack Vectors

Power systems face an entirely new scale of cyber-security challenges as they become increasingly inter-dependent and interconnected. Both progressive digitalisation and the rapid diffusion of CER/DER 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. In this context, existing SCADA and DERM systems will require integration with external systems, security, and interoperability standards to ensure their functionality is not undermined by vulnerabilities to cyber-attack.

All future scenarios of Australia's power system transition anticipate the continued deployment of both digitalisation and CER/DER at scale. While this brings with it numerous opportunities for CER/DER to provide a range of valuable grid services, it also involves growing dependence on these devices and the communications networks that connect them, including the internet.

Such configurations present a significant shift from the traditional dependence 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 CER/DER-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 CER/DER 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.

Non-cyber Structural Considerations Critical for Layered Defences

The major commonality across most current 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 defences, should be applied.

One such layer of defence 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 organisational considerations can result in serious vulnerabilities, and addressing this critical gap in Australia's security considerations will require the mapping of cyber-physical relationships and data flows that are institutionally embedded in the legacy power system.

Cyber security in this context extends to any third parties that will have access to sensitive grid data or connectivity to any utility systems. Since people are key factors in the various cyber security processes, it is necessary to understand the staffing and training of staff for any organisation that has direct or indirect access to sensitive utility systems and data, including locations of the people (important to understand what physical, organisational, or even geopolitical boundaries may be crossed by connectivity and data flow).

c. Solution Requirements

Both power system digitalisation and the rapid emergence of millions of CER/DERs are expected to continue unabated. In this context, cyber-security best practice requires that a layered approach with multiple classes of defence 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.

- Study and risk analysis of broader cyber-physical attack strategies, e.g. measurements of current and voltage can be interfered with in the physical domain, to throw off the state estimator and potentially blind the operators to operational issues.
- Analysis and documentation of non-cyber structural vulnerabilities that:
    - Are currently present in the existing legacy structures of the NEM and WEM
    - 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 CER/DER devices.
- Identification of structural treatment options that significantly mitigate or entirely avoid the non-cyber vulnerabilities identified.
- Application of graph theory analysis and resilience modelling to evaluate alternate structures and treatments.
- Finally, as noted earlier, VPP data management must be handled as a national security issue. This is because the data is being handled by third parties who are not subject to the same kind of oversight as regulated utilities. The personnel, the locations where the data is stored and processed, the internal technical measures and procedures used to protect data, are all potential vulnerabilities. In cases where the VPPs may be able to affect grid operation directly, this raises additional security concerns.

4.3.2 Data Sharing Risks

Data sharing in increasingly distributed power systems involves complex functional relationships and hidden constraints that are embedded in legacy system structures. While promising digital technologies are promoted by different entities no single, comprehensive solution to grid data sharing needs exists. All data exchange options require the application of formal architectural analysis to make visible issues that directly impact the scalability, extensibility, resilience, cyber-security and interface design of proposed solutions.

a. 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 CER/DER and EV.

Specific technologies cannot be successfully implemented without a disciplined, comprehensive and multi-stakeholder approach to developing the systems architectures that must underpin them. The failure to do so significantly increases the risk of structurally brittle solutions that impact interoperability and exacerbate security vulnerabilities.

Systems architecture provides a robust basis for informing data exchange design options by applying information theory, analytic transformations and layered decomposition to organise multi-tier bidirectional data flows to be scalable.

b. 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 CER/DER and EVs.

In what remains a comparatively nascent area in the power sector, three approaches are typically being implemented or proposed for consideration. These options 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.
3. Decentralised data exchange.

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 noted[27]:

"...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,*
  - *System operators managing minimum demand,*
  - *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 can perform well in clinical scenarios but can face scalability and extensibility issues when having to handle more problem variables than what was allowed for in trials. This is compounded by each organisation's system typically having its own primary data sources, communication systems, data formats, and protocols.

Further, where there are multiple organisations providing functionally equivalent data (e.g. meter data, CER/DER and EV data from aggregators, DOE data from DNSPs, etc.), any given system may have to contend with multiple interfaces and representation schema for essentially the same categories of information. This makes interoperability more costly given the effort required to reconcile duplication, bifurcation, and untraced modification of data. In this context, the Project EDGE report also noted the following[27]:

> *"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."*

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 unsynchronised 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 is responsible for the accuracy of the data?
- Who owns the privacy rights of the data before transmissions?
- 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. It should also be noted that while well-known techniques such as mirroring provide a degree of redundancy, they do not provide anything like the resilience of a distributed solution. Mirrored facilities can be cyber-compromised almost as easily as single ones.

Further, offshore data centres have a similar vulnerability; even though they have great redundancy. Loss of communications isolates the data centre or centres from the grid's operational systems. The same is true of onshore facilities. Depending on the number of organisations involved, the central data store approach can also raise two types of scalability challenges: data volume, and number of communication connections. While both can be managed, they are non-trivial.

Finally, power sector actors are often reluctant to share operational data before they can '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 scalability and minimise or avoid Single Point of Failure (SPOF) risks.
- Are modular, flexible and interoperable.
- May be more secure, trustworthy and auditable.
- Support greater standardisation and fairness though the application of ecosystem wide standards.

It should be noted that DLT does not resolve the issue of data flow management (meaning it does not provide a structural means to specify data source/sink relationships, data flow rates, or access control. Scalability claims should be considered in the light of how DLT creates ever-expanding ledgers that must be updated with all transactions, thus causing the stored data volumes to grow approximately linearly with both time and the number of participating elements. Similarly, DLT security claims should be considered in light of the experiences in the cryptocurrency industry.

It is also important to note 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, CER/DER devices and EVs.
- Include consideration of both requirements for the current state and the most plausible emerging future state configurations.

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 a significantly 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 manage both data in motion and archived data sets. Modern network streaming protocols and cyber security are well developed for this application and have extensive experience bases.

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 single-point-of-failure 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. If the interfaces are specified by the system architecture (as is appropriate) then the number and types of interfaces can be optimised.

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.

By applying system architecture methods and tools such as analytic transformation, it is possible to structure data flows so that each entity provides information (as opposed to just data) to other entities. This approach makes it possible to manage the scalability of 'upward' data flows from the grid edge through the DNSPs and DSOs to TNSPs and AEMO.

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.

c. Solution Requirements

While there is significant hype about the potential of technologies such as DLT and digital platform solutions, as a relatively immature area in the power sector, there is no single or perfect solution to the data sharing needs of 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.

By addressing the structural issues using system architecture methods and tools early on, the logical information flows (and corresponding data flows), the analytic transformation structures, and the locations/forms/functions of system interfaces can be understood and validated by all entities in advance so that ad hoc approaches and uncontrolled proliferation of data exchange formats can be minimised.

4.3.3 Solution Scalability Risks

Greater focus on the whole-system functionality, scalability and potential unintended impacts of new technology and solution innovations, including but not limited to Dynamic Operating Envelope (DOE) solutions, to identify and pre-emptively address cyber-physical issues that will otherwise only manifest during mass-deployment of solutions post-trial phase.

a. Cross Cutting Issue

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 CER/DER deployment. The application of DOE solutions has significant potential for supporting Australia's highly distributed power system transformation.

In the context of the structural separations embedded in the NEM, development of DOE solutions originated with a focus on providing flexible export limits to CER/DER to provide more advanced distribution network capacity management. From these origins, Australia's market, regulatory and innovation funding bodies now anticipate an expanding range of contributions that DOE solutions may make to overall power system optimisation and customer benefits.

Despite the relevant structural separations, the Laws of Physics interact with the NEM as one integrated system. Accordingly, the full benefits-realisation of any promising technology originally developed in one tier/layer of the supply chain will be advanced by applying a whole-system view to its further development. This is particularly important as power system operations increasingly depend on dynamic interoperability between across the Transmission-Distribution Interface (TDI).

Conversely, the failure to apply such a holistic approach heightens the risk of unintended consequences emerging when solutions are deployed and activated at mass scale (i.e. in the hundreds of thousands or more). In the case of DOEs, this could include the propagation of significant instability issues in the form of unstable oscillations at the TDI. Other outcomes may include non-linear behaviours, structural complexity and fragility, and stakeholder concerns over the equity of capacity allocation mechanisms.

b. Contributing Factors

Potential for Whole-system Benefits

There is a growing recognition that decarbonised power systems will need the bulk power, transmission and distribution systems – together with millions of demand-side CER/DER – to function much more holistically to enable reliable and efficient operation. In this context, Australia's market, regulatory and innovation funding bodies are also anticipating a wider range of contributions that DOE technologies may make beyond 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 EV charging and faster charging by allowing for higher loads during off-peak times, again including vehicle-to-grid EV discharging.

- Managing fluctuations in solar output that significantly impact instantaneous and average voltage, making 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.
- Reduced curtailment of distributed solar PV and lower wholesale electricity prices due to increased supply.

Market and regulatory bodies note that this may enable business models that provide participating CER/DER owners with greater access to financial returns through:

- Bulk power market services including wholesale energy, FCAS, or Reliability & 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 CER/DERs.

Potential Instability & Latency Issues

An advanced 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 CER/DER 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 CER/DER and load location and phase connectivity.
- Distribution network impedance values.
- 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: Geographic Information System (GIS), Outage Management System (OMS), Distribution Management System (DMS), Advanced Metering Infrastructure (AMI), head end, substation and line sensors, and CER/DER. 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 CER/DER 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 can create 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:

- Where mass deployment and activation of DOEs occurs, this may result in unstable oscillation at the TDI. This is neither an observability problem nor a technology problem. It is a control systems issue, related to latency stacking and close loop control system stability, potentially exacerbated by the structural issues described above.
- The mass deployment of DOE will co-exist with other distribution network control systems (Volt/Var regulation, Distribution Management System (DMS), Distributed Energy Resource Management System (DERMS), Fault Location, Isolation and Service Restoration (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, which is particularly problematic if DOEs are to be updated in near-real time ($\leqslant$ 5-min updates) to reflect current and local conditions as is currently asserted [28].
- 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 trialling 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 – GridQube deployment, and
- SAPN – Flexible Exports and VPP projects

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 operating environments 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 critical data flows, these questions must ultimately be empirically resolved as a basis for future-ready mass deployment.

Key Concepts L

Scalability

A central consideration of architectural analysis focusing on the degree to which a complex system can securely and efficiently accommodate scale growth. 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.

Cyber-physical

Tightly integrated computational and physical/engineered elements that create a close coupling between the virtual and physical. In cyber-physical systems, computer-based algorithms and capabilities are embedded in, and interact with physical/engineered processes, often in real or near real-time.

Ultra-Large-Scale (ULS) system

Extremely large, and inordinately complex systems that consist of an almost unparalleled volume and diversity of hardware and software, data storage and exchange, computational elements and lines of code, participants and stakeholders, together with multiple complicated structures that are 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.

GW-scale grids are prime examples of ULS systems, and arguably some of the world's largest and most complex.

'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 [4].

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.

c. Solution Requirements

In a context where LV-connected CER/DER and EV are projected to continue strong upward growth as a proportion of all 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 CER/DER 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 CER/DER, EVs, DNSP/DSOs, VPPs and AEMO and ensure a range of negative architectural Issues are avoided.
- Availability of real-time mappings of VPPs to CER/DER devices for the purpose of managing variable network configurations.
- Avoidance of latency cascading closed loop control circuits which would otherwise cause performance issues and aggravating instability.
- Application of layered decomposition methods to achieve scalable and equitable resolution of capacity allocation optimisation problems [29].

4.4 Sectoral Alignment & Participation Models

The following section examines considerations relevant to the future scalable assignment of roles and responsibilities and new mechanisms for supporting the seamless engagement and beneficial participation of millions of Consumer Energy Resources (CER/DER).

4.4.1 Roles & Responsibilities Assignment Risks

The secure and efficient operation of GW-scale power systems depends on an intricate web of relationships across numerous functions, entities, structures, system boundaries, interfaces and hand-off points. As decarbonising power systems become increasingly volatile and bidirectional, this inherent complexity grows and new capabilities such as Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models are required. Given their deeply interconnected role in future system operations, the assignment of related DSO and TDC roles and responsibilities must be underpinned by formal structural and behavioural analyses to avoid unintended consequences, sub-optimal outcomes, cost escalation and the need for substantial rework and role reallocations.

a. Cross Cutting Issue

As noted throughout this series of reports, Australia's power systems are becoming increasingly volatile and bidirectional as the forces of decarbonisation and the mass deployment of CER/DER continue to advance. Formally defined as an Ultra-Large Scale (ULS) complex systems, their secure and efficient operation depends on an intricate set of relationships between cyber-physical structures, system functions, transactional mechanisms and system/sub-system boundaries, many of which span multiple entities and systems.

If the aim is to progressively ready the power system for more deeply decarbonised, flexible and whole-system operation, due diligence requires a structurally informed approach to interrogating these underpinning functional relationships, feedback loops and precise hand-off points between systems and entities. While at a high-level this may not immediately appear necessary, in the context of a transforming ULS system like the NEM, it is a critical part of:

- Avoiding the unintentional propagation of architectural issues described in Sections 4.2.1 – 4.2.3 above[14]; and,
- Enabling the objective, evidence-based and defensible assignment of future roles and responsibilities in a manner that minimises the risk of requiring significant future rework and re-assignment of roles.

[14] Refer also to Key Concepts K.

Key Concepts M

Structure

Every functioning system created by humans has an underpinning structure. The structure of a system consists of the formal, stable connections, interactions, relationships and interdependencies that exist between the numerous components of the system and enable it to reliably achieve specific purposes.

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.

Capability

The ability to perform certain actions or achieve specific outcomes.

Function

Any of a set of related actions contributing to a larger action; a task, operation, or service. Functions combine to implement capabilities.

Role

A set of connected behaviours, actions, or processes carried out by an entity (a person or an organisation) to animate, direct, or manage one or more functions.

Responsibility

A duty or obligation for which an entity is held accountable. One or more responsibilities attach to a given role.

b. 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. Not dissimilar to – but more complex than – the multi-structure combination of the overlaid systems embedded in advanced passenger aircraft such as a Boeing 787 or Airbus A380, the formal interrogation of structural dependencies is critical.

Properly understood as a Network of Structures, modern grids 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 various tiers/layers of the electricity supply chain including bulk power, transmission and distribution systems, energy retailers, aggregators and customers.

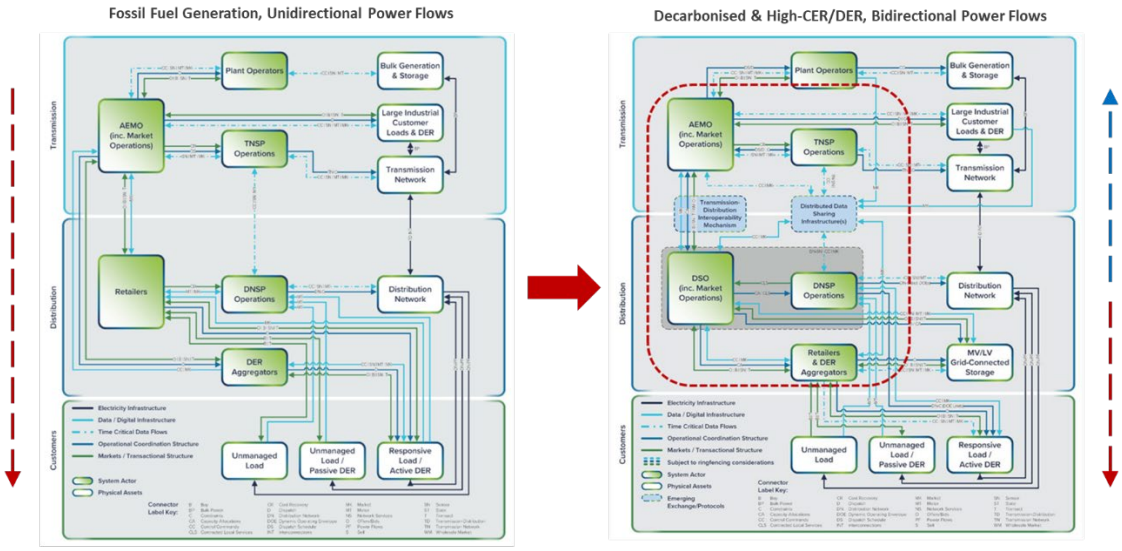


Figure 14: One credible view of how the NEM's legacy structures will need to change to enable high-CER/DER futures similar to AEMO's Step Change scenario [6].

Having the capability to formally interrogate the structures and dynamic behaviours is pivotal to the robust and objective assignment of roles and responsibilities in a manner that minimise the need for significant later rework. This is ultimately because formal Systems Architecture methodologies enable the following critical steps:

1. Mapping of the most plausible phases through which essential new capabilities such as Distribution System Operator (DSO) and Transmission–Distribution Coordination (TDC) models will need to evolve and mature as distribution-connected energy resources continue to grow as a proportion of net system resources.
2. Detailed analysis of the as-built structures, entity relationships, interfaces, hand-offs and data flows embedded across the legacy power system.
3. Interrogation of the most credible options for how these structural and functional relationships, interfaces and hand-off points between systems and entities may need to be changed to enable secure and efficient operation in the longer term, supported by high fidelity dynamic behaviour and scalability analyses.

These steps are inextricably linked to the least regret assignment of roles and responsibilities. The formal, structurally informed approach significantly reduces the risk of unintended consequences, sub-optimal outcomes and the potential need for substantial latter rework.

To illustrate further, Figure 14 above provides one credible view of how the NEM's legacy structures, interfaces and hand-off points between entities, systems and subsystems will need to change to enable high-CER/DER futures even broadly similar to AEMO's Step Change scenario [1]. Stakeholder perspectives, preferences and the consideration of individual use cases are all important inputs to the wider process of considering future roles and responsibilities. However, in the context of such a complex and functionally interdependent system, they are not sufficient for providing a credible, systemic basis for the detailed assignment of roles and responsibilities. Where the more subjective considerations are not underpinned by more objective structural analyses, the risk of unintended consequences and cost excursions is significantly elevated.

Critical Emerging Topics that Require Formal Structural Analysis

As indicated above, readying a legacy power system like the NEM for more deeply decarbonised, flexible and whole-system operation will require several new system capabilities that materially impact future roles and responsibilities. In particular, both DSO and TDC models are being actively explored and deployed in the United Kingdom, the European Union and the United States [8], [9], [10] as follows.

- **Distribution System Operator (DSO):** In contexts where a growing proportion of net energy resources are distribution-connected, new formalised responsibilities for the real-time operation, optimisation and integrated planning of high-CER/DER distribution systems, together with their interoperation with the bulk power system, become essential. In the context of Australia's deeply distributed grid transformation, the holistic range of functions required by emerging DSOs here will arguably be some of the world's most expansive.
- **Transmission-Distribution Coordination (TDC):** Power systems that host growing volumes of VRE and CER/DER experience increasing volatility and more bidirectional power flows. As a result, simultaneously ensuring system adequacy, security, reliability and cost-efficiency will require much greater levels of dynamic interdependence between the bulk power and transmission system and the distribution system. As Reports 4 & 5 of this series note [33] [34], this will require many existing and new functions and protocols between the individual DSOs and the system operator (AEMO) to be formalised and automated.

Such matters are fundamentally architectural by nature and must therefore be prominent in the detailed design of future roles and responsibilities. For example, in discussing FERC Order 2222[31] (which relates to DER integration in wholesale markets), the expert Electricity Advisory Board to the United States Department of Energy (DOE) has noted [21]:

> *"...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."*

As noted above, in ultra-complex systems there are direct relationships between the underpinning architecture of the system, the need for high-resolution analysis of the cyber-physical relationships, and the definition of future roles and responsibilities.

c. Solution Requirements

The secure and efficient operation of GW-scale power systems depends on an intricate web of relationships across numerous functions, entities, structures, system boundaries, interfaces and hand-off points. As decarbonising power systems become increasingly volatile and bidirectional, the inherent complexity of legacy systems like the NEM expands further requiring new capabilities such as DSO and TDC models to be developed and deployed.

Given their deeply interconnected role in future system operations, the assignment of DSO and TDC roles and responsibilities must be underpinned by formal structural and behavioural analyses to avoid unintended consequences, sub-optimal outcomes and cost escalations. As noted earlier in Section 4.1.2, this is because additional complexity is unavoidably driven into an already complex system where more functionality is required of it. This compounding complexity is exacerbated where structural constraints are not analysed, identified and targeted interventions applied [3].

Given the central role that DSO and TDC models will increasingly play, it is important that near, medium and longer-term needs are all considered when formally assigning roles and responsibilities as follows:

- Critical near-term issues are scoped through multi-stakeholder workshopping and the development of individual use cases (a 'present-forward' orientation).
- Formal analysis of the as-built structures, entity relationships and data flows embedded in the power system is applied to identify specific functional relationship that must be transitioned to enable longer-term requirements (a 'future-back' orientation).
- Viewed from both the current state and plausible future states, and supported by formal structural analysis, the most plausible options can then be evaluated via multi-stakeholder workshopping to shortlist the preferred transition pathways.

In summary, the targeted application of System Architecture disciplines and tools such as Model-Based Systems Engineering (MBSE) enables a far more holistic and stepwise view of the system's transformation, including how key roles and responsibilities will need to evolve 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.

As illustrated in Figure 15 below, the seven-step process developed by Dr Jeffrey Taft, former Chief Architect at Pacific Northwest National Laboratory (PNNL), commences by outlining an integrated set of desired DSO and TDC capabilities. An exploration of these capabilities, including how they may evolve over time, is provided in Reports 4 and 5 of this series [33], [34].

Having identified the desired capabilities, the distinct and non-overlapping functions needed to implement each of the desired capabilities are then distilled. Each individual function may then be allocated to the most relevant cluster of functions, and each cluster of functions is then assigned to only one formal role. While each role may be assigned to only one entity, an entity may be assigned more than one role.

The result of applying this stepwise approach is that roles and responsibilities are assigned in a structurally informed manner that automatically avoids conflicts, duplications and ambiguities.

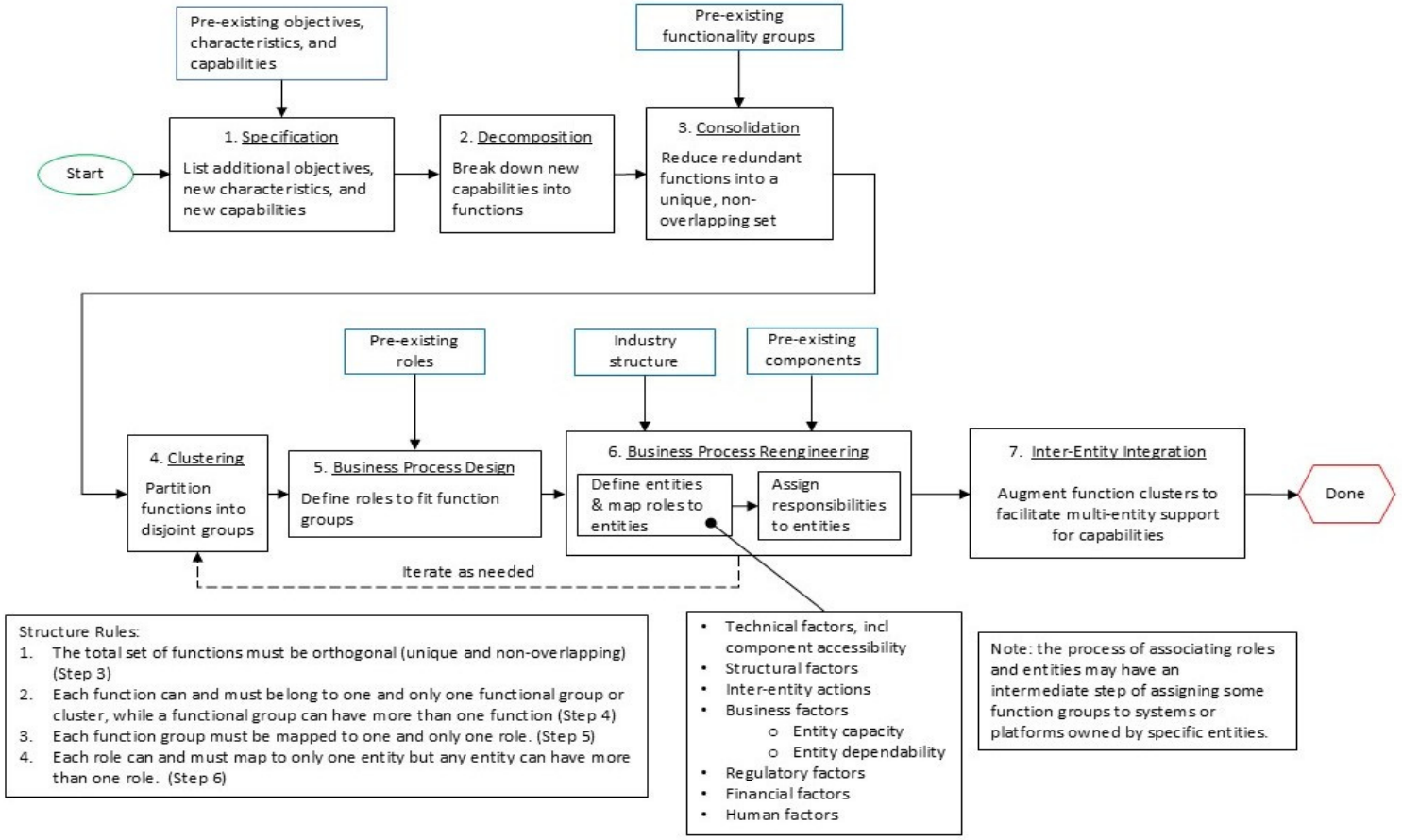


Figure 15: Structurally informed process for the assignment of roles and responsibilities[35]

4.4.2 CER/DER Scale Participation Risks

Future scenarios highlight the important role millions of orchestrated CER/DER, BESS and EVs could play in supporting more secure and efficient future power systems. Without a holistic strategy for scaling mass adoption and sustained participation, current trends suggest that achieving the scale of participation required will continue to prove challenging if not infeasible.

a. Cross Cutting Issue

As noted earlier, AEMO's Step Change scenario envisions a future NEM that involves very high levels of orchestrated CER/DER, BESS and EVs participating in energy markets and providing beneficial flexibility and other grid services. At present, however, the current level of orchestrated market participation remains relatively low, with most customer-owned resources being installed and operated with little or no external coordination capability.

As noted throughout this report, the design of Australia's power systems and markets was based on unidirectional power flows and largely passive consumers. Generation and grid services were provided almost exclusively by a few hundred large, upstream merchant resources.

In other words, today's highly centralised power systems and their supporting market and tariff structures did not originate in a world approximating the increasingly distributed future that Australia now anticipates. By contrast, the creation of an advanced value ecosystem capable of unlocking the full 'value stack' of CER/DER services relies on a sophisticated interplay of technology, policy, regulation, market structures, and stakeholder coordination. While complex efforts to reverse engineer access to multiple value streams available via legacy mechanisms by some innovators, this has yet to achieve mainstream status.

Considered from a whole-system perspective, many of the same Systemic Issues examined in this report similarly underpin and reinforce a status quo where accessing the full value of CER/DER participation is difficult if not impossible for most customers.

b. Contributing Factors

Factors that may further contribute to the limited update of CER/DER orchestration include:

- Limited customer awareness, trust and simplicity:
    - Energy literacy remains low, and the average customer may not fully understand or appreciate the potential benefits of orchestration services
    - The solutions currently on offer can be complex, require dedicated attention and lack a wider societal context that underpin 'norming' and exponential scaling\, and
    - Privacy, trust and/or warranty concerns, with many customers preferring autonomy over their energy assets in the absence of certainty.

- Inadequate financial incentives:
    - While customised solutions do exist, mass market offerings are not perceived as offering seamless access to the whole-system 'value stack' necessary to justify mass CER/DER orchestration
    - The up-front cost of the necessary enabling technology may exceed near-term financial returns, and
    - Energy market regulations and connection standards vary across jurisdictions, making it hard for CER/DER aggregators to scale offerings nationwide.
- Technology and interoperability challenges:
    - Standardisation and interoperability challenges between CER/DER technologies, platforms, and VPPs limits the ease of orchestration, and
    - Older systems may lack API access or controllable inverters, requiring costly upgrades.

c. Solution Requirements

In almost all other consumer-facing sectors, a wide range of simple, customisable solutions are available to diverse customer segments. Self-service, product comparisons and solution customisation are often made quick and easy though holistic, engaging digital experiences which provide rapid access to multiple sources of value.

The full exploration of potential future solutions is beyond the scope of this report. However, some considerations that may be relevant to empowering Australian electricity customers – homeowners, renters, businesses – to become active participants at significant scale include:

- Aggregate the full CER/DER 'value stack':
    - Evaluate the longer-term market architectures needed to value, monetise, aggregate and transact the full 'value stack' of energy, flexibility and grid services across all tiers/layers of Australia's power systems
    - Ensure emerging market designs reinforce the beneficial operational coordination of millions of CER/DER, BESS and EVs, co-optimised across all vertical tiers/layers of the power system, and
    - Standardise energy market regulations and participation standards across jurisdictions to enable national scaling of service offerings.
- Establish unified digital platform(s) that provide customers with simple, trusted access to value-added service offerings, including:
    - Real-time energy usage, generation and storage monitoring enhanced with AI-enabled customised options for immediate efficiency gains
    - Easy self-serve comparisons of alternative CER/DER service offerings and their projected monthly and annual financial benefits, and

- Rapid subscription to the preferred CER/DER offerings supported by trusted in-field deployment and guaranteed minimum returns.

- Deploy a multi-year national campaign aimed transitioning CER/DER orchestration from a relatively niche option to a mainstreamed cultural norm. This may include:
  - Energy literacy campaigns that inform customers on the range of value-added, low-risk participation opportunities
  - Inclusion programs that support equitable access across socioeconomic, regional and property type and ownership divides
  - Financing mechanisms that support CER/DER installation and participation, including leasing models, green loans, energy-as-a-service offerings, etc, and
  - Incentives and gamification that engage, inform and support mass participation.

Key Concepts N

Market Mechanism

Any form of exchange mechanism between buyers and sellers of electricity services that enables the monetisation and transaction of their economic value via a range of means, including tariffs, contracts, auctions and digital platforms.

Market-Control System

A market-control system in a power system is the integrated set of mechanisms, processes, and technologies that coordinate electricity market operations with real-time grid control. It enables efficient energy trading, ensures the balance of supply and demand, maintains system reliability, enforces regulatory compliance, and supports financial settlement. By aligning economic signals with operational needs, it facilitates transparent pricing, incentivises investment, and enables the integration of diverse energy resources into the grid.

Value Stacking

The process of providing valuable physics-based services to several vertical tiers/layers of the power system (e.g. bulk power system, transmission network, distribution network, etc) for the purpose of maximising the simultaneous value of providing these services in manner that does not create unintended negative impacts.

Co-optimisation

A structured approach to ensuring that energy resource services dispatched and/or financially incentivised in one vertical tier/layer of the power system are not driving unintended negative consequences in other tiers/layers of the system.

5 Conclusion

The transformation of Australia's power systems involves a structural reconfiguration of some of the most complex systems developed by modern society. The legacy assumptions that underpinned the unidirectional system architecture of the 20th century no longer hold in a context of a system that is becoming increasingly volatile and bidirectional.

As illustrated throughout this report, many of the key emerging challenges are cross-cutting and systemic in nature. They cannot ultimately be resolved by any number of issue-in-isolation treatments.

Fifteen significant systemic issues have been identified, many of which are structurally embedded across multiple subsystems. The findings of this report function as invaluable inputs into the consideration of both Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models. It is arguable that the consideration of scalable and future-ready DSO and TDC models is simply not possible without the input provided by this report.

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Appendix A: Principles, Methodologies & Acknowledgements

This section provides an overview of the guiding principles and integrated disciplines and tools employed in the development of this reference set.

A1 Guiding Principles

Following are a set of principles and characteristics embedded in the Power System Architecture discipline that have guided the development of this reference set.

1. **Stakeholder / User-centric:** Systems architecture methodologies are grounded in a detailed exploration of the *Future Customer & Societal Objectives (Report 1)* for the power system to ensure the grid can deliver a balanced scorecard of societal outcomes.
2. **Contextually Informed:** Systems architecture methodologies give priority to examining the full range of *Emerging Trends Driving Transformation (Report 2)* 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. **Structural Focus:** Systems architecture methodologies give particular attention to examining the underpinning legacy 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).
4. **Principles-based:** Systems architecture methodologies are grounded in established principles and formal bases, ensuring conceptual integrity through consistent, traceable and verifiable processes, that enhance multi-stakeholder trust, and minimise the potential for unintended consequences.
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 & Business Model 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 one proprietary solution or commercial model.
8. **Complexity Management:** By making the underpinning structures of a legacy system explicitly articulated, systems architecture enables the decomposition of inherent complexity, identification of legacy structural constraints, 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 in the context of the whole system.
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.

A2 Integrated Disciplines & Tools

Following are a set of disciplines and tools that have informed and enabled the development of this reference set.

Design Thinking	A human-centered, iterative methodology for solving complex problems through empathetic understanding, creative ideation, and rapid experimentation. The purpose of Design Thinking is to foster innovation by prioritising human needs, reframing challenges as opportunities, and developing actionable solutions that balance desirability (user appeal), feasibility (technical viability), and viability (economic sustainability). It functions as a non-linear process that bridges creative exploration with practical implementation, enabling teams across disciplines to navigate ambiguity and deliver user-centric outcomes.
Model-Based Systems Engineering (MBSE)	An approach to Systems Engineering that uses software-based models to represent various aspects and behaviours of a complex System. It provides dynamic modelling of System requirements, design, analysis, verification and validation activities in a manner that ensures requirements traceability, reduced errors and enhances multi-stakeholder collaboration in near real-time. MBSE leverages graphical and textual representations to capture, analyse, simulate, and communicate the requirements, designs, and behaviours of the System. Applied from the conceptual design phase and continuing throughout development and later life cycle phases, it enhances traditional Systems Engineering processes by providing a more structured, integrated, and visual representation of the Architecture and Functions of a System.

Power Systems Architecture (PSA)	An integrated set of disciplines that support the structural transformation of legacy power systems, enabling them to more effectively serve evolving customer and societal objectives. At its most fundamental, PSA reflects the application of systems engineering to the transformation of the power system. In recognising each power system as a 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 system priorities and objectives including the role and responsibilities, operational coordination and co-optimisation across all vertical tiers/layers. • 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). • Future-resilient decision making by surfacing hidden structural constraints early which may otherwise propagate a range of architectural Issues including computational constraints, latency cascading and cyber-security vulnerabilities, providing greater assurance that new investments will be scalable and extensible under all plausible futures. PSA provides a formalised toolkit for decomposing and 'taming' the massive complexity inherent to a transforming power system. The PSA toolkit empowers more informed, multi-stakeholder participation by making critical content explicit and tractable that would otherwise remain opaque and intractable. It is designed to enhance decision quality, timeliness and traceability to support full benefits-realisation and avoid the propagation of unintended consequences.

Strategic Foresighting	A systematic, collaborative process for exploring plausible futures, identifying emerging trends, disruptions, and opportunities to inform resilient long-term strategies. The purpose of Strategic Foresighting is to enable organisations to proactively shape or adapt to future environments by reducing uncertainty, challenging assumptions, and aligning decisions with potential scenarios. It ensures that systems, architectures, and investments remain viable amid evolving technological, societal, economic, and regulatory landscapes. Strategic Foresighting functions as an upstream enabler of the Systems Architecture process. It facilitates cross-disciplinary dialogue to anticipate future needs, risks, and innovations before architectural decisions are formalised. By analysing weak signals, drivers of change, and systemic interdependencies, it provides context for defining robust requirements in the Reference Architecture phase and ensures Detailed Architecture designs embed adaptability.
Structural Analysis	In the context of electricity system transformation, structural analysis refers to the systematic evaluation of the physical, operational, and organisational structures of the power system to determine the changes necessary to transition from a conventional, fossil-fuel-based, unidirectional grid to a decarbonised, distributed, and bidirectional grid. This process involves assessing how new technologies (such as distributed energy resources, storage, and electric vehicles), market mechanisms, and control strategies will alter the system's topology, power flows, stability characteristics, and resilience requirements. The goal is to ensure that the restructured grid can accommodate variable renewable energy sources, enable two-way energy and information flows, and maintain security, reliability, and affordability under future scenarios. Key components of structural analysis include: • Physical Structure: Reconfiguration of transmission and distribution networks for bidirectional flows. • Operational Structure: Adaptation of protection systems, frequency control, and flexibility measures. • Institutional/Market Structure: Integration of distributed generation, demand-side participation, and new pricing models. • Resilience and Stability: Ensuring robust system performance under uncertainty and high penetration of renewables.

Systems Architecture	A formal discipline within Systems Engineering that supports objective and collective reasoning about the foundational structure and organisation of a complex system. This includes its components, interfaces, feedback loops, and other critical behaviours. The architecture of a system exerts a disproportionate influence on what the system can reliably and efficiently accomplish. Accordingly, a system should not be viewed merely as the sum of its parts, but rather as the product of the interactions among those parts—interactions that are enabled and constrained by the underlying architectural design. Although architecture plays a pivotal role in shaping system performance, it is often less tangible and more difficult to discern than the system's individual components. The discipline of Systems Architecture, therefore, provides formal methods and tools to analyse how system components are interconnected, to identify emergent behaviours that arise from these interactions, and to explore robust options for modification and improvement. By enabling a deeper understanding of how legacy systems function and how their structures can evolve, Systems Architecture empowers stakeholders to visualise relationships, evaluate trade-offs, and make informed decisions that enhance the system's capacity to meet current and future demands.
Systems 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.
Systems 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.

A3 Acknowledgements & Foundational Sources

The Energy Catalyst team has benefited from the expertise of and privilege of collaborating with many global organisations and experts. While it would be impossible to exhaustively recognise all relevant entities, individuals and sources, the following are particularly relevant to the development of this reference set, noting that any errors are those of Energy Catalyst alone.

Entities

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- Dr John Ward

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The following sources provide key principles and bases for the application of the disciplines and tools employed in developing this reference set.

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Appendix B: Glossary of Terms

Term	Definition
Active CER/DER	Consumer Energy Resources (CER/DER) that are capable of automatically altering their operating behaviour in response the needs of the wider power system. This may be in response to changes in the price of energy, the operating conditions of the local distribution network and/or upon receipt of instructions, control inputs or data feeds from authorised external entities. Active CER/DER are significantly more valuable to the power system than Passive CER/DER as they can provide specific Electric Products in a manner that is highly correlated with the time, location and physics-based needs of the power system.
Active Network Management (ANM)	The coordinated, real-time management of network assets, consumer demand, customer-owned CER and large community or third-party DER to optimise the performance of the distribution network. ANM uses digital technologies, data analytics, and automated control systems to actively manage network issues such as voltage fluctuations, congestion and fault levels. Supported by advanced network models and situational awareness, ANM allows more efficient use of existing network assets and facilitates the integration of high levels of renewable energy, electric vehicles, and flexible loads. Key capabilities of ANM typically include: • Dynamic control of generation/export/import; • Voltage regulation through reactive power support; • Real-time monitoring and forecasting of network conditions; and, • Coordination with flexibility markets and CER/DER aggregators. Observability is foundational to ANM as it relies on accurate, real-time knowledge of the network state to make dynamic decisions about network operation (e.g., voltage control, curtailment, dispatch of flexibility resources). ANM is distinct from traditional, passive network management, which relies primarily on static planning and reinforcement to manage system limits.

Architecture	A holistic conceptual framework that defines how diverse components within a system—spanning physical, informational, operational, and transactional domains—are interconnected through foundational structural relationships. This architecture enables the entire system to operate cohesively in pursuit of specific, often complex, objectives. At its core, a systems architecture articulates the structural linkages, interdependencies, and interactions among components, capturing the essential logic that binds them into an integrated whole. In simplified terms, while the boxes of a block diagram represent the system's constituent elements, it is the connecting lines—the architecture—that illustrate how these elements cooperate to achieve functionality. A primary function of systems architecture is to expose and support collective reasoning about how all components interact to deliver intended capabilities. This includes identifying non-scalable legacy structures that may hinder future performance. While individual components are often more visible, it is the underlying architecture—those hidden yet critical relationships—that exerts disproportionate influence over system-wide capabilities, resilience, and limitations. In times of rapid change or transformation, ensuring that legacy structural relationships can adapt and scale is vital. This adaptability is crucial to maintaining secure, reliable, and cost-efficient operation in the face of evolving requirements and technological disruption.
Architectural Issues	Following are eight important structural issues that the Power Systems Architecture disciplines address that will otherwise negatively impact the operability and resilience of decarbonising power systems: • Tier/Layer Bypassing: The creation of information flows or coordination signals that 'leapfrog' a vertical tier/layer of the power system's operational hierarchy. • 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. • Hidden Coupling: Two or more control entities with partial views of system state issue simultaneous but conflicting coordination signals to a CER/DER or component of the power system.

	• Cluster Coupling: Where CER/DER are addressed in groups that do not allow for separation of edge device commands by specific criterion: location, device type, device service provision, etc. • Latency Cascading: Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations. • Computational Time & Cost Excursions: Where massive data volumes, latencies and processing 'bottlenecks' occur, compounded by unresolved structural issues, optimisation engines risk hitting a computational 'time wall' where no amount of computing resource will be adequate to solve the optimisation problems in an acceptable time and at an efficient cost.[15] • Cybersecurity Structural Vulnerabilities: Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration. • 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.

[15] It is important to note that in this context, computation resources grow exponentially or even faster (factorially) relative to the amount of data required to be processed. This results in a self-perpetuating pattern of rising computation cost and computation power for less return on investment. As a GW-scale power system is a highly complex cyber-physical system (not only a digital system) deployed over a wide area and involving many separate entities, these effects are compounded where there is a failure to address the underlying structural root causes.

Bidirectional	In the context of a decarbonising power system served by high levels of both Variable Renewable Energy (VRE) and Consumer Energy Resources (CER/DER), conventional one-way system operations progressively transform to become increasingly two-directional. As a significant departure from traditional system operations, this drives a profound structural shift toward two-way flows of power, information and market services as follows: • Bidirectional power flows: Where the output of CER/DER periodically exceeds local demand, with surplus capacity being fed upstream to the wider system. • Bidirectional information flows: Two-way data flows between upstream and downstream actors and resources become essential, spanning System Operator, TNSPs, DSOs, VPPs, CER/DER, etc. • Bidirectional market participation: Millions of customers become both producers and consumers and may provide services to energy markets and the wider system.
Capability	The ability to perform certain actions or achieve specific outcomes.
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.
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.

Consumer Energy Resources (CER/DER)	A diverse range of small to medium scale energy resources that are located behind-the-meter at residential, commercial and industrial premises and are owned and operated by the customer. CER/DER are a multi-application resource that include the following types of technologies: • Distributed Photovoltaics (DPV) and embedded generators • Battery Energy Storage Systems (BESS), including small and medium-scale batteries • Electric Vehicles (EV) • Smart Inverters, and • Flexible Resources (Distributed). The term Distributed Energy Resources (DER) is appropriately used of these technologies where they connected directly to the distribution system (i.e. front-of-meter).
Consumption	The total electricity used over a duration of time, expressed as kilowatt hours (kWh), megawatt hours (MWh), gigawatt hours (GWh) and terawatt hours (TWh).
Co-optimisation	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.
Customers	The human individuals, families, organisations, institutions and whole societies served by the power system and that are the fundamental reason it exists. Customers may choose only to receive, consume and pay for services from the power system. They may also elect to provide services to the power system, in the form of valuable Electric Products consistent with technical requirements, in exchange for some form of value or additional benefit.
Cyber-physical	Tightly integrated computational and physical/engineered elements that create a close coupling between the virtual and physical. In cyber-physical systems, computer-based algorithms and capabilities are embedded in, and interact with physical/engineered processes, often in real or near real-time.

Decentralisation Ratio	The ratio of CER/DER capacity to total installed capacity.
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. It is important to understand the difference between Decentralised Systems and Distributed Systems.
Demand	The electricity needed at a point in time, expressed as kilowatts (kW), megawatts (MW), gigawatts (GW) and terawatts (TW).
Detailed Architecture	Based on a prior Reference Architecture process, a Detailed Architecture process provides unambiguous technical direction for system realisation, ensuring all structural elements, data flows, protocols, and performance criteria are fully specified to meet stakeholder requirements. It translates the high-level vision of the Reference Architecture into a buildable blueprint. The development of a Detailed Architecture functions as the second major phase of the Systems Architecture process. It necessitates deep technical rigor and multi-stakeholder collaboration to progressively identify and resolve dependencies and define exact interfaces. It eliminates abstraction by specifying quantifiable attributes (e.g. throughput, latency, scalability targets) and implementation choices (e.g., software frameworks, hardware models, network topologies). This creates a foundation for the development of a Detailed Engineering Design.
Distributed Energy Resources (DER)	A diverse range of small to medium scale energy resources that are connected directly to the distribution system (i.e. front-of-meter). Refer to Consumer Energy Resources (CER/DER).
Distributed System	A network of independent Components that are federated or interconnected in a manner which respects their autonomy but also enable them to work together to achieve a common goal. It is important to understand the difference between Distributed Systems and Decentralised Systems.

Distributed Photovoltaics (DPV)	Solar photovoltaic panel installations connected to the distribution network. In many cases, these resources are located behind-the-meter at residential and commercial customer properties.
Distribution Market Mechanisms	A general term reflecting a spectrum of approaches and mechanisms to value, incentivise, procure and operationally coordinate energy, flexibility and other system services from CER/DER and flexible loads. In its most basic form, this may include tariff-based incentives and/or bilateral contracts. In more advanced forms, it may include distribution-level markets for the procurement of temporally and spatially dynamic system services, providing clear dispatch signals of the time, location and type of services required and enabling 'value stacking' of services in a manner co-optimised with bulk power markets.
Distribution Network Model	A structured digital representation of the physical and operational characteristics of a distribution system. It typically includes: • Topology: Nodes/buses, transformers, feeders, etc.; • Parameters: Impedance, line capacities, switch status, etc.; • Asset data: Load and generation types, ratings, etc.; and, • Geographic data and schematic layouts. These models support power flow analysis, fault location, load forecasting, and control applications in distribution system operation and planning.
Distribution System Operator (DSO)	The entity responsible for both the active management and optimisation of a high-CER/DER distribution system, and its two-way interoperation with the bulk power system, as the decarbonised grid becomes more volatile and bidirectional. In this more dynamic context, distribution system operation involves real-time coordination of the 'system' of network assets, flexible and inflexible demand, customer-owned CER and large-scale DER to deliver enhanced technical and economic outcomes not possible by managing network assets alone. Somewhat analogous to a conventional bulk power system operator, distribution system operation requires both advanced controls and market mechanisms to ensure firm response and incentivise mutually beneficial participation, underpinned by transparency and neutrality. As distribution systems continue transforming to become an

	increasingly complex energy ecosystem, the active engagement of customers, CER/DER aggregators and third-party service providers, supported by advanced digital infrastructure and engagement tools, also becomes a critical focus of the DSO.
Dynamic Operating Envelope (DOE)	Distinct from Static Operating Envelopes, DOE's provide Dynamic Export Management from DER/CER to the Power System, based on the operating characteristics of the Distribution Network or wider Bulk Power System, in a manner that varies over time and location.
Electric Products	The valuable physics-based services that may be provided to the power system by CER/DER in exchange for some form of value or additional benefit. All beneficial grid services are derivatives of the following '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 AC systems while maintain 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.
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), Consumer Energy Resources (CER/DER) and various forms of energy storage and firming resources.
Flexible	The capacity of a decarbonising power system to anticipate, adapt to and manage the variability and volatility of supply and demand across all relevant time scales – from seconds to seasons – while maintaining reliability, affordability and system stability. Flexibility is recognised as foundational to power system decarbonisation, sometimes being equated to being 'the new baseload'. A key indicator of power system flexibility is the ability to integrate very high levels of both centralised and distributed Variable Renewable Energy (VRE) sources with minimal curtailment.

Flexible Resources – Distributed	Certain categories of CER/DER that can, in a reliable and firm manner, modify their operational behaviour in response to bulk power system, transmission network and/or local distribution network needs in a manner acceptable to the customer or owner/investor. Enabled by advanced approaches to Operational Coordination, large fleets of these resources can beneficially alter the demand profile of a feeder, substation, distribution network, transmission network and/or the bulk power system. Examples include various types of responsive loads such as water pumping, industrial process loads, battery charging, EV charging, heating loads, cooling loads, etc. (Note: The terms demand management, demand response, load shifting, controllable load and interruptible load are generally synonymous with this concept).
Function	Any of a set of related actions contributing to a larger action; a task, operation, or service. Functions combine to implement capabilities.
Interdependent Grid	A set of structural and functional arrangements that formalise how the combination of centralised and distributed system management jointly underpins the secure and affordable operation of a decarbonising power system as operational volatility and bidirectional power flows increase. In a conventional grid, most generation was located upstream, connected to the transmission network and system operations were comparatively hierarchical and 'top-down'. By contrast, as millions of diverse, participating energy resources emerge across all tiers/layers of the grid, a more interdependent power system enables coordination and dynamic decision-making across all supply chain entities in near real-time. Supported by an architecturally informed digital infrastructure, the system operator, transmission networks, DSOs, aggregators and market platforms are capable of operating with greater levels of visibility, predictability and alignment. This provides the scalable foundation for both whole-system operational coordination and supply-demand balancing as a decarbonising, high-CER/DER grid becomes more volatile and bidirectional.

Interface	A point of interaction or boundary where different subsystems, components, or modules communicate and exchange information or energy. It defines the protocols, standards, and methods through which these interactions occur, ensuring compatibility and coordination among the interconnected parts of the system. Interfaces are crucial for the integration and functionality of complex systems, allowing diverse elements to work together effectively.
Interoperability	The capability of two or more systems, components or applications to share, transfer, and readily use energy, power, information and services securely and effectively with little or no inconvenience to the user. Future-ready approaches to Interoperability recognise that is has an intrinsic relationship to the underpinning Structure and Roles & Responsibilities of the wider system, both in their current state form and as they will plausibly need to evolve to enable an increasingly decarbonised future system.
Inverter-Based Resource	A diverse range of energy resources that, unlike many conventional resources, do not have moving components that rotate synchronised with the frequency of the power system. In contrast, resources such as wind turbines, solar photovoltaics (solar PV) and battery energy storage systems (BESS) are interfaced with the power system via power electronic converters known as inverters, which electronically replicate the standard operating frequency of the grid.
Layered Decomposition	A foundational strategy for managing complexity in large, complex systems by breaking them into semi-independent, logically structured layers, each of which provides services to the layer above and uses services from the layer below. Based on formally established mathematical techniques, it is employed in many sectors, such as aerospace, internet and communications protocols, cloud computing and autonomous vehicles, to solve Ultra Large Scale (ULS) optimisation problems. It reduces coupling, increases resilience and enables scaling, making it a hallmark of modern complex engineered systems. As decarbonising power systems face growing levels of volatility and bidirectional power flows while transitioning from hundreds to millions of participating resources, layered decomposition provides an empirical basis for solving the many critical structural issues that

	impede whole-system visibility and the operational coordination of millions of diverse participating resources. In contrast with more traditional 'top-down' 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.
Market Mechanism	Any form of exchange mechanism between buyers and sellers of electricity services that enables the monetisation and transaction of their economic value via a range of means, including tariffs, contracts, auctions and digital platforms.
Market-Control System	A market-control system in a power system is the integrated set of mechanisms, processes, and technologies that coordinate electricity market operations with real-time grid control. It enables efficient energy trading, ensures the balance of supply and demand, maintains system reliability, enforces regulatory compliance, and supports financial settlement. By aligning economic signals with operational needs, it facilitates transparent pricing, incentivises investment, and enables the integration of diverse energy resources into the grid.
Market/System Operator (MSO)	An entity that combines the functions of the Market Operator and System Operator to ensure secure, reliable and efficient provision of electricity services with a primary focus on the bulk power system. At the highest level, this will include responsibility for: • System forecasting and planning: to ensure resource adequacy over various time horizons; • Real-time system operation: maintaining the instantaneous balancing of supply and demand; and, • Market operations: to value, incentivise, procure and coordinate the provision of energy, capacity, flexibility and/or ancillary services.
Megashift	A term derived from the Strategic Foresight discipline which refers to a large-scale, systemic transformation that reshapes the underlying structures and behaviours of an industry, sector, society and/or the natural environment over an extended time horizon. Key characteristics of a Megashift include:

	• Scale and Scope: Global or near-global in impact, typically affecting multiple domains at the same time. • Multiple Drivers: Broader than individual trends or emerging issues, typically reflecting the cumulative effects of many converging drivers. • Temporal Depth: Unlike short-term perturbations, Megashifts unfold over decades and often fundamentally reshape structures and systems for the long-term.
Minimum Operational Demand	The lowest amount of electrical Power instantaneously delivered, or forecast to be delivered, in a defined period (day, week, month, season or year), either at a specific Connection Point, network segment or for the entire Power System. Measured in kiloWatts (kW), MegaWatts (MW) or GigaWatts (GW).
Model-Based Systems Engineering (MBSE)	An approach to Systems Engineering that uses software-based models to represent various aspects and behaviours of a complex System. It provides dynamic modelling of System requirements, design, analysis, verification and validation activities in a manner that ensures requirements traceability, reduced errors and enhances multi-stakeholder collaboration in near real-time. MBSE leverages graphical and textual representations to capture, analyse, simulate, and communicate the requirements, designs, and behaviours of the System. Applied from the conceptual design phase and continuing throughout development and later life cycle phases, it enhances traditional Systems Engineering processes by providing a more structured, integrated, and visual representation of the Architecture and Functions of a System.
Network of Structures	While it is customary to refer to the power system in the singular, a modern electricity system is in reality a 'super-system' of seven structures, four of which are functionally interdependent on a days-to-sub second timescale (coral-coloured nodes) GW-scale power systems like the NEM and WEM consist of an intricate web of the following seven inter-dependent structures that must ultimately be transformed holistically: • Electricity Infrastructure (Power Flows) • Digital Infrastructure (Information/Data Exchange, Storage and Processing)

	• Operational Coordination Structure • Transactional Structure • Industry / Market Structure • Regulatory Structure; and • Sector Coupling Structures (Gas, Water, Transport, etc).
Observability	The ability to infer the complete internal state (e.g., voltages, power flows, system frequency, and phase angles at all buses) of the system based on available measurements (e.g., SCADA, PMUs, smart meters) and the network model. A power system is said to be observable if it is possible to uniquely determine the system's state from available data.
Operability	The capability to plan and operate the power system reliably, securely and efficiently under all expected conditions. Core prerequisites for operability include predictability, which is the ability to forecast system behaviour accurately, and dispatchability, which is the ability to control and adjust generation or demand in response to system needs. Operability is a multidimensional system attribute, not a single metric, and encompasses the ability of system operators and control mechanisms to: • Maintain supply–demand balance at all times; • Keep voltage and frequency within allowable limits; • Ensure thermal loading of equipment remains within capacity; • Respond to contingencies, such as generator or network outages; • Manage ramping, variability, and uncertainty (especially from renewable sources); • Coordinate resources and orchestrate flexibility (from generation, demand, or storage); and, • Respect operational and market constraints and interfaces (e.g., congestion, availability, ramp rates, dispatchability).

Operational Coordination	The management and coordination of decisions, actions, and information flows across multiple actors, assets and system tiers/layers to ensure the secure, efficient, and stable operation of the power system. It includes the systematic operational alignment, across timescales from day-ahead to real-time operation, of the following: • System Operator and Distribution System Operators (DSOs); • Generators, Energy Storage, Consumer Energy Resources (CER/DER), etc.; • Transmission and Distribution network assets; • Market participants, CER/DER Aggregators, etc.; and, • Adjacent sector couplings (e.g. gas, transport, water, etc). Supply-Demand Balancing is a critical outcome of successful Operational Coordination as it enables the right resources to be activated or curtailed in the right locations in the right timescales to maintain this balance. The goals of Operational Coordination also include network constraint management, voltage support, frequency regulation, outage management, and system restoration. While both Operational Coordination and Supply-Demand Balancing were traditionally the sole or primary responsibility of the MSO, multi-level Operational Coordination will be increasingly required as power systems become more decentralised and volatile as the scale deployment of VRE and CER/DER continues.
Orchestration	The coordination of dispatchable Energy Resources, including but not limited to Consumer Energy Resources (CER/DER), in a manner that moderates negative Power System impacts and may include facilitating the provision of Electric Products to various Tiers/Layers of the System under a commercial arrangement.

Passive CER/DER	Consumer Energy Resources (CER/DER) 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 or Distribution System Operator (DSO). Passive CER/DER are significantly less valuable to the power system than Active CER/DER due to their inability to alter their behaviour in response to significant operational conditions experienced by the wider system. As a result, where deployed at scale they will both impose operational inefficiencies and escalate Minimum Operational Demand risks to the reliability of the power system as a whole.
Power Systems Architecture (PSA)	An integrated set of disciplines that support the structural transformation of legacy power systems, enabling them to more effectively serve evolving customer and societal objectives. At its most fundamental, PSA reflects the application of systems engineering to the transformation of the power system. In recognising each power system as a 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 system priorities and objectives including the role and responsibilities, operational coordination and co-optimisation across all vertical tiers/layers. • 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). • Future-resilient decision making by surfacing hidden structural constraints early which may otherwise propagate a range of architectural Issues including computational constraints, latency cascading and cyber-security vulnerabilities, providing greater assurance that new investments will be scalable and extensible under all plausible futures. PSA provides a formalised toolkit for decomposing and 'taming' the massive complexity inherent to a transforming power system. The PSA toolkit empowers more informed, multi-stakeholder participation by making critical content explicit and tractable that would otherwise remain opaque and intractable.

	It is designed to enhance decision quality, timeliness and traceability to support full benefits-realisation and avoid the propagation of unintended consequences.
Reference Architecture	A Reference Architecture process develops an integrated set of documents and diagrams that capture the essence of the structural relationships, linkages and interdependencies that enable the functioning of a complex system. The purpose of a Reference Architecture is to provide shared clarity on how the underpinning structures and relationships of a system are currently configured, including how they may need to change to enable future needs and stakeholder requirements. The development of a Reference Architecture functions as the first major phase of the systems architecture process. The process facilitates a shared understanding across multiple organisations and disciplines of the current and plausible alternative structural arrangements. Necessitating a level of abstraction, it reflects the qualities and intrinsic nature of the system rather than its full detail. This provides a foundational step toward the subsequent Detailed Architecture and Detailed Engineering Design phases.
Responsibility	A duty or obligation for which an entity is held accountable. One or more responsibilities attach to a given role.
Role	A set of connected behaviours, actions, or processes carried out by an entity (a person or an organisation) to animate, direct, or manage one or more functions.
Rough consensus	A collaborative model developed by the Internet Engineering Task Force (IETF), the premier standards development organisation for the Internet, for effective multi-stakeholder problem solving in an ultra-complex systems environment. It provides a collaborative approach to achieving general agreement among multiple participants, rather than strict unanimity or a formal majority. It emphasises general alignment of the direction while allowing for areas of dissent. Points of disagreement are weighed and collectively explored rather than ignored. Decision making largely based on voting outcomes, without understanding and addressing meaningful technical concerns, is avoided.

Scalability	A central consideration of architectural analysis focusing on the degree to which a complex system can securely and efficiently accommodate scale growth. 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.
Smart Inverter	An advanced type of power inverter that converts direct current (DC) into alternating current (AC) while incorporating smart technology features. These features often include grid support functions, remote monitoring, real-time data communication, and the ability to adjust power output to optimize energy usage and efficiency. Smart inverters are commonly used in renewable energy systems, such as solar and wind power installations, to enhance grid stability and integrate seamlessly with smart grids and other modern energy management systems.
Structure	Every functioning system created by humans has an underpinning structure. The structure of a system consists of the formal, stable connections, interactions, relationships and interdependencies that exist between the numerous components of the system and enable it to reliably achieve specific purposes.
Structural Analysis	In the context of electricity system transformation, structural analysis refers to the systematic evaluation of the physical, operational, and organizational structures of the power system to determine the changes necessary to transition from a conventional, fossil-fuel-based, unidirectional grid to a decarbonised, distributed, and bidirectional grid. This process involves assessing how new technologies (such as distributed energy resources, storage, and electric vehicles), market mechanisms, and control strategies will alter the system's topology, power flows, stability characteristics, and resilience requirements. The goal is to ensure that the restructured grid can accommodate variable renewable energy sources, enable two-way energy and information flows, and maintain security, reliability, and affordability under future scenarios. Key components of structural analysis include: • Physical Structure: Reconfiguration of transmission and distribution networks for bidirectional flows.

	• Operational Structure: Adaptation of protection systems, frequency control, and flexibility measures. • Institutional/Market Structure: Integration of distributed generation, demand-side participation, and new pricing models. • Resilience and Stability: Ensuring robust system performance under uncertainty and high penetration of renewables.
Structural Intervention	In the context of power system transformation, a structural intervention refers to the deliberate modification or redesign of the physical, operational, and institutional components of the system to enable, for example, the transition from a centralised, fossil-fuel-based, unidirectional grid to a decarbonised, distributed, and bidirectional grid. Structural interventions go beyond incremental operational adjustments; they involve fundamental changes to the system's architecture and governance to ensure it can support developments such as: • High penetration of renewable energy sources • Two-way energy and information flows • Distributed generation, storage, and flexible demand • New market structures and regulatory frameworks These interventions may include network reinforcement and reconfiguration, deployment of advanced digital infrastructure, implementation of new control and protection schemes, and policy and market redesign to maintain reliability, resilience, and economic efficiency in the evolving energy ecosystem.
Supply-Demand Balance	Where volume of electricity delivered by all operating generation (supply) is maintained in equilibrium with all electricity consumed by customers (demand) during each second. Maintaining this instantaneous balance is crucial for the stable operation of the power system as imbalances lead to frequency and voltage deviations, which can cause cascading outages.

Supply-Demand Balancing	The continuous process of ensuring that total electricity generation (supply) matches electricity consumption (demand) every second. Maintaining this instantaneous balance is crucial for the stable operation of the power system, with imbalances leading to frequency and voltage deviations, which can cause cascading outages. Enabled by formal Operational Coordination mechanisms, the maintenance of supply and demand in constant equilibrium involves: • High levels of operational visibility and observability in real-time; • The real-time dispatch of centralised and decentralised generation and energy storage; • The activation of flexible demand, for example to align with periods of peaks or troughs of Variable Renewable Energy (VRE) generation; and, • Activation of reserves and ancillary services as needed. Supply-Demand Balancing was traditionally the responsibility of the Market/System Operator and employed a Load-following Operational Paradigm as most generation plant was both dispatchable and connected to the transmission system. As the scale deployment of VRE and Consumer Energy Resources (CER/DER) continues, and power systems become more volatile and decentralised, multi-level balancing will increasingly be required. This may also require increasing time-windows where a Supply-following Operational Paradigm is employed.
Supply-side	The upstream end of a conventional power system where almost all generation plant was traditionally located. More broadly, the term includes all parts of the power system upstream of the customer connection point, including the bulk power system, transmission networks and distribution networks.
Synchronous Generation	Generation plant which is directly connected to the power system and rotates in synchronism with the frequency of the grid.

System	An interconnected set of components that are formally linked together by a set of structural and functional relationships to achieve specific purpose(s). A system always involves three things: • Components or elements, which may be many or few, tangible or intangible • Structural and functional relationships, which link or relate all the components together in a manner that enables interdependent operation; and • One or more purpose(s), which provide the ultimate reason for the system's existence, and toward which the collective functions of all the components are directed, enabled by the architectural structures. While the components of a system are often the most visible/tangible, the underpinning structure or architecture always has a disproportionate influence on the essential limits of what the system can reliably and efficiently perform.
Systemic Issue	In the disciplines of Systems Architecture and Systems Engineering, a Systemic Issue refers to a cross-cutting problem that stems from the fundamental structure, design, or interactions within a system, rather than from isolated component failures or random anomalies. These issues emerge from the way the system is intrinsically organised and how its parts interrelate. In the context of system transformation, Systemic Issues typically surface when existing, legacy arrangements are placed under stress by the cumulative impact of Emerging Trends –- developments and dynamics that were not anticipated during the original design of the system. For example, in electric power systems, Systemic Issues often appear across one or more of the seven inter-dependent technological, market, and regulatory structures outlined in the Network of Structures framework. Identifying, analysing, and documenting Systemic Issues is a powerful and holistic approach to problem definition in complex, systems. Compared to traditional methods that examine numerous individual trends or develop extensive use case libraries, focusing on Systemic Issues enables practitioners to distil a limited set of high-leverage problems. Addressing these through targeted structural interventions can deliver transformative, system-wide benefits.

Systems Architecture	A formal discipline within Systems Engineering that supports objective and collective reasoning about the foundational structure and organisation of a complex system. This includes its components, interfaces, feedback loops, and other critical behaviours. The architecture of a system exerts a disproportionate influence on what the system can reliably and efficiently accomplish. Accordingly, a system should not be viewed merely as the sum of its parts, but rather as the product of the interactions among those parts—interactions that are enabled and constrained by the underlying architectural design. Although architecture plays a pivotal role in shaping system performance, it is often less tangible and more difficult to discern than the system's individual components. The discipline of Systems Architecture, therefore, provides formal methods and tools to analyse how system components are interconnected, to identify emergent behaviours that arise from these interactions, and to explore robust options for modification and improvement. By enabling a deeper understanding of how legacy systems function and how their structures can evolve, Systems Architecture empowers stakeholders to visualise relationships, evaluate trade-offs, and make informed decisions that enhance the system's capacity to meet current and future demands.
Systems 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.
Systems 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.

Theory of Change	A structured framework that outlines the causal pathways through which interventions are expected to lead to desired outcomes. Collaboratively developing a theory of change helps key stakeholders interrogate how and why an approach to transformation is expected to work, and surface and constructively debate differences early. In a complex, multi-stakeholder context, this enables more efficient and effective interventions by making the assumptions underlying interventions explicit, identifying the necessary conditions for success, and describing the logical sequence of events that are expected to result in the intended changes.
Tier/Layer	The vertical segments of a GW-scale power system which include the bulk power system, transmission networks and distribution networks. In historical context, these tiers have been largely managed as relatively discrete elements of a unidirectional supply chain. As whole-system operations become increasingly volatile and bidirectional, a significant deepening of two-way operational interdependence between the current and emerging entities such as DSOs becomes necessary.
Transmission-Distribution Interface (TDI)	The physical points at which the bulk power/transmission system and a particular distribution system interconnect, typically at one or several major substations. In a conventional, unidirectional power system this has been commonly known as the Bulk Supply Point (BSP), where electricity from the bulk power system is delivered via the transmission network to regional and metropolitan distribution networks. While conventional aspects of the BSP remain unchanged, the TDI concept represents the need to transition to a more active, two-way interface model capable of enabling the required Transmission-Distribution Coordination (TDC) functions in support of effective whole-system operation.

Transmission–Distribution Coordination (TDC)	A formalised and increasingly automated approach for aligning system planning, operational and market interactions and related data exchanges across the System Operator (AEMO), Transmission Networks and emerging Distribution System Operators (DSO) to enable secure, scalable and cost-efficient operation of a decarbonising power system. TDC becomes necessary as power systems decarbonise, conventional sources of generation and flexibility are progressively withdrawn, and significant new volumes of supply, flexibility, buffering and system services must be sourced both upstream and downstream. Unlike conventional grids where services were largely provided by upstream merchant resources, the transforming landscape will require generation capacity and system services to be sourced from thousands of utility-scale and millions of distributed resources. In this increasingly dynamic environment, active operational interdependence between upstream and downstream entities, resources and systems becomes essential to efficiently source, coordinate and co-optimise these services with the spatial and temporal needs of the end-to-end system. Priority areas of TDC design are expected to include enhanced, low latency data transformations and exchange relevant to the joint management of frequency, voltage, congestion, energy flows, essential system services (ESS) and supply-demand balancing underpinned by end-to-end visibility and operational coordination models.

Ultra-large Scale (ULS)	Extremely large, inordinately complex Systems that consist of an unparalleled volume and diversity of hardware and software, data storage and exchange, computational elements and lines of code, participants and stakeholders, together with multiple complicated Structures that are 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. GW-scale Power Systems are prime examples of ULS systems, and arguably some of the world's largest and most complex.
Value Stacking	The process of providing valuable physics-based services to several vertical tiers/layers of the power system (e.g. bulk power system, transmission network, distribution network, etc) for the purpose of maximising the simultaneous value of providing these services in manner that does not create unintended negative impacts. Value Stacking is closely related to the topic of Co-optimisation.
Variable Renewable Energy (VRE)	A generic term for intermittent forms of generation powered by renewable resources that are inherently variable, such as wind and solar energy. While some forms of CER/DER are considered VRE, the term is mostly 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.

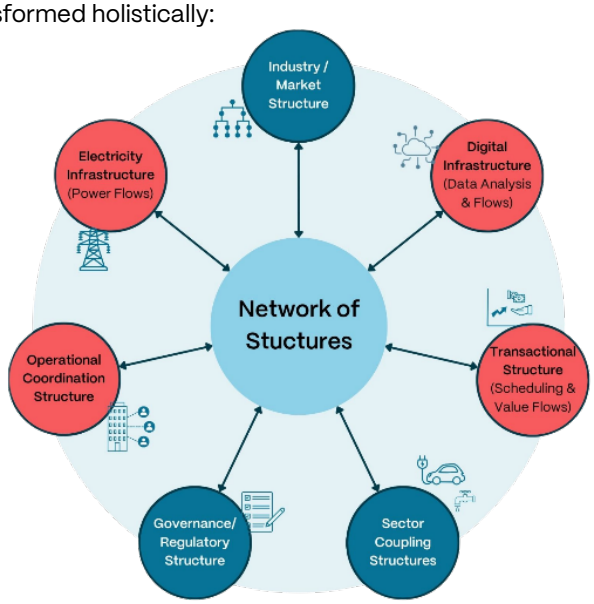
Visibility	The degree to which information on energy resource characteristics and operational status is available to the System Operator, Distribution System Operator (DSO), and other authorised third parties. Examples include real-time or near real-time information on electrical demand, generation output, state of charge for energy storage, availability of demand response, system voltages and system frequency, and power flows on major network elements. Statistical data filtering methods also allow establishing trustworthiness of the obtained data enabling the visibility, and reconcile them amongst each other, and with respect to network models, to identify bad and / or malicious data.
Volatility	Rapid, significant, and often unpredictable fluctuations in electrical parameters such as voltage, frequency, and power flows, typically caused by fast-changing conditions in generation or demand. In the context of power systems, volatility is differentiated from general variability or uncertainty by the speed and magnitude of the resulting changes and their impact on the stability and operational control of the grid. At a high level, system volatility affects: • Voltage stability: Sudden shifts in reactive power demand or generation can cause local voltage spikes or drops. • Frequency control: Large, fast imbalances between supply and demand challenge the system's ability to maintain frequency within acceptable limits. • Power flow dynamics: Bi-directional flows from distribution-connected resources can change direction unpredictably, stressing infrastructure and protection systems.
Whole-system	A systems-based approach to power system transformation that recognises the Laws of Physics interact with end-to-end system as one integrated whole, blind to historical structural separations.

Appendix C: Network of Structures

While it is customary to refer to the power system in the singular, a modern electricity system is in reality a 'super-system' of seven structures, four of which are functionally interdependent on a days-to-sub second timescale (coral-coloured nodes)

GW-scale power systems like the NEM consist of an intricate web of the following seven inter-dependent structures that must ultimately be transformed holistically:

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



The seven inter-dependent structures that make up the Network of Structures are now described in more detail below.

1. Electricity Infrastructure (Power Flows)

Infrastructures and subsystems that provide for the generation and physical movement of Electricity across the end-to-end Power System, including Generation Plant, Transmission Networks, Distribution Networks, Substations, Embedded Networks, Microgrids and diverse Energy Resources.

While historically designed for unidirectional operational, today Electricity Infrastructure increasingly experiences bi-directional Power Flows, especially in the Distribution Networks. A sample of conventional and emerging examples include:

- Power Flows from the Bulk Power System through the Transmission Networks to Bulk Supply Points (BSP).
- Power flows from BSP through Distribution Networks to Connection Points for each Customer.

- Storage of excess Renewable Energy output for subsequent injection to the Power System at periods of Peak Demand.
- Customer-owned Distributed Photovoltaics (DPV) and Battery Energy Storage Systems (BESS) that provide Power to their own Loads and/or exports to the local Distribution Network.

2. Digital Infrastructure (Information/Data Exchange, Storage, and Processing)

Infrastructures and subsystems that provide for all information and data exchange required to maintain the safe and reliable operation of the Power System and underpin its coordinated operation. A sample of conventional and emerging examples include:

- Signals and data used for real-time control of the Power System such as State Estimation, Frequency monitoring, Topology configuration monitoring, etc.
- Energy Resources participating in the Wholesale Market submit real-time asset performance reports to the Market/System Operator (MSO).
- MSO and Distribution System Operators (DSO) exchange system condition information across the relevant Transmission-Distribution Interface (TDI) to support the conjoint Power System management.
- Energy Retailers and Aggregators participating in the Wholesale Market and Distribution-level Markets submit telemetry to the relevant entities to indicate asset performance in real-time.

3. Transactional Structure

Infrastructures and Subsystems that provide for the valuation, procurement, sale and measurement of Energy, Capacity and Essential System Services (ESS) at any Tier/Layer of the Power System through market or other financial arrangements. This may include participation in Wholesale Market, Distribution-level Markets, advanced Tariffs/Rates. This also includes market schedules and Dispatch instructions.

A sample of conventional and emerging examples include:

- Energy Resources participating in the Wholesale Market provide bids/offers to the Market/System Operator (MSO) who subsequently schedules the Dispatch of participating resources.
- Relevant to the Operational Coordination of the Power System, both the legacy and emerging market structures are calibrated to ensure Co-optimisation of Energy Resource behaviours across the different Tiers/Layers of the system.

- Energy Retailers and Aggregators procure and contract services from Distributed Energy Resources (DER/CER) and other Flexible Resources (Demand-side) and sell them in various Wholesale Markets and/or Distribution-level Markets.
- Support more granular 'market-control' alignment to incentivise and activate targeted provision of valuable services in the form of Electric Products when and where most needed.

4. Operational Coordination Structure

Infrastructures and Subsystems that support the systematic operational alignment of both Utility and non-Utility assets as Power Systems move from hundreds to tens of millions of participating Energy Resources. In an operational context characterised by greater Volatility, advanced Operational Coordination is essential for safe, secure and efficient Power System operation in a manner that has a high level of Resilience, Scalability and Extensibility.

A sample of conventional and emerging examples include:

- Market/System Operator (MSO) exerts control over Energy Resources participating in the Wholesale Market by sending Dispatch instructions and basepoints to secure necessary services.
- MSO exerts control over the Transmission Network in response to a constraint or contingency to preserve System Security and Reliability.
- Aggregators provide the MSO and Distribution System Operator (DSO) resource availability forecasts for Energy Resources.
- The MSO and DSO conjointly manage their respective sides of the Transmission-Distribution Interfaces (TDI) due to the growing dependence on Energy Resources located on both sides of the TDI.
- Aggregators orchestrate contracted CER/DER in response to the various market structures for procuring the Electric Products required by different Tiers/Layers of the system.

Advanced Operational Coordination models are ultimately required to enable the transition to a more holistic Transmission-Distribution-Customer (TDC) model of system coordination.

5. Industry / Market Structure

The range of Entities involved in operating an end-to-end Power System, across its vertical Tiers/Layers and various markets, and within the boundaries of their formal Roles and Responsibilities, as set out in the legal and regulatory arrangements of a specific jurisdiction. Some examples of these Entities include:

- Market/System Operator (MSO);

- Generators;
- Transmission Network providers;
- Distribution Network providers;
- Distribution System Operators (DSO);
- Energy Retailers; and,
- Aggregators.

6. Governance / Regulatory Structure

The range of Entities involved in the governance and regulation of an end-to-end Power System and its related markets, as set out in the legal arrangements of a specific jurisdiction. In Power Systems Architecture, this structure focuses on the mapping of various governance and regulatory relationships, with an emphasis on which Entity regulates which types of organisations as represented in the Industry / Market Structure. These may include:

- Federal governments and agencies;
- Federal regulatory bodies;
- State governments and agencies;
- State regulatory bodies; and,
- Trans-national bodies.

7. Sector Coupling Structures

As decarbonisation advances, the proactive management of Interfaces between the Power System and other sectors becomes an increasingly critical part of enabling a more flexible and adaptive Grid. 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; and,
- Electricity and the emerging Green Hydrogen sector.

Appendix D: Power Systems Architecture vs Enterprise IT Architecture – Important Distinctions

When considering technological systems, the term 'architecture' can be used in several different ways. This can reduce the accuracy of communication between stakeholders, particularly in sectors that less mature in the adoption of Systems Engineering practices. In the global power sector, this has sometimes resulted in an unhelpful confusion of terms, lower quality decisions and unnecessary impediments to timely decision making.

A common mistake is that a focus on 'digital architecture' is the primary or singular focus of architectural disciplines when applied to Power System transformation. While digital architecture is indeed vital, it is one of seven overlaid structures that constitute the Architecture of a modern Power System. This is critical to the holistic consideration of transformation options as all seven structures have a significant influence on each other, four of which are dynamically inter-dependent on a hours-to-milliseconds basis (i.e. electricity infrastructure, operational coordination structure and transactional structure).

A closely related error is an assumption that the more generally known concept of Enterprise IT Architecture is broadly the same as Power System Architecture. As such, the following table originally developed by Eamonn McCormick and Stuart McCafferty provides a practical illustration of both the similarities and key differences that must be appreciated to enhance clarity of communication and quality of decision making in an inherently complex area.

Area of Comparison	Power Systems Architecture	Enterprise IT Architecture
Target System	GW-scale Power Systems	Enterprise IT systems
Technological Focus	Cyber-physical and transactional systems	Digital systems
Focus/Scope	Employs the Network of Structures model to interrogate the seven structures spanning an end-to-end Power System and across its vertical Tiers/Layers. This enables holistic, structured consideration of current, transitionary and future states and the targeted structural interventions required to move from one to the other.	Focuses on Digital Infrastructure at enterprise level. For enterprises operating within the power sector, this will likely include consideration of interfaces between the Enterprise IT Architecture and the wider Power Systems Architecture.

Complexity & Risk	Industry Level: Ultra-Large-Scale (ULS) Complexity. Helps manage risk within and across the end-to-end Power System.	Enterprise Level: Large Scale Complexity. Helps manage risk within the enterprise.
Stakeholders	Diverse stakeholders including policy makers, regulators, industry, customer groups, environmental groups, etc.	Internal enterprise stakeholders, and generally reporting to CIO. Primarily reflects focus on corporate IT systems.
Motivation	Power Systems Architecture is focused on clearly identifying specific Power System challenges and opportunities that require structural interventions to resolve. Defines essential industry limits/constraints.	Focused on the various challenges and opportunities that an enterprise must address internally.
Requirements	Defines qualities and properties of the future end-to-end 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	Employs the Network of Structures model to interrogate and map the 'as built' Power System structures and the relationships across: • Electricity Infrastructure (Power Flows); • Digital Infrastructure (Information/Data Exchange, Storage & Processing); • Operational Coordination Structure; • Transactional Structure; • Industry / Market Structure; • Governance / Regulatory Structure; and,	Defines the current state of the enterprise: • Strategic enterprise objectives mapped to capabilities; • Enterprise principles; • Business Architecture; • Information System Architecture; and, • Technology Architecture.

	• Sector Coupling Structures (Gas, Water, Transport, etc).	
Target Future State	Supports the collaborative development of a future vision for the Power System and employs the Network of Structures model to interrogate and map the most credible enabling structural interventions to achieve the vision across: • Electricity Infrastructure (Power Flows); • Digital Infrastructure (Information/Data Exchange, Storage & Processing); • Operational Coordination Structure; • Transactional Structure; • Industry / Market Structure; • Governance / 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; and, • Technology Architecture.
Transition Planning	Provides a framework underpinning the progressive transition of a GW-scale Power System from its historical current state to the desired future state.	Develop enterprise roadmap to move from current state to target future state.