AUSTRALIAN RESEARCH IN POWER
SYSTEMS TRANSITION (STAGE 4)

Energy Catalyst

REPORT 2 OF 5

Emerging Trends Driving Grid Transformation

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Energy Catalyst

Navigating to 2035 en route to 2050

This report presents an expansive survey almost 100 trends that are driving change in Australia's power systems and around the world. It highlights that grid transformation is driven by the convergence of multiple technological, societal, institutional, and geopolitical shifts, many of which are outside the direct control or influence of the sector's regulatory and governance mechanisms. The content directly underpins the identification of a finite set of Systemic Issues in Report 3 that provide strategic points of leverage for enabling timely, efficient and scalable grid transformation.

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Executive Summary

It is not an overstatement to recognise that our GW-scale power systems are experiencing the largest scale of change to impact their structure and operation in a century. The resulting transformation from unidirectional bulk delivery systems to deeply decarbonised and increasingly bidirectional systems may be correctly categorised as a structural '*megashift*'.

This report provides a wide-ranging scan of the Emerging Trends that are reshaping Australia's power systems with a focus on the National Electricity Market (NEM). It identifies almost one hundred drivers of change, which are clustered under twelve categories relevant to power system transformation. In doing so, it highlights that this profound transformation is the result of multiple technological, societal, institutional and geopolitical forces converging.

Indeed, it is the sheer scale of change drivers and their convergence that is deepening the dynamic complexity of navigating grid transformation and necessitates a transition from conventional 'issue-in-isolation' problem solving to more systemic models of change.

This report provides an evidence base from which a set of fifteen cross-cutting Systemic Issues are derived in Report 3 [143], informed by the Future Customer & Societal Objectives for the grid identified in Report 1 [142]. Together, Reports 1 – 3 provide the foundational base for the detailed study of Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models.

Chapter 1 and Chapter 2 introduce the purpose, context and development approach for the report. Chapter 3 then outlines the twelve categories under which all of the Emerging Trends have been clustered, namely:

1. Societal expectations.
2. System structure.
3. Generation diversification.
4. Load and demand.
5. Storage and buffering.
6. Control dynamics
7. Data and digitalisation.
8. Long-term system planning.
9. Near-term system operations.
10. Market structures and operations.
11. Sector coupling and electrification.
12. Emerging technologies

Chapter 4 then provides a detailed mapping of the almost one hundred individual trends identified, clustered under their respective categories. Importantly, the mapping of so many trends is of little practical benefit without the ability to derive a concise set of cross-cutting issues that may then be addressed. Chapter 5 concludes the report by outlining how this content informed the distillation of fifteen Systemic Issues in Report 3 which directly informed the detailed consideration of DSO and TDC models in Report 4 [144] and Report 5 [145] respectively.

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List of Acronyms

A-TNSP	Advanced Transmission Network Service Provider
AR-PST	Australian Research in Power System Transition
ADMS	Advanced Distribution Management System
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
ARPANS	Australian Radiation Protection and Nuclear Safety (Act)
AWS	Amazon Web Services
BESS	Battery Energy Storage Systems
BTM	Behind the Meter
CER	Consumer Energy Resources
COP	Conference of the Parties
CSIP	Common Smart Inverter Profile
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DER	Distributed Energy Resources
DERMS	Distributed Energy Resources Management System
DLP	Distributed Ledger Technology
DMO	Distribution Market Operator
DNSP	Distribution Network Service Provider
DOE	Dynamic Operating Envelopes
DPV	Distributed Photovoltaics
DSO	Distribution System Operator
DSSE	Distribution System State Estimation
EC	Energy Catalyst
EGS	Enhanced Geothermal Systems
EPBC	Environment Protection and Biodiversity Conservation (Act)
ESS	Essential System Services
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FCAS	Frequency Control Ancillary Services
FFR	Fast Frequency Response
FTM	Front the Meter
GFLI	Grid-following Inverter Technology
GFMI	Grid – Forming Inverters
HEMS	Home Energy Management Systems
HV	High Voltage

IBR	Inverter-Based Resources
ICL	Imperial College London
ICT	Information and Communication Technologies
IDP	Integrated Distribution Planning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRP	Integrated Resource Provider
ISO	International Organization for Standardization
ISP	Integrated System Plan
IoT	Internet of Things
LCOE	Levelised Cost of Energy
LPWAN	Low-Power Wide Area Networks
LV	Low Voltage
MSO	Market/System Operator
MV	Medium Voltage
NEM	National Electricity Market
NESO	National Energy System Operator
OEM	Original Equipment Manufacturer
OP	Operational Technology
PHES	Pumped Hydro Energy Storage
P2P	Peer to Peer
PFR	Primary Frequency Response
PSA	Power Systems Architecture
PV	Photovoltaic
REZ	Renewable Energy Zones
RoCoF	Rate of Change of Frequency
R&P	Roles and Responsibilities
SCADA	Supervisory Control and Data Acquisition
SMR	Small Modular Reactor
SO	System Operator
SPS	Stand-alone Power Systems
TDC	Transmission – Distribution Coordination
TDI	Transmission – Distribution Interface
TNSP	Transmission Network Service Provider
TOTEX	Total System Expenditure
UoM	University of Melbourne
US DOE	United States Department of Energy

V2B	Vehicle to Building
VPP	Virtual Power Plant
VRE	Variable Renewable Energy

1 Report Purpose, Context & Rationale

1.1 Purpose

Electric power systems such as Australia's National Electricity Market (NEM) 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.

As a result, the legacy GW-scale power systems established in the last century must now be progressively transformed to meet the needs of the rest of the 21st century. Due to their continental scale, multi-disciplinary and multi-stakeholder nature, mapping the major drivers of change impacting the end-to-end system is a critical first step toward prioritising integrated and efficiently targeted change initiatives. It is a first critical step toward answering the question:

> *How might we holistically comprehend the evolving context to design targeted change initiatives that deliver maximum whole-system benefit?*

Therefore, this report provides a survey of almost one hundred emerging trends that are driving change across the full length of the NEM – from the bulk power system to customer properties and including the tangible and intangible elements, processes and structural relationships that constitute the system. While diverse in nature, the trends provide windows on the emerging future.

Naturally, such an effort will never be exhaustive or exact and the numerous drivers of change have varying degrees of impact and in different timescales. Nevertheless, it provides a critical first step in providing the evidence base to shortlist a much smaller, more actionable list of cross-cutting Systemic Issues that provide high-value points of leverage for efficiently targeting change initiatives (refer Report 3).

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 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.

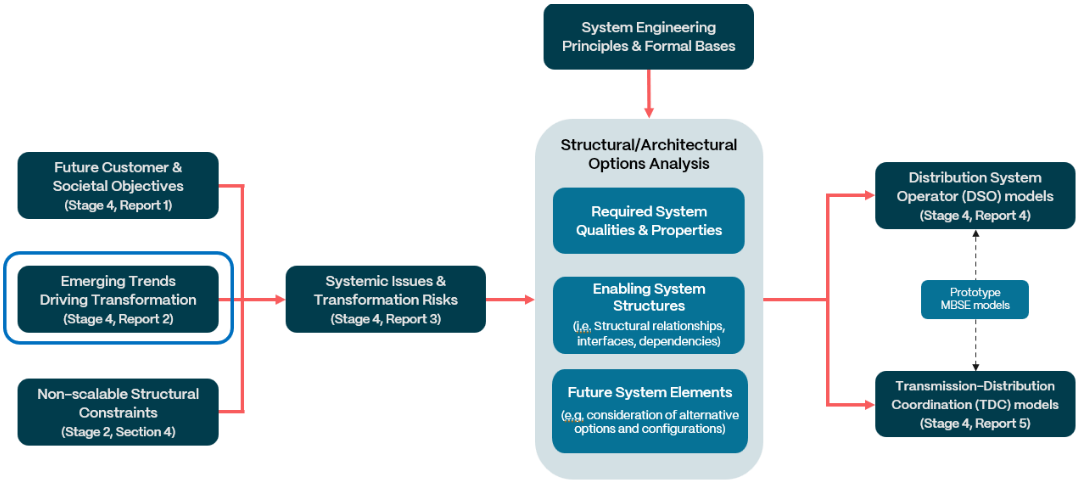

Figure 1: This report is part of an integrated set of five reports designed to support a systems-based approach to Australia's grid transformation.

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)

Informed by Design Thinking, the first of the five reports explored customer and societal objectives for our future power systems. This directly informed the development of the entire reference set and encouraged an overarching perspective that placed human and societal interests at the centre of the development process. While more can always be done, and it must, this constructively challenged the application of technical, structural and other analyses employed to constantly recalibrate against supporting the achievement of diverse human and societal interests.

Together the five reports are designed as an integrated set of reference content for navigating to Australia's future grid over the next decade and beyond.

1.3 Practical Rationale

Following the Hilmer reforms and establishment of the National Electricity Market in the late 1990's, much of Australia's power sector has operated within structurally separated functional siloes across bulk generation, transmission, distribution, energy retail, etc. As a bulk delivery system operating in a period of comparatively slow change, these structural arrangements designed for a unidirectional grid functioned effectively.

Over the last decade, the NEM has experienced waves of change with the deployment utility-scale and distributed renewable energy. Not only has the end-to-end system become more volatile, it has also become increasingly bidirectional – trends that are only projected to continue. This presents an entirely new set of physics-based challenges that have whole-system implications which cannot be addressed primarily within existing functional siloes.

To illustrate, the critical function of supply-demand balancing has historically been managed by the bulk power system, largely through the dispatch of large merchant generation. By contrast, as the proportion of dispatchable synchronous generation declines, balancing an increasingly bidirectional grid will require an unprecedented scale of dynamic interdependence between upstream and downstream energy resources and flexible loads. This is one of many issues that is being driven by changes that impact the full length of a system like the NEM which require a whole-system approach to address as illustrated by Table 1 below.

In other words, global power systems are at one and the same time being impacted by a transformation that is multi-dimensional, multi-disciplinary and multi-timescale. In an end-to-end system that is becoming significantly more interdependent, changes impacting one segment increasingly propagate up and downstream in both predictable and unpredictable ways.

Therefore, this report provides a survey of almost one hundred emerging trends that are driving change across the full length of the NEM. This provides a foundational step for analysing the problem/opportunity space and identifying plausible transformation options.

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 & Limitations

As illustrated in Table 1 above, a holistic analysis of the Emerging Trends driving transformation provides a key input to the integrative transformation approach enabled by the Systems Architecture disciplines. Key aspects of the report development are 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 a related set of 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.

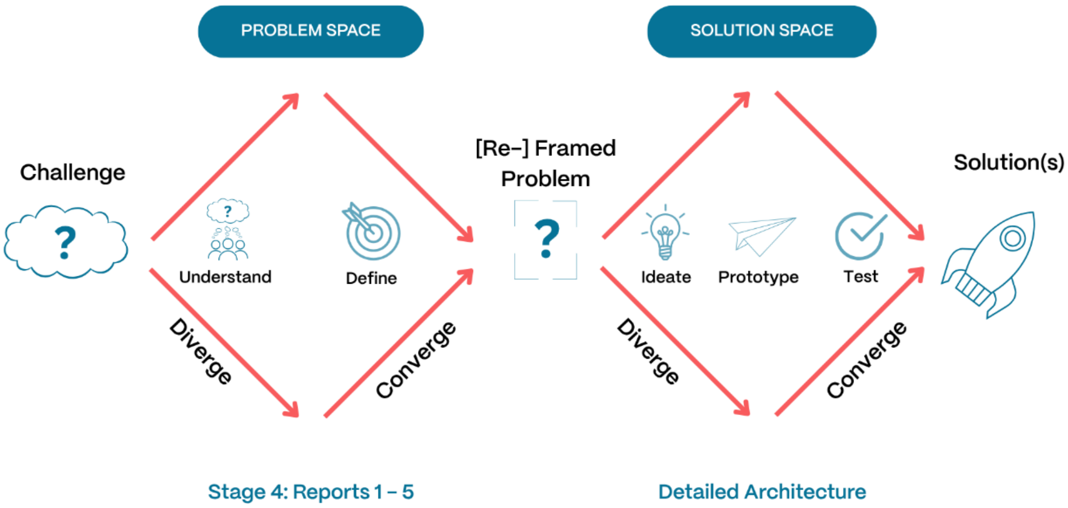

Figure 2: The reference set of five reports applies a Design Thinking approach to whole-system transformation underpinned by Systems Engineering and related disciplines

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.

2.2 Working Definition

In developing the report, the following definition of an Emerging Trend was distilled:

> *A driver of change that may significantly influence the transformation of Australia's GW-scale power systems over the next decade and beyond.*
>
> *Such drivers of change present new opportunities and potentialities and/or challenges and impediments that are either probable or plausible (not simply possible). They directly impact one or several functional segments of the power system and may also directly or indirectly drive or amplify whole-system issues or opportunities.*
>
> *While these drivers of change may be endogenous to the power system, they are more typically exogenous, including the impacts of evolving customer and societal expectations of the future power system.*

2.3 Development Methodology

The development process of this report included several iterative loops which ultimately identified almost one hundred clustered under twelve different categories. Guided by the principles and methodologies outlined in Appendix A: Principles, Methodologies & Acknowledgements

, and informed by a similar document developed previously for the United States Department of Energy (US DoE) [92], the major process steps included:

- A critical review of the US DoE document to evaluate the relevance of the structure, approach and content to the Australian context.
- A rigorous cross-sectional literature review of almost 150 reports and papers relevant to the topic a diverse range of Australian and global sources.
- The progressive review and update of the structure and content informed by the iterative loops of development.

Each Emerging Trend is clustered under one of twelve different categories, its observable characteristics described, and its plausible systemic implications summarised.

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: Principles, Methodologies & Acknowledgements
- .

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: Glossary of Terms

- 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.

3 Report Structure

This report examines almost one hundred Emerging Trends which are impacting power systems today and are expected to drive change over the next decade and beyond.

Consistent with the integrative and whole-system approach to grid transformation enabled by the application of Systems Architecture disciplines, the diverse range of Emerging Trends are under the following twelve categories, each forming a subsection in Section 4, "Emerging Trends Driving Grid Transformation". Each subsection contains anywhere from half a dozen to a couple dozen trends, with individual trends being articulated with a static description and an overview of associated implications.

Emerging Trend Categories & Definitions	
Category	**Definition**
1. Societal Expectations	Exogenous and evolving expectations with respect to energy affordability, reliability, decarbonisation, accessibility and equity. These drivers of change can be observed in policy formulations, customer advocacy, consumer technology trends and adoption and news media.
2. System Structure	Trends that are challenging the efficacy of legacy structural arrangements of the power system. Broadly, these trends reflect the erosion of the historically dominant supply-side / demand-side bifurcation of the system as it transitions from a unidirectional past to a bidirectional future.
3. Generation Diversification	Trends relevant to shifts in the types, location, number and economics of the generation mix. Primarily, these trends are arising from decarbonisation goals, ageing coal fleets, the deployment of utility-scale VRE and mass customer adoption of CER/DER.
4. Load & Demand	Changes in electricity consumption patterns driven by the electrification of transport and industrial processes, distributed generation, and increasing demand volatility. These trends challenge traditional approaches to forecasting, system flexibility, and the role of demand-side participation in grid stability.
5. Storage & Buffering	Trends that relate to the increasing uptake and capabilities of Front-of-the-Meter (FTM) and Behind-the-Meter (BTM) energy storage systems including EVs. These developments provide potential avenues to provide a buffer to support supply-demand balancing where the system is experiencing greater volatility with the deployment of VRE and CER/DER at scale.

6. Control Dynamics	Developments that are increasing the complexity of maintaining real-time power system stability as traditional synchronous generation is displaced by inverter-based resources. This includes new control and coordination considerations and approaches for faster system dynamics, declining inertia, and the proliferation of distributed assets.
7. Data & Digitalisation	Trends relevant to the rapid expansion of data from power electronics, sensors, smart meters, DERMS, utility servers, OEM cloud platforms, HEMs and other digital services and devices. These include related cybersecurity risks, latency challenges, and scalability issues that are reshaping how power systems are monitored and managed.
8. Long-term System Planning	Trends in the practice of long-term system planning that reflect the need for bottom-up and top-down whole-system planning approaches. This includes enhancing current approaches, such as the ISP, alongside more rigorous demand-side modelling and analysis together with the expanded application of strategic foresighting.
9. Near-term System Operations	Challenges arising from the increasing complexity of real-time operational coordination. These include the need for enhanced visibility and predictability across the Transmission-Distribution Interface (TDI), new mechanisms for operational forecasting, and advanced control room capabilities to navigate growing uncertainty and volatility.
10. Markets Structures & Operations	Trends in existing and new market structures and operations arising from the increasing share of low marginal cost resources and the transition to a bidirectional system hosting large volumes of distribution-connected energy resources. This includes market-based mechanisms for flexibility services and valuation mechanisms for Essential System Services.
11. Sector Coupling / Electrification	Trends in sector coupling and electrification driven by interdependencies between electricity and other sectors, such as transport, industry, gas, and water. These trends highlight new optimisation opportunities and systemic risks that require careful management.
12. Emerging Technologies	Transferable emerging technology trends that may potentially drive transformative impacts on power system operations, security, and optimisation. These include AI, power electronics, IoT, 5G, and distributed ledger technologies.

4 Emerging Trends Driving Grid Transformation

4.1 Societal Expectations

Exogenous and evolving expectations with respect to energy affordability, reliability, decarbonisation, accessibility and equity. These drivers of change can be observed in policy formulations, customer advocacy, consumer technology trends and adoption and news media.

Emerging Trend	Implication/s
4.1.1 Energy affordability has become a critical societal issue due to economy-wide inflationary pressures, cost-of-living impacts and industry policy implications.	
While the real cost of electricity gradually declined over several decades to the early 2000's, subsequent years have seen significant upward price pressure which, most recently, has intersected with global cost-of-living increases. Wholesale electricity and gas prices continue to place upward pressure on retail prices, reflecting the combined impacts of many factors, including: • Withdrawal of conventional thermal generation • Unplanned outages with the remaining thermal generation fleet • Geopolitical instability impacting gas prices • Extreme weather events which have affected coal supplies and electricity demand • Increasingly high-demand variability driving up the cost of hedging for retailers	The real and perceived affordability of electricity has become regular news headlines in Australia, particularly in the wider global context of cost-of-living increases. Multiple factors are expected to place continued upward pressure on power system costs. These include: • Rising inflation • Increases in the cost of capital • Global supply chain disruptions • Labour shortages • The scale and pace of the power system expansion requirements Upward electricity price pressures are commonly politicised in a context where cause and effect relationships are poorly understood by the public. Depending on the position being advanced, this dynamic is commonly employed to argue variously for different technology solutions (e.g. more or less renewables, nuclear generation, etc). A core implication is the potential for confusion, growing public distrust in the sector and the erosion of social licence.

4.1.2 System reliability continues to be a key societal expectation which, although muted under normal operational conditions, is rapidly politicised in the event of system failures.	
System reliability is a core expectation of energy consumers, businesses, and policymakers. Under normal operating conditions, reliable power supply is typically taken for granted, with minimal public discourse or scrutiny. By contrast, when reliability is compromised due to technical failures, extreme weather events, etc, public attention intensifies rapidly.	While Australia's power systems have typically operated with comparatively high levels of reliability, in the event of major outages, governments and regulators often face significant pressure to respond with new interventions, increased oversight, and direct financial or other penalties. Similar to the public discourse about affordability, system failures generally trigger mainstream politicisation of liability placement and polarisation of solution options and responsibility. Once again, a core implication is the potential for confusion, growing public distrust and the erosion of social license.
4.1.3 Energy system decarbonisation continues to be advanced at pace, with a wider range of technologies and approaches entering the public debate.	
Energy system decarbonisation is progressing as government, industry and investors prioritise the reduction of carbon intensity in generation and consumption. Early decarbonisation efforts in Australia focused largely on utility-scale wind and solar generation and the adoption of rooftop solar by consumers. More recently, with the combination of both technological advances and increased politicisation of energy, the range of solutions being debated is expanding. Some examples include: • Pumped hydro • Long-duration energy storage • Green hydrogen • Carbon capture and storage • Advanced nuclear reactors	Power system transformation is a complex undertaking, and all credible technologies and other solutions need to be evaluated in an objective, evidence-based and whole-system manner. Arguably, a critical weakness in much of the Australia's public debate is the widespread propensity, both within and outside the electricity sector, to fixate on individual technological solutions as 'the answer'. By contrast, the electricity system is 'a system'. The recurring tendency to focus on parts rather than the whole has now resulted in more than a decade of distracted and often incoherent public debate.

4.1.4	Many energy consumers continue to invest in solutions that increase their agency, autonomy and ability to participate in new market structures to access additional value.
A growing number of energy consumers are transitioning from passive recipients of electricity to active participants in the energy system. This shift is enabled by falling costs of distributed energy resources (DER) and more sophisticated energy management technologies. Consumers are not only optimising their energy use and reducing costs, but they are also making attempts to assert greater agency in how their energy is generated, stored, shared, and valued. This behavioural shift reflects a broader societal expectation that customers should be able to derive meaningful benefits from participating in the energy transition. For many, investment in rooftop solar, batteries, electric vehicles, and home energy management systems represents a pathway to greater autonomy, resilience, and financial empowerment. These behaviours can stem from two broad attitude shifts in consumers, one being more awareness of their role in supporting decarbonisation, and the other being decreasing confidence in the power system's willingness and competence to serve customers. Consumers who invest in their own energy assets are investing in energy independence that has the added benefit of saving them money in the long run.	One significant operational implication for the power system is the growing complexity of operational coordination as millions of consumer-owned assets interact dynamically with the system. Traditional centralised control hierarchies are being supplemented – or in many cases disrupted – by decentralised energy flows, necessitating new regulatory frameworks and coordination mechanisms. Another key operational implication is the potential redistribution of economic value within the energy sector. As consumers generate and store their own energy, current regulated funding models for utilities may not be fit for purpose, and retailers may need to adapt their business models to remain competitive. A more fundamental implication of this change is: are consumers investing in their own energy resources because they are quietly deciding that– as individual households – they can service their own long-term energy needs better than the alternative of being passive consumers serviced by the grid. A separate but adjacent implication of this trend is equity considerations for those not in a position to invest in their own agency and autonomy, see 4.1.5 below.

4.1.5 There is growing advocacy for expanding options that allow energy consumers — particularly those unable to invest in new energy solutions — to equitably access additional value.	
The power system is moving toward greater consumer participation, and a growing concern is ensuring equitable access to the benefits of emerging energy solutions. While many consumers can invest in technologies like rooftop solar, home batteries, and electric vehicles (EVs), a significant portion of the population – particularly renters, low-income households, and those in multi-resident buildings – lack the financial means or property rights to do so. These consumers (or advocates speaking for them) increasingly expect alternative pathways to access the economic and reliability benefits of the evolving energy system without direct ownership of assets.	As expectations for equity in energy access continue to grow, market structures and policy frameworks will need to adapt to ensure the benefits of the energy transition are distributed across all consumer segments. One major implication is the increasing pressure for policy interventions that balance incentives for private investment in DER with mechanisms that ensure non-participating consumers are not disproportionately burdened. Without structured policies, cost shifts may emerge where wealthier consumers who invest in private energy solutions reduce their reliance on the grid, leaving lower-income consumers to bear a greater share of network costs. Another implication is the potential evolution of energy retailing and new business models focused on inclusivity. As younger generations. Retailers may increasingly adopt subscription-based or shared energy models that decouple energy benefits from asset ownership. A manifestation of this is Germany's Bürgerwerke energy cooperative, which demonstrates how collective ownership structures can provide broader access to renewable energy benefits [141]. Community battery initiatives, such as Western Power's community battery program in Australia [139], enables consumers without home storage to access shared battery services, reducing peak demand charges and increasing solar energy utilisation. Similarly, in the United States, Arcadia Power offers virtual solar subscriptions that allow consumers to receive credits from remote solar farms [140], making renewable energy access more inclusive.

4.2 System Structure

Trends that are challenging the efficacy of legacy structural arrangements of the power system. Broadly, these trends reflect the erosion of the historically dominant supply-side / demand-side bifurcation of the system as it transitions from a unidirectional past to a bidirectional future.

Emerging Trend	Implication/s
4.2.1 Power systems are transitioning from hundreds of large, transmission-connected resources to millions of diverse, participating resources located on both sides of the Transmission-Distribution Interface (TDI).	
Australia's power systems are being reshaped by the combined impact of the '4Ds': decarbonisation, digitalisation, democratisation and decentralisation. This involves a complex range of societal, technological, economic and commercial forces, many of which are outside the direct influence of traditional power sector regulatory and planning mechanisms. At a macro level, it involves the transition from hundreds of large, dispatchable, merchant generators to a vastly more heterogenous range of participating resources. As noted above, this involves a massive uplift in the volume of utility-scale VRE and rooftop DPV that the system will depend on. Similarly, it involves a dramatic expansion in dependence on a wide range of technologies including Battery Energy Storage Systems (BESS) and Distributed Energy Resources (DER). In summary, Australia's power systems are transitioning from hundreds of large, transmission-connected generation resources to tens of millions of highly diverse and heterogenous resources that are near ubiquitous across transmission and distribution systems.	The growth in system complexity arising from this vastly more diverse, dynamic, numerous and inter-dependent base of resources is without parallel in Australia's power systems. Ensuring least-cost societal outcomes in a context where power systems are becoming more complex will require significantly enhanced Operational Coordination to unlock new system optimisation opportunities. For example, as coal-fired generation is withdrawn, a growing proportion of Essential System Services (ESS) and system flexibility will need to be sourced from diverse energy resources variously connected across Australia's HV, MV and LV systems. Given the temporal and spatial sensitivity of power system requirements, this will require computationally scalable approaches that incentivise and activate: • The right physics-based service (energy, power, essential system services) • At the right time (seasonal, days, hours, minutes, seconds, microseconds) • At the right network layer / location (bulk power, Tx system, Dx system, Dx feeder) Importantly, service provision must be co-optimised such that energy resources dispatched and/or financially incentivised at one layer of the system are not driving unintended and undesirable consequences at other layers of the power system.

4.2.2 Significant new capacity is required across generation, transmission and distribution systems. This includes the need for both physical and operational infrastructure upgrades to support growing electricity demand from electrification and to replace retiring conventional generation.	
Australia's COP26 commitments involve a significant dependence on large-scale electrification [131]. In particular, there is an expanding focus on the electrification of transport, industrial processes and building services to replace more carbon-intensive fuels such as natural gas and petroleum. AEMO's 2024 Integrated System Plan Step Change scenario [125] calls for investment that would triple grid-scale VRE by 2030, and increase it six-fold by 2050.	The unprecedented volume of new system capacity required within a finite timeframe presents major challenges and risks in terms of approvals, social license, funding and construction. As a national and multi-stakeholder undertaking, extensive stakeholder collaboration will be required to maximise alignment, mitigate duplication of effort and substantially expand the necessary social license required for timely progress. In addition, given the critical issue of energy affordability (refer 4.1.1 above), it will be essential that all materially significant existing and emerging system optimisation options are fully examined. The construction of new capacity should be contingent on all optimisation options having been exhausted. Given this system expansion will occur at a time of accelerated investment in other forms of national infrastructure, investment coordination to alleviate supply chain constraints, project cost escalation and schedule slippage will be critical.

4.2.3 The once dominant 'supply-side / demand-side' bifurcation is eroding as power systems move from a one-directional past to a bi-directional future.

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

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

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

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

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

Importantly, unlocking the efficiencies of 'demand-side' participation – estimated to be worth $20 – 30bn over the next two decades [128], will require the successful incentivisation and mass activation of the expanding fleet of privately owned resources.

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

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

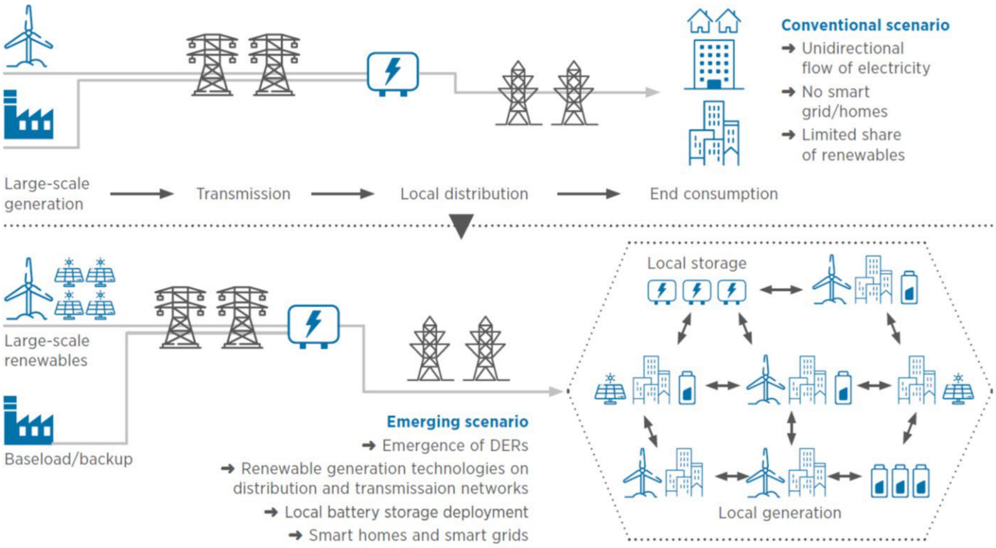

Figure 3: The NEM is transitioning from hundreds to tens of millions of participating energy resources, and the traditional 'supply-side/demand-side' bifurcation is eroding [54].

4.2.4 As power systems become increasingly bi-directional, a new level of focus on end-to-end interoperability, visibility and operational coordination is required as the system manifests increasingly 'tidal' behaviours over each 24-hour period.	
Rooftop solar, battery storage, electric vehicles (EVs), and demand-side participation now contribute actively to supply and demand fluctuations, creating more complex system behaviours and network interactions. This transition requires enhanced end-to-end interoperability, greater real-time visibility across the grid, and improved operational coordination between transmission and distribution networks. A key characteristic of this shift is the emergence of more 'tidal' system behaviours, where energy exports from consumer-owned DER surge during midday solar peaks, followed by steep demand ramps in the evening as solar generation declines. Managing these fluctuations requires advanced forecasting, dynamic grid management, and enhanced digital infrastructure.	One significant challenge is ensuring that network infrastructure and market mechanisms can efficiently accommodate these tidal energy patterns without causing grid instability or unnecessary curtailment of renewables. Another key implication is the need for greater coordination between transmission and distribution system operators, as energy transactions increasingly occur between consumer-level assets, network service providers, and wholesale markets via aggregators. The development of local flexibility markets reflects an emerging shift toward a more decentralised power system structure where consumers and DER owners can actively provide grid services.
4.2.5 Power systems are becoming more volatile as Variable Renewable Energy (VRE) is deployed at scale and conventional thermal generation is progressively withdrawn.	
Australia's GW-scale power systems have historically been heavily dependent on coal-fired generation which consisted largely of various forms of utility-scale, synchronous resources. System management focused on the security constrained economic dispatch of merchant resources to meet customer demand, which was comparatively predictable. This situation has changed starkly over the last decade with unprecedented levels of deployment of weather-dependent Variable Renewable Energy (VRE) and Distributed PV (DPV). This expanding fleet of resources: • Largely consists of various types of Invertor-based Resources (IBR)	With increased penetrations of VRE and DPV and the related increasing volatility at all levels of the system, the underlying nature of the power system is changing fundamentally. AEMO has noted that by 2025, the NEM is projected to have sufficient renewable resource potential to completely serve demand during key time windows. Looking further out, AEMO's Step Change scenario [125] anticipates that by 2050 the NEM will need to securely accommodate the following: • 6x Centralised VRE: Six-fold increase in installed capacity of utility-scale solar and wind generation (from 20GW combined to 58GW and 69GW respectively)

<table>
<tr>
<td>Includes many different types of generation, storage and flexibility resources
A significant proportion of these resources were not installed for the primary purpose of functioning as a merchant resource
In parallel, based on current projections, 60% of Australia's coal-fired generation capacity will have been withdrawn by 2030, with the entire coal-fired fleet withdrawn by 2043.

Simultaneously, significant demand volatility is also being introduced by the operational behaviour of DPV, creating additional challenges and opportunities for the instantaneous balancing of supply and demand.</td>
<td>4x Distributed PV: A four-fold increase in Australia's already world-leading levels of DPV generation
4x Dispatchable Firming Capacity: A four-fold increase in installed firming capacity that can respond to a dispatch signal
97% passenger vehicle electrification
In addition, the implementation of new resource types is driving significant increases in the speed at which grid events occur, both at transmission and distribution.

In this context, the System Operator and network service providers all face much greater levels of uncertainty, dynamics and complexity. This will require a significantly expanded range of capabilities in support of more advanced forecasting, planning, analytics, visibility, controllability, incentivisation, etc.</td>
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<tr>
<td colspan="2">4.2.6 System flexibility and balancing services will be required from an expanding range of alternative sources as the grid becomes more volatile and the proportion of dispatchable thermal generation declines.</td>
</tr>
<tr>
<td>As the generation fleet transitions, the proportion of system flexibility and firming services that can be provided by traditional supply-side resources is decreasing.

In addition, system balancing is considerably aggravated by stochastic generation sources such as VRE, the operation of which is ultimately inconsistent with the standard 'load-following' paradigm of power system control.

Beyond direct balancing issues, unmanaged oversupply of VRE output is also driving voltage regulation problems, transmission congestion issues, negative marginal prices and curtailment-related investment issues.</td>
<td>Power systems dominated by VRE and DPV generation will require new sources of system flexibility and firming on both supply and demand-sides of the system.

Supply-side sources of flexibility and firming services include:
Existing hydro generation, both storage and run-of-river types, which rely on natural inflows rather than pumping to operate.
New utility-scale Battery Energy Storage Systems (BESS) and Pumped Hydro Energy Storage (PHES) options across various capacities, typically spanning 6-48 hours of energy in storage.
Existing and new gas-fired generation will be crucial for complementing BESS and PHES</td>
</tr>
</table>

	capacity during periods of peak demand, particularly during long 'dark and still' weather periods. As the maturity of zero-emission gas turbines improves and input fuel costs fall, their participation in the NEM will also need to be supported with relevant policy levers.
4.2.7 Leveraging the full system value of demand-side resources is becoming a greater priority as conventional large-scale generation and transmission projects experience budget and schedule escalations.	
As the energy transition accelerates, many regions, including Australia, face significant delays in the expansion of supply-side transmission infrastructure and large-scale generation projects. The rising costs of materials, skilled-labour shortages, protracted permitting processes, land-use restrictions, and extensive community consultation requirements are pushing project timelines further out and increasing financial risks. These escalating constraints make it increasingly difficult to expand supply-side infrastructure at the pace required to meet rising electricity demand. As a result, demand-side solutions are being prioritised as a faster, lower-cost alternative to alleviate pressure on the grid without relying solely on costly new transmission and generation projects. Where well-coordinated, demand-side resources—such as distributed energy resources (DERs), demand response, and flexible loads can be cost-effective alternatives to mitigate supply-side constraints. These solutions enable consumers to participate actively in balancing demand and supply, helping reduce peak demand and shifting loads to times when renewable generation is more abundant. By reducing peak loads, demand-side flexibility can directly lessen the need for	A shift towards demand-side solutions provides several key benefits, including reduced pressure on constrained infrastructure and improving grid stability, flexibility, and cost efficiency. By enabling consumers to adjust their usage or leverage DERs, power system operators can reduce reliance on costly and time-intensive transmission projects, thereby moderating infrastructure costs and improving overall investment efficiency. This also helps optimise existing network capacity, allowing for better management of renewable intermittency and mitigating the risk of blackouts during high-demand periods. Demand-side solutions promote consumer empowerment, allowing households and businesses to play a direct role in reducing the need for additional supply-side investment. With adequate incentives and technology, consumers can benefit financially while supporting the grid. Such models, which treat demand-side flexibility as an integral part of system operations, could also reduce the need for future investments in supply-side infrastructure by managing demand more effectively at the local level. However, to enable increased demand-side solutions, several key capabilities are essential: advanced digitalisation, real-time data management, and responsive grid coordination. Incentivising demand-side

costly new network infrastructure or upgrades. For example, demand response programs incentivise consumers to adjust their electricity use during periods of high demand or low supply. DERs like rooftop solar, batteries, and electric vehicles (EVs) can store and dispatch energy, helping to buffer supply-demand imbalances without requiring additional transmission capacity.

participation at scale is also critical to ensuring that it can act as a viable alternative to expensive new infrastructure. Smart meters and IoT-enabled devices provide the granular, real-time data needed for effective demand forecasting and consumer engagement, allowing operators to monitor and respond to demand patterns dynamically.

DER management systems and AI-powered analytics further support demand-side flexibility by automating demand response and adjusting loads based on grid conditions. Additionally, stronger market frameworks and regulatory support are crucial to incentivise participation, ensuring that consumers and businesses are financially motivated to reduce or shift their energy usage. Finally, secure and interoperable communications infrastructure is needed to link DERs, EVs, and other flexible loads seamlessly with grid operations, ensuring a coordinated approach that enhances grid stability and optimises resource deployment.

4.2.8 Power systems with significant volumes of utility-scale VRE and distributed CER/DER may need to progressively transition from the conventional load-following paradigm to a more hybridised approach capable of accommodating supply-following attributes.

Traditionally, power systems have operated under a load-following paradigm, where centralised generation is dispatched to meet fluctuating electricity demand. However, as the share of variable renewable energy (VRE) such as wind and solar grows—alongside consumer energy resources (CER) and distributed energy resources (DER)—the conventional approach is becoming increasingly strained.

Unlike traditional dispatchable generation, VRE is weather-dependent, has very low marginal costs, and cannot be ramped up or down on demand, requiring power systems to integrate supply-following mechanisms that adjust consumption patterns and grid

One major challenge is ensuring that system flexibility resources, including storage, demand-side response, and flexible generation, are sufficiently developed and integrated to maintain system stability. Without these balancing mechanisms, power systems risk increased curtailment of renewable generation, price volatility, and grid congestion. Additionally, shifting to a supply-following model will require new market and tariff structures that incentivise real-time demand responsiveness. Time-of-use pricing, flexible demand contracts, and automated demand response technologies are emerging as key tools to facilitate this transition. As these market mechanisms evolve, the

operations in response to real-time generation availability. This shift is prompting exploration of new operational strategies, including demand flexibility, grid-responsive storage, and dynamic pricing mechanisms to better align energy consumption with renewable supply.	success of this transition will depend on effective coordination between system operators, regulators, and technology providers to ensure economic efficiency while maintaining system security and reliability.
4.2.9 Whole-system approaches to planning and operations are growing in focus as the entire fleet of participating resources is located on both sides of the TDI.	
The energy transition has pushed many countries, to adopt a "whole-system" approach to energy system design and operation. A major driver of this shift is the increasing need to coordinate planning and operations across both sides of the Transmission-Distribution Interface (TDI), where a growing fleet of participating resources—including utility-scale renewables, distributed energy resources (DERs), and demand-side flexibility—must be effectively integrated. Rather than managing transmission (Tx) and distribution (Dx) networks in isolation, a whole-system approach considers the entire network as an integrated system. This strategy optimises Tx-Dx interactions, improves cross-boundary coordination, and enables more efficient utilisation of both centralised and distributed assets. The UK's energy transformation reflects this trend through the creation of the National Energy System Operator (NESO) and the evolution of Distribution System Operators (DSOs) [97]. NESO is tasked with overseeing a holistic, cross-sector energy strategy that integrates electricity, gas, and emerging energy sources to ensure grid stability and efficiency under decarbonisation pressures. The expansion of DSOs highlights the increasing need for system operators to actively manage DERs and demand-side resources at the distribution level, supporting real-time coordination across the TDI.	Adopting a whole-system approach brings key benefits and efficiencies to energy systems, particularly as they transition toward decarbonisation. By enhancing Tx-Dx coordination through whole-system planning, the UK's NESO and maturing DSOs can more effectively balance supply and demand across the entire system [97], optimising all generation sources and leveraging flexible demand. This coordination also enables faster, more precise integration of utility-scale renewables and DERs, which are essential for decarbonisation targets. For instance, DSOs' coordination of DERs helps reduce congestion, avoids curtailment, and improves the operational visibility of resources on both sides of the TDI. Additionally, whole-system approaches facilitate better resource deployment, ensuring that investments in grid infrastructure are more efficient and adaptable to evolving TDI dynamics. NESO and DSOs working in tandem enable the UK to take a proactive stance in mitigating risks associated with renewable intermittency, ensuring a stable transition to a low-carbon grid. The increasing focus on TDI integration suggests that countries like Australia, aiming for ambitious decarbonisation targets, would benefit from similar whole-system frameworks. This strategy can improve system reliability, allow for more robust integration of renewables and storage, and

As the TDI becomes more active and bi-directional, whole-system coordination is becoming essential. DSOs, whose roles (DNSPs) were once limited to managing local distribution, now coordinate DERs and demand-side resources to support system-wide stability. This level of whole-system coordination is critical in optimising not only regional energy needs but also national objectives, as the grid becomes more complex with higher levels of renewable penetration and decentralised resources.	support consumer empowerment across all levels of the grid.
4.2.10 Expanding system dynamics and cyber-physical complexity are highlighting the need to ensure underpinning system structures/architectures are scalable and future-ready.	
Australia's rapid energy transition highlights the importance of considering legacy structural constraints that will result in non-scalable features that hinder long-term transformation. Structural limitations within the current grid—originally built around centralised generation—are proving inadequate for the demands of decentralised, renewable-heavy systems. The need to revisit the underlying architecture of the National Electricity Market (NEM) aligns with approaches in the UK and EU, where grid flexibility and interoperability are increasingly prioritised as a means of ensuring power system structures remain future-ready. In the UK, for instance, the National Grid's Whole System Strategy emphasises "whole-system" thinking and interoperability across distribution and transmission levels to support decarbonisation targets while ensuring the grid remains scalable as system complexity increases. Similarly, the EU's Clean Energy for All Europeans package promotes structural reforms to foster distributed energy resources and flexibility mechanisms.	Detailed consideration of legacy and future structural settings has been limited in recent decades. In a much more dynamic system, new approaches are now required to tame the inherent complexity involved in interrogating current and future architectures that will be fit-for-purpose. Tools such as Model-Based System Engineering, and the Power System Architecture methodology have shown promise in identifying the minimum set of constraints within which system designers can implement solutions that align with customer and policy-maker objectives.

4.2.11 Mass electrification, geopolitical instability and national security imperatives are heightening the need to mitigate single-point-of-failure risks through more resilient, modular grid structures.

Geopolitical tensions, exemplified by events such as the ongoing conflict in Ukraine, underscore the critical need for resilient and decentralised energy systems. Conventional, centralised infrastructures are vulnerable to targeted attacks, natural disasters, and large-scale disruptions. For instance, Ukraine's centralised power systems have faced severe challenges due to Russian bombardments.

Decentralisation, characterised by the deployment of microgrids and distributed energy resources (DERs), emerges as a robust solution to such vulnerabilities. Microgrids, which can operate independently of the centralised power system, have proven instrumental in maintaining energy access during outages. They provide localised generation and storage capabilities, reducing reliance on large, interconnected networks that are often single points of failure. Examples from Ukraine include community-focused microgrids that integrate renewable energy sources like solar and battery storage to ensure energy continuity even during widespread grid outages.

Moreover, decentralisation aligns with the broader transition to low-carbon energy systems. Distributed generation—supported by technologies such as rooftop solar, wind turbines, and local storage—enhances flexibility and adaptability. This approach not only builds resilience against external shocks but also accelerates decarbonisation efforts globally.

Decentralisation significantly enhance resilience by reducing the risks associated with disruptions like geopolitical conflicts, natural disasters, or attacks by non-state malicious actors. By distributing generation capacity across smaller, autonomous units, decentralised systems prevent widespread blackouts that can cripple entire regions. For countries such as Australia, this model offers a practical safeguard for critical infrastructure, mitigating vulnerabilities to both physical and cyber threats.

Energy security is also improved as decentralisation lessens reliance on imported energy and centralised power systems and enables greater independence from global supply chains and associated geopolitical dependencies.

Operational and cost advantages further underscore the appeal of decentralised grids. By reducing the need for long-distance transmission, these systems minimise energy losses and infrastructure maintenance costs. Local generation also alleviates stress on centralised networks, allowing for more efficient resource allocation and system reliability.

Updating regulatory frameworks to accommodate decentralised models will require significant effort, as will investment in smart grid technologies to manage the complexity of operationally coordinating distributed systems. Furthermore, decentralisation may increase the number of cyber-attack vectors, requiring more robust cybersecurity measures at lower-levels in the power system to protect these systems from potential threats.

4.2.12	Power system operations are being impacted by an increased frequency and intensity of extreme events including bushfires, high winds and flooding, driving the need for more resilient, modular grid structures.
Power system infrastructure has been challenged by a range of exogenous factors over the last decade, including an increased frequency and intensity of extreme events such as bushfires, high winds, and flooding. While this is confronting traditional methods for system planning, construction, operation, outage management and outage recovery, regulatory frameworks continue to focus primarily on reliability.	Legacy power systems were developed with a focus on a few key requirements, among them reliability, safety, and affordability. Current mechanisms do not provide the sector with adequate means to identify or plan investments, specify more modular and resilient system architectures, or create alternate designs that enhance power system behaviour in the face of infrequent but high impact events. The distinction between reliability and resilience is an important one. Reliability is focused on the average system performance and seeks to minimise outage duration and frequency during normal conditions. By contrast, the capacity of a power system to prepare for and recover from infrequent but extreme events is generally referred to as resilience. As such, existing definitions and methods make it very difficult to isolate root causes, identify investments and carry out planning clearly related to specific elements of the overall power system. New definitions are required to provide greater precision to guide cost-effective action. For example: • Reliability must change from a backwards-looking conflation of power system behaviour with externalities to a forward-looking approach as used in other sectors such as aerospace and electronics. • Similarly, resilience must change to be about the grid's ability to avoid, withstand or adapt to external stresses. An enhanced focus on system resilience will be key to expanding the range and cost-efficiency of resilience options considered.

	Supported by commensurate regulatory treatments, investment mechanisms and planning tools, this will enable options ranging from traditional grid hardening to more advanced adaptive and modular approaches to system resilience.
4.2.13 While the future need for scalable CER/DER aggregation and Virtual Power Plant (VPP) business models is widely referenced, their commercial viability has proven challenging in some jurisdictions.	
Virtual Power Plants (VPPs), which aggregate and coordinate DERs, have faced significant challenges in developing viable business models in many jurisdictions. The original promise of VPPs rested on the ability to optimise DERs for grid services, such as balancing supply and demand or providing frequency regulation, while generating revenue through market participation. However, the economic realities of these models have often fallen short of expectations. Key barriers include the high costs associated with customer acquisition, DER installation, and ongoing engagement. Many VPP operators also struggle with revenue recognition issues tied to performance-based contracts, which demand precise coordination of DERs to meet stringent market requirements. Additionally, the thin profit margins typical in the energy sector amplify financial risks, especially when aggregated intermittent resources underperform. Some firms have pivoted away from the traditional VPP model, focusing instead on niche services such as software for DER management or hardware sales, as seen with companies like Tesla and SunRun. Others have exited the market entirely, unable to sustain operations under the financial constraints [129]. This trend underscores the difficulty of scaling VPPs in regions where market	The challenges faced by VPPs in certain jurisdictions have significant implications for the energy transition and market evolution. First, the retreat of VPP operators may slow the adoption of DER and consequently, their contribution to system flexibility and resilience. The pivot of many VPP businesses towards software-as-a-service (SaaS) models or hardware sales indicates a shift away from integrated product offerings, potentially fragmenting the DER ecosystem. This may result in consumer confusion, inefficiencies and suboptimal DER utilisation. Regulatory and market reforms may be necessary to make VPPs economically viable. This could involve introducing performance incentives that lower financial risks for operators or designing tariffs that reflect the true value of services provided by DERs. Without such changes, incumbent retailers or large corporations may dominate the space, potentially stifling innovation and limiting consumer participation in energy markets.

structures or regulatory frameworks do not adequately support them.	
4.2.14 The number and scale of new third-party actors exerting significant influence on the power system without full visibility of, or responsibility for, the resulting systemic implications of their actions is expanding.	
A growing number of large, multi-national 'new energy' actors in various nations are managing many GWs of DER and EV load. These aggregators and super-aggregators manage their DER and EV fleets in response to various market signals and other commercial drivers. Given the growing scale of these actors, the risk of significant system impacts arising due to a failure to fully appreciate the systemic implications is significantly expanding.	To the extent that such entities influence or participate in real time power system operation, formal Roles & Responsibilities must be defined, and coordination mechanisms created that function within a comprehensive and scalable structure. Planning processes must be able to obtain appropriate information regarding the non-utility entities and their intended operations. Appropriately secure communications systems, methods, and standards must match both utility needs and third-party roles and capabilities. For shorter-term purposes, this presents operational challenges as multiple entities with different and potentially conflicting objectives make decisions independent of one another, without a common or complete view of the operational environment of the resources under control. Addressing this dilemma requires that resource controllers are provided the necessary data to make complimentary decisions. Over longer time horizons, the System Operator, network service providers, policy makers and regulators will require an ever-expanding range of data for their planning, investment and strategic functions.

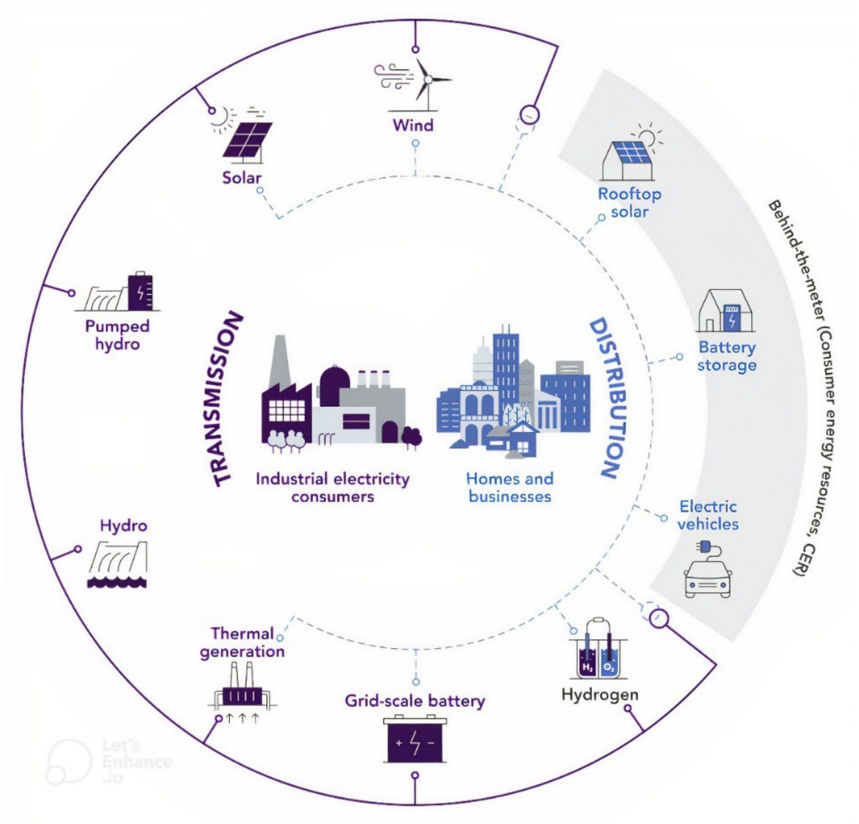


Figure 4: The impact of interactions between the power system and individual and aggregated customer resources is increasing [136].

4.2.15 Expanding grid dynamics and the range of third-party actors are driving the reconsideration of formal power system functions, roles and responsibilities.

With increased penetrations of VRE, IBR and DERs, the underlying nature of the power system is changing fundamentally.

To maintain the stability and functionality of the power system, the key system actors are having to adapt in ways that are not comprehensively provided for in the traditional governance arrangements.

Where power systems are experiencing fundamental change and unprecedented levels of volatility, a significant range of new or evolved system functions and related roles and responsibilities will be required.

For example, emerging system dynamics will require detailed consideration of:

- Distribution System Operator (DSO) models, and potentially, Distribution Market Operator (DMO) models
- Advanced Transmission Network Service Provider ('A-TNSP') models
- Transmission-Distribution Interface (TDI) designs capable of advancing whole-of-

	system responsiveness, flexibility and interdependence, and, • System Operator (SO), A-TNSP and DSO relationships. Importantly, given that the Laws of Physics are blind to the structural demarcations currently embedded in the NEM, each of these emerging functional roles must be considered holistically to ensure the desired 'whole-system' outcomes are achieved.

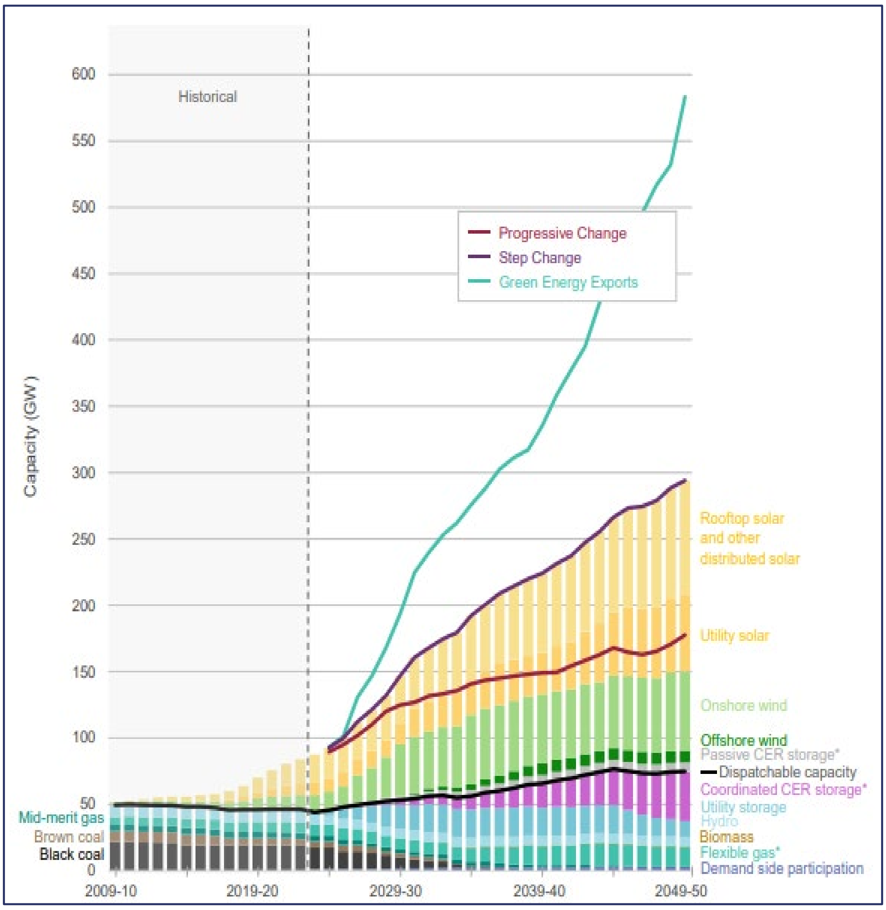


Figure 5: Unprecedented levels of NEM capacity expansion anticipated to 2050 under AEMO's Progressive Change, Step Change, and Hydrogen Superpower scenarios [136].

4.3 Generation Diversification

Trends relevant to shifts in the types, location, number and economics of the generation mix. Primarily, these trends are arising from decarbonisation goals, ageing coal fleets, the deployment of utility-scale VRE and mass customer adoption of CER/DER.

Emerging Trend	Implication/s
4.3.1 The withdrawal of conventional thermal generation and its replacement with utility-scale VRE is being accelerated by market forces and policy imperatives.	
The withdrawal of Australia's coal-fired, synchronous generation fleet is accelerating, with the original closure dates typically being brought forward from original announcements. Based on current announcements, 60% of conventional generation capacity will have been withdrawn by 2030. The entire coal-fired fleet will have been withdrawn by 2043. In parallel, Australia is installing utility-scale Variable Renewable Energy (VRE) faster than at any time in history.	The current record rate of utility-scale VRE deployment will need to be maintained every year for a decade to triple VRE capacity by 2030 – then almost double it again by 2040, and again by 2050. Synchronous generation is typically the largest source of firming flexible energy and Essential System Services (ESS) by a wide margin. Therefore, as the proportion of asynchronous Inverter-based VRE generation increases, resource availability must be managed carefully to ensure that sufficient alternative sources of firm, flexible capacity and ESS come online. It is noteworthy that in a modern power system, many of these services may be provided by resources located on both the supply and demand sides of the system. In addition, alternative inverter control methods such as those offered in Grid-Forming Inverters (GFMI) will increasingly be required to help achieve a secure, stable, reliable, IBR-dominated power system. This, in turn, will require new control methods as well as new protection schemes.
4.3.2 The withdrawal of Australia's aging coal-fired generation continues to outpace replacement VRE capacity needs.	
The timeline for coal exit in Australia's power generation fleet is accelerating. The shift is driven by the increasing penetration of cheap renewable energy and battery storage, making coal-fired power stations increasingly economically unsustainable.	The accelerated retirement of coal generation in Australia is having a significant impact on the NEM. As coal plants close earlier than expected, AEMO forecasts that a substantial increase in renewable energy capacity and firming technologies such as utility-scale batteries and pumped hydro will

In the 2024 ISP, AEMO forecast the entire coal fleet to exit the market by 2037-38 under the Step Change scenario [136].	be required to support better grid reliability. The rapid coal exit also poses challenges for system strength, inertia, fault current and market dynamics, as the NEM must balance the intermittent nature of renewables with the need for consistent power supply. Overall, the faster-than-expected retirement of coal generation is accelerating Australia's energy transition, but it also demands careful planning and investment to maintain a resilient, stable and efficient power system.
4.3.3 Nuclear energy options gain increased political visibility, with intensifying national debate despite ambiguous electoral support.	
The discussion around nuclear generation in Australia has been ongoing since the 1930s. However, nuclear power generation is currently prohibited in Australia under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act), and the Australian Radiation Protection and Nuclear Safety Act 1998 (ARPANS Act). In the lead-up to the 2025 federal election, nuclear energy re-entered national discourse through controversial proposals to repurpose former coal plant sites for nuclear development, including small modular reactors. This renewed focus prompted the establishment of a federal inquiry on 10 October 2024 to examine the feasibility and implications of nuclear deployment in Australia [130]. Public criticism has largely focused on the lack of comprehensive policy frameworks rather than the suitability of nuclear energy itself.	The consideration of nuclear power in Australia is fraught with numerous challenges and uncertainties. One of the primary concerns is the high Levelised Cost of Energy (LCOE) associated with nuclear power, which makes it less economically competitive compared to other energy sources such as firmed wind and solar. Additionally, nuclear projects are notorious for cost overruns, often exceeding initial budget estimates by orders of magnitude. The time required to deploy and commission nuclear plants also presents significant issues, as these projects typically take many years to complete, which can result in delays that render them impractical for meeting near to medium-term system needs. Waste disposal presents another challenge, given the long-term environmental and safety concerns associated with storing radioactive materials. Furthermore, regulatory changes are required to lift the existing nuclear ban, and navigating this complex legislative landscape can be a protracted and contentious process. Finally, obtaining social license is a critical hurdle, as public opinion on nuclear energy is divided, with concerns about safety and

	environmental impact often outweighing perceived benefits.

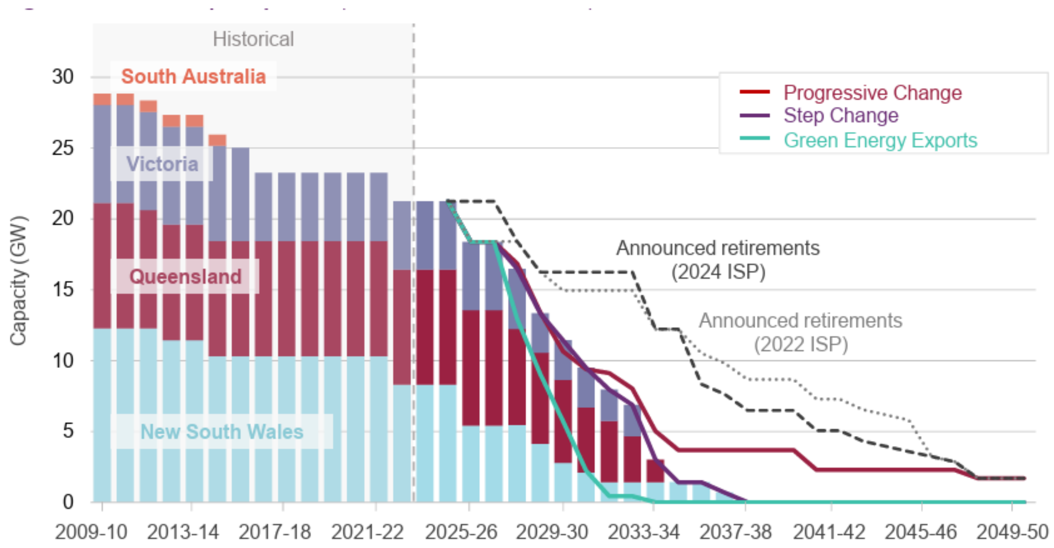


Figure 6: AEMO's forecast Coal capacity to 2049–50 under three different scenarios [136]

4.3.4 Many new utility-scale VRE deployments are experiencing long transmission connection queues and related project risks.	
In the past four years, 121 new large-scale wind and solar projects have connected to the NEM with many more on the way. This is driving a wave of major new transmission projects to carry the generated energy to market. Given the scale of VRE deployment, a critical challenge is the timely and least-cost delivery of major transmission projects that will support the changing generation mix. These large and complex projects have been prone to delays and cost-increases through planning and approval stages and are occurring in an environment of upward pressures on network costs.	As the withdrawal of coal generation accelerates, it is increasingly urgent that these transmission projects advance. This will require new approaches to coordinating investments and resource mix, and the development of Renewable Energy Zones (REZ) for the prioritised siting of new VRE capacity will be a key focus. Furthermore, given the massive scale of transmission build anticipated, additional consideration of options for whole-system optimisation will be increasingly valuable for moderating the scale and sequencing of new transmission construction.

4.3.5 Many existing and new utility-scale VRE deployments face curtailment risks due to congestion management issues.	
Given the scale of VRE deployments and the related transmission capacity issues that are emerging, network congestion is becoming an increasing challenge. This is resulting in VRE generation being curtailed off the network for periods of time.	Significant work will be required to mitigate market disruptions arising from curtailment risks to VRE generation as the coal-fired generation fleet retires. This may include a range of considerations including: • New variable transmission circuit structures • Variable flow control • Expanded buffering / energy storage • Moderation of build through targeted system optimisation

4.3.6 Gas-powered generation is increasingly prominent as a transitional source of flexible generation but faces gas shortfall risks.	
As the coal-fired generation fleet is progressively withdrawn, new sources of flexible generation are increasingly required to meet demand in daily peak periods and/or when the output utility-scale VRE and other generation sources is low.	Without significant increases in long-duration storage and demand response, gas-powered generation will likely be the key source of flexible generation in the medium term. Looking further out, the Step Change scenario also anticipates a longer-term role for gas-powered generation with up to 15GW of capacity in 2050 [136]. Gas shortfalls could, however, constrain the availability of gas generators and/or lead to higher prices. These shortfalls pose direct risks to gas system security in the event that inventory at storage facilities falls below the minimum levels required to support gas flow from them. Curtailments of this sort ultimately then restrict flexible generation availability, which highlights the challenges associated with closely interconnected markets.

4.3.7 Continued high levels of DPV adoption by residential, commercial and industrial customers are driving rooftop solar toward becoming near ubiquitous.	
Many of Australia's states have experienced world-leading levels of roof-top Distributed Photovoltaics (DPV) adoption, initially by residential customers and increasingly by commercial and industrial customers. In this context, rooftop DPV is anticipated as being a ubiquitous feature of Australia's future power system. The time windows in which some distribution network elements must operate with >70% of instantaneous demand being served by local DPV will continue to increase in frequency and duration.	The generation model of the power system is shifting from a traditional centralised, transmission-connected paradigm to an increasingly hybridised system as the proportion of distribution-connected generation expands. This shift changes power system operations drastically, introducing bi-directional power flows and other effects not included in original power system design assumptions.

<table>
<tr><th colspan="2">4.3.8 Energy resources are bifurcating into two locational classes: Centralised / HV-connected and Distributed / LV-connected.</th></tr>
<tr><td>Historically, the generation fleet was largely connected to the transmission system, which functioned as a one-directional, bulk delivery system.

As noted above, an additional class of generation is now emerging at significant scale which is highly distributed and connected to Australia's LV distribution systems. This is a fundamental and profound structural change to the power system and one that has developed organically, not as a result of design.</td><td>The bifurcation of Australia's generation fleet into two major locational classes involves a dramatic shift as follows:

• From a wholly centralised generation fleet located at one end of the power system
• To an increasingly hybridised generation fleet that is located at both ends of the power system

As noted above, this changes power system operations drastically. And because the change was not planned, the underlying grid systems are not aligned with this major structural shift, except to the extent that minor incremental changes have been made.

Major revisions of power system control and coordination is needed to fully realise the benefits and mitigate the risks of this fast-emerging new paradigm.</td></tr>
<tr><th colspan="2">4.3.9 Energy resources are bifurcating into two primary functional/investment classes: Merchant resources and Customer/private resources.</th></tr>
<tr><td>Historically, the generation fleet largely consisted of merchant resources installed for the primary or singular purpose of providing energy and services to the relevant markets.

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

Being installed primarily for customer purposes, however, compared with merchant resources, large scale provision of services will involve:

• Different motivational dynamics and engagement approaches
• New procurement and remuneration models
• Advanced automation to ensure the right physics-based services are provided when and where required most</td></tr>
</table>

	In other words, power systems will increasingly need to be able to accommodate energy resources that they cannot directly control. This introduces a new dynamic class of constraints into the power system control challenge, as well as new observability issues.
4.3.10 The progressive withdrawal of synchronous generation means that Essential System Services (ESS) must increasingly be provided by an expanding range of alternative sources.	
Essential System Services (ESS) help keep the power system in a safe, stable, and secure operating state. These critical services, which have traditionally been by-products of synchronous generation, include inertia, frequency regulation, system strength and operating reserves. As the proportion of conventional synchronous generation sources decline, inertia, frequency, system strength and operating reserve services must be provided by alternative sources, both centralised and decentralised.	In a power system dominated by IBR-based VRE generation and DER, new sources of ESS will be required. This will require new: • Frequency support services arrangements, including performance parameters for very fast frequency response and siting and capacity requirements of FFR resources • Voltage support services arrangements, including identification of conventional Volt/Var/OLTC equipment capabilities operating in an IBR-dominated system and orchestration requirements for distribution-connected energy storage systems • Performance assessment metrics, including evaluation of existing metrics used to assess the quality of ESS and their suitability in an IBR-dominated power system, and • Financial domain, including the sustainable integration of new sources of ESS into the market and coordinating DER-provided ESS with bulk power and transmission requirements.

4.3.11 The growing proportion of inverter-based generation is driving the need to integrate more grid-following and grid-forming inverter technology.	
Power electronic connected generation, also known as inverter-based resources (IBR), are increasingly the dominant means to connect new generation to the Australian electricity grid. To date, almost all applications of IBR have been based on Grid-following Inverter Technology (GFLI). Essentially, this means that these energy sources rely on other resources, mainly thermal and hydro synchronous generation, to set grid voltages and frequency.	As synchronous generation is progressively withdrawn, the availability of essential grid services to manage voltage and frequency is increasingly at risk. Alternative inverter control methods such as those offered in Grid-Forming Inverters (GFMI) will help achieve a secure, stable, reliable, IBR-dominated power system and compliment other sources of grid services such as synchronous condensers. Development of these methods requires exploration of control strategies, protection schemes and modelling approaches for IBR-dominated grids. This will need to include a particular focus on the contribution of advanced IBRs to frequency stability, voltage stability, real and reactive power flow control, and interaction mitigation and oscillation damping between aggregated IBRs.

4.3.12 Technology multinationals are increasingly considering grid-connected and islanded localised generation to supply their data centres.	
Tech-giants Amazon, Google, and Microsoft have each announced plans and partners to explore nuclear energy to meet the escalating power demands of their data centres and AI operations. For instance, Google has signed a deal with Kairos Power to purchase energy from a fleet of SMRs, with the first reactor expected to be online by 2031 [109]. Similarly, Amazon Web Services (AWS) is investing over $500 million in developing SMRs in collaboration with Dominion Energy [110]. These privately funded investments reflect a broader trend towards self-sufficiency and energy independence among large corporates with high energy needs. In parallel, Meta and Google are leading pilot trials of enhanced geothermal systems (EGS), which tap into deep underground heat reservoirs to generate electricity [108]. If	Big-tech are uniquely positioned to deploy private generation given their proclivity for innovation, familiarity with complex projects, ability to provide necessary capital investments and clear and compelling use case in data centres. If they are successful in operationalising private generation, they may provide the economies of scale to reduce the cost of technologies such as Small Modular Reactors (SMRs) and gain traction with a broader range of proponents. Under such a scenario, SMRs could play a significant role in future power systems. However, long lead-times and a high degree of uncertainty mean that SMRs are unlikely to contribute to the short to medium term generation mix. Standalone power systems raise questions around power system fragmentation and

successful, EGS could provide a new source of baseload renewable energy, diversifying the energy mix and supporting grid stability.	participation, network investment, and regulatory treatment. Policymakers and investors will need to weigh these risks against the potential benefits of long-term, low-carbon energy production co-located with major load centres.

4.4 Load & Demand

Changes in electricity consumption patterns driven by the electrification of transport and industrial processes, distributed generation, and increasing demand volatility. These trends challenge traditional approaches to forecasting, system flexibility, and the role of demand-side participation in grid stability.

Emerging Trend	Implication/s
4.4.1 Overall system load growth (TWh) is expected to be unprecedented with the electrification of transport, industrial processes and building services.	
Australia's COP26 commitments [131] involve a significant dependence on the large-scale electrification of transport, industrial processes and building services to replace a range of more carbon-intensive fuels such as natural gas and petroleum. Significant efforts are currently underway across many sectors to advance decarbonisation through electrification.	The NEM currently delivers approximately 200 TWh of electricity to industry and homes per year (including approximately 20 TWh supplied by CER) [136]. Based on AEMO's 2024 Step Change scenario [136], the capacity of the NEM would need to reach 410 Twh by 2048-50 to meet expected levels of electrification. This would involve an unprecedented level of change and scale of investment over the coming decade with significant risks that will need to be carefully managed.
4.4.2 Minimum Operational Demand (GW) records continue to be broken with the continued deployment of Distributed Photovoltaics (DPV) at scale.	
Minimum system load records in the NEM continue to be broken due to the rapid increase in distributed energy resources (DERs) like rooftop solar. As more households and businesses install solar panels, the amount of electricity generated during daylight hours often exceeds local demand, leading to record low levels of minimum system load. To maintain sufficient levels of system inertia to handle disturbances such as a sudden loss of a transmission line, some larger synchronous generators are required to stay online. These large generators have minimum operating levels, which must be accommodated in matching supply and demand. Under certain conditions, high levels of generation from rooftop PV results in an	This trend poses challenges for power system stability. Traditional power plants that do not operate efficiently at low output levels are at the same time needed to provide sufficient system strength, inertia and fault current. The first tranche of emergency backstop measures have been implemented urgently to avoid near term instability. However, these efforts are only temporary measures and will not be sufficient to maintain system security as levels of DER penetration continue to scale. The key role of distribution-connected rooftop PV in combination with AEMO's responsibility for ensuring system-level stability necessitates that a whole-system approach be taken to managing minimum system load events. This includes agreement on operational coordination mechanisms and

over-supply such that secure-limits cannot be maintained by the inclusion of these dispatchable large generators. This has required the introduction of new "emergency backstop" mechanisms to allow rooftop PV systems to be curtailed or turned off briefly, if necessary, in rare emergency conditions, similar to the capabilities normally required of any large scale generator.	supporting architectures that avoid unintended consequences.
4.4.3 The intensity of the 'evening ramp' in demand (GW) is increasing in comparison to average midday demand.	
Increasing penetration of both distributed and utility solar PV as a generation resource is causing an increasing need for non-solar resources to ramp up output as the sun sets to replace the fading solar production. The so-called 'evening ramp' occurs as the decline in solar PV output occurs quite rapidly in the late afternoon. There is an increasing need not just for replacement resources, but resources that can ramp up output to match both the drop-off of bulk solar and the increase in apparent demand (and during heating seasons real demand) as the sun sets. In addition, vehicle charging demand is increasing in the evening as the electrification of transportation grows, further exacerbating this ramping issue.	The penetration of solar PV complicates the makeup and operation of the generation resource set by introducing a non-controllable (albeit predictable) generation fluctuation that the power system was not designed to handle. Neither solar PV nor wind turbines are in themselves 'ramp-able', unless under curtailment. This is creating an expanding need to match resources and demand dynamically via rapid ramping capacity in the resource mix, multi-hour storage, load shifting, or other means to manage what is effectively an emerging volatility in generation. This also complicates day-ahead and intra-day grid management, as well as intermediate and long-term grid planning and investment strategies.
4.4.4 Wide-ranging shifts in demand/load composition profiles are occurring which present increasing challenges to the accuracy of forecasting.	
Loads are changing from simple passive forms to more active forms dominated by non-linear power supplies and by increasing embedded intelligence. In addition, significant new sources of load are emerging from sector coupling such as the electrification of transport and industrial processes and the emergence of the green hydrogen sector. Decreases in traditional loads are also resulting from energy efficiency initiatives,	Enhanced approaches to load forecasting will be needed as new types of loads emerge, some traditional loads decline and the deployment of DPV and DER continues apace. This will need to include: • More sophisticated computation of alternative load scenarios that may arise from different customer investment choices

large industrial closures, and consumer grid defection.	• Ongoing, advance monitoring of the emergence of significant new / non-traditional sources of load • Ongoing monitoring of potential decreases in traditional loads • More advanced and ubiquitous deployment of short and medium horizon solar resource forecasting relevant to DPV output
4.4.5 The deployment of DPV at scale is masking real demand and exacerbating 'demand-side' volatility.	
The deployment of DPV at scale is reducing net customer demand from the power system. However, due to the stochastic nature of DPV operation, the power system must still be capable of supporting the entire instantaneous load, with very short notice, where DPV output suddenly drops.	The operational behaviour of DPV effectively introduces new levels of apparent demand volatility. The operational behaviour of DPV introduces new levels of apparent demand volatility, posing challenges for system balancing and obscuring key signals required for capacity forecasting. This can lead to misinterpretations in capacity markets, potentially indicating a lower need for traditional generation than what is actually required to back up non-firm DPV. Increasingly, more advanced control methods will be required to provide a sufficiently integrated approach to bulk power and distribution systems coordination. This will also need to include short and medium horizon solar resource forecasting relevant to DPV output. Due to fast dynamics, this may require storage buffering with automatic control, since markets will not be able to respond quickly enough to handle fast power fluctuations. The above are expected to emerge in the context of industry efforts to define and develop new industry structures such as Distribution System Operator (DSO) models and Transmission-Distribution Interface (TDI) designs.

4.4.6 The mass-electrification of transport is driving an entirely new phenomena of load, demand and storage portability at scale	
The transition to electric vehicles (EV) began relatively slowly in Australia but is now gaining pace. EV ownership is expected to surge from the late 2020s, driven by falling costs, greater model choice and availability, and more charging infrastructure. At the same time, EV batteries are increasing in size, weight and energy storage capacity, and increasing penetration is creating an entirely new phenomena of load, demand and storage portability at scale.	Most traditional network analysis and constraint analysis is currently based on the assumptions that: • Energy supply is provided by locationally fixed generation resources • EV charging is primarily a load source during charging This inadequately considers the potential significance of energy portability via road transport. This may result in OEM solutions and employer benefits that, for example, encourage workers to charge their EV with 'free' solar PV at work and then discharge it to power their home via Vehicle to Building (V2B) technology. While this may not make a significant impact at first, as with DPV it may result in significant shifts of energy via roads over time.
4.4.7 Behind-the-meter (BTM) energy resources have increasing ability to provide flexibility, firming and ESS.	
Traditionally, customer loads were largely considered passive in terms of power system management and generally forecastable in terms of demand aggregated to the feeder level and above. Increasingly, loads are becoming more responsive with participation in various demand response programs. While demand response has been used for decades, in many cases this has focused on commercial and industrial customers and been activated through non-automated processes. With the development of smart appliances / devices and new interoperability standards, a growing proportion of residential, commercial, and industrial technologies located behind the meter have the latent ability to provide a	Rather than being limited to supply-side sources, a proportion of flexibility services may be provided by Behind the Meter (BTM) resources in a modern power system. Unleashing the full potential of under-utilised customer resources, however, will require a new range of systems architecture enablers, communication links and financial incentives. Ultimately, the Operational Coordination of the power system will need to extend beyond the historic system boundary to efficiently manage the level of dynamic interactions at scale. This will require an 'extended grid' paradigm that actively involves BTM assets not owned by utilities) and the observability and controllability issues for grid will extend to include responsive loads.

range of services to the power system in exchange for a share of the value created.	

4.4.8 Data centres are driving exponential load growth in relevant segments of the power system.

The rapid growth of artificial intelligence (AI) technologies is driving significant demand for data centre infrastructure, especially for training and deploying machine learning models. AI applications require vast computational power, leading to energy-intensive operations within data centres. As cloud-based services and AI use cases expand across industries, this increased energy demand is becoming a material factor in the overall energy consumption of national grids. Large tech companies are investing in renewable energy to power their data centres, but the scale of AI's future energy requirements remains a concern, particularly for electricity grids already under pressure from integrating intermittent renewables.	The energy demand from AI-driven data centres is expected to place substantial pressure on electricity grids, especially during peak periods. This could lead to increased grid instability if renewable energy supply does not keep pace with demand growth. Data centres may need to focus on improving energy efficiency and investing in energy storage systems to buffer their impact on the power system. Policymakers and system operators will also need to consider the spatial and network-topological distribution of data centres and their energy requirements to avoid regional grid stress. Additionally, managing the demand spikes from AI workloads will require smarter load balancing and potentially new market mechanisms that reward flexibility.

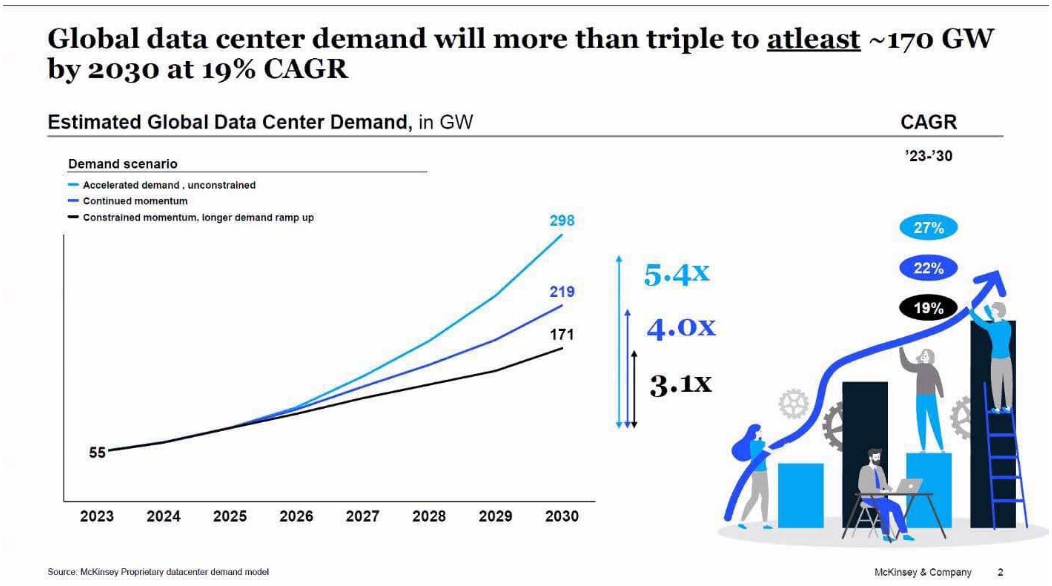


Figure 7: Estimates of global data centre demand [111].

4.5 Storage & Buffering

Trends that relate to the increasing uptake and capabilities of FTM and BTM energy storage systems including EVs. These developments provide potential avenues to provide a buffer to support supply-demand balancing where the system is experiencing greater volatility with the deployment of VRE and CER/DER at scale.

Emerging Trend	Implication/s
4.5.1 Large-scale pumped hydro projects continue to fall behind schedule and/or face cancellation.	
Large-scale pumped hydro projects in Australia continue to face significant delays and cancellations, impacting the country's renewable energy transition. The Snowy Hydro 2.0 project, a major pumped-hydro expansion of the Snowy Scheme, has experienced numerous setbacks due to complex design elements, variable site conditions, and the COVID-19 pandemic. Despite these challenges, the project is progressing, with the target date for commercial operation of all units set for December 2028 [112]. On the other hand, Queensland's Pioneer-Burdekin Pumped Hydro Project, which was slated to be the largest renewable energy project of its kind in the world, has been scrapped by the new state government [113]. The project faced financial, environmental, and social challenges, including a cost blowout to $37 billion and lack of Traditional Owner consent.	Storage is a key element of a power system dominated by intermittent renewable energy sources. Large-scale hydro projects are uniquely positioned to provide large amounts of storage (MWh), at high output (MW) over long durations. Delays and cancellations impact the overall systems ability to buffer volatility. The challenges faced by large-scale hydro highlight the intricate balance required between technological ambition, financial viability, environmental stewardship, and social responsibility to ensure the successful implementation of large-scale projects in Australia.

4.5.2 Battery Energy Storage System (BESS) costs continue to fall below forecast learning rates.	
The cost of battery storage technology has been dropping more rapidly than expected, driven by innovations in battery chemistry, increased production scale, and improved supply chains. Batteries are a critical component in enabling the reliable integration of renewable energy sources like solar and wind by storing energy for use when generation is low. As costs fall, batteries are becoming more economically viable at both utility and residential scales, leading to greater deployment of energy storage systems across the grid. This is accelerating the shift towards a more flexible, decentralised energy system.	The unexpected acceleration in battery cost reductions has broad implications for the energy sector. With cheaper batteries, energy storage becomes more accessible, supporting the grid during periods of high renewable generation and helping to smooth demand peaks. This also means more households and businesses are likely to adopt battery storage solutions, increasing the overall resilience and flexibility of the grid. However, the rapid deployment of battery systems will require updates to regulatory frameworks and network infrastructure to ensure they can be integrated and coordinated smoothly to provide maximum benefit without causing operational challenges or network congestion.
4.5.3 The scale and diversity of BESS deployed across all layers of the power system continues to accelerate.	
A significant development in an increasingly volatile power sector is the advent of increasingly cost-competitive energy storage. As a form of 'buffering', different types of energy storage can provide a new range of services across different functional time horizons, including: • Shallow / ESS (< 4-hours) • Medium / Intraday shifting (4 – 12-hours) • Deep / RE drought (> 12-hours) This is especially noteworthy as, unlike most other supply chains, power systems have not traditionally had buffering mechanisms to manage volatility. In supply chain logistics systems, for example, the buffers are warehouses. In gas and water systems, the buffers are storage tanks. In communication systems, they are called jitter buffers.	Given that the power system and its regulatory frameworks were developed in the absence of viable, large-scale energy storage options, significant changes may be required to effectively integrate this category of resource. For example, the Australian Energy Market Commission (AEMC) recently made several changes in support of this [132], including: • A new registration category, the Integrated Resource Provider (IRP), that allows storage and hybrid generation and storage systems to register and participate in a single registration category rather than under two different categories. • Clarity for the scheduling obligations that apply to different configurations of hybrid systems, including DC-coupled systems, so that operators of these systems have the flexibility to choose

	whether to be scheduled or semi-scheduled. • Allowing hybrid systems to manage their own energy behind the connection point, subject to system security limitations. • Clarifying that the current approach to performance standards that are set and measured at the connection point will apply to grid-scale storage units, including when part of a hybrid system. • Transferring existing small generation aggregators to the new category and enabling new aggregators of small generating units and/or storage units to register in this category.

4.6 Control Dynamics

Developments that are increasing the complexity of maintaining real-time power system stability as traditional synchronous generation is displaced by inverter-based resources. This includes new control and coordination considerations and approaches for faster system dynamics, declining inertia, and the proliferation of distributed assets.

Emerging Trend	Implication/s
4.6.1 Large volumes of transmission-connected VRE and distribution-connected CER/DER are increasing system volatility in a manner that may propagate in either direction.	
Volatility is a phenomenon that can occur on a wide range of time scales. While much focus is on very short-term effects, it is increasingly necessary to consider this as a multi-scale issue. For example: Variation on the scale of sub-seconds to minutes is increasingly a problem at the distribution edge, where no 'law of large numbers' effects exists to smooth out the variations – leading to voltage regulation issues at the local feeder and service drop levels. Fluctuations in apparent load in the seconds to minutes time scale can appear as fluctuations at the Transmission-Distribution Interface, including even reverse power flows caused by DPV export into the grid. Hourly to longer fluctuations in customer resources contribute to overall duck curve effects at the bulk level, which is how a ramping deficit can develop. Volatility of bulk solar and wind not only introduces volt/VAR and frequency / balance fluctuations that affect LV systems, but they also exacerbate market price volatility which ultimately affects customers. On a diurnal, and seasonal basis, changes in load and in availability of wind and solar constitute volatility on slower scales, affecting planning, investment and prices at both HV and LV levels.	Volatility is both a technical and an economic problem for electric grid operators and customers. Traditional means of managing volatility via spinning reserves are becoming increasingly inadequate as the coal-fired generation fleet retires. In most other kind of engineered systems or supply chains, it is standard to provide buffering mechanisms to manage volatility. In logistics systems, for example, the buffers are warehouses. In gas and water systems, the buffers are storage tanks. In communication systems, they are called jitter buffers. A grid dominated by VRE requires buffering to operate reliably. The scale, placement and control of such buffering elements is a key aspect of power system transformation.

4.6.2 With the progressive withdrawal of conventional synchronous generation, the power system is experiencing a significant loss of system rotational inertia and increasing challenges in managing frequency.

As the power system decarbonises, frequency management is becoming more challenging due to the reduction in mechanical inertia.

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

By contrast, wind turbines have low mechanical inertia, which is not always available, and solar PV has no inertia. Historically, NEM mainland inertia has never been below 68,000 megawatt seconds (MWs), however, by 2025 AEMO forecasts that inertia could drop to as low as 45,000 MWs.

As mechanical inertia decreases, an increased volume of frequency services, or services that can respond quickly in response to transient phenomena in a low inertia system will be necessary to arrest the change in frequency before technical limits are exceeded and risk system collapse.

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

Further, understanding the behaviour of DER technologies, including how they impact system dynamics and existing primary, secondary, and tertiary frequency controls is becoming increasingly important as penetrations rise.

4.6.3 The power system faces increasing challenges in managing voltage.

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

- Decreasing levels of synchronous generation being online
- Increasing levels of Distributed PV (DPV)
- Increasing levels of VRE generation in distant locations
- Low daytime customer demand
- Structural changes in demand characteristics
- Dependence on forms of manual control between power system entities
- Increasing volatility at the distribution edge, where DPV dynamics are not

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

The growth of DPV installed behind the meter by households and businesses reduces demand on the transmission system, which causes voltage rise and reverse flows into the bulk system. This causes voltage rise on the distribution system, as power is fed back from the end of long feeders. In addition, as DPV has

moderated by 'law of large numbers' effects.	grown, falling daytime demand is increasing the usage of already ageing reactive plant which was originally sized to manage differences between night-time minimum and maximum demand. The increased need for reactive plant to manage daytime minimums for a greater proportion of the year also reduces the available critical maintenance windows during off peak periods. Increasing distributed generation is changing the reactive flow between the transmission and distribution system. This requires the System Operator to manually interact with distribution networks to adjust reactive power interchange at the Transmission-Distribution Interface (TDI). While there is increasing reactive capability connecting at the distribution system, in many cases, there may not be established processes to immediately act on the instruction.
4.6.4 The power system is experiencing decreasing latency tolerance as faster system dynamics propagate across grid operations and functions.	
Power system dynamics are increasing in speed by orders of magnitude as latency tolerance declines. The implementation of new power system capabilities has resulted in significant increases in the speed at which grid events occur. This is especially true with distribution networks but is also impacting transmission systems. In the last century, aside from protection, distribution control processes operated on a time scale stretching from about five minutes to much longer, and human-in-the-loop was (and still is) common. With the increasing presence of technologies such as IBR-based VRE and DPV and power flow controllers, active time scales are moving down to sub-seconds and even to milliseconds.	Automatic control is becoming essential, and this brings with it the need to obtain data on the same times scales as the control must operate. This is the result of somewhat of a 'double impact': • Many more new devices to control • Much faster dynamics for each device This requires vast new data streams and increasing dependence on ICT for data acquisition and transport, analysis, and automated decision and control. Existing human-in-the-loop control is therefore becoming unsustainable and existing control systems and related applications are becoming unable to keep up with real-time grid behaviour. Additionally, data acquisition is impacted since latency and latency skew become

	much more significant as control time cycles decrease.

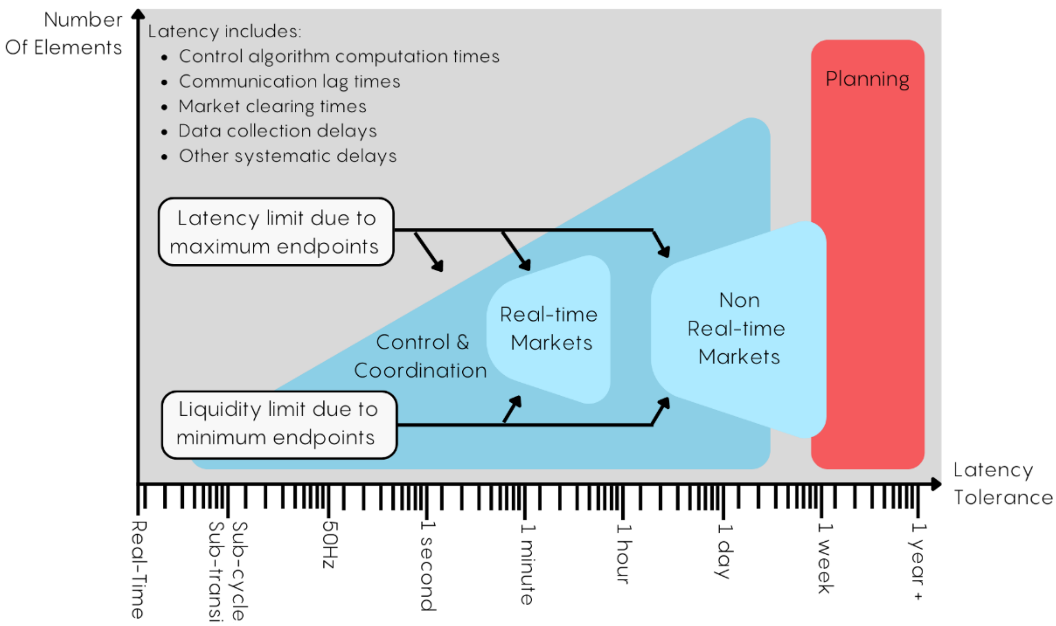


Figure 8: Market and control interactions as power systems experience faster system dynamics and decreasing latency tolerance.

4.6.5 A new level of computational and system optimisation challenges is emerging due to the number and complexity of new functions, roles and actors required by the future grid.	
Power system control problems are becoming increasingly complex as we add new functions and requirements. This is typically involving a growing diversity of objectives for system optimisation which, for example, may variously focus on: • Load profile optimisation • Carbon emission optimisation • Volt/VAR optimisation • Variable grid structure control and logical multi-way power flow (to be resolved into real flows) • Embedded storage management • EV charging optimisation, etc End users are also wanting to perform 'selfish' control optimisation that, in many cases, may conflict with optimal system control.	Large scale, multi-objective optimisation is increasingly required across multiple layers of the power system. This will be necessary to coordinate controls and optimise to various objectives. It will also need to consider complex constraints and solve distributed control problems. The presence of large volumes of mixed DER ultimately constitutes an entirely new kind of optimisation and scaling challenge for power system control. Conventional power system control architectures, however, were not structured for such large scale, multi-objective optimisation needs. Key challenges include the establishment of sufficient optimisation capacity to manage the huge numbers of constraints and conflicting objectives that must be accommodated across power system layers. Related computational loads will also grow exponentially and risk computational 'time walls' emerging.

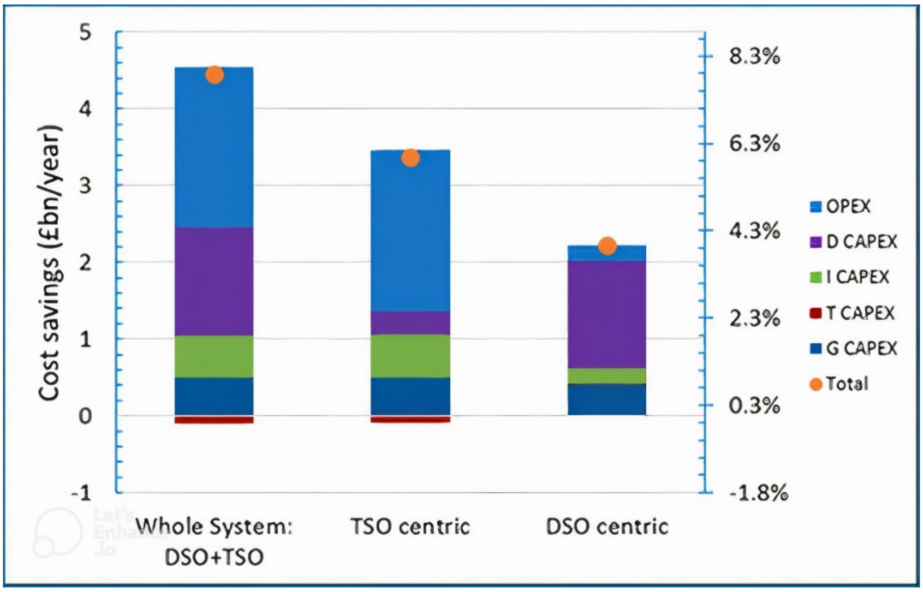


Figure 9: Potential benefits of improved transmission and distribution control interfacing, modelled by the Imperial College London [133].

4.6.6 The operational coordination of millions of energy resources located on either side of the Transmission-Distribution Interface (TDI) is presenting a new scale of system balancing challenges.	
Modern power systems are increasingly requiring enhanced Operational Coordination mechanisms due to: • The level of system volatility experienced as decarbonisation deepens. • The number and diversity of participating resources as the system transitions from hundreds to tens of millions of energy resources. • These resources becoming near-ubiquitous across all vertical layers of the power system and blind to historical bulk power, transmission and distribution boundaries. • With the retirement of synchronous generation, increasing volumes of system flexibility, balancing and ancillary services will be required from the traditional demand-side of the system.	Imperial College London (ICL) estimated that whole-system-based coordination of demand-side flexibility could deliver substantial system-wide cost savings, with potential reductions in total system expenditure (TOTEX) of up to £4.7 billion annually for the UK power system [133]. Given the inseparable cyber-physical-economic nature of the power system, comprehensive 'market-control' alignment will be required to incentivise and activate service provision in a reliable and mutually reinforcing manner. The balance between market-like and control-like methods must evolve as the structure and dynamics of the power system change. Economic incentivisation and cyber-physical automation elements must be tightly coupled across each power system layer for energy, capacity, flexibility, and essential system services to be delivered when and where needed by the system. Ultimately, advanced Operational Coordination models must be capable of maintaining instantaneous supply and demand balance every millisecond of the year.

4.7 Data & Digitalisation

Trends relevant to the rapid expansion of data from power electronics, sensors, smart meters, DERMS, utility servers, OEM cloud platforms, HEMs and other digital services and devices. These include related cybersecurity risks, latency challenges, and scalability issues that are reshaping how power systems are monitored and managed.

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

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

4.7.3	The cyber-security of power systems and related datasets is increasingly recognised as presenting critical national security risks in an evolving geostrategic environment.
Power systems are transitioning from centralised, privately networked, single-application control systems with hub-and-spoke communications to more distributed control architectures. These increasingly rely on vendor-developed solutions, multi-application digital infrastructure, and data exchange over public meshed networks. While these advancements enhance operational efficiency, they also blur the boundary between secured Operational Technology (OT) and more open, accessible Information Technology (IT), creating new vulnerabilities. Simultaneously, cyber-security risks to critical power infrastructure are escalating due to both technological evolution and geopolitical dynamics. The expanding interconnectivity and digitalisation of power systems have significantly increased the attack surface, making them more susceptible to cyber-threats from both state and non-state actors	As digital infrastructure, data, and power systems become more tightly coupled, cyber-security risks are expanding in scale and complexity, with the potential for disruption exceeding that of natural disasters and conventional contingency events. The energy sector's reliance on digital technologies for monitoring, control, and management makes it a prime target for cyber threats, with successful attacks capable of causing widespread outages, destabilising grid operations, disrupting supply chains, damaging physical assets, and eroding public trust in system reliability. The financial burden of strengthening cyber-security and recovering from attacks also diverts investment from other critical areas. Risk assessments and resilience planning are having to increasingly prioritise cyber-security, requiring the maturation of existing strategies alongside the adoption of new

seeking strategic advantage. The integration of IoT, AI, and cloud computing into grid operations further amplifies these risks by providing new entry points for exploitation. Cyber-attacks are growing in frequency and sophistication, with power systems far from immune. For example, in 2015, hackers successfully disabled 30 substations in Ukraine, disrupting electricity supply to 230,000 residents [115]. The increasing reliance on digital communication and cross-border data exchange further heightens the risk of disruptions, data breaches, and threats to national security.

tools, methods, and processes. Third-party systems providing customer-facing products and services introduce additional vulnerabilities, as an attack on a widely adopted technology could trigger system-wide disturbances. For example, a hacker gaining access to the management system of all EVs from a particular brand could manipulate large-scale load variations in short cycles, disrupting grid stability.

Beyond direct cyber threats, the redundancy of communications networks is also a key concern. Certain power system functions may depend on digital infrastructure that, in turn, relies on the power system itself. This interdependence could lead to cascading failures during a power outage, particularly in critical scenarios such as black-start restoration. As digitalisation and the integration of renewable energy sources continue to evolve, robust cyber-security frameworks are essential to maintaining grid resilience and stability.

4.7.4 Legacy power system architectures and data routings are increasingly recognised as containing structural vulnerabilities that elevate cyber-security risks.

The legacy system architecture emerged in an era when digital infrastructure played a much more limited role in supporting the power system, particularly at the distribution level of the system.

In recent years there has been a growing focus on cyber-based security considerations. While limited in Australia, some jurisdictions are recognising that legacy power systems also contain non-cyber structural vulnerabilities that heighten cyber-security risks.

Cyber-secure communications can be significantly enhanced by analysing legacy and alternative structural arrangements for data flows and communications routing.

Such analysis can provide new architectural features that have inherent non-cyber capacities to resist cyber-attack. This may include the application of Resilience Algebra to identify structural configurations that are inherently cyber-threat resistant and support the placement buffering to resist/minimise the efficacy of cyber-attacks.

4.7.5	Legacy power system architectures are increasingly recognised as presenting bottlenecking and latency cascading risks as system dynamics, data and endpoint volumes and the number and diversity of system actors expand.
The power system was historically configured as highly centralised, and its control systems designed to align with this paradigm. In general, data has been routed to centralised systems for analysis that informs system operation and resource coordination. Massive volumes of data are produced as more sophisticated near real-time management is required in a context where the level of system dynamics, and the number and type of endpoints, are dramatically expanding. Several jurisdictions are now recognising that both legacy and hybrid power system architectures may face bottlenecking and latency cascading risks as endpoint and data volumes expand.	Centralised models of data flows and processing risk bottlenecking and latency cascading as the number of endpoints and volumes of data expand. Analysis of legacy and alternative structural arrangements, including options such as Layered Decomposition structural models will be required to ensure communications systems are scalable and extensible. Similarly, application-specific data and communications systems will need to shift to more data-centric approaches, whereby data is freed from siloes and its value unlocked by making it available to other consuming applications.
4.7.6	**Significant interoperability efforts are increasingly at risk of being impeded without the parallel consideration of evolving systems architectures.**
The maturity of existing DER interoperability systems and related technologies is limited when compared with the needs of a high-DER power system. Australia is currently contributing to international efforts to develop common communications protocols and technical standards for DER interoperability. 'CSIP-Aus' is an Australian adaptation to the Common Smart Inverter Profile (CSIP) IEEE 2030.5 Implementation Guide for Smart Inverters. The full benefits of this work, however, risk being impeded due to the absence of agreed and future-ready architectural configurations of the power system (i.e. cyber-physical structural settings that are scalable and extensible to plausible future scenarios).	While interoperability standards provide clarity about what and how data is exchanged between technologies, systems architecture is needed to formalise the relationships and structural interdependencies between the actors of a complex system and their related portfolio of technology and market structures. A holistic approach to interoperability, therefore, is inextricably linked to question of the evolving Roles & Responsibilities (R&R) required by the future power system. To realise the full potential of interoperability, systems architecture tools must be applied to analyse the cyber-physical constraints that pertain to existing and alternative future R&R configurations (in addition to mitigating the related risks of bottlenecking and latency cascading as above).

4.7.7 Significant interoperability standards development are underway but risk being impeded by proprietary 'walled gardens' and/or superseded by consumer-focused standards.

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

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

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

What traditional power sector standardisation approaches may not adequately appreciate is that DPV and DER are perhaps more analogous with consumer electronics technologies than traditional power system assets. For example, *ISO/IEC 15067-3:2012* [134], *Model of a demand-response energy management system* recently redefined the concept of demand response to include indirect incentives such as price changes to motivate customers to control demand locally.

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

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

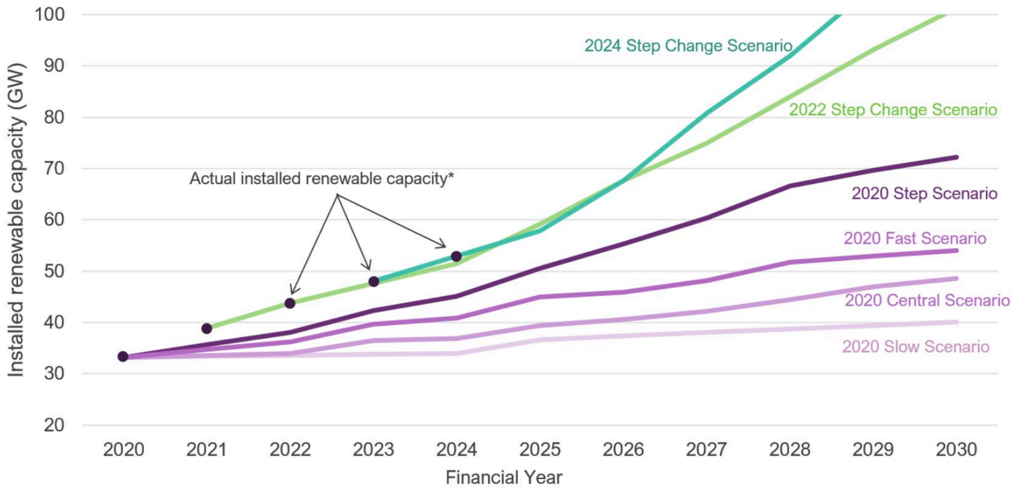
As distributed energy technologies evolve, energy management will be enabled by on-premises control of power usage in response to fluctuations in power availability and cost from all sources, especially sources on the premises or nearby. Energy management equipment (hardware and software) will increasingly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

4.7.8 Inadequate access rights to operational data are becoming more problematic as the number of participating resources and associated platforms expands.	
Energy service providers have been and are expected to continue to be aggressive in asserting their Intellectual Property as it relates to their fleet management systems and control of distributed resources, including EVs, aggregation, demand response and distributed storage. Electric Vehicle Supply Equipment (EVSE) vendors, for example, collect a large amount of data from their customers. Beyond enabling intelligent managed charging services, this is of significant commercial value as it can be used to enhance vendor platforms, target new products and services, and tailor solutions to their customers. Similarly, data associated with DPV is increasingly accessible to DER aggregators but is not so readily accessible by network operators. More generally, when useful data resides in proprietary platforms, system operators are unable to access otherwise valuable information for real-time operational decisions and longer-range planning functions.	A 2019 report [135] commissioned by the UK Government, Innovate UK and Ofgem and compiled by the Energy Data Taskforce found that a lack of common data standards, no openly shared data repository, and a culture of data hoarding was preventing competition, innovation and new business models. It recommended that, given the power and potential of data, a culture of 'presumed open' be embedded across the sector. Reluctance to share data is expected to continue unless provisions are made for secure, authorised and controlled data access and management. Commercial entities may be willing to provide access to useful data, however, where suitable undertakings from the receiving party protect their interests. Such provisions would ideally be standardised sector wide, avoiding a patchwork of bi-lateral arrangements or a multitude of schemes that cause confusion. A shared and secure data platform backed by a universal credentialing may be one such option.

4.8 Long-term System Planning

Trends in the practice of long-term system planning that reflect the need for bottom-up and top-down whole-system planning approaches. This includes enhancing current approaches, such as the ISP, alongside more rigorous demand-side modelling and analysis together with the expanded application of strategic foresighting.

Emerging Trend	Implication/s
4.8.1 The transformation of Australia's National Electricity Market is most closely aligned with AEMO's Step Change scenario [125] and progressing faster than anticipated by the scenario.	
The transition of the National Electricity Market (NEM) towards increased renewable energy is progressing swiftly. The actual installed capacity of renewables surpasses the fastest Step Change scenario outlined in the 2020 Integrated System Plan (ISP) [126]. The newly released 2024 ISP [136] reflects this advancement by including it in the updated Step Change Scenario. Total installed renewable capacity hit a new high of 72.1% in October 2023.	The substantial integration of renewable energy sources presents difficulties in sustaining system strength, inertia, and adequate fault current levels, as most inverter-based resources lack the ability to provide these essential system services. Furthermore, the increased levels of DER penetration also mean that operational forecasting has to change to account for the variability of renewable energy. This includes forecasting generation from rooftop solar at the distribution level and aggregating the data at the transmission level to provide visibility to the transmissions system operator.



*Renewable capacity includes the following technology types: hydro, utility storage, coordinated consumer energy resources (CER) storage, passive CER storage, offshore wind, onshore wind, utility solar, rooftop solar and other distributed solar.

Figure 10: Actual installed renewable capacity and ISP Step Change scenario forecast [127].

4.8.2	Forecasting for system planning is facing new challenges in a more diverse and volatile power system.
Traditional methods of forecasting remain necessary but are no longer sufficient as both load and generation output become more volatile and stochastic, while also remaining temporally and spatially sensitive. Planning practices have traditionally adopted deterministic approaches to represent the long-term drivers of system expansion, historically associated with annual load growth, using simplified representations of system operation. The increasing operational and technological complexity of power systems, as well as the levels of uncertainty about the future system, market, and policy developments, are diminishing the effectiveness of traditional approaches. Long-term uncertainty is also increasingly influenced by factors including emerging technologies and business models, policy environments, and climate change, which all represent daunting challenges to system reliability and resilience.	The planning and operation of low-carbon power systems dominated by IBR-based VRE generation and DER requires new modelling capabilities and tools. This includes more sophisticated and flexible representations of the plausible futures, along with enhanced decision-making tools capable of optimising planning outcomes across multiple scenarios. New metrics and methodologies that account for the technical and economic risks faced by multiple stakeholders during the energy transition must also be included. To the extent that bulk energy storage becomes an integral part of the power system, planning methods will need to evolve to properly represent what such technology can do for the grid. This will include how all other aspects of power system operation can and should change to take advantage of the inherent buffering capability of storage, as distinct to merely treating storage as 'generation with negative output' or attached ancillary service devices. The interface between power systems and other energy systems and sectors (i.e., natural gas, hydrogen, transport) also needs to be properly designed to capture the impact of and flexibility created by multi-energy systems and sector coupling in planning studies and to prevent negative consequences of cross-coupling and cross-export of volatility.

4.8.3	Conventional planning paradigms focused on discrete segments of the system face new challenges as the end-to-end power system becomes more inter-dependant.
Conventional planning processes have primarily focused on individual segments of the power system (e.g. bulk power, transmission, distribution). As the end-to-end power system becomes more dynamically	Conventional planning tools and methods are increasingly unable to account for the structural changes and operational behaviour/control requirement changes needed to accommodate and capitalise on power system transformation.

interdependent, this is unlikely to fully unlock 'whole system' optimisation benefits. However, as noted earlier (refer to 4.2 above), Australia's power systems are: • Becoming more diverse and dynamic • Transitioning from hundreds to tens of millions of participating energy resources • Experiencing a progressive erosion of the traditional 'supply-side / demand-side' bifurcation In this context, many jurisdictions are recognising that conventional planning models are facing new challenges as power system complexity and interdependencies increase due to the profound structural changes impacting the power system.	Planning methodologies increasingly need to be cross-organisational and cross-functional. Enhanced analytic tools must be able to adequately represent the behaviour of newer technologies such as utility-scale VRE, various types of bulk energy storage and numerous DER types and configurations. New integrated resilient planning methodologies and tools will also be needed to fully unlock the enhanced resilience potential afforded by the targeted implementation of new technology options. Such integrated planning will need to span organisational boundaries and functions, including across the traditional (but increasingly arbitrary) Transmission – Distribution boundary.
4.8.4 It is increasingly recognised that more integrated joint planning of sector coupling relationships will be required to realise optimisation opportunities	
While many non-electric sectors have had dependencies on the electric sector (and vice versa) the importance of sector coupling is accelerating in the cases of transportation, buildings, and manufacturing. As these sector convergence trends proceed, independent autonomous planning of the individual sectors is increasingly incapable of recognising joint opportunities for capturing functional requirements and potential operational and investment efficiencies.	Capturing these opportunities will require joint planning methods and cross-observability over sectors experiencing emerging coupling/convergence. Data sharing for planning across sectors will be necessary, on time scales ranging from sub-minute to years, just as the planning processes must operate. Further, the planning processes must mesh (synchronise) by accommodating planning and implementation process sequence requirements. Regulatory processes must also allow and encourage cross-sector collaboration.

4.8.5 More advanced planning automation is required to fully realise emerging system optimisation opportunities.	
Many jurisdictions are recognising that existing planning tools are lagging both the	New and improved planning tools that combine production cost type analysis with

scale and pace of grid transformation and the rapid increase in optionality and system optimisation provided by new power system technologies. For example, production planning tools often treat bulk energy storage as analogous to generation. New approaches are emerging that have far greater efficacy but the full benefits of such are not currently represented in the planning tools. Increasingly faster grid dynamics (especially near the distribution edge) are shortening the time available to perform core operational planning and control functions. Emergence of issues such as evening ramping in the presence of extensive solar PV are likewise rendering existing planning, simulation, and evaluation methods less effective. Operational paradigms, control and coordination, and protection schemes are falling behind advances in device technologies, such as storage, inverters, and VRE. Existing market methods and tools are becoming ineffective as generation resources increasingly move toward low to zero marginal cost.	advanced control simulations and include models for advanced components such as storage and IBR must be developed, along with the method and processes for using them. Advanced Operational Coordination and new market-control approaches and tools must be developed to operate the future grid. Existing roles and responsibilities must adjust to new grid capabilities and new roles and responsibilities must be created to address gaps between current grid capabilities and those needed in the future grid.

4.8.6 Microgrid, energy storage and related technologies are maturing in a manner that enables power system planning that is more modular and resilient.	
Micrograds and more general variable structure grids are emerging to develop a capability to modularise distribution systems. Bulk energy storage technologies are also emerging as key components of such grid architectures for purposes of stabilisation and grid outage ride-through. Various models for microgrid ownership and integration with distribution systems are also emerging. These include multi-user microgrids that make use of the distribution system versus wholly private microgrids that are attached only at a single point to a distribution system.	Integrated resilient planning is needed to characterise and organise such modular and variable structure grids. New methods for evaluation for grid resilience that support architecture and design decision-making are needed. New approaches to grid management and control and protection that take into account islanding, grid support from the microgrid are also needed.
4.8.7 The politicisation of modelling and forecasting tools	
As Australia's energy transition accelerates, technical modelling and forecasting tools — such as AEMO's Integrated System Plan (ISP), CSIRO's GenCost report, and emissions trajectory modelling—are increasingly being drawn into political and media narratives. While contestability and transparency are important for public discourse, the increasing politicisation of modelling risks undermining trust in technical institutions. Rather than fostering healthy debate, commentary has sometimes been focused on perceived bias instead of constructive interrogation.	This may deter technical experts from engaging in public-facing work or push institutions to overly sanitise or generalise modelling outputs to avoid controversy—both of which reduce the clarity and usefulness of the analysis provided. Politicised commentary can delay action and oversimplify the complexity of the system. In some cases, this can artificially increase investor risk and undermine confidence in and consensus on long-term system planning and direction of travel.

4.9 Near-Term System Operations

Challenges arising from the increasing complexity of real-time operational coordination. These include the need for enhanced visibility and predictability across the T-D Interface (TDI), new mechanisms for operational forecasting, and advanced control room capabilities to navigate growing uncertainty and volatility.

Emerging Trend	Implication/s
4.9.1 System Operators are experiencing new levels of uncertainty and complexity in managing the reliability, security, and stability of the power system	
Historically, management of the power system was oriented toward the security constrained economic dispatch of dozens or hundreds of merchant resources that were typically limited to various forms of synchronous generation. As the power system decarbonises, however, the Market/System Operator (MSO) faces greater levels of uncertainty and complexity. With increased penetrations of VRE, DER and cross-coupling with other sectors, the underlying nature of the system is changing. While having a large variety of existing tools and methods to underpin their operating decisions, many of these tools are largely based upon power system phenomena relevant to synchronous machines. These changes will both limit the applicability of some existing tools and methods as well as dictate the development of new tools and methods to ensure the reliability, security, and stability of the power system.	Faster processes and new methods are required to identify the emerging issues brought on by the transitioning power system. As AEMO's Control Room of the Future work has highlighted [12], new analytical tools that enhance operational decision making in an IBR-dominated power system must be developed. This includes tools to: • Mitigate uncertainty arising from changing system behaviour arising from the adoption of new technologies and the volatility of weather-driven generation. • Capture the interactions and impact of IBR control algorithms that can be detrimental, or beneficial, to the power system's stability and performance. • Conduct stability analyses, which are particularly challenging with time-domain analysis tools. • Aid real-time decision making and management of power system security.

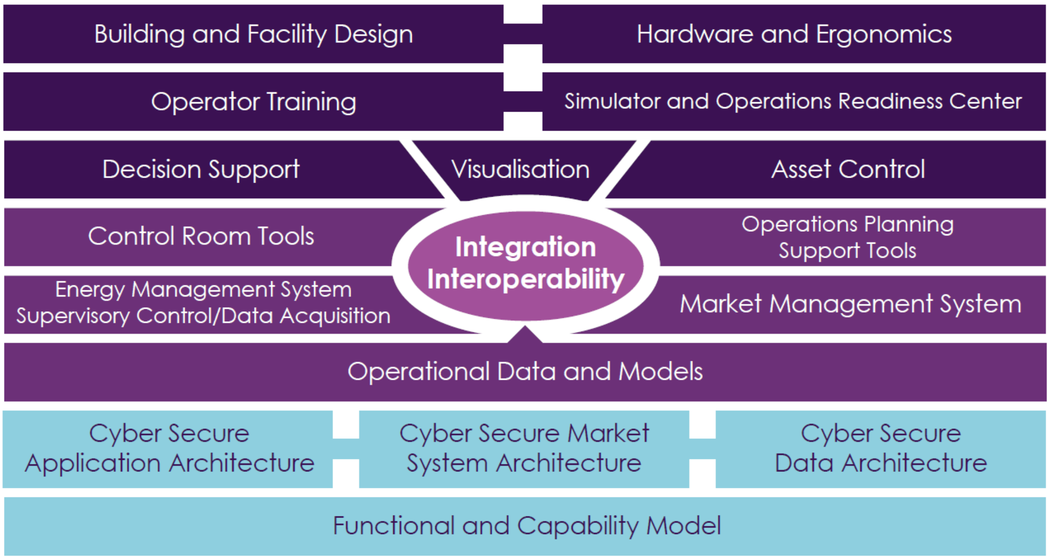


Figure 11: AEMO Control Room of the Future and Future Operations Framework adapted by [12]

<table>
<tr><th colspan="2">4.9.2 Conventional control room capabilities are facing a wide range of emerging demands that require significant capability uplift</th></tr>
<tr><td>Many Market/System Operator control rooms were designed early in the era of large-scale electricity grid interconnection, beginning in the 1970's and they haven't significantly changed since.

Market systems have not materially changed since market start in 1998, and security assessment tools are rapidly becoming obsolete in a power system increasingly dominated by IBR-based VRE generation. As such, this will become particularly pronounced for maintaining energy supply through large and highly volatile weather events, that are occurring more frequently.</td><td>Conventional MSO control rooms cannot effectively manage future power system operations. A significant uplift in capability is required that will involve identification of wider industry needs, building on the existing projects in transmission and distribution operations and maximising national alignment.

The uplift in control room capabilities and their integration with the wider system are expected to require a particular focus on:
• Functional & capability model and underpinning architectures
• Data modelling, data streaming and standardisation
• New advanced analytics and visualisation tools
• Energy and Market Management Systems and real-time simulation
• Operator capabilities, process digitalisation and human factors
• Buildings, facilities and hardware</td></tr>
<tr><th colspan="2">4.9.3 System restoration and black start arrangements are becoming significantly more complex</th></tr>
<tr><td>As the number of system actors and energy resources increases, and much of the synchronous generation fleet retires, system restoration / 'black start' arrangements are becoming significantly more complex.

This is because conventional processes have been largely designed for a power system dominated by synchronous machines. With increased penetrations of VRE, IBRs, and DERs, the huge growth in the number of participating energy resources, and increasing coupling with other sectors, new systems and procedures will be required.</td><td>The following two new black-starting alternatives need to be evaluated. The first involves new specifications for grid-forming IBRs to enable them to directly black-start or to significantly assist with the restoration process.

The other involves new methods, procedures, and analysis techniques to black-start a power system with various penetrations of IBRs, including up to 100%. This may require bulk energy storage devices as energy sources and temporary loads to prevent collapse during start-up.</td></tr>
</table>

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

<table>
<tr><th colspan="2">4.9.5 Distribution networks are informally transitioning toward providing a range of Distribution System Operator (DSO) functions</th></tr>
<tr><td>
With increased penetrations DPV and DER being deployed, the underlying nature of both distribution systems and the entire power system is changing fundamentally.
Traditional system functions and their related organisational roles and responsibilities were originally developed in a context that involved:

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

</td><td>
With the phenomenon of DPV mass adoption by consumers has come the recognition that the traditional roles of distribution network management are needing to evolve.
Globally, this transition is commonly seen as a transition toward the need for an expanding range of functions under the rubric of a Distribution System Operator (DSO). This role is often considered most likely to emerge as an evolution of the existing distribution network businesses.
While alternative models exist, DSO functions are commonly seen as including some or all of the following:

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

</td></tr>
</table>

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

4.9.7	Decarbonising power systems are requiring more advanced Operational Coordination models scalable to millions of participating energy resources
Due to the level of operational volatility experienced by lower-carbon power systems, the expanding volume of participating resources, and the diversity of their types, locations and ownership models, new models of DER coordination are being trialled. As noted earlier this is particularly relevant as Australia's power systems are: • Becoming more diverse and dynamic • Transitioning from hundreds to tens of millions of participating energy resources • Experiencing a progressive erosion of the traditional 'supply-side / demand-side' bifurcation.	Advanced Operational Coordination involves structured mechanisms for coordinating many millions of participating energy resources and embedded grid controls. This must occur in a manner that ensures whole-system stability and enhances efficiency. It must also be co-optimised across all power system layers to ensure that energy resource services dispatched and/or financially incentivised in one layer of the power system (e.g. wholesale market, transmission or distribution system) are not driving unintended negative consequences in other layers of the system. Given the inseparable cyber-physical-economic nature of the power system, close 'market-control' alignment is required to incentivise and activate service provision in a reliable and mutually reinforcing manner. These economic incentivisation and cyber-physical automation elements must be coupled across each power system layer for energy, capacity, flexibility, and essential system services to be delivered when and where needed by the system (from days to milliseconds).

4.9.8	A significant proportion of small-scale Inverter-Based Resources (IBRs) currently behave undesirably when exposed to voltage depressions
Studies have revealed that following large system disturbances, many DPV and DER inverters can behave unpredictably in response, which represents a threat to system security. Current benchmarking in Australia suggests that over 50% of IBR-based DPV behave undesirably [137], in terms of disconnection or power curtailment, when exposed to distribution voltage depressions such as those that occur during transmission level faults.	The sudden, unexpected loss of DPV generation has historically been offset by the disconnection of load. However, with DPV generation increasingly the largest generation source during some time windows, these disturbances now represent a net loss of generation during daylight hours. This can coincide with the loss of the largest single generating unit, increasing the size of the largest credible generation contingency. Without an accurate understanding of how inverters operate, it is difficult for the

Similar inverter technologies will drive energy storage systems, hybrid storage inverters, commercial and industrial systems, and vehicle charging. As such, the continuous assessment of inverter performance to the types of faults and grid disturbances they are exposed to is becoming increasingly critical.	Market/System Operator (MSO) to adequately prepare for and respond to disturbance events. This will require laboratory testing, in-field data analysis, and simulation to build a comprehensive understanding of DER behaviours during disturbances and apply this knowledge to broader system planning and operations. Also need appropriate standards and means to address inadequacies in existing installed base. With increasing DPV uptake, should this undesirable behaviour continue unabated, it will present unmanageable generation contingency sizes.

4.10 Market Structures & Operations

Trends in existing and new market structures and operations arising from the increasing share of low marginal cost resources and the transition to a bidirectional system hosting large volumes of distribution-connected energy resources. This includes market-based mechanisms for flexibility services and valuation mechanisms for Essential System Services.

Emerging Trend	Implication/s
4.10.1 The roles and efficacy of energy-only markets in a near zero-marginal cost future are increasingly under question	
As the world moves toward greater VRE generation and a near zero-marginal cost future, liberalised electricity markets face a crisis of purpose. Up to now, thermal generators – particularly natural gas-powered generators – have had a dual function, providing both physical stability and market stability to our electricity systems. The roles and efficacy of energy-only markets in a near zero-marginal cost future are coming under question and may need to be fundamentally redesigned to adapt. Key questions being asked include: • What role will wholesale energy-only market pricing play in the future? • How must electricity markets evolve to produce clear price signals and drive effective investment decisions?	While electricity systems may be able to function physically without natural gas, electricity market pricing will break down if other solutions don't replace the role that gas plays in setting wholesale spot market prices for electricity. How electricity markets are adapted in the long term may largely depend on which types of technology become the dominant firming solutions (e.g. zero-emissions gas, highly flexible demand, or energy storage). As such, market designers can't make decisions in isolation from technology. In addition, if net-zero electricity systems are to become a reality, they must take care that their reforms go beyond solving today's issues and ensure that their designs are compatible with likely technological development.
4.10.2 New market arrangements that explicitly value capacity are being considered	
Transitioning to a lower-emissions generation profile involves higher levels of near-zero marginal cost VRE generation. Under current energy market arrangements, however, new investment in generation relies on wholesale prices being at sufficient levels long enough to provide adequate confidence, certainty and returns to investors. Where the spot price is not high enough, and expectations of sustained future wholesale prices are not held with enough confidence, sufficient investment may not occur.	To support the magnitude of new generation build required over the next decade, new market arrangements will be required that explicitly value capacity (separate from the energy price) to encourage investors to take long-term capacity risk. A combination of incentives is being considered to support the orderly retirement of thermal generators and timely investment in an efficient mix of resources (firm flexible generation, variable renewable energy and storage) to maintain reliability.

4.10.3	New market arrangements that explicitly value the provision of Essential System Services (ESS) are being considered
Essential System Services (ESS) help keep the power system in a safe, stable, and secure operating state. These critical services, which have traditionally been by-products of synchronous generation, include inertia, frequency regulation, system strength and operating reserves. As the proportion of traditional generation sources decline, inertia, frequency, system strength and operating reserve services must be provided by alternative sources, both centralised and decentralised.	In a power system dominated by IBR-based VRE generation and DER, new market arrangements that explicitly value the provision of ESS will become critical. This will need to include the procurement of services such as frequency support and voltage support services from resources located on both the supply and demand-sides of the system.
4.10.4	**New market arrangements that explicitly value the provision of flexibility and/or network services are being considered**
As the generation fleet transitions, the proportion of system flexibility and firming services that can be provided by traditional supply-side resources is decreasing. In addition, system balancing is increasingly aggravated by stochastic generation sources such as VRE, the operation of which is ultimately inconsistent with the standard 'load-following' paradigm of power system control.	Power systems dominated by VRE and DPV generation will require new sources of system flexibility and grid services on both the supply and demand-sides of the system. This may increasingly require flexibility markets to monitor energy flows and create dynamic market signals that motivate changes in supply and demand, supported by automated activation. Similarly, network services markets may also provide the means to procure physics-based services required to support network stability, power quality and economic efficiency.
4.10.5	**Distribution-level flexibility markets continue to mature around the world as an integral element of whole-system coordination.**
Distribution-level flexibility markets are evolving globally as a crucial component of whole-system solutions. These markets enable the trading of flexibility services at the distribution level, helping to manage congestion, defer network augmentation, and integrate renewable energy sources more effectively. The maturation of these markets is driven by the increasing penetration of DERs and the	The development of distribution-level flexibility markets has significant implications for the energy sector. By enabling local trading of flexibility services, these markets can help to alleviate network congestion and reduce the need for costly infrastructure upgrades. This can lead to more efficient use of existing assets and lower overall system costs.

need for more dynamic and responsive orchestration of them. Flexibility procurement is seen as essential for the beneficial integration of renewable sources, allowing DSOs to ensure secure and stable system operation.

Various research projects and trials are underway to design and test these markets, addressing key challenges such as liquidity, market design, and regulatory frameworks.

In the UK, the landscape for DSOs is maturing rapidly, with significant volumes of demand-side flexibility being procured. This approach has resulted in substantial network augmentation savings, highlighting the financial benefits of flexibility markets. For instance, the UK's National Grid has implemented a Whole System Strategy that emphasizes the integration of flexibility services across distribution and transmission levels, leading to optimised power system operations and cost savings.

Additionally, flexibility markets provide an additional lever to balance supply and demand, enhancing system stability and reliability. The ability to trade flexibility locally also empowers consumers and businesses to participate actively in the energy market, promoting greater social license and investment in DERs. However, the success of these markets depends on the establishment of clear regulatory frameworks, robust market designs, and effective coordination between System Operators and other market participants.

Australia's adoption of Dynamic Operating Envelopes (DOEs) across distribution networks has been world leading. However, there has been comparatively little momentum towards distribution-level flexibility markets. While DOEs help manage the integration of DERs, they do not provide the same level of market-driven flexibility that can benefit local network and system-level needs.

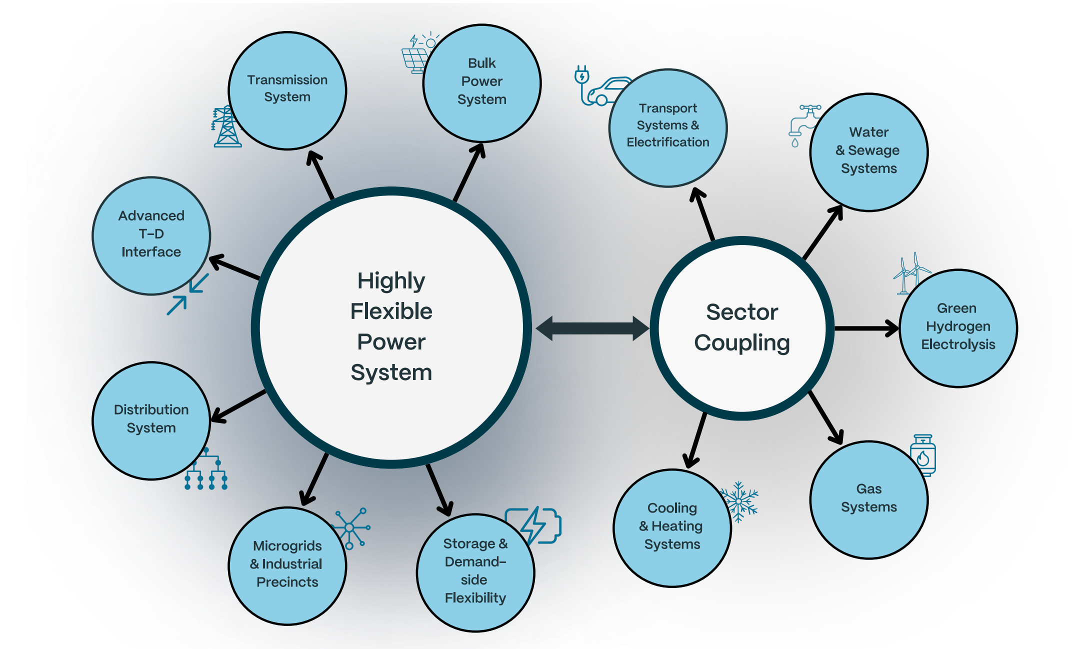


Figure 12: System optimisation benefits emerge through advanced sector coupling.

4.11 Sector Coupling / Electrification

Trends in sector coupling and electrification driven by interdependencies between electricity and other sectors, such as transport, industry, gas, and water. These trends highlight new optimisation opportunities and systemic risks that require careful management.

Emerging Trend	Implication/s
4.11.1 The global focus on the 'Electrification of Everything' continues to expand while also creating elevated single-point-of-failure risks if not effectively managed.	
Sector coupling refers to the integration of energy-consuming sectors (such as heating, transportation, and industry) with the power sector to achieve greater energy efficiency, reduce emissions, and accelerate decarbonisation across multiple sectors. By linking these sectors, energy systems can be optimised through shared infrastructure and cross-sector flexibility, allowing for a more resilient and flexible grid. In Australia and globally, sector coupling is driven by a need to maximise renewable energy utilisation and minimise reliance on fossil fuels across all sectors. Examples include the use of EVs as flexible grid resources, power-to-heat systems, and green hydrogen for industrial applications. However, as more critical infrastructure becomes electrified, the growing interdependence of energy systems increases the risk of systemic failures. A disruption in one sector—whether due to cyberattacks, grid failures, or extreme weather events—can cascade across multiple industries, amplifying the impact. Integrating different sectors enables optimised use of energy infrastructure and resources, which can lead to significant cost savings. For example, surplus renewable electricity can be used for heating or converted to hydrogen for industrial processes rather than being curtailed. This coordinated approach reduces wastage and makes better use of the energy produced, lowering overall costs. It also opens the door	While sector coupling offers significant benefits for decarbonisation, efficiency, and new business opportunities, it also brings challenges, including the need for infrastructure upgrades, enhanced data management, cybersecurity, and regulatory alignment. Increased cross-sector interdependencies may also result in outages and faults causing disruptions to multiple critical systems simultaneously — transportation, heating, manufacturing, and beyond. Similarly, increased coupling between sectors increases cybersecurity risks. Sector coupling also introduces new regulatory and policy challenges, as multiple sectors must work together under coordinated frameworks. Aligning policy objectives across power, transport, heating, and industry would require careful planning and regulatory adaptations.

to new market opportunities and innovative business models. Sector coupling may also introduce new challenges, particularly where demand for electricity surges, potentially outpacing expansion of power system capacity and requiring significant upgrades in infrastructure.	
4.11.2 The electricity and gas sectors are experiencing greater interdependency.	
New sources of flexible generation are replacing coal to meet demand in daily peak periods and when VRE output is low. Gas-powered generation is required as a transition technology as a key source of flexible generation in the medium term. Natural gas also has a key role to play in setting prices in today's wholesale energy-only electricity markets. Because of the way prices are set in these markets, gas prices have disproportionate influence on the price of electricity. As the entry of substantial VRE generation and storage causes coal-fired generators – and subsequently gas-fired generators – to close, it has the potential to undermine this mechanism.	As the withdrawal of coal generation accelerates, new approaches to ensuring strategic investments in gas-powered resources may be required to support transition. Given the price-setting role of gas, the eventual retirement of gas-powered resources will also need to be managed carefully to avoid high and unstable electricity prices. As traditional gas-fired generators withdraw from the market, zero-emission gas-fired generators could prove to be a major stabilising force in the NEM in future years. As the maturity of zero-emission gas turbines improves and input fuel costs reduce, their participation in the NEM should be encouraged with relevant policy levers.
4.11.3 An expanding range and diversity of industrial processes are being considered for fuel-substitution and electrification.	
Heavy industry and manufacturing facilities are actively exploring options for decarbonising industrial processes through electrification. Fossil fuel generated process heat is responsible for a significant share in Australia's emissions. Electrical heating technologies, such as industrial heat pumps, electromagnetic heating, electrical resistance heating, and electric arc heating will likely replace many carbon-intensive industrial	Industrial precincts and processes that actively electrify will significantly increase demands on both distribution and transmission networks. Wider industrial electrification will require significant amounts of additional firmed VRE generation. Many such industrial processes may be configured to function as major sources of system flexibility in exchange for financial incentives. In such cases there will be a need for more advanced coordination between

technologies for high-temperature heating in manufacturing and processing. The use of Green Hydrogen is another indirect route to electrifying industry.	industrial load centres, aggregators and power system control functions.
4.11.4 Passenger and commercial transport are experiencing a growing transition away from petroleum-based fuels to electrification.	
The transition to electric vehicles (EV) began relatively slowly in Australia but is now gaining pace. EV ownership is expected to surge from the late 2020s, driven by falling costs, greater model choice and availability, and more charging infrastructure. According to AEMO's Integrated System Plan, 97% of all vehicles are expected to be battery EVs in 2050 under the Step Change scenario [136].	Such a massive increase in EVs will require large scale deployment of residential, commercial and public charging facilities. This will present challenges for all parts of the power system. An electrified transport fleet has the potential to significantly influence the shape and location of load – for better or worse. Effectively coordinated EV charging through incentives and automation may play a key role in system optimisation and better utilisation of excess VRE generation during the day. Conversely, poorly coordinated EV charging will exacerbate system constraints, augmentation costs and operational risks. Integrating EV, EVSE and electrified transport generally with the electricity sector will be essential to both a stable power system. Without proactive policy, standards, and customer-centric management, system costs incurred to support EVs could increase consumer bills dramatically.
4.11.5 An expanding range and diversity of building services are being considered for fuel-substitution and electrification.	
Like heavy industry and manufacturing facilities, commercial and residential building owners are actively exploring options for decarbonising building services through deeper electrification. Building and water heating provided by gas or electric resistance sources are responsible for a significant proportion of Australia's building services emissions.	Precincts that actively electrify may increase demands on the local distribution network. Wider electrification will also require significant amounts of additional firmed VRE generation. Where coupled with an appropriate building envelope configuration, some building services may function as a valuable source of system flexibility in exchange for financial incentives. In such cases there will be a need for more advanced coordination between

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

<table>
<tr><td>At the same time, ICT technology and infrastructure is becoming increasingly dependent on the electricity system. Data centres continue to grow in number and size – along with their overall share of electricity consumption. The deep interdependencies between the power system and both mobile telephony and internet service provision are also well known.</td><td>Sector coupling risks and opportunities presented by power system / ICT interdependencies.
Application of advanced cyber-security tools and methods commensurate to the level of interdependency, including the structural routing considerations noted earlier.</td></tr>
<tr><td colspan="2">4.11.8 The emerging Green Hydrogen sector has significant potential for beneficial convergence with the electricity sector as it matures.</td></tr>
<tr><td>Australia is aggressively pursuing the development of a major new Green Hydrogen export industry.

AEMO's 'Green Energy Exports' scenario describes a future where underlying electricity consumption almost doubles that of the Step Change scenario primarily due to load growth from production for export [136].</td><td>Should the Green Hydrogen sector develop at the targeted rate and scale, interdependence with the wider power sector will increase dramatically. Key areas of convergence are likely to include:
Green Hydrogen providing a key source of long duration energy storage, balancing multi-day and seasonal disparity in renewable energy generation.
Electrolysis emerges as a productive use of surplus daytime electricity from VRE that would otherwise be curtailed, with the added benefit of smoothing the daily load profile.
Improved utilisation of transmission infrastructure in low load periods as VRE is transported to electrolysers.
Provision of an additional fuel source, either exclusively or blended with natural gas, for utility-scale electricity generation – primarily by peaking plants.
An alternate zero carbon fuel source for on-site backup power generators.
An alternative fuel source for heavy transport and machinery, and high-temperature heating in manufacturing and processing.</td></tr>
</table>

4.12 merging Technologies

Transferable emerging technology trends that may potentially drive transformative impacts on power system operations, security, and optimisation. These include AI, power electronics, IoT, 5G, and distributed ledger technologies.

Emerging Trend	Implication/s
4.12.1 Artificial Intelligence (AI)	
AI is emerging as a promising complimentary tool for system and network operators, enhancing their ability to manage and optimise their operations effectively. AI-driven analytics may allow operators to assess real-time and historical data for demand and supply forecasts, facilitating proactive adjustments that improve network stability and resource efficiency. Additionally, predictive maintenance supported by AI may assist asset management, as intelligent algorithms could detect potential failures early, reducing downtime and maintenance costs. AI also offers tools for optimising employee productivity and operational decision-making. Through automated and augmented data analysis, AI reduces manual, repetitive tasks, allowing employees to focus on complex problem-solving and decision-making. However, deploying AI in distribution systems presents challenges, such as managing data privacy, cybersecurity, and ensuring data quality. As SOs integrate AI solutions, they also require robust training programs and tools to monitor and control AI performance, ensuring consistent and safe operations in a highly digitalised environment.	AI's influence extends across the broader distribution network, significantly impacting SOs and the integration of DERs. In distribution networks, AI enables more precise control and forecasting, which helps SOs manage grid stability as they incorporate variable renewable energy sources. For instance, AI supports DER management by analysing real-time data from smart meters and other devices, which is essential for handling the fluctuating nature of solar and wind energy. AI-driven algorithms can determine optimal load balancing, reduce grid congestion, and enhance fault detection, making distribution networks more resilient and adaptive to changing demands. For DER integration, AI could play a crucial role in managing complex, decentralised energy flows and in forecasting DER output to optimise grid participation. By automating congestion management and load shifting, AI can mitigate issues arising from high DER penetration, such as voltage instability or overloading. Furthermore, AI could aid in enabling flexible demand response programs, where consumers adjust their energy usage based on grid conditions, thus balancing supply and demand in real time.

4.12.2 Generative AI	
Generative AI is expanding the toolkit for system and network operators by automating content creation and supporting advanced decision-making across various operational areas. Many energy system actors can leverage generative AI for tasks such as documentation, data analysis, and even customer interactions. By synthesising complex information into actionable insights, generative AI can help system and network operators generate operational reports, forecasts, and respond to customer queries more efficiently. Generative AI can also enhance internal knowledge management by retrieving and summarising stored information, aiding employees in making more informed decisions. This capability is particularly useful in areas such as incident response and network management, where quick access to past data and predictive models can support timely interventions. However, challenges like data privacy, content validation, and intellectual property rights require careful management, as generative AI often relies on high-quality training data and consistent monitoring to avoid biases or inaccuracies.	Generative AI presents several opportunities to energy system actors. For distribution networks, generative AI may support proactive network management by synthesising real-time data into practical insights and creating predictive models for hosting capacity and fault detection. For system operators, generative AI can provide control rooms with additional information for decision-making. It could also simulate scenarios involving high DER penetration, allowing operators to anticipate issues like voltage fluctuations or congestion and prepare for proactive intervention. Furthermore, generative AI could help SOs optimise customer-centric interfacing.
4.12.3 Cloud & Edge Computing	
Cloud computing and edge computing are two distinct approaches to data processing and storage. Cloud computing involves delivering computational resources like data storage and processing power over the internet from centralised data centres. This allows for near-limitless scaling and flexible pricing, making it ideal for handling large-scale data and complex analytics. On the other hand, edge computing processes data closer to the source, such as at local devices or edge data centres. This reduces latency and bandwidth use, making it suitable for real-time applications and localised decision-making. While cloud	Edge computing plays a crucial role in enhancing the resilience and adaptability of distribution networks, especially as DER integration grows. By enabling real-time, localised data processing, edge computing helps SOs better manage the variability of renewables like solar and wind. For example, during periods of high DER output, edge devices can locally monitor and adjust energy flows, reducing network congestion and minimising the risk of supply-demand imbalances. The integration of edge computing also empowers SOs to improve the reliability of distribution networks by enhancing fault

computing excels in centralised storage and complex data processing, edge computing is better suited for scenarios requiring immediate data processing and low latency.

As the grid decentralises, many customers are turning to Home Energy Management Systems (HEMS), which act as edge computing controllers, making local, real-time decisions about energy generation and consumption.

At the same time, cloud-supported computing platforms like Distributed Energy Resource Management Systems (DERMS) and Advanced Distribution Management Systems (ADMS) enable DNSPs to monitor and coordinate thousands of DERs across their networks.

detection and response capabilities. In a decentralised operational environment, edge devices can autonomously detect and isolate faults, restoring normal operations without delay. This capability is essential for high-DER grids, as it reduces the operational strain on central systems and supports grid stability.

As edge computing technology continues to evolve, SOs will be able to create smarter, more autonomous distribution networks that can handle the complexities of a decarbonised energy future.

4.12.4 Internet of Things

The Internet of Things (IoT) offers DSOs powerful tools to enhance monitoring, control, and optimisation of distribution networks. By interconnecting devices like smart meters, sensors, and other grid components, IoT allows DSOs to collect and analyse data in real-time, supporting a range of operational improvements. Through IoT-enabled devices, DSOs gain greater visibility into network performance, asset health, and demand patterns, making it easier to identify potential issues before they escalate. This real-time monitoring enables more efficient grid management, as DSOs can proactively manage load distribution, reduce outages, and improve response times.

IoT also enhances DSOs' ability to integrate DERs. With IoT, DSOs can track DER output and adjust grid operations to accommodate the variable nature of renewables, such as solar and wind. Additionally, IoT-driven analytics can support predictive maintenance, enabling DSOs to reduce maintenance costs and improve asset lifespans by addressing issues before they result in failures. However, integrating IoT into distribution systems also

IoT has strong potential for creating smarter, more flexible distribution networks, enabling DSOs to adapt to the increased complexity brought by high DER penetration. In distribution networks, IoT facilitates automated data gathering across various grid points, which enhances grid stability and operational efficiency. For example, sensors placed along distribution lines and substations provide detailed data on voltage, current, and power quality, helping DSOs to monitor grid health and quickly address disturbances. This also enables finer control over voltage regulation, making the grid more resilient to fluctuations from renewable energy sources.

For DER integration, IoT provides DSOs with the necessary insights to manage and optimise decentralised energy flows. With data from IoT-enabled DERs, DSOs can predict energy output, adjust grid operations in real time, and balance demand and supply more effectively. IoT further supports demand response initiatives by enabling real-time communication with consumer devices, allowing DSOs to shift loads during peak times and reduce grid strain.

raises challenges, particularly regarding data security and interoperability across different devices and platforms.	
4.12.5 5G for areas that lack broadband infrastructure	
The rollout of 5G technology presents a significant opportunity for system and network operators, providing ultra-fast, low-latency, and highly reliable wireless communication essential for real-time grid management. With 5G, system and network operators, can monitor power quality and asset performance in real time, allowing for quicker responses to faults and improved predictive maintenance, particularly valuable for managing distributed energy resources (DERs).	5G supports the operation of smart meters, sensors, and IoT devices, which enhance system and network operators' ability to collect and act on data from across their service territory. This is particularly useful in areas lacking broadband infrastructure or where traditional communication networks may be unreliable. For system and network operators to fully leverage 5G, they need to adapt their operations to work with telecom providers, who will typically own and manage 5G networks.
4.12.6 Distributed Ledger Technology (DLT)	
Blockchain technology offers system and network operators a secure, decentralised ledger system that can improve transparency and efficiency in energy transactions and grid management. For SOs, blockchain provides a means to streamline processes that involve multiple stakeholders, such as tracking renewable energy certificates, verifying DER contributions, and facilitating peer-to-peer (P2P) energy trading among consumers. By securely recording and verifying transactions on a decentralised ledger, blockchain reduces the need for intermediaries, making these processes more efficient and trustworthy.	Blockchain has the potential to reshape distribution networks by enabling decentralised and secure transactions between energy producers, consumers, and prosumers. This decentralisation allows SOs and NSPs to manage and verify DER contributions more effectively, facilitating transparent energy accounting and trading at the distribution level. For instance, blockchain can support microgrids and community energy projects by providing a secure platform for P2P energy trading, allowing users to buy and sell locally generated renewable energy without the need for a central authority.
4.12.7 Advanced Communications to support IoT devices	
Advanced communication technologies—including fibre optics, low-power wide-area networks (LPWAN), and advanced wireless solutions—are essential to manage the increasingly complex and data-intensive nature of modern distribution grids. These communication systems enable to the transmission of high volumes of data rapidly	Advanced communications play a pivotal role in enhancing the flexibility, responsiveness, and resilience of distribution networks, particularly as DER integration continues to rise. By providing high-speed, reliable data transmission, these systems enable SOs and NSPs, to monitor and control DERs, such as solar panels, batteries, and EVs, in real time.

and reliably, supporting functions such as real-time monitoring, control, and automation. With these advanced networks, Sos and NSPs can gather data from smart meters, sensors, and DERs, allowing them to monitor and adjust grid operations on a much finer scale. For SOs and NSPs, advanced communications improve coordination across grid assets, facilitating seamless integration of DERs and enabling more responsive load management. These systems also support improved cybersecurity through secure, dedicated networks that reduce the risk of data breaches and cyber threats. However, deploying and maintaining these communication networks requires significant investment and close collaboration with telecom providers, as well as robust cybersecurity measures to protect against potential vulnerabilities.	This connectivity allows SOs and NSPs, to balance supply and demand more effectively, stabilising the grid despite the variability of renewable energy sources. Furthermore, advanced communication networks facilitate demand response programs, where SOs and NSPs can send real-time signals to consumer devices and DERs, instructing them to adjust energy usage or generation based on grid needs. These systems also enhance fault detection and outage management by enabling faster response times, as SOs and NSPs can identify and isolate faults quickly to minimise downtime. As advanced communication infrastructure becomes more widespread, SOs and NSPs will be better equipped to manage a decentralised grid, support consumer engagement in energy markets, and ensure reliable service amidst growing demand and renewable integration.

5 Conclusion

This report provides a consolidated view of the many disparate, exogenous and endogenous trends reshaping Australia's power system. Informed by Systems Engineering principles, the analysis has highlighted the breadth, interdependence, and accelerating pace of change. The trends span technical, operational, market, regulatory, and societal domains, revealing a system undergoing not isolated shifts, but a deep, structural reconfiguration.

Taken together, these trends illustrate that the energy sector is transitioning from a historically stable, centralised model to one that is decentralised, data-rich, customer-oriented, and increasingly shaped by external forces. Managing this complexity will require moving beyond incremental adjustments and siloed solutions. Paradigm shifts in planning, governance, and investment thinking are essential.

Identifying the broad expanse of Emerging Trends serves a foundational purpose: to inform the identification of a much smaller set of systemic issues that frame the problem domain as a targeted shortlist of actionable whole-system challenges. This distillation is the focus of the next Report 3 – Systemic Issues and Transformation Risks. By distilling a finite set of cross-cutting issues from the nearly 100 Emerging Trends interrogated, Report 3 provides a focused set of issues that directly inform the consideration of DSO and TDC models.

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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

- Australian Energy Market Operator (AEMO)
- Commonwealth Scientific Industrial Research Organisation (CSIRO)
- Energy Systems Catapult (ESC)
- Massachusetts Institute of Technology (MIT)
- Pacific Northwest National Laboratory (PNNL)
- Rocky Mountains Institute (RMI)
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Individuals

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- Eamonn McCormick
- Dr Ron Melton
- Peter Senge
- Dr Jeffrey Taft
- 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 Walls: Where excessive data volumes, latencies and processing 'bottlenecks' occur, optimisation engines will hit a computational 'time wall' at some point where no amount of computing resource will be adequate to solve the optimisation problems in a reasonable time. • 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.
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. A modern power system is an Ultra-Large Scale (ULS), geographically distributed cyber-physical system. It is characterised by the deep, real-time integration of computational intelligence, communication networks, and sensing (cyber) with massive, physics-governed electromechanical infrastructure (physical). This creates bidirectional feedback loops where cyber elements continuously monitor the physical state, execute control algorithms, and actuate physical devices, while the physical processes directly determine the inputs and constraints for the cyber layer. The grid's stability, security, and functionality emerge from this continuous, dynamic interaction operating under strict temporal constraints dictated by the laws of electromagnetism and thermodynamics.
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	The market-control system of an electricity system is the integrated set of mechanisms, processes, and technologies that coordinate market operations with real-time grid control. It enables efficient energy trading, supports the balancing of supply and demand, system security and reliability, regulatory compliance, and 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.