AUSTRALIAN RESEARCH IN POWER SYSTEMS TRANSITION (STAGE 4)

Energy Catalyst

REPORT 4 OF 5

Distribution System Operator (DSO) Models

AUGUST 2025

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Energy Catalyst

Navigating to 2035 en route to 2050

Australia's power systems are transitioning from a past of hundreds of large, upstream generation plant to a future with tens of millions of resources participating across all tiers/layers of the grid. Well-designed DSO models can play a critical role in facilitating the mutually beneficial participation of millions of distributed resources as an integral part of Australia's future grids. They will also play an increasingly important role in collaboration with the system operator to support whole-system operability via Transmission-Distribution Coordination.

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Executive Summary

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

This is the largest scale of change to impact the structure and operation of these critical systems in their 100-year history. The resulting transformation from unidirectional bulk delivery systems to deeply decarbonised and increasingly bidirectional systems may be correctly categorised as a structural '*megashift*'.

Given the deeply distributed nature of Australia's grid transformation, this report focuses on Distribution System Operator (DSO) models as an integral part of whole-system transformation. While respecting the historical context of the power system, DSO models are noted as inherently future-facing new capabilities. Therefore, the development approach has avoided a primary dependence on extrapolating from the unidirectional past to determine the DSO capabilities needed for Australia's increasingly dynamic and bidirectional future. While this has demanded a much wider review of the extensive Australian and global literature, DSO deployment experience and significant first-principles analyses, no other development option appeared credible.

An additional feature of this report is that it attempts to consider DSO models from the dual perspectives of the distribution system and its relationship with the wider power system. While the legacy unidirectional system has been quite siloed, the 'problem space' to which DSO models respond is one in which high-CER/DER distribution systems will play an increasingly important role in supporting whole-system operations via collaboration with the system operator. In doing so, the report focuses on a range of strategic and operational questions as the basis for analysis, such as:

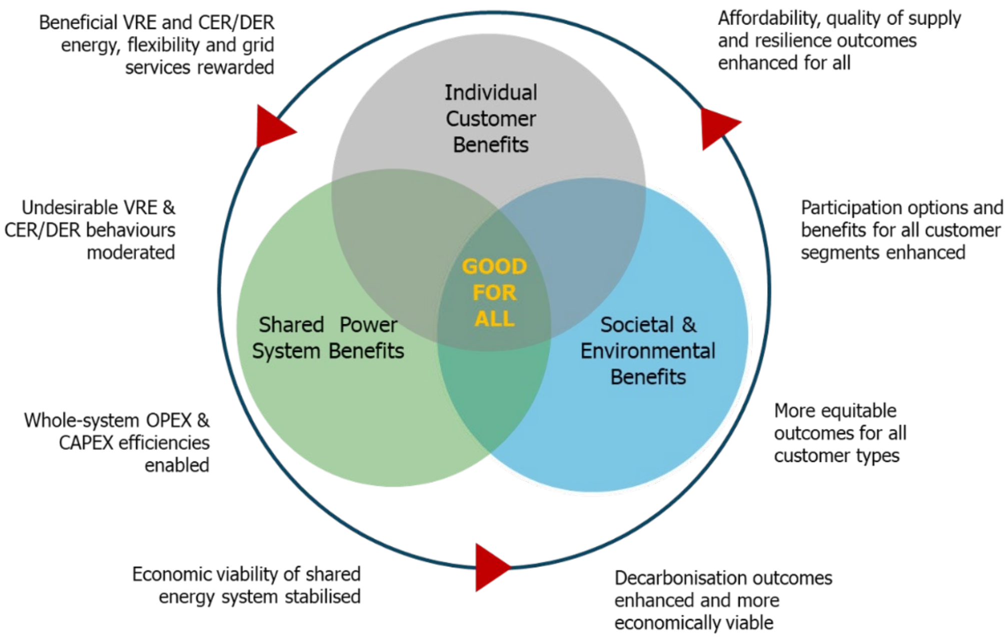
- What are DSO models, what do they do, and toward what objectives?
- Why are DSO models critical in a decarbonising high-CER/DER power system, both locally within each distribution system and within a whole-system approach to grid transformation?
- What key architectural and design considerations are required to advance stepwise implementation, ensure long-term scalability, minimise rework and unintended consequences?

As part of an integrated reference set of five reports, Chapter 1 and Chapter 2 provide an overview of the set and its relevance to DSO models. Developed through the lens of Design Thinking and underpinned by Systems Engineering, Systems Architecture and a range of related disciplines, the reference set is designed to enable a subsequent Detailed Architecture process for DSO and TDC[1] models.

[1] Transmission-Distribution Coordination (TDC)

Chapter 3 then briefly discusses the relationship between this report and National Consumer Energy Resources Roadmap (NCERR) initiative. In simple terms, while distinct and independent both bodies of work are complementary. The related DSMO work package primarily focuses on the next most necessary steps toward implementing DSO models. In parallel, the development of this report has primarily focused on DSO development over the next decade to 2035 and beyond.

In setting the context for considering DSO and TDC models, Chapter 4 describes the unfolding structural transformation in which these capabilities become critical. It focuses on the inherent variability of weather-dependant generation which contributes to growing operational volatility. This is compounded by increasingly two-way power and information flows as the proportion of transmission-connected energy resources gradually declines and the volume of distribution-connected continues to grow. Key challenges arising from these trends are explored given their direct relevance to considering DSO models that are capable of serving near-term requirements while also being capable of scaling to efficiently serve 2035 and beyond.



A DSO orchestrates the 'system' of network assets, flexible and inflexible demand, customer-owned CER and large-scale DER to deliver enhanced technical, economic and customer outcomes not possible by managing network assets alone.

In light of these developments, Chapter 5 then explores the need for new sources of operational flexibility as volatility increases, and conventional sources of flexibility are withdrawn. The importance of flexibility is discussed and characterised across several time scales, and a range of potential new sources considered. The need for more interdependent operation of the end-to-end system is discussed in the context of increasingly bidirectional power flows, enabled by operational coordination models that span the various system tiers/layers that were originally designed to support unidirectional operations. While recognising the important role of digitalisation and interoperability standards, the chapter concludes by noting that a wider set of disciplines including Systems Architecture and control theory are required to achieve this level of operational interdependence.

Informed by the wider structural transformation described above, Chapter 6 then considers the transition to DSO models as being not less than a necessary structural intervention[2] to prepare Australia's power systems for a deeply decarbonised and high-CER/DER future. As a still maturing area, it is noted that the nature and capabilities of DSOs have been characterised in diverse ways globally and in Australia. In response, the analysis identifies and addresses five key questions about DSO models that enable convergence on a more integrated set of definitions. How DSOs are characterised globally is first reviewed and the results tabulated to allow readers to note the similarities and differences. Key elements of the problem definition that underpin the need for DSOs are then explored, followed by an examination of the strategic objectives toward which DSO actions may be directed over near, medium and longer-term. A working definition of DSO is then developed and a range of features that differentiate them from conventional distribution network businesses are discussed. Finally, the five key functions that are intrinsic to fulfilling the DSO's operational responsibilities are described.

In recognising the emergence of DSO models as an essential element of whole-system grid transformation, Chapter 7 then highlights how national and/or transnational policy, regulatory and innovation initiatives have underpinned and accelerated the DSO transition in the United Kingdom (UK) and the European Union (EU). Recognised as a key part of enabling whole-system grid transformation, the consideration of DSO models will be significantly enhanced where informed by the wider policy, regulatory and innovation landscape.

Given the scale of change in which DSO models become essential, Chapter 8 then applies formal Systems Architecture principles to evaluate three structural archetypes that have been repeatedly proposed as the context in which DSO models may be deployed. Relevant legacy structural features of the existing power system are discussed to highlight why the inherited structural arrangements are increasingly ill suited for enabling Australia's high-CER/DER future. The discussion then focuses on assessing the advantages and disadvantages of the two most plausible structural archetypes in which DSO and TDC models may be deployed.

Having considered the wider structural archetypes for DSO and TDC deployment, Chapter 9 then explores the functional relationships between a DSO and the various other entities involved in managing a decarbonising, high-CER/DER power system. Informed by the prior analysis, this provides an indicative comparison of the operational complexity between the two most plausible structural archetypes. The coordination relationships are considered in more detail between the DSO and horizontal, upstream and downstream entities, again considering the comparative complexity of the two options. The chapter concludes by considering how the structural alternatives impact the ability of the DSO to provide the system operator visibility, predictability and operational coordination of millions of CER/DER together with well-integrated TDC functions.

Having established the wider structural context in which DSO models exist, Chapter 10 then examines the five core DSO functions identified earlier in Chapter 6 at a next level of detail. While a wide range of sources have informed this analysis, much of the content has been developed on a first principles basis as the detailed tabulation of DSO functions and subfunctions in the global literature is limited and context specific. Having considered each of these functions individually, their operational independence is then illustrated to highlight how each of the five functions either leads, supports or benefits from the other functions to achieve different target outcomes.

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

Chapter 11 then highlights that transparency, neutrality and trust are essential requirements for DSO design, operation and governance. A DSO is uniquely responsible for achieving its objectives via the real-time coordination of the 'system' of network assets, flexible and inflexible demand, customer-owned CER and large-scale DER. This trusted neutrality particularly extends to the consistent and verifiable equal treatment of network and non-network assets and their incentivisation. Initial perspectives are provided on how different jurisdictions are approaching governance to ensure operational neutrality and stakeholder trust. In addition, two alternative approaches from the United Kingdom are provided for illustration. In a context where theoretical options and diverse opinions abound, the chapter concludes by providing observations that demonstrate how the targeted application of architectural and physics-based considerations helps differentiate the governance options that have the greatest practical relevance from those that are ultimately implausible.

Zooming out from the detailed considerations of the previous chapters, Chapter 12 collates a range of benefits that the transition toward DSO models is enabling. Consistent with the reference set of five reports, the diverse range of benefits are correlated against the most relevant Future Customer & Societal Objectives (Report 1) or Systemic Issue & Transformation Risk (Report 3). These wide-ranging examples illustrate how DSO models are enabling early outcomes while also readying the system for the more comprehensive transformation that will continue unfolding over the next decade and beyond.

Informed by the analysis undertaken, Chapter 13 then provides an integrated set of ten recommended priority actions to underpin the development of future-ready DSO and TDC models as follows:

1. Recognise that 21st century distribution systems are becoming renewable energy zones that will self-supply >50 – 150% of local demand.
2. Reconceptualise the 21st century transmission-distribution relationship as intrinsically bidirectional, collaborative and mutual-beneficial.
3. Recognise that DSO & TDC models are transformational enablers, not simply enhancements to the legacy grid structures.
4. Recognise that activities focused on 'keeping the lights on' and 'creating the future power system' are equally necessary and require parallel paths of focus and effort.
5. Accept that in times of profound transformation, there is no textbook, no perfect knowledge and no single entity with all the answers.
6. Build sector-wide capacity for identifying and addressing structural constraints in addition to upgrading components and targeted enhancements.
7. Establish a strategic and collaborative program of Systems Architecture development to underpin DSO, TDC and related NCERR initiatives.
8. Advance DSO & TDC designs as interdependent structural enablers.
9. Formalise DSO & TDC roles using a structurally informed approach.
10. Distinguish between transitional and enduring DSO & TDC structures and functions.

The transition to DSO models is a complex and challenging but critical topic that requires a structured, respectful and evidence-based process of debate. As such, readers should be aware that the development team has seen its key responsibility as presenting the most representative and technically credible content and options without fear or favour. This has meant consciously avoiding attempting to please everyone, rushing to compromise positions and/or proposing definitive solutions where none yet exist. While far from the final word on this topic, we trust the report makes a tangible contribution to informed, respectful debate both in Australia and globally.

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List of Acronyms

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

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

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

1 Report Purpose, Context & Rationale

1.1 Purpose

Australia's large scale power systems are transforming from a past involving hundreds of large generation plant to a future involving tens of millions of diverse energy resources connected across all vertical tiers/layers of the grid.

As multiple drivers of change converge, Australia's power sector now finds itself on the global frontier of large-scale grid transformation. This involves navigating physics-based phenomena never previously experienced in a continental-scale grid as the nation's power systems become increasingly volatile and bidirectional.

Consistent with global trends, decarbonising power systems are moving from a relatively stable, unidirectional past to increasingly dynamic and bidirectional future. In Australia this has been accelerated with world-leading adoption of Distributed Photovoltaics (DPV), large-scale deployment of utility-scale Variable Renewable Energy (VRE) and the progressive withdrawal of the aging coal-fired generation fleet.

Arguably representing the largest scale of change to impact the structure and operation of our power systems in their 100-year history, this scale of transformation is accurately categorised as a structural '*megashift*' in how power systems such as Australia's National Electricity Market (NEM) function.

As distribution networks host an ever-increasing proportion of Australia's energy resources in the form of Consumer Energy Resources (CER/DER), this report focuses on the critical topic of Distribution System Operator (DSO) models. Informed by the extensive global and Australian literature, and practical learnings from the implementation of DSO models, the report identifies that the move toward DSO models is not simply a further addition to the inherited 20^{th} century system architecture. Rather, it is ultimately a key part of the essential, strategic response to provisioning Australia's power systems for an increasingly decarbonised, distributed and participative future.

Given the wide-ranging nature of the report, its development has been informed by a range of key strategic questions such as:

> *What are DSO models and what do they do? What are their key strategic and operational objectives? How are they similar and different from conventional distribution businesses?*
>
> *Why are DSO models critical in a decarbonising high-CER/DER power system, both locally within each distribution system and as part of an integrated, whole-system approach to grid transformation?*
>
> *What key architectural considerations are required to advance stepwise DSO implementation, ensure long-term scalability, minimise unintended consequences, significant rework and/or stranded investments?*

As such, this report respects the historical context in which our power systems originally developed without attempting to primarily extrapolate from the past arrangements into a very different future. It has, therefore, been developed from a future-facing perspective that considers DSO development over the next decade to 2035 and beyond. This will enable more scalable action in the present and reduce the risk of unintended consequences and subsequent rework in the future. Further, the report also considers DSO models from the dual perspectives of the distribution system and its relationship with the wider power system. This is because high-CER/DER distribution systems will play an increasingly important future role in supporting whole-system operations in collaboration with the system operator (AEMO).

Finally, given the breadth of matters relevant to the consideration of DSO models, this report should be read in light of the development approach and limitations which are outlined in Chapter 2 below.

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[3] 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.

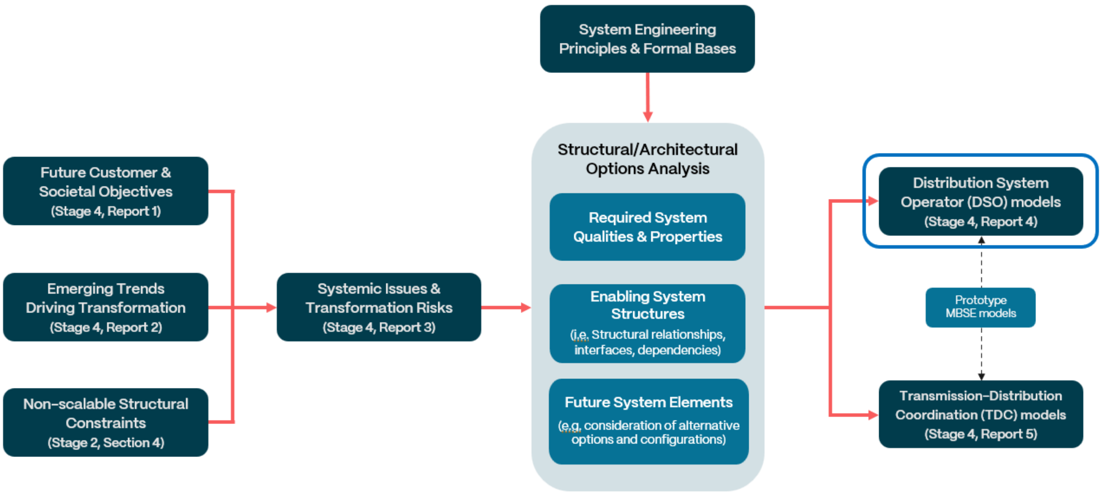

Figure 1: This report is one of five which, as a reference set, are designed to support an integrative approach to Australia's power system transformation

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

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

In the context of Australia's increasingly decarbonised and distributed power systems, a key aim of this reference set is to support the emergence of robust and future-scalable DSO models together with the related Transmission-Distribution Coordination (TDC) capabilities.

Importantly, these capabilities are not an end in themselves. Rather, they are a necessary response to the profound forces of change now transforming how power systems like the NEM operate. While DSO and TDC models are themselves deeply transformative, it is the wide range of transformational forces impacting our century old power systems that are driving their emergence as priorities.

As a still maturing area, however, it is noteworthy that scores of reports exist which address different aspects of the need for DSO models in a high-CER/DER context. Unfortunately, however, no universally accepted definition of what a DSO is, nor body of knowledge or taxonomy outlining what a DSO does is known to exist. Even more problematic, while extensive discussion of the many technical functions a DSO may perform exists (albeit, often using different terms and framing), there is a general lack of definition of the short, medium and long-term objectives which decisively establish the reason for establishing DSOs. This is particularly the case regarding DSO objectives in the medium and longer-term and including how DSOs will benefit the wider decarbonising grid, not just the distribution system. While this was less important in the past, it is now becoming vital as power and information flows become increasingly bidirectional and the system must function in a far more interdependent manner end-to-end.

In the context of GW-scale power systems like the NEM that are experiencing deep decarbonisation while also becoming increasingly distributed, the reference set necessarily culminates with a detailed focus on DSO and TDC models. A unique contribution this series attempts to make is examining these topics in the wider context of future customer and societal objectives (Report 1), the dozens of externalities driving grid transformation (Report 2) and the cyber-physical structural context that will significantly influence the success or otherwise of even the best DSO or TDC model.

Ultimately, this particular report attempts to fill a key gap by bringing together a logically structured synthesis of the global literature and practical experience relevant to DSO models that is broadly contextualised to Australia. At a practical level, it is designed to underpin and help accelerate a subsequent, collaborative Detailed Architecture process that involves all relevant actors across the NEM value chain. Reviewing and updating the system architecture of any complex system can only be successfully undertaken as a 'team sport'. Therefore, this foundational set of content is designed to enable multiple stakeholders to more rapidly converge on the key structural issues and opportunities that must be addressed if we are collectively to ensure the NEM is made future-ready at least cost.

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

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

2 Report Development Approach & Limitations

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 [1].

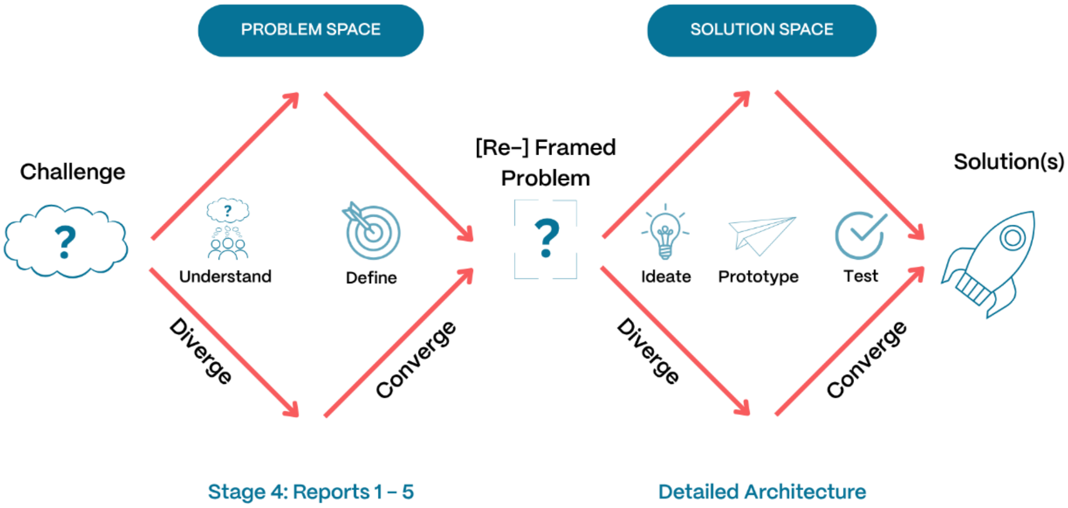

Figure 2: The reference set of five reports applies a Design Thinking approach to whole-system transformation underpinned by Systems Engineering and related disciplines

As noted previously, the reference set is designed to underpin a subsequent Detailed Architecture process that provides an integrated approach for navigating Australia's timely and efficient deployment of DSO and TDC models (i.e. 'solution space'). As illustrated in Figure 2 above, 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 this report, the following definition of a DSO was distilled:

> *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.

While a wide range of different terms and concepts are used across the global and Australian literature, the analysis identified the following five core functional areas intrinsic to a DSO:

1. Active System Management
2. Distribution Market Mechanisms
3. Integrated Distribution Planning
4. Advanced Data Analytics and Sharing
5. Transmission-Distribution Coordination

Each of these are examined in some detail in their structural and functional context.

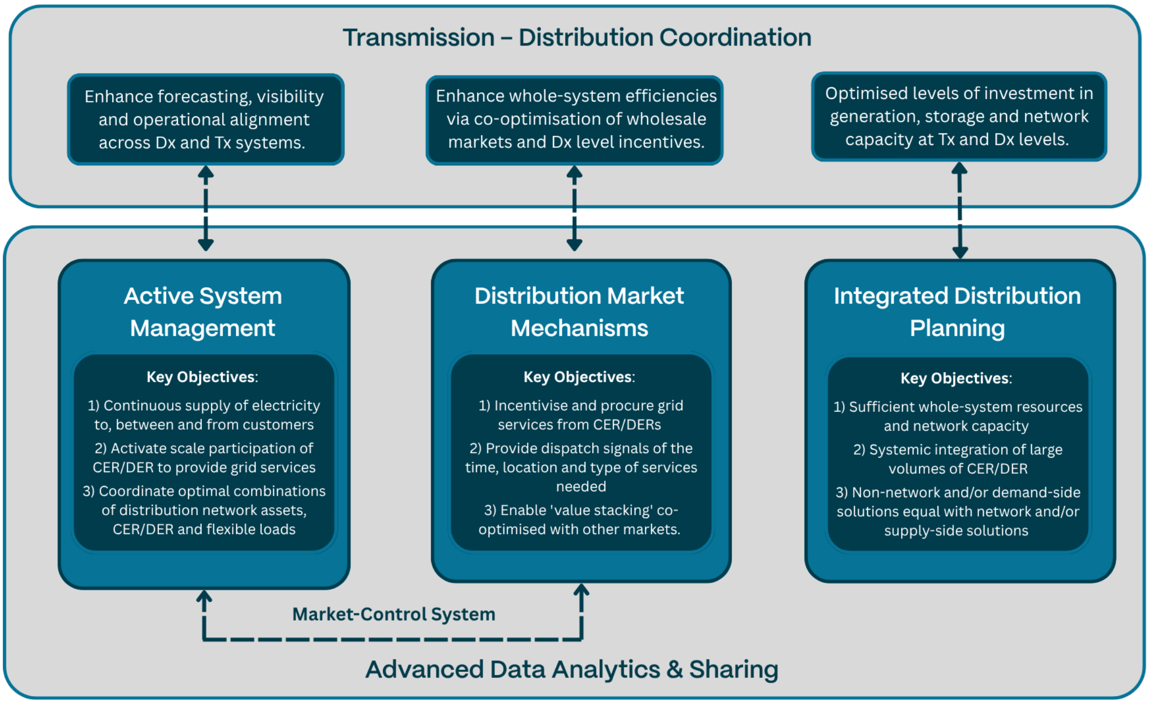

Figure 3: A high-level view of the five functional areas intrinsic to a DSO

2.3 Development Methodology

The global literature relevant to DSO models numbers in the hundreds of sources which apply a wide range of approaches and are mostly context specific. As a still maturing area, a wide diversity of terms and concepts are also commonly employed and no universally accepted definition of what a DSO is or does is known to exist.

In an effort to help address these gaps, the development of this report involved multiple iterative loops in consultation with several Australian and global experts from industry and academia. Guided by the principles and methodologies outlined in Appendix A, the process moved through the following steps:

- Clarify the scope and purpose relevant to Australia and synthesise a working draft table of contents for stakeholder review and feedback.
- Update and progressively iterate the report structure informed by feedback provided by CSIRO, AEMO and DNSP staff and other stakeholders.
- Identify the most relevant sources from the expansive global literature with a particular focus on the United Kingdom, the United States, the European Union and Australia.
- Interrogate the relevant industry, government and academic literature, capturing relevant insights and converging the findings where degrees of consensus emerged.
- Employ structural analysis to examining the critical cyber-physical relationships between the most commonly discussed DSO models and structural archetypes to identify key strengths and potential weaknesses.
- Conduct first principles-based analysis and synthesis to fill various gaps that receive limited treatment in the published industry, government and academic literature.
- Further iterate the report structure and content, comparing and contrasting it with the global literature and expert opinion.
- Synthesise key findings into the corresponding report sections progressively submit the relevant material for external review.
- Receive, evaluate and integrate stakeholder feedback and finalise the report.

The transition to DSO models is a complex but critical topic that requires a structured, respectful and informed process of debate. As such, readers should be aware that the development team has seen its key responsibility as presenting the most holistic, representative and technically credible content and options without fear or favour. This has meant consciously avoiding attempting to please everyone, rushing to compromise positions or proposing definitive solutions where none yet exist. While far from the final word on this topic, we trust the report makes a tangible contribution to informed, respectful debate both in Australia and globally.

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.
- Over two hundred sources have been considered in the development of the reference set, many of which have either explicitly or implicitly informed the thinking of the development team. Appendix B provides recognition of the particular sources that have most fully informed our thinking on several key topics addressed in this report as the global sector experiences a profound contest of ideas.
- 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 C and many report sections contain Key Concept breakouts designed to support clarity of communication.
- The reference set focuses on several emerging areas of consideration and is designed to assist navigation of the 'emerging future' over the next decade and beyond. It is therefore a consolidation of the development team's understanding at the time of publishing and will likely benefit from a comprehensive update on at least a bi-annual basis.
- While a range of tools and models are employed as a basis for reasoning about how the power system and its wider societal context may evolve, it is recognised that reality is far more complex than any model or archetype can ultimately represent.
- Recognising the inherent complexity of the topics explored, the diversity of perspectives and terminology, and the many thousands of pages of global content that is more or less relevant, the following points should be noted:
    - The reference set is inherently explorative and spans numerous overlapping topics and developments, many of which are yet to mature to a point of industry consensus, either in Australia or globally.

- Therefore, it is inevitable, expected and healthy that different readers will draw different conclusions on some or several of the topics addressed.
- Particular content will mean more to some system actors and/or those with particular discipline expertise than others. The standpoint of the reader and the time horizon they are primarily focused on will likely influence how the desirability or otherwise of particular content is evaluated.
- Accurately predicting the future and/or foreseeing all eventualities is impossible. Therefore, it is anticipated that some of the content contained in this reference set will prove to be incorrect. For that reason, stakeholder feedback is strongly encouraged and a formal mechanism to do so is provided below.
- In summary, the information contained in the reference set comprises general statements based on research. No claim to represent the official policy of CSIRO, AEMO or any other third party is made.

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

2.5 Accessing the Reference Set & Providing Feedback

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

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

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

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

Key Concepts A

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.

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).

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.

3 Policy Context: National CER Roadmap

In July 2024, state and federal Energy Ministers published the National Consumer Energy Resources Roadmap which set out an extensive program of work to unlock the value of CER/DER at scale [1].

Given the critical role of the Roadmap process, some of the most salient points relevant to the topic of DSO models are outlined below together with some brief observations. These focus on the Roadmap Vision, Power System Operations and Markets workstream objectives.

3.1 Roadmap Vision

> Consumer Energy Resources are an integral part of Australia's secure, affordable and sustainable future electricity systems, delivering benefits and equitable outcomes to all consumers through efficient use which smooths the transition, rewards participation and lower emissions.

Key aspects of the Roadmap vision relevant to DSO models include:

- CER/DER must be holistically enabled to function as an integral part of Australia's future power systems
- The active, beneficial support of CER/DER will enable Australia's power systems to be more secure, affordable and sustainable
- Australian consumers will receive tangible benefits and equitable outcomes through millions of CER/DER being intelligently integrated into the wider system; and
- Sustained benefits will arise through well-integrated CER/DER operating in more grid-friendly and efficient ways, which helps smooth the transition, rewards active participation and accelerates reductions in Australia's carbon emissions.

3.2 Power System Operations objective

> The electricity system will need to adapt to high CER/DER uptake. Projects in this workstream aim to enable secure and optimised system operation of the distribution network, helped by the adoption of nationally consistent standards and processes.

Key aspects of the Power System Operations workstream objective relevant to DSO models include:

- A recognition that Australia's power systems must fundamentally adapt to the continued high levels of CER/DER uptake
- This adaptation must ensure that the systems integration of CER/DER at scale is configured in a manner that underpins the secure and optimised operation of Australia's distribution networks; and
- The adoption of nationally consistent processes and standards are recognised as a critical enabler of achieving this.

3.3 Markets objective

Electricity markets will need to adapt to a system high in CER/DER uptake. Projects in this workstream are aimed at developing well-designed markets and incentives to optimise utilisation of CER/DER and existing grid assets and reduce the need for system augmentation. In turn this will unlock significant value for market participants, including networks and consumers. Incentivising efficient investments in electricity markets provides an efficient way to accelerate emissions reductions.

Key aspects of the Markets workstream objective relevant to DSO models include:

- The need to focus on well-designed markets and incentives relevant to facilitating sustained CER/DER participation at scale
- These markets and incentives must optimise the utilisation of both participating CER/DER and existing electricity grid assets
- This optimisation of CER/DER and asset utilisation must be capable of driving reductions in the need for system augmentation (where CER/DER-base alternatives are available); and
- This work is ultimately targeted at unlocking significant value for market participants, including networks and consumers, and providing efficient ways to accelerate emissions reduction.

3.4 Relationship to this report

The work of the CER Taskforce including its DSMO work package and the development of this report are independent activities which were advanced under different sponsorship and funding.

While no formal relationship exists, several points of informal discussion between both teams occurred to exchange information. This provided mutually beneficial additional perspective and the opportunity to maximise complementarity while also maintaining process independence.

Both bodies of work inform the other. In simple terms, the DSMO work package primarily focuses on the next most necessary steps toward implementing DSO models. In parallel, the development of this report has primarily focused on DSO development over the next decade to 2035 and beyond.

4 Transformational Context: Increasingly volatile and bi-directional power systems

Australia's GW-scale power systems are recognised as experiencing some of the world's fastest and most transformational change [2] As explored in Reports 1-3 of this series, changing customer and societal expectations [3], the convergence of almost one hundred emerging trends [4], and cross-cutting systemic issues and transformation risks [5] are driving profound shifts to these critical societal systems.

In this context, Australia now finds itself on the global frontier of grid transformation navigating operational physics never previously experienced in a GW-scale power system. All vertical tiers/layers of the grid are impacted, including bulk power, transmission and distribution, resulting in an increasingly volatile and bidirectional power system [6], [7], [8].

This scale of transformation provides the specific context in which both Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models become critical to future power system operations.[4] This chapter, therefore, describes the unfolding structural transformation that provides the context or 'problem space' in which these new capabilities become critical. It focuses on the inherent variability of weather-dependant generation which contributes to growing operational volatility. This is compounded by increasingly two-way power and information flows as the proportion of transmission-connected energy resources gradually declines and the volume of distribution-connected continues to grow. Key challenges arising from these trends are explored given their direct relevance to considering DSO models that are capable of serving near-term requirements while also being capable of scaling to efficiently serve 2035 and beyond.

4.1 A profound structural transformation

Similar to power systems in all developed economies, the structure of Australia's NEM was originally designed for centralised, one-directional operation to largely passive consumers. Almost all generation capacity was provided by large, fossil-fuel generators located on the 'supply-side' of the system, typically hundreds of kilometres upstream from the population centres served.

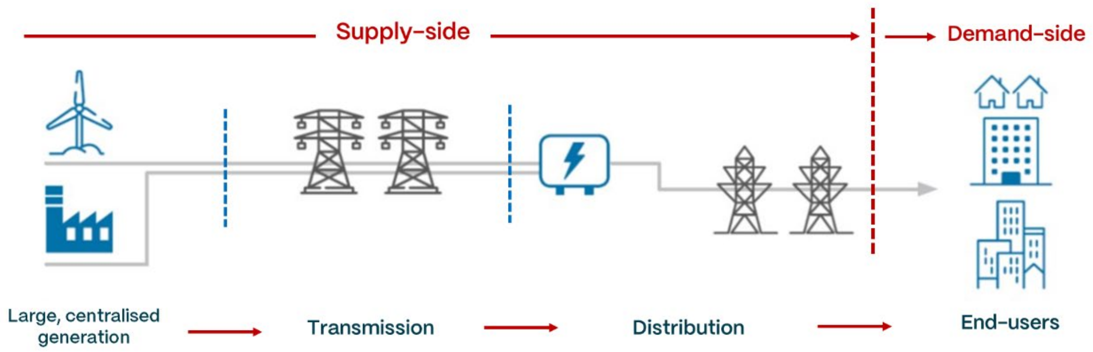

Figure 4: 20th century power systems were designed as unidirectional bulk delivery systems, with almost all electricity generated upstream by large, merchant resources

[4]DSO and TDC models are distinct but complementary, the latter being explored in Report 5 of this series.

With adequate generation capacity almost always at the ready, changing levels of consumer load was the major source of variability, which was still comparatively predictable in aggregate. The system operator, AEMO, would maintain the instantaneous supply-demand balance critical to system security by dispatching upstream merchant generation capacity to match peaks and troughs in downstream customer demand.

Over the last decade, however, global power systems have experienced the combined impacts of decarbonisation, digitalisation and democratisation which, in many cases, has led to a more deeply distributed value chain, increasing operational volatility and more bidirectional power flows. Notably, the '4 x Ds' are themselves underpinned by a complex mix of societal, technological, economic, commercial and geopolitical shifts, many of which fall outside the direct control of traditional regulatory and governance mechanisms.

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

1. An escalating ***locational and operational diversity*** of energy resources as the system moves from a past of hundreds of large, upstream merchant resources to a future involving ***tens of millions of diverse technologies*** participating across all tiers/layers of the system
2. Increasing ***whole-system dynamics*** as dispatchable, synchronous generation is progressively withdrawn and an ever-increasing proportion of net generation capacity is provided by ***variable, inverter-based resources***
3. Structural shifts in ***customer demand, variability and predictability*** are being driven by the mass deployment of distribution-connected CER/DER and compounded by the electrification of transport, industrial processes and data centres
4. The ***erosion of once-dominant operational paradigms***, such as a strict 'supply-side/demand-side bifurcation' and the universal 'load-following operational paradigm', both inherent to the functioning of a unidirectional power system
5. With the progressive withdrawal of dispatchable, synchronous generation, ***coordinated new sources of system flexibility, buffering and ancillary services*** located on both sides of Transmission-Distribution Interface (TDI) are increasingly required
6. An ***expanding set of operational responsibilities*** must be coordinated ***across several different entities***, including AEMO, TNSPs, DSOs and large third-parties that are increasingly capable of influencing system stability, either directly or indirectly; and
7. An increasing need for ***whole-system digitalisation of power system*** to enable alignment across multiple upstream and downstream entities, enable advanced operational visibility and coordination, and reduce traditional infrastructure overbuild risks.

Objectively considered, this arguably represents the largest scale of change to impact the structure and operability of GW-scale power systems in their 100-year history.

To illustrate further, with Australia's world-leading levels of Distributed Photovoltaics (DPV), the NEM has whole regions experiencing close to 100% of instantaneous demand being served by distribution-connected CER/DER on sunny, low load days. Later the same evening, these same regions are almost 100% supplied by the centralised system. This is now resulting in a 24-hour operational profile that is essentially 'tidal', and the transformation still has a very long way yet to go.

Ultimately, such profound shifts were inconceivable for the original architects of the system. As a result, they challenge the structural underpinnings of the power system and related market operations. As such, they accurately be categorised as a structural '*megashift*' in how continental-scale power systems like the NEM function.

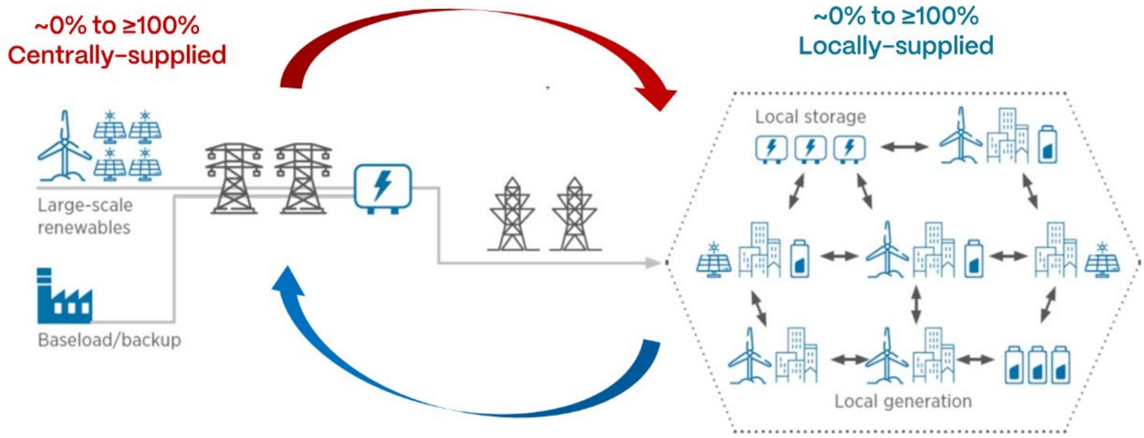

Figure 5: Decarbonising power systems require an entirely new level of whole-system interdependence between the conventional 'supply-side' and 'demand-side'

4.2 Increasingly volatile power systems

In the context of a decarbonising power system served by high levels of both Variable Renewable Energy (VRE) and Consumer Energy Resources (CER/DER), growing levels of operational volatility occurs as the level of reliance on weather-dependent generation increases. This results in rapid, significant, and often unpredictable fluctuations in voltage, frequency and power flows that require structural interventions and active management to address.

Both the NEM and WEM are now experiencing significant growth in operational volatility. In the case of the NEM, this is driven by the accelerating transformation of the generation fleet with almost 40% of average supply now being provided by renewable sources, peaking during some time windows closer to 75% of total instantaneous production.

Much of the recent and anticipated growth relates to weather-dependent VRE, whether utility-scale or distributed. Looking further out, AEMO's Step Change scenario anticipates a requirement for around 83 GW of utility-scale wind and solar capacity by 2035, rising to 127 GW by 2049-50, over five times the current 25 GW. In considering the growing volatility of the NEM, a key observation from the analysis in Table 2 below is the inverse relationship between the anticipated increase in weather-dependent VRE generation and the sizable comparative decline in dispatchable firming/flexibility over the same period.

Table 2: Current and future load, generation and firming/buffering volumes informed by AEMO's Step Change scenario [9]. A key observation is the inverse relationship between the anticipated growth of weather-dependent VRE generation and the significant decline in dispatchable firming over the same period.

	Total Generation		Weather-dependent VRE Generation			Dispatchable Firming / Flexibility		
Year	Annual Volume (TWh)	Total Capacity (GW)	Utility-scale Wind & Solar (GW)	Distributed Solar (GW)	% Net Generation	Supply-side (GW)	Demand-side (GW)	% Net VRE Generation
2020	200	70	15	15	43%	45	0	150%
2025	250	90	25	25	56%	47	0	94%
2035	350	190	83	55	73%	48	12	43%
2050	500	295	127	115	82%	35	40	31%

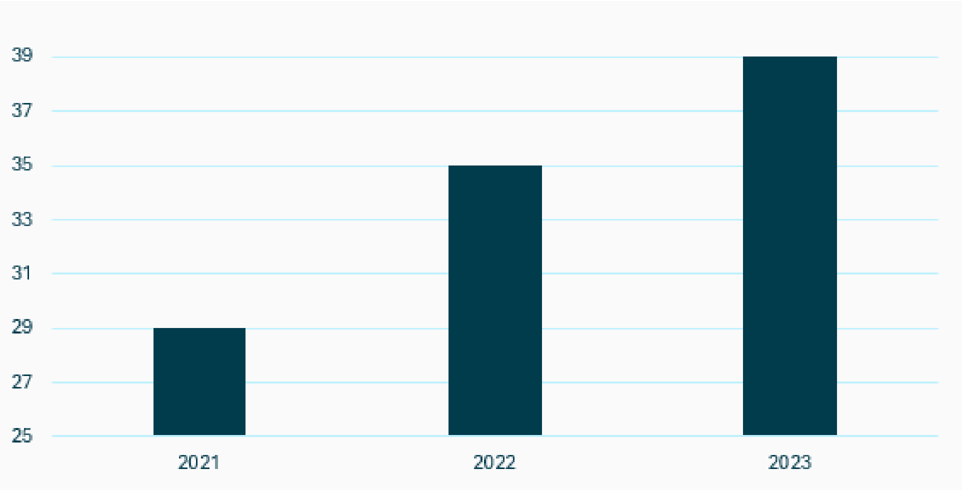

Figure 6: The percentage of total electricity generation provided by renewables in the NEM has grown substantially over the 2021 – 2023 period [9]

The resulting growth in operational volatility presents increasing challenges to the critical function of maintaining instantaneous supply-demand balance. This is where the volume of electricity delivered by all operating generation (supply) is maintained in equilibrium with all electricity consumed by customers (demand) during each second of grid operations. 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. Under conventional system operations, thermal generation capacity was flexibly dispatched to match demand over the 24-hour operational cycle.

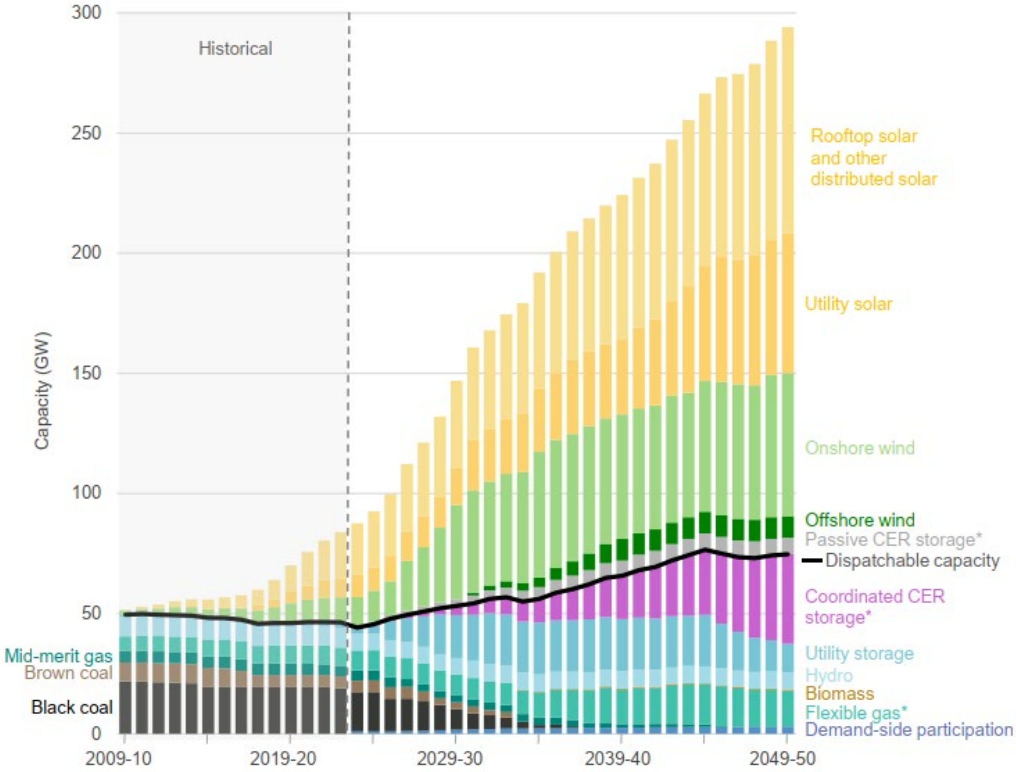

Figure 7: Power capacity in the NEM under the Step Change scenario [9]

By contrast, as the volume of generation output from utility-scale VRE and millions of CER/DER grows, maintaining the critical supply-demand balance involves the curtailment or 'spill' of excess renewable output rather than being supplied to customers. As a result, as the percentage of VRE generation in the NEM has grown, this capacity increase has been paralleled with the growing curtailment of renewable output. Under the current operational arrangements, failing to do so would place system security at risk. At a practical level, using Q4 2023 as an example, this resulted in approximately 215 MW of renewable capacity on average not being available to customers for productive use [11], or in energy terms, approximately 475 GWh of curtailed energy in Q4 2023.

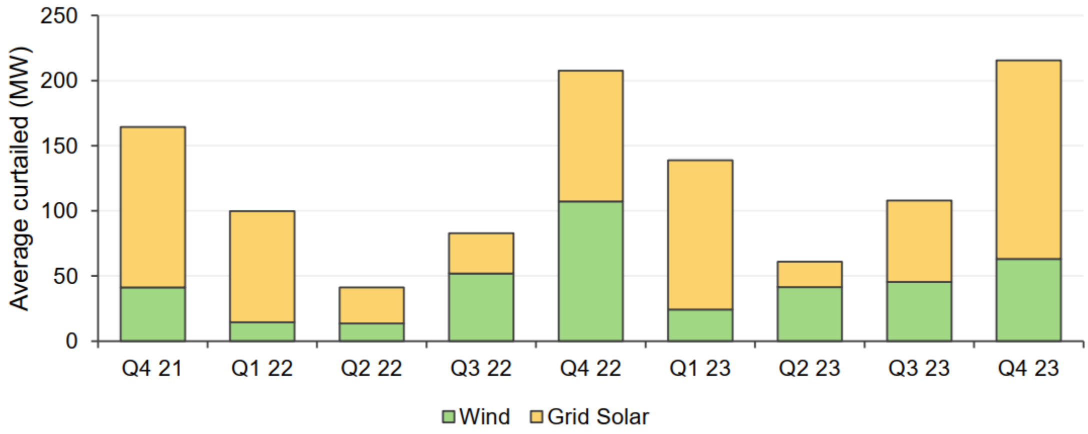

Figure 8: VRE quarterly average curtailment of wind and grid solar[12]

Further, when considered from a market operations perspective, in 2025 almost one quarter of market dispatch intervals NEM-wide already clear at zero or negative prices. This clearing price outcome is already closer to 40% in South Australia [12] as oversupply of capacity from utility-scale and distributed VRE routinely overwhelms instantaneous demand. As illustrated in Figure 9, the negative prices being experienced occur predominantly during daylight hours between approximately 07:00 and 17:00, with peak occurrences around midday. This is due to high solar PV generation, both rooftop and utility-scale, which is leading to oversupply during periods of low daytime demand. As the deployment of both utility-scale and distributed VRE continues, the time windows in which negative prices are experienced is expected to intensify at the peak and broaden further into the morning and evening shoulders, increasing the frequency and duration of negative pricing events.

Looking further out, AEMO's Step Change scenario anticipates that the NEM will require annual generation volume potentially up to 500 TWh in 2050 [9]. In this context, the importance of adequate firming and buffering capacity across the system to manage this new magnitude of VRE, and by extension, volatility, cannot be underestimated. Well before that, as the remaining coal-fired generation plant is withdrawn, by 2035 the NEM will be dependent upon renewable sources for approximately 90% of annual generation output. Managing the resulting level of operational volatility will require a tripling of the existing firming capacity using a combination of large batteries, pumped hydro, gas turbines and millions of distributed resources.

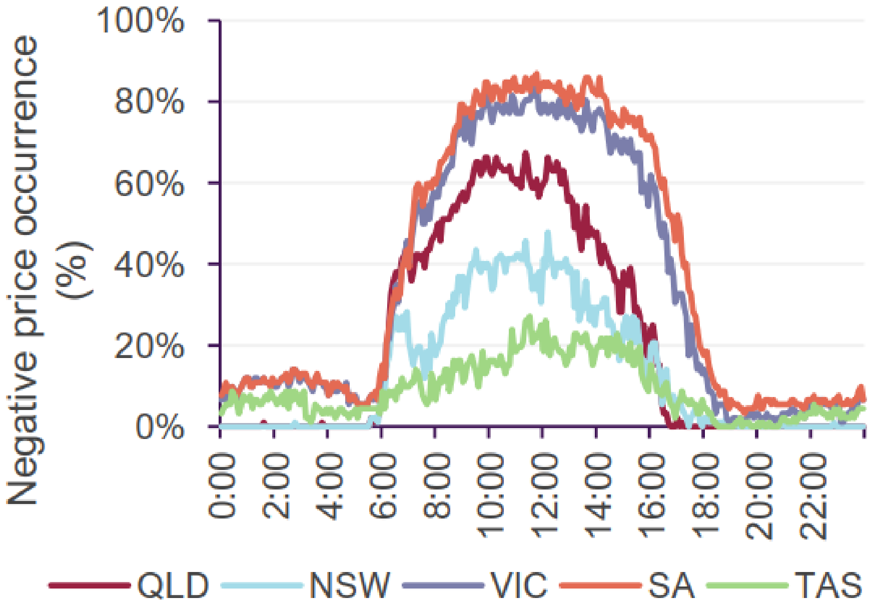

Figure 9: Negative price occurrence by state and time of day in Q1, 2025 [13]

Key Concepts B

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 electric 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.

Bidirectionality

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.

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.

4.3 Increasingly bidirectional power systems

In the context of a decarbonising power system served by high levels of transmission-connected VRE and millions of distribution-connected CER/DER, conventional one-way system operations progressively transform to become increasingly bidirectional. This reflects a major structural shift in the way electric grids operate, requiring significant new capabilities to efficiently accommodate and beneficially leverage two-way flows of power, information and services.

In Australia, the volume of CER/DER in the form of DPV has grown seven-fold over the last decade to a total current nameplate capacity of 22.6 GW operating in the NEM. This is resulting in 30-minute intervals where renewable generation exceeds 70% of total NEM supply, despite still requiring sufficient minimum operational demand to maintain system security.

In the state of South Australia, DPV regularly generates more electricity than total state demand during daylight hours. Similar trends are also emerging across New South Wales, Queensland, and Victoria, where reverse power grid flows and negative pricing intervals are more commonly being experienced, particularly in the middle hours of the day when solar output peaks [9]. At the same time, falling minimum operational demand is posing increasing stability and security risks for the system as a whole.

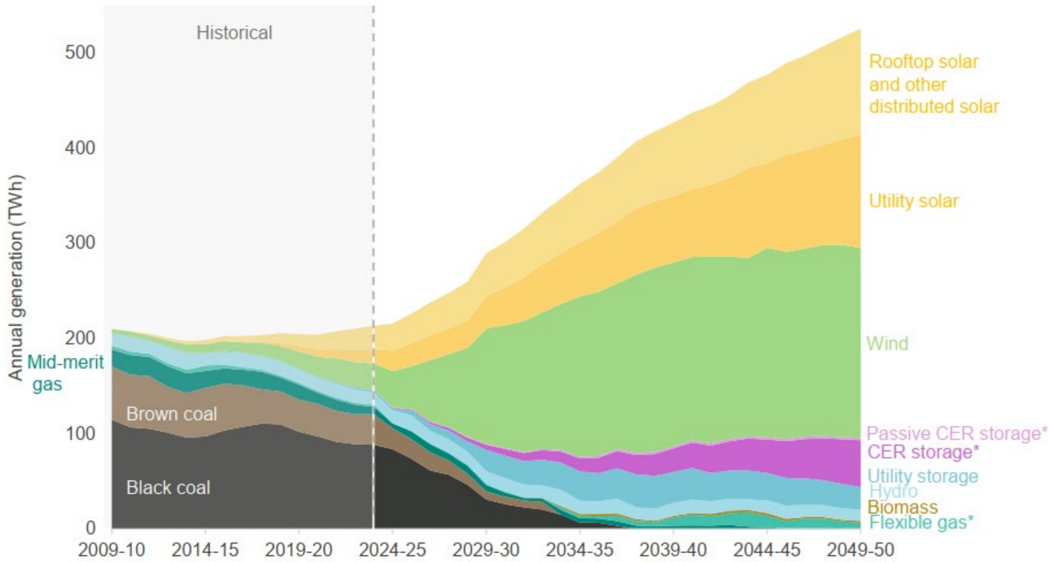

Figure 10: TWh Generation mix evolution in the NEM under the Step Change scenario[9]

Considering the longer term, AEMO's Step Change scenario anticipates DPV capacity reaching approximately ~55GW/70TWh by 2035. In this context, the NEM is expected to regularly experience time windows where most of its power is flowing 'upstream' from the distribution system. Minimum operational demand is also anticipated to continue falling towards zero in several regions.

By 2050, NEM operations will be predominantly bidirectional with ~115GW/100TWh capacity provided by DPV, representing a further fourfold increase on Australia's already world-leading levels in 2025. In this case, a key role of centralised energy resources will be to provide backup and support balancing services to a vast network of distribution-connected energy resources.

4.4 Challenges arising from a more volatile and bidirectional system

The combined impact of increasingly volatile and bidirectional operations drives unprecedented new challenges for a power system originally designed for comparatively stable, unidirectional operation. While targeted treatments may assist for a time, enduring scalable solutions will require structural interventions such as formalised DSO and TDC models that are underpinned by a scalable and fit-for-purpose systems architecture.

A wide range of Systemic Issues relevant to the transformation of the NEM are documented in Report 3 of this series [5]. Informed by this wider analysis, following are a subset of challenges that arise in an increasingly volatile and bidirectional power system:

- **Grid Stability & Control:** Traditionally, large synchronous generators provided inertia and control mechanisms that helped stabilise voltage and frequency. In a bidirectional system dominated by Invertor-Based Resources (IBR), the reduction in system inertia leads to greater frequency volatility and less predictable system dynamics. Maintaining voltage within permissible limits also becomes more difficult, particularly at the distribution level, where reverse power flows from rooftop solar can lead to voltage rise and variability. These dynamics demand new control strategies and adaptive operational frameworks to ensure the reliability of the system.

- **Protection System Complexity:** The design of legacy protection systems relies on the assumption of unidirectional power flow. However, with multiple sources injecting power at various points in the grid, fault current levels and directions become much less predictable. This undermines the effectiveness of traditional protection schemes, such as overcurrent relays, potentially resulting in incorrect fault isolation or delayed response. Advanced adaptive protection systems and directional relays must be implemented to accommodate new power flow patterns and enhance safety [14].

- **Operational Visibility of CER/DER:**[5] The cyber-physical architecture of conventional power systems did not need to provide the system operator with visibility of generation located behind-the-meter (BTM). While this was not previously an issue, as the scale of installed CER/DER has escalated, the lack of real-time visibility of BTM generation, storage, and consumption makes it difficult for the system operator to forecast load and ensure system stability [15]. Effectively addressing this while respecting the roles and responsibilities of all supply chain entities will require the transition to a layered systems architecture.

- **Forecasting & Uncertainty:** With bidirectional flows and increasing electrification, apparent load profiles are becoming less predictable. At a whole-system level, the System Operator needs the ability to forecast not only traditional demand but also CER/DER generation, energy storage charging/discharging behaviours, flexible loads, etc. Heightened uncertainty compounded by inadequate visibility complicates real-time operations and requires a new level of collaboration across all supply chain entities [16].

[5] Refer Key Concepts C.

- **Balancing & Operational Coordination:**[6] Australia's world-leading volumes of CER/DER can provide valuable services such as generation capacity, voltage support and flexibility services and will play an increasingly critical role in system balancing and operational coordination. To unlock these capabilities, however, participating CER/DER must be capable of being coordinated with the temporal and spatial needs of the system in near real-time. Market participation of CER/DER must also be co-optimised across the different market layers as they evolve. Achieving this at massive scale requires a layered structure of roles and responsibilities underpinned by future-ready systems architecture.

- **Network Congestion & Optimisation:** Distribution networks were not originally designed to host significant volumes of generation capacity. High levels of CER/DER can lead to congestion and thermal overloading of transformers and feeders, with reverse flows potentially breaching operational voltage limits, particularly during low-load and high-generation periods. Addressing these issues and optimising network utilisation necessitate an integrated set of responses including hosting capacity analyses, dynamic operating envelopes, CER/DER orchestration, the monetisation of flexibility services, etc.

- **Cybersecurity & Data Management:** As the power system becomes both more digitalised and decentralised, it also becomes more vulnerable to cyber threats. While conventional cyber-based protections are critical, a vital additional layer of security must focus on structural (re)configuration of data flows to minimise or avoid routings which unnecessarily create vulnerabilities. This plays a significant role in reducing attack vectors.

[6] Refer Key Concepts K.

Key Concepts C

Visibility

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

Examples include real-time or near real-time information on electrical demand, generation output, state of charge for energy storage, availability of demand response, system voltages and system frequency, and power flows on major network elements. Statistical data filtering methods also allow establishing trustworthiness of the obtained data enabling the visibility, and reconcile them amongst each other, and with respect to network models, to identify bad and / or malicious data.

Observability

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

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

Operability

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

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

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

5 Future Grid Characteristics: More flexible and inter-dependent power systems

As noted in the last chapter, as power systems such as Australia's NEM decarbonise, they experience escalating levels of operational volatility and bidirectionality. Originally designed for unidirectional power flows in a comparatively stable operating environment, they must now become inherently more flexible, adaptive and interdependent end-to-end.

A more *flexible* power system can anticipate, adapt to and manage variability and volatility of supply and demand across all relevant time scales. A more *interdependent* grid enables the dynamic coordination of millions of large and small energy resources across the full length of the value chain in the context of more dynamic, two-way power and information flows. As GW-scale power systems like the NEM become increasingly volatile and bidirectional, both flexibility and interdependence become essential to system operability and the instantaneous balancing of supply and demand.

In light of these developments, this chapter explores the need for new sources of operational flexibility as volatility increases, and conventional sources of flexibility are withdrawn. The importance of flexibility is discussed and characterised across several time scales, and a range of potential new sources considered. The need for more interdependent operation of the end-to-end system is then discussed in the context of increasingly bidirectional power flows, enabled by operational coordination models that span the various system tiers/layers that were originally designed to support unidirectional operations. Finally, the chapter concludes by recognising the important role of digitalisation and interoperability standards as key enablers while noting that a wider set of disciplines are required to achieve this level of operational interdependence including the application of Systems Architecture, control theory and structural analysis.

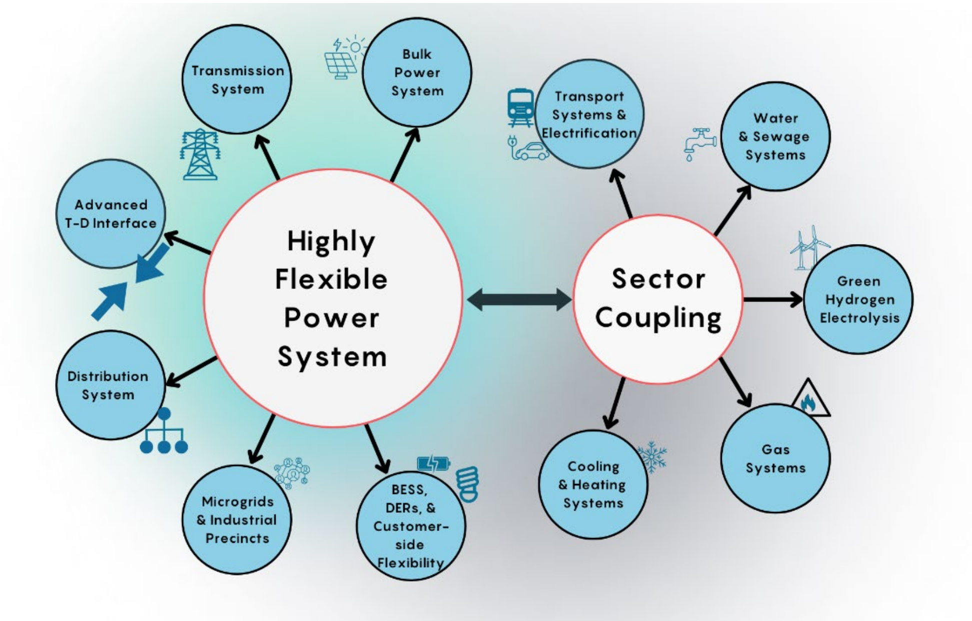

Figure 11: A highly flexible grid requires dynamic interdependence across the end-to-end power system and deeper levels of sector coupling over time. Image adapted from [17]

The diverse range of global and Australian sources that have informed this section are provided in the Flexible Power Systems and Interdependent Power Systems section of Appendix B: Key Topic Bibliography.

5.1. A more flexible power system

Fundamental to the secure operation of an electric power system is the concept of supply-demand balance. This is 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 congestion and flow problems as well as frequency and voltage deviations, which can cause cascading outages.

Given the essential role played by flexibility in a decarbonising power system, it may be considered a 'no-regrets' sphere of investment as has been recognised by analysis in the United Kingdom [18]:

> *"…flexibility always delivers a net saving ranging between £9.6-16.7bn/yr and supports a cost-effective decarbonisation of the energy system. This value is delivered by a portfolio of flexibility technologies including: battery storage, thermal storage (in homes and integrated with heat networks), interconnectors and a range of demand side response technologies across domestic, non-domestic and EV demands.*
>
> *"The savings predominantly come from avoidance of gas generation (CapEx and OpEx), reduced reliance on carbon negative technologies and reduced network reinforcement. Beyond technologies such as these, flexible operation of systems like hybrid heat pumps and coordination of the hydrogen system (production, storage, conversion and use) help to maximise synergies with the wider system.*
>
> *"High levels of flexibility deployment are required from different sources to help deliver the scale of savings in a net zero system. Up to c.48GW of flexibility from EVs, 12GW from domestic smart appliances, 11GW from non-domestic DSR, 83GW of battery storage and 900GWh of thermal storage are deployed across the different scenarios."*

Flexibility: Past and future

Power system flexibility has always been important for managing supply-demand balance. As noted previously, varying consumer demand was the major source of power system variability. This was managed by the system operator through the dispatch of upstream thermal generation capacity in line with the peaks and troughs in downstream customer demand. In other words, dispatchable centralised generation provided the primary source of system flexibility in a context where changing customer load was one of the primary operational variables.

By contrast, however, a decarbonising power system like the NEM now experiences a major additional source of volatility with the scale deployment of weather-dependent generation. In addition, as operational volatility has been increasing the major conventional source of system flexibility has progressively been withdrawn in the form of dispatchable thermal generation. The physics of power system operation, therefore, require an expansive new range of system flexibility sources commensurate to managing the volatility now increasingly experienced on both the supply and demand sides of the system.

Flexibility defined

As noted above, a decarbonising power system may be considered flexible if it can anticipate, adapt to and manage variability and volatility of supply and demand across all relevant time scales. At a practical level, this means that the power system is capable of the following (adapted from [17]):

1. Meet peak loads and peak net loads and avoid loss of load events.
2. Maintain the balance of supply and demand at all times, ensuring the availability of sufficient capability to ramp up and down, sufficient fast-starting capacity and the capability to operate during low net loads.
3. Have sufficient storage capacity (both energy storage and sector coupling) to balance periods of high VRE generation and periods of high demand but low VRE generation.
4. Incorporate capabilities to adjust demand to respond to periods of supply shortages or overgeneration.
5. Maintain capabilities to mitigate possible events that could de-stabilise the power system through maintaining an adequate supply of ancillary services at all times.
6. Operate under a well-designed market where flexibility services are promoted and activated.

Curtailment of VRE and CER/DER output is also a last resort source of flexibility but naturally comes at a significant economic cost over the longer term.

Flexibility timescales

Power system operations must be considered over a wide range of timescales spanning from sub-seconds, minutes and hours to weeks, months and seasons. As a fundamental characteristic of secure and efficient power system operations, flexibility must similarly be considered across a range of temporal domains as follows [2]:

- **Very Short Term (sub-second to minutes):** Flexibility services in this temporal domain will generally relate to supporting frequency control, synthetic inertia, and fault response. While for a long time these have been categorised as Essential System Services and delivered by synchronous machines, they are increasingly being enabled by flexible resources, such as grid-forming inverters, utility-scale batteries, and dynamic load response (e.g. industrial motors, smart appliances). Although not traditionally labelled 'flexibility' services, their ability to rapidly modulate output in response to system needs demonstrates a critical dimension of operational flexibility at the fastest timescales.
- **Short Term (minutes to hours):** Flexibility services in this temporal domain will generally relate to real or near real-time system balancing. Historically provided by maintaining sufficient spinning reserve and ramping support within a load-following operational paradigm, these are increasingly being provided by dispatchable gas turbines, battery energy storage, aggregated CER/DER fleets and flexible loads.

- **Medium Term (days to weeks):** Flexibility services in this temporal domain generally relate to ensuring near-term resource adequacy. Historically provided by generation scheduling, outage management and targeted capital augmentation, these services may increasingly be provided by pumped hydro storage, utility-scale BESS, industrial load curtailment agreements, the orchestration of CER/DER and flexible load at massive scale and sector-couplings with adjacent energy vectors such as gas and transport. An important consideration here is that weather forecasts, storage capacity planning and asset coordination are significantly more influential factors in the flexibility function than sub-second control.
- **Long Term (months to seasons):** Flexibility services in this temporal domain generally relate to ensuring long-term resource adequacy. Historically provided by major capital investments in centralised generation and transmission capacity, these services may increasingly be through a portfolio of options including: dispatchable gas turbines, pumped hydro storage, long-duration battery storage, green hydrogen production and re-electrification, demand-side flexibility management with seasonal load shifting (e.g. industrial process scheduling), sector-coupling with adjacent energy vectors (e.g. heat networks, synthetic fuels), and enhanced interregional transmission to access geographic diversity in supply and demand.

Key Concepts D

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.

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 misalignment between demand and supply.

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.

Collectively, these four temporal domains reflect the vital role of flexibility in a decarbonising power system. While the requirement for flexibility is not new, what is changing is the scale, diversity, location and technical characteristics of how, where and when it is provided.

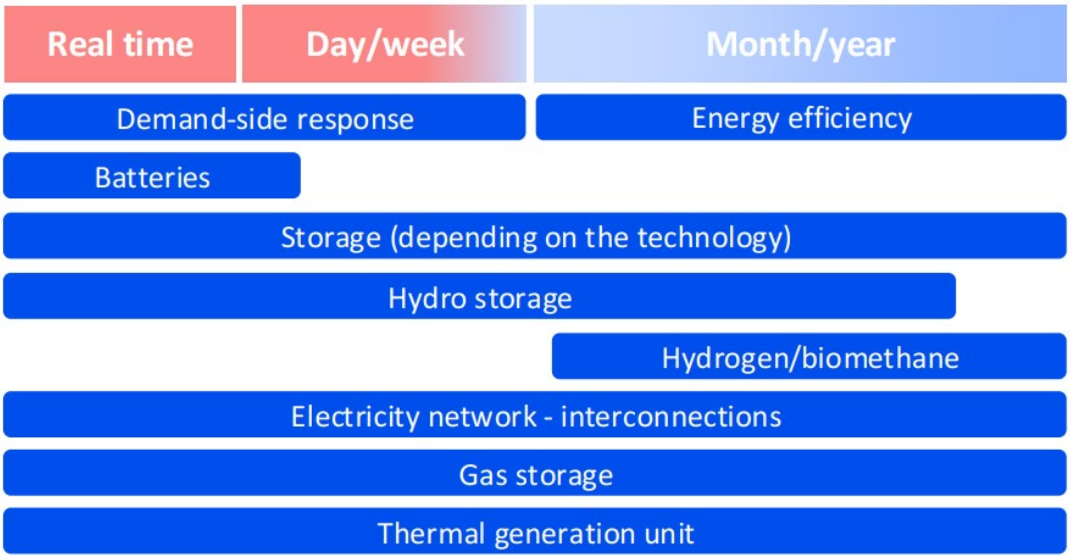

Figure 12: Temporally-arranged flexibility services provided by various technologies [19]

Flexibility sources and enablers

As noted above, system flexibility has always been important for managing supply-demand balance and varying consumer demand was the major source of power system variability. This was managed by the system operator through the dispatch of upstream thermal generation capacity in line with the peaks and troughs in downstream customer demand.

The dispatchable coal-fired generation that provided the NEM's primary source of system flexibility is declining as a proportion of the total generation fleet. At the same time, the NEM is experiencing significant growth in operational volatility with the scale deployment of weather-dependent generation connected to both the transmission and distribution systems. A new generation and scale of system flexibility services will therefore be required from a diverse range of conventional and new sources across the end-to-end system, several of which are outlined below.

- **Supply-Side Flexibility:** Fast-ramping resources such as reservoir-based hydro generators and open-cycle gas turbines are likely to continue playing a key role in providing operational flexibility. As the role of conventional gas turbines will likely be impacted as environmental constraints tighten, emerging alternatives also include pumped storage-based hydro generators and hydrogen-ready turbines that operate on a blend of natural gas and hydrogen. Different forms of large-scale energy storage are also beneficial over different time scales with pumped hydro, synchronous flywheels and compressed air energy storage (CAES) able to support inertia in case of a sudden loss of generation. Chemical energy storage is also used time scales of seconds to minutes for the provision of operational reserves, and pumped hydro, long-duration batteries, thermal storage and CAES may provide supply-side flexibility over a variety of time periods, where Figure 13 illustrates the benefits of coordinated energy flows into and out of these storage points [17].

- **Demand-Side Flexibility:** As conventional sources of system flexibility are withdrawn and operational volatility increases, AEMO's ISP scenarios recognise that the role of demand-side flexibility at very significant scale becomes increasingly vital [9]. In the context of enabling digital infrastructures, near real-time data, automation and fit-for-purpose market mechanisms, a diverse range of flexibility services can be provided by flexible loads and Consumer Energy Resources (CER) located behind the meter at commercial and industrial premises and across millions of residential properties. For instance, coordinated EV charging, smart HVAC control in large commercial buildings and responsive industrial process loads can offer high-value sources of flexibility. Similarly, larger-scale Distributed Energy Resources (DER) connected directly to the distribution network, including community solar, community battery and microgrid installations, also have significant potential to provide flexibility services at scale.
- **Enabling Infrastructures:** A more dynamic power system that depends on a much wider range of flexibility sources sited both upstream and downstream requires robust transmission and distribution networks to exchange flexibility services and balance supply and demand across various scale geographies. Further, the dynamic performance of these more conventional 'hard' network infrastructures may also be enhanced by dynamic line rating, real-time power flow control and dynamic connection solutions. Importantly, aligning the provision of flexibility services by millions of diverse sources with the temporal and spatial needs of the power system requires a scalable, architecturally informed digital infrastructure. In an increasingly complex system, a layered architecture is vital to enabling greatly enhanced levels of operational visibility, observability and the coordination of millions of participating resources. This must be underpinned by aggregated data flows between all relevant entities, flexibility market mechanisms and, in time, capable of enabling multi-layer buffering and balancing [17].

As the NEM continues to decarbonise and experience growing levels of operational volatility and bidirectionality, coordinated system flexibility services will be required from millions of both upstream and downstream energy resources. Achieving this in a secure, scalable and cost-efficient manner will require the end-to-end power system to function in a far more dynamically interdependent than was ever imagined during its first century of unidirectional operation.

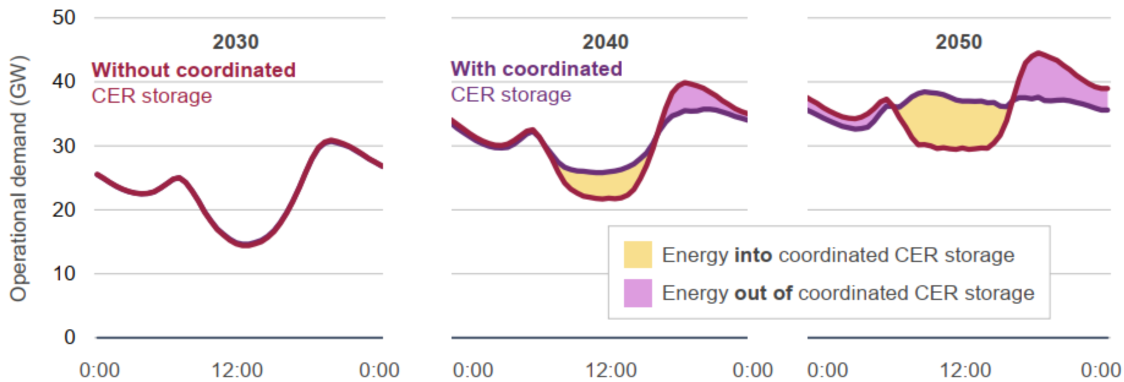

Figure 13: Impact of coordinated storage on average operational demand by time of day[9]

5.2 A more interdependent power system

As discussed earlier in Chapter 4, not only are Australia's GW-scale power systems becoming more volatile, but power flows are also becoming more bidirectional. Whereas a top-down model of system management was appropriate for a unidirectional grid, an increasingly bidirectional grid will require a more collaborative and interdependent model of system management. This is a key premise underpinning the need to move toward DSO models in a high-CER/DER context.

Erosion of a central operating paradigm

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

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

The significance of the erosion of this paradigm, which played a pivotal role in shaping the legacy power systems underpinning architecture cannot be overstated. As AEMO has noted:

> *"As penetrations of passive DPV continue to increase and become significant at the regional level, the aggregated impact affects almost all core duties of the bulk system operator in some way..."* [22]

This is especially the case in Australia due to our world-leading scale and pace of DPV adoption by customers. While our distribution systems remain the location of major load centres, they are transforming to host an ever-expanding fleet of CER/DER and Electric Vehicles (EV). Although the measurable effects emerge over time, the overall trajectory involves one of the most profound transformations in a century of grid operations.

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

The emergence of a new operating context

Australia's fleet of energy resources is bifurcating into two major locational classes: transmission-connected and distribution-connected. This involves an historically unprecedented shift:

- *From* a past where over 95% of Australia's generation fleet was concentrated at one extremity of the power system (transmission-connected).
- *To* a fast-emerging future where the generation fleet is located across two opposite extremities of the power system. Under AEMO's widely noted 2050 Step Change scenario [9], this will involve:
    - A progressive narrowing of the differential between transmission-connected generation capacity in comparison to the proportion that is distribution-connected.
    - Significant regions of NEM increasingly needing to be capable of operating reliably during periods where 100% of instantaneous demand is met by renewable sources, both transmission-connected and distribution-connected.
    - Whole regions experiencing increasing time windows periods where 100% of instantaneous demand is met by distribution-connected DPV, especially at solar zenith on days with low levels of demand.
    - Power system operations becoming increasingly 'tidal' as these regions are increasingly supplied by local generation during daylight hours and then largely dependent upon utility-scale wind generation and other centralised resources overnight.
    - Over time, the entire NEM must be provisioned to operate reliably for increasing frequency and duration of time windows where 100% of instantaneous demand is served by IBR, whether centralised, decentralised or a combination of both.

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

Key Concepts E

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.

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.

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.

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.

The increasingly critical role of the 'demand-side' in whole system operations

As noted previously, the downstream extremity of the power system was almost exclusively considered a load centre. Commonly known as the 'demand-side', millions of diverse customers were considered passive receivers and consumers of the electricity generated by 'supply-side' resources and delivered via transmission and distribution networks.

In light of the emerging operational context, however, the term 'demand-side' is becoming increasingly imprecise[7]. While remaining the location of major load centres, distribution systems now host an ever-expanding proportion of Australia's fleet of energy resources which will ultimately number in the tens of millions. As conventional dispatchable generation is withdrawn, this huge fleet of resources is becoming increasingly critical for the operability of the entire power system in the form of generation, buffering (storage), flexibility and the provision of essential system services.

As decarbonisation advances and coal-fired generation is withdrawn, distribution-connected energy resources have the potential to play a valuable role in enabling Australia's secure and cost-efficient future power systems. However, the need for energy and grid services constantly varies both temporally and spatially, and the alignment between local distribution and bulk power system needs cannot be assumed. Unlocking the full value of millions of distribution-connected resources, therefore, requires both a fit-for-purpose systems architecture and the new organisational capabilities that underpin a level of interdependent whole-system operations simply not required by the twentieth century grid.

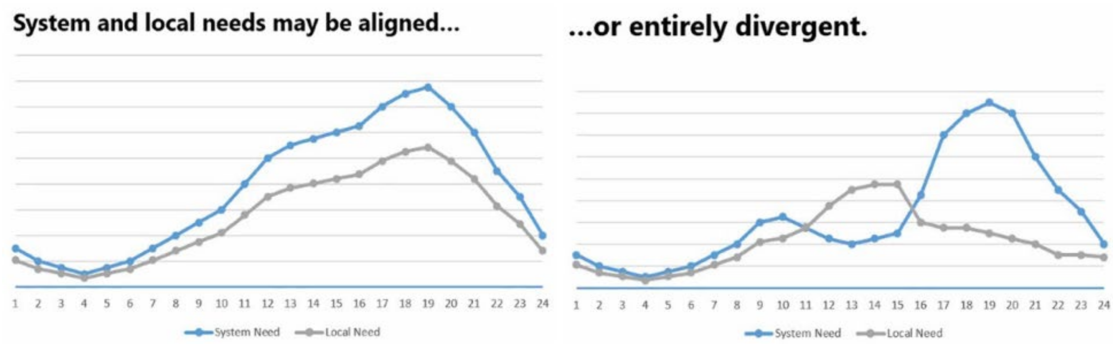

Figure 14: The need for energy and grid services varies temporally and spatially; alignment between local distribution and bulk power system needs cannot be assumed [20]

[7] The term 'demand-side' is used in this report as no better alternative is yet to emerge. Its usage primarily refers to the extremity of the system to which the majority of end-use customers are connected. Further, its usage assumes that a growing proportion of these customers will also participate in provision of various energy services to meet their own needs and, under the right circumstances and incentives, will also provide them to the system.

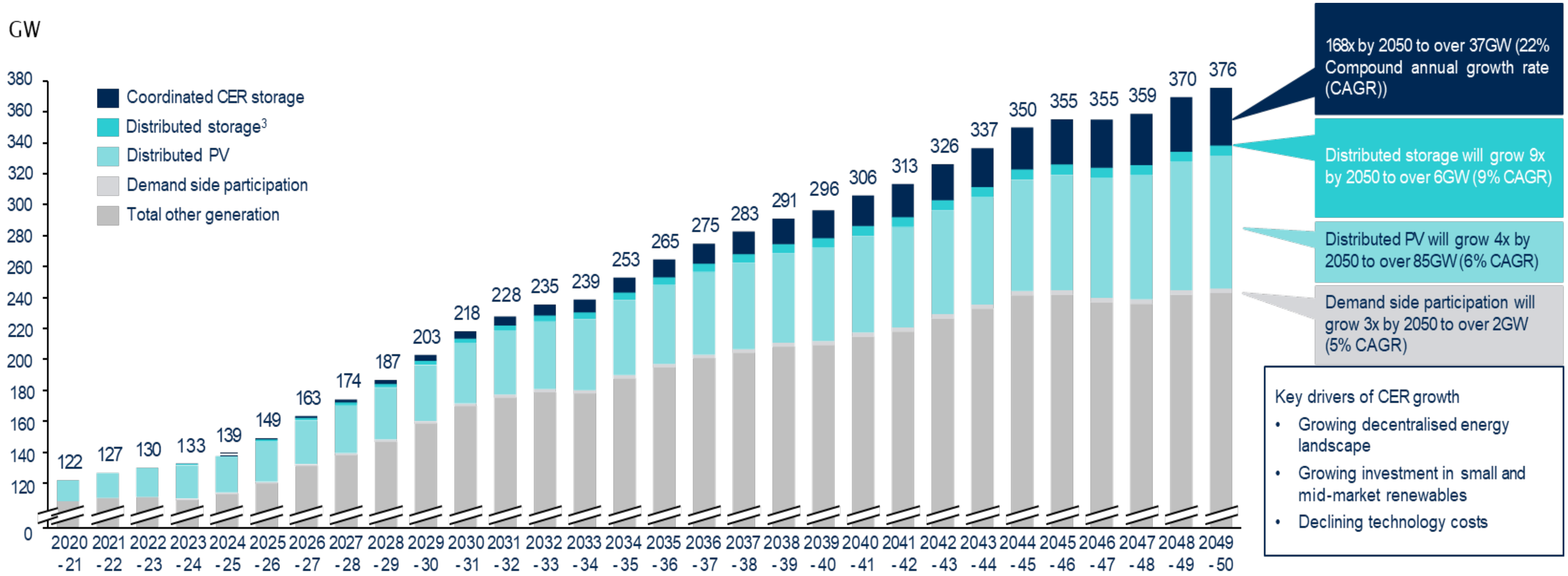

Figure 15: CER installed capacity in the NEM based on AEMO's Step Change scenario (2020–2050) [21]

The structural context for considering DSO models

In a context where most generation was located upstream, and connected to the transmission network, 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, an increasingly volatile and bidirectional system requires a more whole-system approach to visibility, operational coordination, buffering and supply-demand balancing. The unprecedented numerical, temporal, locational and computational scale and complexity of such a shift cannot be credibly enabled without an increasingly distributed, layered and multi-entity model of system management.

This is the critical context in which DSO models must be considered. While the credible architectural options for enabling such a transformation are discussed in more detail in Chapter 8, the pivotal concept is that multiple coordinated centres of decision-making become critical to manage the different layers of an increasingly volatile and two-way grid. In this context, the system operator (AEMO), regional TNSPs, regional DSOs and third parties such as CER/DER aggregators and microgrid operators each play formalised roles in a far more dynamically interdependent model of system management.

While explored in more detail in the next chapter, this begins to illuminate some of the important distinctions between the objectives and functions of a conventional DNSP and that of a DSO. Without an architecturally informed approach to the design of DSO models as a key enabler of future distribution systems and an active collaborator in wider future power system operations, some of the critical issues that will continue to emerge include the following [5]:

- **Operational Visibility Risks:** The lack of a layered, end-to-end approach for providing operational visibility of CER/DER across all relevant entities increases risks to the security, operability and cost-efficiency of the bulk power, transmission and distribution systems.
- **System Coordination & Balancing Risks:** As bidirectional power flows and operational volatility increase, the absence of scalable, whole-system models for operational coordination similarly places instantaneous system balancing and overall economic efficiency at growing risk.
- **Whole-system Buffering Needs:** As power flow volatility is propagated across the end-to-end system with the scale deployment of VRE and CER/DER, multi-layer system buffering will increasingly be required to successfully augment operational coordination and system balancing. This similarly requires scalable, whole-system models of coordination.
- **Multiple Aggregator / VPP Risks:** The involvement of multiple CER/DER aggregators at scale introduces an additional level of structural and functional complexity across the power system. The absence of a holistic, structurally based approach to their coordination will increase the potential for significant operational conflicts and inefficiencies.

A key reason the critical issues of visibility and operational coordination continue to be so challenging in all high-CER/DER power systems is that they transcend conventional power system tiers/layers, as illustrated conceptually in Figure 16 below. The system architecture of an historically top-down power system simply did not require or enable this level of bottom-up insight as the significant majority of energy resources were transmission connected.

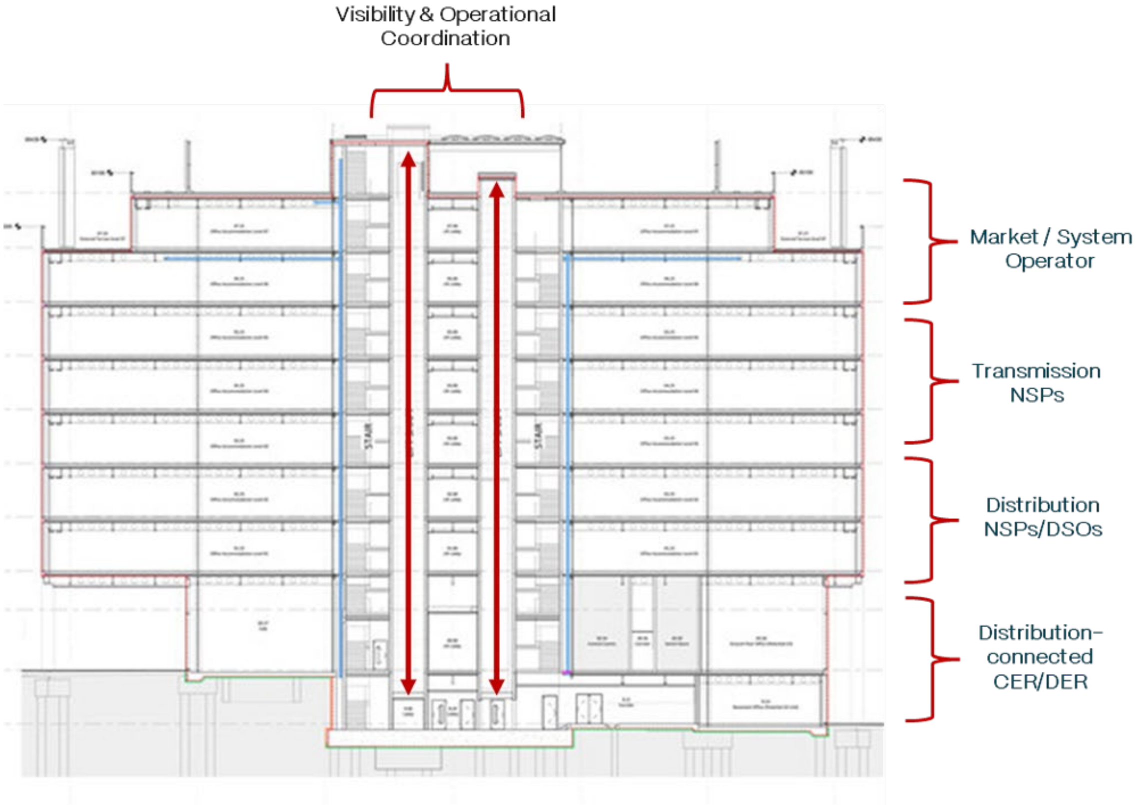

Figure 16: A conventional grid is somewhat like a multi-level building which means that end-to-end visibility and operational coordination function, structurally, like vertical elevator shafts

As illustrated above, if a conventional GW-scale power system is analogous to a multi-level building, it is helpful to consider visibility and coordination as equivalent to the vertical elevator shafts that must seamlessly transit all levels of the building. This is because all authorised floors in the building need to be rapidly and efficiently served. To extend the analogy, and regardless of the DSO model adopted, where the wider structural considerations remain unaddressed, enabling end-to-end visibility and coordination will still involve a circuitous path of climbing multiple flights of fire stairs, navigating numerous fire walls and periodically confronting locked fire doors. Reliable, scalable and cost-efficient solutions cannot ultimately be achieved without the combination of fit-for-purpose DSO models plus targeted structural interventions.

Systems Architecture, control theory, digitalisation and interoperability all needed

Importantly, the above discussion is not an argument for (nor against) vertical integration at the organisational level. However, as a modern power system is ultimately a highly complex cyber-physical system, it does highlight the need for 'virtual integration' across the end-to-end value chain. And while a level of coordination has long existed in unidirectional power systems, existing data exchange and coordination arrangements are far from adequate to meeting future needs. As a challenge around the world, the UK's Department for Energy Security and Net Zero has noted [22]:

Currently, data sharing across the energy sector is managed and carried out on an organisation-by-organisation basis. This has led to limited scalability, increased divergence between datasets and variety of bespoke approaches. The lack of common sector wide data-sharing practices (agreed set of procedures, processes, data licensing, handling conditions, and mechanisms) for sharing data securely between organisations creates a significant barrier to exchange of critical operational, financial reconciliation and price signals needed to enable innovation, provide optionality for future policymaking, and reduce the future system cost.

More broadly, while recognising the critical need for the deep digitalisation of the power system, a danger is that the term or concept itself can be deployed in a superficial manner. Digitalisation – and for that matter, interoperability – are both means to an end, not an end in themselves. Neither digitalisation nor interoperability have any intrinsic ability to resolve features of the twentieth century grid that were purpose-built for operating a unidirectional bulk delivery system but are not scalable to efficiently enabling Australia's most plausible high-CER/DER futures.

This is not a trivial or academic distinction. Significant confusion arises when strategies are implemented that assume the power system can be transformed in a similar manner to a purely digital system. While there are areas of similarity, this profoundly misunderstands the fact that a GW-scale grid is an Ultra-Large Scale (ULS) geographically distributed cyber-physical system. It has tightly integrated computational and physical/engineered elements that create a close coupling between the virtual and physical. 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.

As Dr Jeffrey Taft, former Chief Architect at Pacific Northwest National Laboratory has noted [23]:

The bifurcation of grid resources into traditional Bulk Power System (BPS) and distribution-connected resources, along with the use of Variable Renewable Energy (VRE) resources (mainly wind and solar) has created deep structural and parametric changes in electric power systems. In other words, the grid is morphing into something we cannot control well with what we have. Information Technology and software engineering do not have the tools sufficient to deal with this transformation.

Table 3: Key distinctions between a ULS cyber-physical system like the grid and a purely digital system

	Cyber-Physical System	Purely Digital System
Core Function	Controls and optimises physical energy flows	Processes information
Time Sensitivity	Strict real-time constraints (milliseconds to minutes)	Tolerant (seconds to hours)
Failure Impact	Physical damage, wide area outages, human safety risks	Data corruption, downtime
Dependencies	Physics (voltage, frequency) and algorithms	Algorithms and network operating systems
Design Focus	Resilience, stability, safety	Speed, scalability, security

In other words, a modern power system is a highly complex cyber-physical which is best illustrated by the Network of Structures[8] model. Consisting of seven overlaid structures, one of which is the digital infrastructure. Recognising this more holistic nature of the grid means that a combined focus on systems architecture, control engineering, digitalisation and interoperability is required to enable a more flexible and interdependent grid, of which effective DSO models are a key part. The is highlighted by the following observation from the Tapestry project at X [24]:

> *Key to the digital grid is defining a widely-accepted architecture that merges communications-based data architecture with the physical elements of the electric grid and will anticipate the evolving needs of the system through flexibility and openness. Despite considerable progress toward identifying the control structures, protocols, data formats and applications for individual digital technologies and components, there is still no widely adopted architecture that ensures reliable, safe and efficient interoperability of all digital grid elements in an increasingly distributed system.*

Recognising that this is a transformative process which must take place in a stepwise manner over several years, the same paper proposes the following timeline over four broad periods: Legacy, Emerging, Scaling and Transformed.

[8] Refer Key Concepts G.

Table 4: Periods of evolution to realising an architecturally based digital grid [24]

Legacy Pre-2020	• High-touch centralised control systems built to manage to least-cost distribution of energy in one direction from large, mainly fossil-fuel powered resources. • Planning and operations accomplished using deterministic modeling based on data inputs in separate models that are individually compiled and held by different grid participants. • Planning prioritises redundancy against outage of large generation or loss of transmission line to ensure reliability. • Inherent characteristics of large resources determine both least-cost economic dispatch solutions and system stability.
Emerging 2020-2030	• Grids have a mix of legacy and digital assets, such as digital inverter-based resources, sensors and IoT devices. • The number, size, type and location of variable renewable inverter-based resources increase significantly. • Digital devices provide visibility throughout the grid, enabling new ways of planning, managing and operating an increasingly complex and bi-directional grid. • Access to quantities of high-quality data provides insight into the grid, connected assets and customer propensity. Paired with artificial intelligence, this allows for new optimisation and coordination methods. • Legacy methods of modeling, planning and operating the grid persist for a time and struggle to accurately depict the behavior of digital assets. • An open Internet-style information architecture is eventually layered on top of the existing physical grid architecture, improving flexible connection and management of generation assets, demand-side optimisation, and stacking asset use cases.
Scaling 2030-2040	• Major interconnections become digital-first as smart assets drive methods of planning, management, and operation. • Data-rich systems, advanced computing and AI-assisted coordination are key characteristics of how the complex energy system maintains reliability while allowing flexible access to and participation in the grid. • Grid assets (notably demand-side and energy storage) materially contribute to ensuring reliability and operational efficiency.
Transformed 2040+	• A distributed, dynamic and delegated grid operates at scale and is characterised by modernised digital grid assets, both known and still to be innovated. • Profound commercial and market transformations become possible, such as micro- transaction energy ledgers, continuously clearing wholesale markets and the obsolescence of traditional ancillary services. • Energy optimisation decisions are bundled into the assets and services that consumers care about and understand, and these are enabled by digital electron buffers.

6 Future Grid Enabler: DSO models a key structural enabler of decarbonised power systems

Australia finds itself on the global frontier of grid transformation. The scale and pace of the nation's grid transformation is arguably unprecedented in the history of electricity systems. As system operations become increasingly volatile and bidirectional, operational dynamics never previously experienced in a GW-scale power system must now be navigated.

In light of this wider context, this chapter considers the transition to DSO models as necessary strategic and structural interventions to prepare Australia's legacy power systems for a decarbonised, high-CER/DER future. As a still maturing area, the nature and capabilities of DSOs have been characterised in many different ways globally and in Australia. In response, the analysis identified five foundational questions about DSO models that enable convergence on a more integrative set of definitions. How DSOs are characterised globally is first reviewed and the results tabulated to allow readers to note the similarities and differences. Key elements of the problem definition that underpin the need for DSOs are explored followed by an examination of the strategic objectives toward which DSO actions will be directed over different time horizons. Finally, a range of features that differentiate DSOs from more conventional distribution network businesses are discussed and a working definition for DSO models is proposed.

Structural shifts require structural interventions

The nature and scale of change that is currently being, and will continue to be experienced, over the next decade or more is transformational and structural. All vertical tiers/layers of system – bulk power, transmission and distribution – are simultaneously being impacted. As the conventional coal-fired generation fleet is progressively withdrawn, to be largely replaced with weather-dependent generation connected at both transmission and distribution levels, the first principles of how electric power systems function are being reimagined.

In response to this unparalleled scale of change, power systems like the NEM must be transformed to enable entirely new levels of flexibility and whole-system interdependence. This scale of change is the specific context in which both Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models become critical to future system operations. While distinct topics, DSO and TDC models are highly complementary and cannot ultimately be separated. Properly understood, they both represent critical structural interventions that are required to avoid resisting or even fighting the Laws of Physics in a decarbonising power system which is inherently more volatile and bidirectional.

Key challenges in the holistic consideration of DSO models

As a still maturing area, a key challenge that arises in the consideration of DSO models is perhaps analogous to evaluating the future roles of a System Operator at the dawn of electrification – by definition there are many unknowns. A further analogy may be attempting to consider all the functions performed by the central station in a railway network which, by definition, ultimately requires having to also consider all the lines in the rail network at least to some extent. In other words, the consideration of DSO models is inherently systemic rather than simply functional.

Interestingly, while scores of global reports relevant to DSO models exist, no authoritative or universally accepted definition of what a DSO is, or body of knowledge outlining what a DSO does, is known to exist. Several initiatives have certainly attempted to tabulate the range of technical functions a DSO may perform with varying degrees of success and transferability. However, beyond nearer term imperatives, a key gap has been a lack of shared clarity about the medium and longer-term objectives for DSO models, particularly from a whole-system perspective. This gap appears to have been compounded by the need for more strategically informed analysis of the underlying problem definition(s) that will require scalable DSO models to play a key part in addressing as both decarbonisation and decentralisation advance.

As a future-facing capability, these gaps are especially prominent when considering the DSO's dual responsibilities, firstly, within the distribution system, and secondly, as an increasingly important part of whole-system operations that are more volatile and bidirectional. Both gaps ultimately impede the ability to design future-facing DSO models that ensure maximum future scalability, holistically address the full range of technical and stranded investment risks and reduce the risk of rework.

Five foundational questions for evaluating DSO models

The above considerations have required a first principles-based approach to the development of this report. Therefore, the remainder of this chapter provides a logical structure of analysis relevant to Australia that is informed by the diversity of Australian and global experience and literature. In doing so, it examines the following five foundational questions:

1. How are DSO models characterised globally? (Section 6.1)
2. What is the problem definition that underpins the need for DSO models? (Section 6.2)
3. What strategic objectives inform DSO priorities and functions? (Section 6.3)
4. What are the key similarities and differences between a DNSP and DSO? (Section 6.4)
5. What are the key functions of a DSO relevant to Australia? (Section 6.5)

This foundational content provides a more robust basis for subsequently considering the functions that are best performed respectively by a DSO and/or a conventional DNSP. This is particularly important as various apparent overlaps exist between what both types of entities must do. In many cases, the absence of clarity on these matters that makes the allocation of functional responsibilities extremely difficult, not least when consideration how each function may need to evolve over time.

The diverse range of global and Australian sources that have informed Chapter 6 are provided in the DSO Design Considerations section of Appendix B: Key Topic Bibliography.

Key Concepts F

System

An interconnected set of components that are formally linked together by 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.

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 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.

6.1 How are DSO models characterised globally?

The DSO concept initially emerged in Europe and the United States in the 2010's as decarbonisation efforts and the adoption of what Australia now refers to as Consumer Energy Resources (CER/DER) were accelerating.

Having evolved over the last decade, the 'DSO' term now broadly refers to a set of responsibilities needed for both the active management of a high-CER/DER distribution system and its relationship with the wider power system. This dual upstream and downstream focus is becoming increasingly critical as entire power systems become more volatile, bidirectional and interdependent.

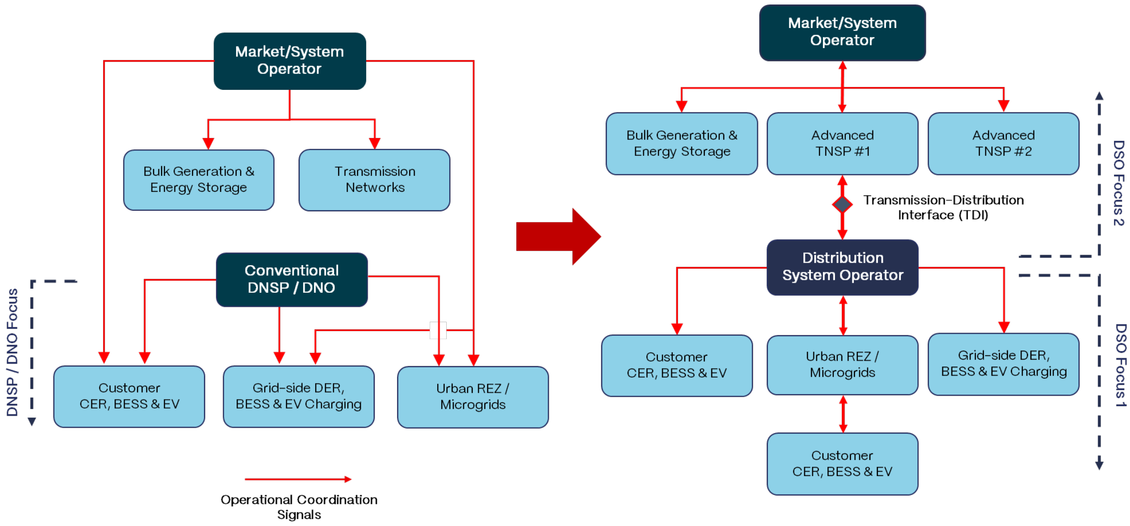

Figure 17: A conventional DNSP/DNO primarily focused on distribution network assets. A DSO focuses both on the distribution system (downstream) as an integral part of the wider power system (upstream)

While the physics-based impacts of power system decarbonisation and decentralisation naturally share many commonalities, there are also jurisdictional variations. These are typically influenced by different policy settings, network topologies, technology mixes, renewable resource availability, levels of CER/DER adoption and participation, etc.

A further complication is that while the 'DSO' acronym is new to most parts of the world, in Europe the term Distribution System Operator has long been used to describe a conventional distribution network business. As a result, the Europeans typically use the term Active DSO for what most other countries simply refer to as a DSO.

Given the evolution of the DSO concept over the last decade or more, before narrowing the focus to more specific considerations, it is valuable to survey how various jurisdictions are characterising what a DSO or Active DSO is. In recognition that not every jurisdiction or organisation has published a concise, formal definition, the attributes outlined in Table 5 below are derived from their publicly available materials.

Table 5: How the attributes of DSO models are variously described globally

Institution	DSO Attributes
United Kingdom	
Ofgem [25], [26]	Distribution System Operation (DSO) is a set of functions and services essential for operating a smart electricity distribution network that benefits energy consumers. A DSO is responsible for planning, operating, and developing an active distribution system that integrates networks, demand, generation, and other flexible distributed energy resources (DERs). It acts as a neutral facilitator of an open and accessible market to enable competitive access and optimal use of DERs.
Energy Networks Association [27], [28]	A Distribution System Operator (DSO) is an entity that brings network decision-making closer to consumers by managing the electricity network at a local level, thereby gaining more control over local supply and demand. This can help to bring more low carbon flexibility services onto the network, reduce the need for reinforcement leading to lower bills, and avoid disruption by increasing performance in local networks.
National Energy System Operator [29]	Distribution system operation (DSO) means the distribution network operators (DNOs) that deliver electricity from the grid to homes and businesses take on more of a system operator role at a regional level. The transition of DNOs becoming DSOs is key to a smarter energy system, more efficient flexibility markets, and achieving net zero.
European Union	
EU DSO Entity [30]	The emerging roles of an Active DSO include: 1) planning and investment to accommodate new technologies; 2) enhancing resilience and sustainability of the grid; 3) facilitating market operations and engaging prosumers; 4) advancing operations and maintenance practices; and 5) promoting digitalisation and data management.
Enedis [31]	An Active DSO encompasses several roles including: 1) enhancing local flexibility to optimise network operations and defer investments; 2) digitalisation and smart grid implementation to enhance real-time monitoring and management of the distribution network; 3) smart connection offers that provide faster, more cost-effective grid connections in exchange for flexibility commitments; 4) DSO-TSO coordination to integrate and share flexibility resources across different grid levels; and 5) stakeholder engagement frameworks across relevant functions impacting communities and DER owners.

SmartEN [32]	An Active DSO is distinguished from a conventional DSO in that it: 1) engages in market-based procurement of flexibility services to address local grid needs; 2) implements transparent and non-discriminatory procedures allowing flexibility providers to participate effectively; 3) coordinates closely with Transmission System Operators to ensure system-wide efficiency and reliability; and 4) facilitates data sharing and interoperability to enhance visibility and integration of DERs and flexibility services into grid operations.
North America	
Ontario Energy Board [33]	A Distribution System Operator (DSO) is defined as an entity with advanced capabilities to integrate, manage, and optimise DERs for both distribution and wholesale market services. The DSO acts as a neutral facilitator, coordinating distributed generation at the local level and enabling open access to the grid. This role is critical in supporting the energy transition and ensuring reliable, cost-effective distribution services.
State of Maine [34]	An entity designed to serve the following roles for the state: 1) oversee integrated system planning for all electric grids; 2) operate all electric grids in the state to ensure optimum operations, efficiency, equity, affordability, reliability and customer service; 3) administer an open and transparent market for distributed energy resources; and 4) facilitate the achievement of the greenhouse gas reduction obligations and climate policies.
EPRI [35]	The active DSO evolves from a traditional operator to one that manages a dynamic, automated, and resilient distribution system. It leverages new data streams, advanced applications, and dispatchable resources to handle increased complexity from DER integration.
Pacific Northwest National Laboratory (PNNL) [36]	A DSO as an entity responsible for the planning and operational functions associated with a distribution system that is modernised to accommodate high levels of DERs. This role includes ensuring safe, reliable, and efficient operation of the distribution network, facilitating DER integration, and coordinating with transmission system operators (TSOs) to maintain overall grid stability. The DSO may also engage in market facilitation, enabling DER participation in energy markets.

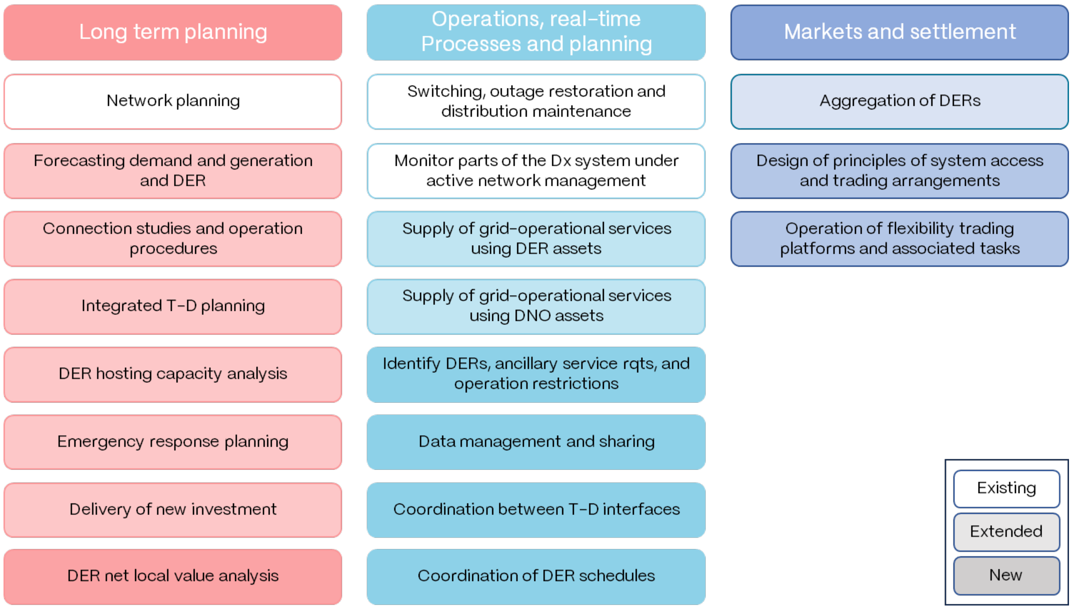

Figure 18: Existing, extended and new functions of a DSO as set out in Ofgem's original position paper [25]

6.2 What is the problem definition that underpins the need for DSO models?

Fundamental to good solution design is effective problem definition. While this is foundational, it can be particularly challenging in highly complex system that is experiencing profound transformation. Put simply, where numerous aspects of the system are undergoing various degrees of change, defining *the* problem can seem almost impossible.

In a sense, this is a prime example of why disciplines such as Systems Engineering and Systems Architecture become essential for supporting complex grid transformations. Originally developed for other complex sectors such as aerospace, defence and advanced manufacturing, they are purpose-built for interrogating and 'taming' the inordinate levels of complexity experienced when large, ultra-complex systems transform.

This is particularly relevant when considering DSO and TDC models, which cannot adequately be considered simply as clusters of new functions. Properly understood, both are significant structural interventions needed for a decarbonising and decentralising grid to be capable of functioning securely and efficiently in a very different operating environment. By comparison, simply evolving the essential characteristics of a conventional DNSP would be much simpler if that was adequate.

System-level Problem Definition

At a whole-system level, the key problem definition underpinning the need for the development of DSO models may be characterised as follows.

System-level Problem Definition

- Power system operations are progressively transforming from a comparatively stable, unidirectional and past to an increasingly volatile, bidirectional future.
- As the dispatchable thermal generation that provided most system flexibility is withdrawn, the power system must leverage a wide range of new sources of flexibility to underpin operability and supply-demand balancing as volatility increases.
- As the time windows where 100% of instantaneous demand served by distribution-connected resources expand, bidirectional power flows over 24-hour periods are occurring in an increasingly 'tidal' manner and whole-system operations must therefore become more interdependent end-to-end.
- As the power system decarbonises, an increasingly flexible and responsive demand-side becomes integral to the security, stability and cost effectiveness of both the distribution system and wider power system.
- As the demand-side of the system transforms to become the location of a large and growing proportion of all participating system resources, real-time management of the 'system' of network assets, generation, storage and flexible resources becomes essential for distribution system and whole-system security and efficiency.

Structural Problem Definition

In response to this unparalleled scale of change, power systems like the NEM must be transformed to enable entirely new levels of flexibility and whole-system interdependence. This scale of change is the specific context in which both DSO and TDC models become critical to future system operations. Properly understood, they both represent critical structural interventions that are required in a decarbonising power system which is inherently more volatile and bidirectional.

Beyond the above system-level problem definition, the formal Systems Engineering discipline provides a means for analysing cross-cutting issues that stem from the fundamental structure of a complex system and/or impedes its ability to transform. Referred to as a 'Systemic Issue', these issues emerge from the way the entire system is structured, rather than from isolated component failures or random anomalies. Informed by the Systemic Issues analysed in Report 3 of this series [5], the following examples selectively highlight issues that well designed DSO models help alleviate.

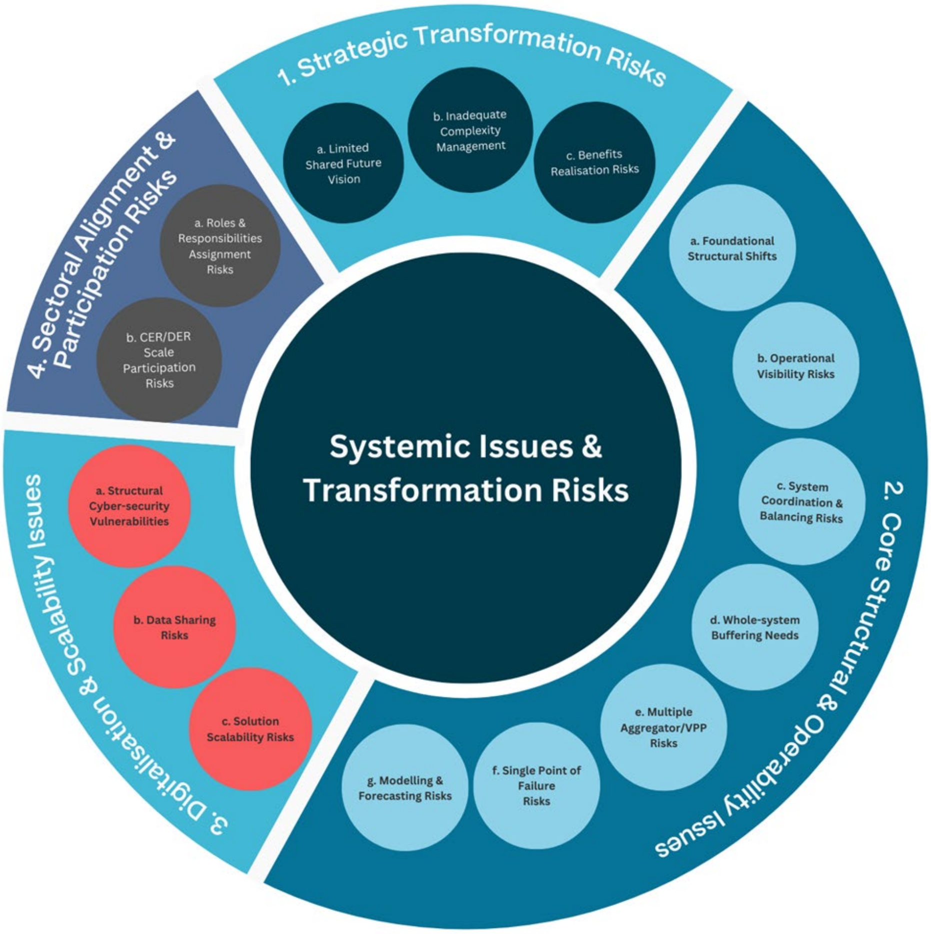

Figure 19: The structural analysis undertaken in Report 3 of this series identified fifteen Systemic Issues & Transformation Risks clustered under four categories [5]

Table 6: Systemic Issues emerging as the NEM decarbonises and becomes increasingly distributed that DSO and TDC models help address at a structural level

Systemic Issues by Category		
Systemic Issue	**Description of Systemic Issue**	**Relationship to DSO & TDC Models**
Category 2: Core Structural & Operability Issues		
Foundational Structural Shifts	A range of inherent constraints are embedded in the legacy grid structures developed for unidirectional power flows and passive consumers. These constraints become increasingly problematic as decarbonisation advances and power flows become more bidirectional and volatile. Impacting the various segments of the grid, their impact is compounded where no single entity is responsible to ensure the system architecture of the end-to-end system is both scalable and future ready.	As noted above, both DSO and TDC models are best understood as critical structural interventions required in a decarbonising power system which is inherently more volatile and bidirectional. In particular, the DSO provides an integrated set of functions required for the active management of a high-CER/DER distribution system and its beneficial operational relationship with the wider power system.
Operational Visibility Risks	As profound structural and operational shifts increase, the lack of a layered, end-to-end approach for providing operational visibility, especially of the growing fleet of millions of CER/DER, risks compromising the operability, reliability and cost-efficiency of the bulk power, transmission and distribution systems serving the NEM.	DSO models deployed in the context of a more layered architecture support enhanced ability to forecast operational demand over a range of time windows and operating conditions. This enables better quantification of the system technical envelope and supports the adequacy and enhanced economic efficiency of the portfolio of centralised and distributed energy resources available for the instantaneous balancing of supply and demand.

Systemic Issue	Description of Systemic Issue	Relationship to DSO & TDC Models
System Coordination & Balancing Risks	Bidirectional power flows and operational volatility are increasing as dispatchable, synchronous generation is being progressively withdrawn. As the NEM and WEM transition from hundreds to many millions of participating resources, the absence of layered, end-to-end models for operational coordination will place instantaneous system balancing and overall economic efficiency at growing risk.	As decarbonisation advances, more whole-system models of operational coordination and balancing become necessary. Functioning together, the DSO and TDC models enable bidirectional interoperability across the TDI, enabling the wider power system to leverage the millions of energy resources connected across the system. This can support more granular market-control alignment models that both incentivise and activate the targeted provision of grid services when and where most needed.
Whole-system Buffering Needs	As a growing proportion of renewable generation is deployed, unprecedented levels of power flow volatility are propagated across the end-to-end system. While most complex systems and supply chains have internal buffering mechanisms (e.g. warehouses, storage tanks), these have not been widely available in conventional power systems. Given the scale of Variable Renewable Energy (VRE) and CER/DER deployment underway, a targeted and whole-system approach to deploying energy storage for system buffering will be required to augment system balancing and operational coordination.	As conventional generation is withdrawn, the integration of IBR at scale into the NEM will require structural changes to the system, particularly with regard to the strategic deployment of buffering throughout the system. The buffering of power flow volatility requires fast bilateral (two-way) energy storage connected to the power system via bilateral power electronics. New forms of control will also be needed to operate these storage devices in the context of an IBR-based power system. This storage-based buffering arrangement will likely need to be structured in a four-tier architecture of (1) bulk power system storage; (2) embedded storage networks located at Bulk Supply Point substations; (3) distribution point-connected storage units; and, (4) behind-the-meter storage.

Systemic Issue	Description of Systemic Issue	Relationship to DSO & TDC Models
Multiple Aggregator/VPP Risks	The involvement of multiple CER/DER aggregators and Virtual Power Plants (VPP) introduces an additional level of structural and functional complexity across several layers of a GW-scale power system. In the absence of a holistic structurally based approach to their integration, system and market operations will face increasing conflicts and inefficiencies where aggregators and VPPs are present at significant scale.	Moving beyond demonstration volumes, the integration of CER/DER aggregators and VPPs into the NEM at significant scale will require advanced forms of coordination, increased distribution level observability, careful definition and aggregation of functions and the rigorous assignment of functions to roles, and roles to specific entities capable of performing them. Coordination between AEMO, DSOs, DNSPs and VPPs must be structured to ensure no hidden coupling to enable scalable approaches to the operational coordination of CER/DER dispatch at scale. Market participation by VPPs must not allow for tier/layer bypassing and interleaved VPP coordination must avoid LV feeder level coupling problems. VPP-to-CER/DER-to-LV Network mappings must also be kept accurate and current.
Category 4: Sectoral Alignment & Participation Risks		
CER/DER Scale Participation Risks	Future scenarios highlight the important role millions of orchestrated CER/DER, BESS and EVs could play in supporting more secure and efficient future power systems. Without a holistic strategy for scaling mass adoption and sustained participation, current trends suggest that achieving the scale of participation required will continue to prove challenging if not infeasible.	Well-designed DSO models can play an important role in helping unlock the full CER/DER 'value stack' essential to maximising customer participation. This may include the establishment of a unified digital platform, for example, provides customers with simple, trusted access to value-added service offerings, energy usage, generation and storage monitoring together with a range of seamless CER/DER participation options that provide both customer and system benefits.

6.3 What strategic objectives inform DSO priorities and functions?

A DSO is by definition a future-facing entity. As articulated by the aspects of the underpinning problem definition explored above, its fundamental reason for being is to provision the power system for secure and efficient operations in a very different operating context.

As noted earlier, significant attention has been given the potential range of functions that may be performed by a DSO, particularly in the nearer term and with a focus on the distribution system. By contrast, there appears to have been far less consideration given to defining the strategic and operational objectives for a DSO, both in the medium to longer term as the system decarbonises, and certainly in terms of the whole-system functions performed by a DSO.

Importantly, these gaps ultimately impede the ability to design future-facing DSO models which ensure maximum future scalability, holistically address the full range of technical and stranded investment risks and reduce the risk of rework. Further, when mainly considered at a functional level, it becomes difficult to resolve key functional overlaps between what a DNSP and DSO have primary responsibility for. In other words, a lack of distinctive objectives will exacerbate the difficulty of:

- Clearly defining and allocating functional responsibilities
- Considering how those functions may need to mature, evolve, scale over time (in accordance with achieving the short, medium and longer-term objectives); and
- Evaluating the structural enablers required for each entity to perform their roles, including how those structures may also need to evolve over time.

Therefore, following is an attempt to synthesise a core set of seven DSO objectives informed by the problem definition examined earlier and calibrated against multiple global sources.

- **Distribution System Objectives**
  - Enable secure integration of CER/DER at scale
  - Enhance reliability, resilience and power quality
  - Enhance asset utilisation and cost efficiencies
  - Enable beneficial customer participation and incentives
- **Whole-system Objectives**
  - Support whole-system visibility, coordination and balancing
  - Support whole-system asset utilisation and cost efficiencies
  - Support whole-system decarbonisation

Table 7: Seven strategic objectives that inform DSO priorities, functions and trade-off choices

Objective	Description
Distribution System Objectives	
Secure Integration of CER/DER at Scale	A DSO enables the distribution network to more securely and efficiently integrate much higher levels of renewable energy than conventional network management approaches are capable of. In the more dynamic context of a decarbonising power system, a DSO typically employs Active Network Management (ANM) capabilities that enable real-time management of network assets, flexible loads and Consumer Energy Resources (CER/DER) to simultaneously support network stability and increased hosting capacity. This is particularly critical given Australia's world leading levels of distributed solar PV (DPV) adoption, where whole regions now have expanding time windows where 100% of instantaneous demand is served locally by distribution-connected resources.
Enhanced Reliability, Resilience & Power Quality	The operational environment of a DSO is significantly more volatile and bidirectional than conventional, unidirectional distribution networks were designed for. The application of ANM employs digital technologies, data analytics and automated control systems to dynamically manage voltage fluctuations, bidirectional power flows, congestion and faults. It can leverage flexible loads and CER/DER to manage intermittency, moderate peak demand and absorb oversupply of renewable resources. This makes the distribution network significantly more adaptive, enhancing power quality and increasing resilience to a wide range of operational disturbances.
Enhanced Asset Utilisation & Cost Efficiencies	A key aim of a DSO is a more cost-efficient distribution network through a wider range of augmentation and system management options. As noted above, DSOs commonly leverage ANM capabilities which also enables the real-time management of power flows to both moderate peaks and fill troughs. The ability to orchestrate a wide range of energy resources enables more efficient utilisation of existing network assets. This expands the potential to defer or avoid targeted capital investments without degrading service quality or reliability. Over the medium-term, higher asset utilisation translates to lower capital expenditures per unit of energy delivered, ultimately reducing distribution network charges for consumers. Stranded asset risks are also mitigated by right sizing the network for a decarbonised future.

Objective	Description
Beneficial Customer Participation & Incentives	As the name suggests, a DSO is focused on the distribution system as a whole, not only the traditional network assets (i.e. poles, wires, transformers, substations, etc.). Therefore, in the increasingly dynamic context of a decarbonised and distributed power system, a DSO promotes the beneficial participation of CER/DER at scale, providing customer-focused platforms and participation options supported by access to essential data. It also actively fosters the emerging ecosystem of new actors, including aggregators, VPPs and community energy initiatives. A target outcome is to expand beneficial participation by enabling CER/DER to provide services when and where needed by the grid and derive value for doing so. A wide range of participation options are offered across residential, commercial and industrial customer segments, and including rental and high-density properties. Ultimately, all customers – even those who do not actively participate – benefit from a more efficient and reliable power system.
Whole-system Objectives	
Whole-system Visibility, Coordination & Balancing	In a decarbonising power system, an expanding responsibility of a DSO is active participation in the two-way coordination of power flows and data exchange between the upstream bulk power and downstream distribution systems. Unlike the conventional unidirectional operation of the grid, Transmission-Distribution Coordination (TDC) plays an increasingly critical role in whole-system operability as power systems become increasingly volatile and bidirectional. For example, architecturally informed DSO and TDC data structures enable end-to-end visibility which also underpins predictability and observability. They also enable the transition to multi-layer operational coordination and the co-optimisation of layered markets should they exist. In practice, by actively managing load flexibility and CER/DER across an entire distribution system, the DSO becomes an active participant in ensuring whole-system security and economic optimisation by providing dynamic, location-sensitive services that complement bulk power and transmission operations.

Objective	Description
Whole-system Cost Efficiencies (CAPEX & OPEX)	In an increasingly volatile power system, the participation of DSOs in actively coordinating two-way flows of power, services and data between the transmission and distribution systems has strong potential to enhance whole-system efficiencies over various timescales. From a system planning perspective, the scale of new upstream generation, storage and transmission investments may be moderated as the utilisation of existing assets is enhanced and an expanding set of system services are enabled through the DSOs. From a system operations perspective, enhanced real-time visibility and predictive analytics, underpinned by architecturally informed data structures, enable much more fine-grained operational coordination across the end-to-end system. As the proportion of overall system generation, storage and flexibility resources which are connected at the distribution level continues to expand, this will become even more critical as the need for multi-layer balancing also grows over time.
Whole-system Decarbonisation	In collaboration with the system operator, the participation of numerous DSOs in active coordination between the transmission and distribution systems is essential to enabling the full decarbonisation potential of the power system. As the proportion of both centralised and decentralised Variable Renewable Energy (VRE) resources continues to grow, joint participation in TDC functions will be required to support effective supply-demand balancing in a more volatile and bidirectional context. In addition to the cost-efficiencies noted above, it is also key to maximising the productive utilisation of VRE capacity, reduce curtailment and spillage, and moderate dependence on fossil-fuel based firming resources. Similarly, DSO participation in TDC is also key to enabling wider electrification underpinned by beneficial 'couplings' with adjacent carbon-intensive sectors including transport, industrial processes, water and wastewater systems, gas systems, etc. Over time, as the diffusion of millions of energy resources across all layers of the system continues to expand, the DSO/TDC relationship will become even more valuable as the need for multi-layer balancing also increases.

6.4 What are the key similarities and differences between a DNSP and DSO?

There are several areas of similarity and potential overlap between a conventional distribution business (DNSP/DNO) and a Distribution System Operator (DSO) which can easily result in a level of confusion. It is also noteworthy that in Australia, with the growing levels of CER/DER deployment, many DNSPs have already had to assume aspects of what a DSO may be expected to perform.

While no summary statement will be comprehensive, following are two brief statements that broadly distil the key areas of focus relevant to a conventional DNSP/DNO and a DSO with key points of difference in bold font.

Table 8: Summary statements that highlight key similarities and differences between a conventional DNSP and a DSO in a decarbonising, high-CER/DER power system

Conventional Distribution Network Service Provider (DNSP)
The entity which **owns, operates and maintains a conventional electricity distribution network**, with a **primary focus on safe, reliable and efficient one-way power delivery to consumers**. Key activities include network management, infrastructure planning, maintenance and augmentation, customer connections, pricing and tariff settings, supporting energy metering and data, and compliance with regulatory requirements.
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.

In summary, a DSO is responsible for achieving a wider set of objectives than a conventional DNSP via the real-time coordination of the 'system' of network assets, flexible demand, customer-owned CER and large-scale DER.

By comparison, a conventional DNSP achieves its key objectives of enabling safe, reliable and efficient power delivery to consumers primarily via the management of network assets in a unidirectional context.

A further comparison is provided in Table 9 below.

Table 9: Key differences and areas of complementarity between a conventional DNSP and a DSO in a decarbonising, high-CER/DER power system

Category	Conventional DNSP/DNO	Distribution System Operator (DSO)
High-level Objective	Safe and reliable one-way power delivery to consumers supported by prudent and efficient network investments.	Active management and optimisation of a high-CER/DER distribution system and its two-way interoperation with the transmission system.
Key Functions	• Manage operation of network assets • Infrastructure planning, maintenance and augmentation • Customer connections • Pricing and tariff settings • Supporting energy metering and data; and • Compliance with regulatory requirements.	• Real-time coordination of the 'system' of network assets, customer demand and CER/DER at scale • Market mechanisms that incentivise mutually beneficial participation • Integrated distribution system planning • Advanced data analytics, sharing and third-party engagement; and • Active coordination with the transmission system.
System Perspective	One-way, passive energy flow from transmission to consumer.	Two-way, dynamic system with decentralised energy participation.
Customer Interaction	Manages physical connections, metering, and basic customer service.	Actively informs and engages customers and third-party service providers in the provision of beneficial grid services.
Technology Focus	Physical network assets, control systems, etc.	Expanded data analytics, advanced forecasting, automation, market mechanisms, etc.
Regulatory & Compliance	Compliance with reliability, safety and service standards under economic regulation.	Also operates under regulated frameworks, with added focus on transparency, data sharing, and neutrality.

6.5 What are the key functions of a DSO relevant to Australia?[9]

As a still maturing area, no universally accepted definition of a DSO is known to exist. Therefore, following is a synthesis of five core DSO functions that are informed by the above problem definition and objectives and calibrated against multiple global sources.

- **Function 1: Active System Management**

  Manage safe, reliable and efficient operation of the distribution system in a two-way power flow environment to ensure the continuous supply of electricity to, between and from customers. This involves the proactive identification and resolution of constraints, congestion management, optimised asset utilisation and enabling the scale participation of CER/DER and flexible loads. In includes actively managing the optimal combinations of distribution network assets, CER/DER and flexible loads in a non-discriminatory manner to provide beneficial services to the distribution system, the wider power system and both participating and non-participating customers.

- **Function 2: Distribution Market Mechanisms**

  Employ 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.[10]

- **Function 3: Integrated Distribution Planning**

  Perform long-term distribution system planning, in active collaboration with the relevant DNSP, upstream TNSP and the system operator, as an integral part of whole-system planning. Ensure sufficient whole-system and distribution-level generation, storage, flexible resources and network infrastructure to serve all customers reliably, including the systems integration required to beneficially leverage large volumes of participating CER/DER and flexible loads. Both non-network and conventional network solutions receive equal, non-discriminatory consideration.

- **Function 4: Advanced Data Analytics and Sharing**

  Enable enhanced network visibility, real-time monitoring and rapid response to dynamic conditions, including fault prediction and network performance optimisation. Support improved real-time forecasting of load, generation and storage operational behaviours. Provide analytics to underpin the operation of flexibility markets by identifying opportunities for demand response and coordinating with market participants to optimise resource utilisation. Facilitate better understanding of customer behaviour and energy usage patterns to offer tailored services and engage customers mutually beneficial initiatives.

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[9] This distillation of core functions is derived from a meta-analysis of the global literature and informed by previous collaboration with Dr Lorenzo Kristov, Matthew McDonnel, Nikhil Balakumar and Dan Cross-Call.

[10] This functional category is intentionally broad and may be achieved by various types of market and/or transactional mechanisms. Refer to Sections 10.3 and 10.8 for additional information.

- **Function 5: Transmission–Distribution Coordination**

  Actively collaborate with the system operator and relevant transmission network to enable operational visibility, support relevant data exchanges, align operational and market interactions, and coordinate longer-term system planning. Key functions include low latency data transformations and exchange relevant to the joint management of frequency, voltage, congestion, energy flows, essential system services and supply-demand balancing.

Each of the above functional responsibilities are explored in more detail in Chapter 10 of this report.

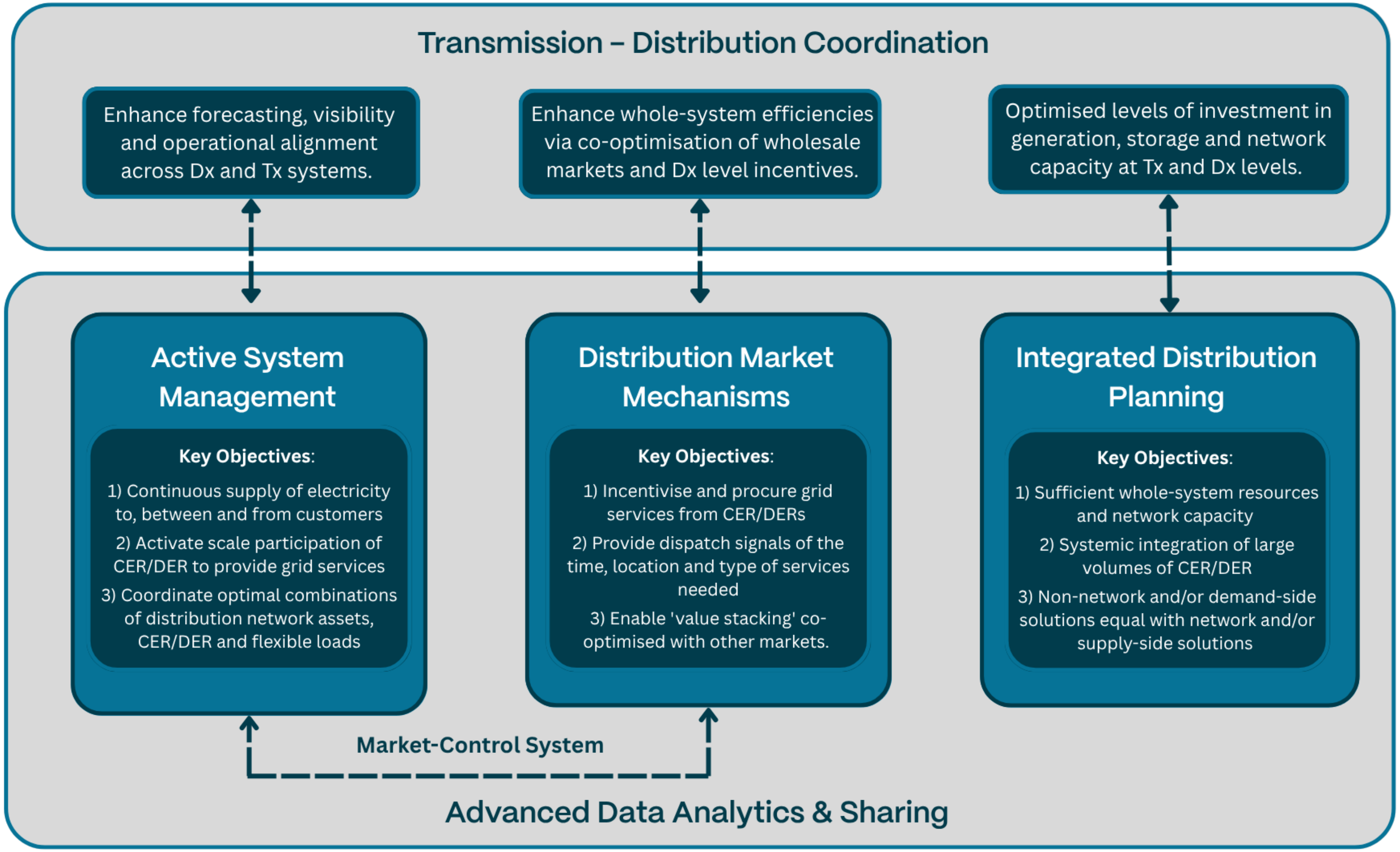


Figure 20: A high-level view of the five core functional areas intrinsic to a DSO as informed by the diverse global literature

7 Strategic Enablers: Policy, regulatory and innovation enablers of the DSO transition

Australia's globally recognised scale and pace of grid transformation provides the context in which the consideration of Distribution System Operator (DSO) models become critical to future system operations. As the end-to-end grid becomes more volatile and bidirectional, DSO and the related Transmission-Distribution Coordination (TDC) models are best understood as structural interventions critical for secure, cost-efficient, decarbonised future power systems.

This chapter briefly highlights how national and/or transnational policy, regulatory and innovation initiatives underpin the DSO transition in the United Kingdom (UK) and the European Union (EU). Recognised as a key part of enabling whole-system grid transformation, the consideration of DSO models will be significantly enhanced where informed by the wider policy, regulatory and innovation landscape.

7.1 United Kingdom

The United Kingdom has moved beyond considering DSO models and now leads the world in deploying and operating them. This has been enabled by several factors, one of which has been strategic policy formulation undertaken by the UK Government and Ofgem which commenced in 2017. For example, the 2021 update of The Smart Systems and Flexibility Plan stated [37]:

> *Achieving our net zero target by 2050 will require a significant transformation to many sectors of the economy, not least energy. This Plan sets out key reforms within our current market structures, to accelerate deployment of low carbon flexibility during the 2020s, to meet the demands of a system with significant volumes of renewables, electric vehicles and electric heat.*
>
> *However, over time some of the fundamental characteristics of our energy system will change. We will shift to a system dominated by zero marginal cost fuels (the wind and sun), where prices to generate are frequently very low (for example when there are periods of high wind and low demand), and where actions by consumers to shift demand patterns are as essential as investing in new generation or network assets. All this while ensuring we have the capacity and operational tools to maintain security of supply in a very different electricity system.*

This was accompanied by a reiteration of these ambitions in the Net Zero Strategy: Build Back Greener document [38]:

> *The Smart Systems and Flexibility Plan sets out a vision, analysis, and actions for delivering a smart and flexible energy system. We will facilitate flexibility from consumers and remove barriers to flexibility on the grid, both for small-scale and large-scale long-duration electricity storage, as well as driving policy to increase interconnector capacity. The Plan also sets out actions to improve market design and coordination so that flexibility providers can secure revenues across multiple markets. Data and digitalisation are a core aspect of the future system; we have set out a strategic approach to digitalisation and opening data across the energy sector through the Energy Digitalisation Strategy.*

In this wider context, Ofgem's substantial innovation incentives for network businesses enabled the comprehensive Open Networks work program involving all UK distribution networks. Led by the UK's Energy Network Association, the program advanced fundamental shared learning on potential DSO models and their practical implementation over the six years from 2017 to 2022 inclusive [39].

Further, Ofgem's RIIO regulatory model applies a TOTEX-based[11] approach. This ensures proposed network expenditures are evaluated in a more holistic manner and provides regulated networks a single operating and capital investment allowance. This removes the potential bias towards expensive capital investment solutions, arguably, better supports the achievement of least cost outcomes for consumers – which is a key objective for implementing DSO models.

In summary, the UK's leadership on DSO models has occurred across a broad range of government, regulatory and industry collaboration supported by relevant funding as outlined in the Table 10 below. As an integral element of the process of whole-system transformation, the further development of the functional relationships between regional DSOs and the recently established National Energy System Operator (NESO) is currently advancing.

Table 10: United Kingdom – Policy and regulatory initiatives relevant to the development, deployment and maturation of DSO models

United Kingdom – Policy & Regulatory Initiatives			
Initiative	Year(s)	Lead Entity	Focus
1. Smart Systems, Flexibility Plan & DSO Strategy	2017–2023	Ofgem, Government	Enabled flexibility services, defined DSO roles
2. Open Networks	2017–2022	Energy Networks Association	Operational DSO model trials and definitions
3. Electricity Network Strategic Framework	2022	Government, Ofgem	Vision for smart distribution networks
4. RIIO-ED2 Price Control	2023–2028	Ofgem	Mandated DSO functionality and incentives
5. Flexibility Market Reforms	2018–2024	Ofgem, DNOs	Enabled local service procurement
6. Digitalisation and Data Policies	2019–Present	Government, Innovate UK	Data and digital infrastructure for DSOs
7. Net Zero / Powering Up Britain	2021–2023	Government	DSO growth via electrification policies
8. Future System Operator Plan	2021–2025	Ofgem, Government	Whole-system alignment with DSO

[11] Total Expenditure = both CAPEX and OPEX.

7.2 European Union

The EU is taking a legislation-first approach. The Clean Energy Package [40], specifically Directives 2019/944 and Regulation 2019/943 [41], legally defined DSOs as active system managers. As such, what the European's refer to as Active DSOs must assess non-network options, procure services competitively, and facilitate participation from prosumers, aggregators, and energy communities. Ownership of flexibility assets by DSOs is restricted to ensure neutrality. As additional context [42]:

The European Commission recently published its Grid Action Plan [43], highlighting the need for significant efforts at the distribution grid level, as most DER, heat pumps (HP) and electric vehicles (EV) will be connected here. However, grid investments alone will not suffice, and flexibility will be crucial to manage fluctuations in renewable energy generation and consumption while reducing grid investment costs.

While the electricity system has traditionally managed flexibility at the transmission level, addressing challenges in the distribution grid requires new solutions and increased flexibility at this level. The rise in DER and the electrification of end-use sectors is also a source of more flexibility within the distribution grid.

Table 11: European Union – Policy and regulatory initiatives relevant to the development, deployment and maturation of DSO models

European Union – Policy & Regulatory Initiatives		
Initiative	**Year(s)**	**Focus**
1. Clean Energy for All Europeans Package	2019	Formal DSO role in flexibility, data, neutrality
2. Establishment of EU DSO Entity	2021	EU-level coordination, network codes
3. Digitalisation of Energy Action Plan	2022	DSO digital capacity and data access
4. Horizon 2020 / Horizon Europe Applied Research Projects	2014–ongoing	Several projects examining Active DSO functions (e.g. flexibility procurement, coordinated planning, market platforms and T-D Coordination)
5. Fit for 55 Package	2021	Electrification and DER drivers
6. Energy Data Spaces	2023	Several projects developing federated data platforms
7. National Energy and Climate Plans (NECPs)	2020–2030	Country-level DSO investment planning

In this context, the DSO Entity was established as the legally mandated body for European DSOs in June 2021. It was established under the EU's Electricity Market Regulation to promote the completion and functioning of the internal market and help drive Europe's energy transition. The DSO Entity's Annual Work Programme 2025 summarises the growing importance of distribution networks across the EU as follows [44]:

> *DSOs are the backbone of the changing energy system*
>
> - *DSOs integrate the largest share of renewable and intermittent power sources.*
> - *DSOs manage volatile energy supply and demand challenges in flexible and decentralised grids.*
> - *DSOs manage the digitalised grid and cooperate with Transmission System Operators (TSOs).*
> - *DSOs enable customers to participate in an increasingly decentralised energy world.*

Given the EU's long-standing commitment to deep decarbonisation, it has also led the world in its focus on enabling more flexible power systems which commenced as early as 2014 with the Universal Smart Energy Framework (USEF) initiative. Combined with the EU's multi-year research funding programs, numerous whole-system research projects focused on grid digitalisation, visibility and coordination have been undertaken, including OneNet [45], SmartNet [46], and Interface [47].

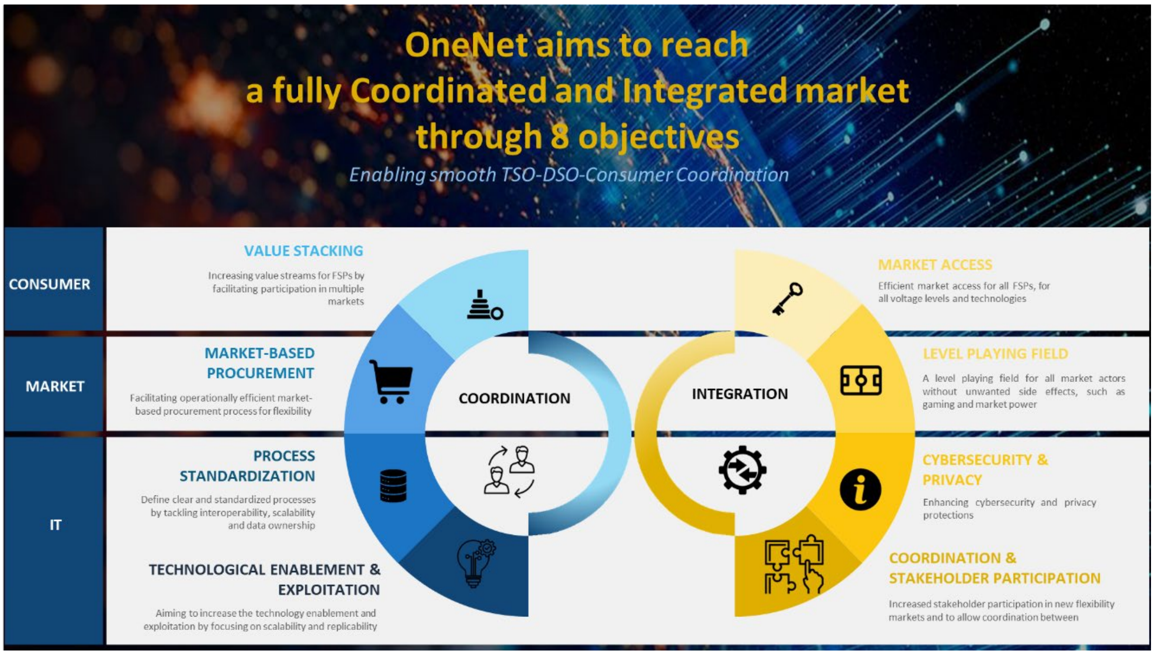


Figure 21: OneNet focused on Transmission-Distribution-Consumer operational coordination[45]

Finally, as a block of 27 member states, the regulatory context is more diverse in the EU than in the UK. Nevertheless, in recognising the critical need to enable a more flexible power system as decarbonisation, decentralisation and electrification advance, the EU Agency for the Cooperation of Energy Regulators (ACER) recently stated [19]:

TSOs and DSOs are often influenced by regulatory frameworks that favour cost estimation based on traditional infrastructure capital expenditures (CAPEX) or operational expenditures (OPEX), instead of a total expenditure (TOTEX) approach that also considers non-wire alternatives. This CAPEX/OPEX bias means that TSOs and DSOs are more likely to invest in physical assets, which are generally seen as more reliable and tangible solutions. As a result, innovative solutions like demand response and other distributed energy resources, which could provide more cost-effective and flexible grid management, remain underutilised due to the lack of appropriate cost accounting and accompanying incentives for cost recovery of demand response procurement.

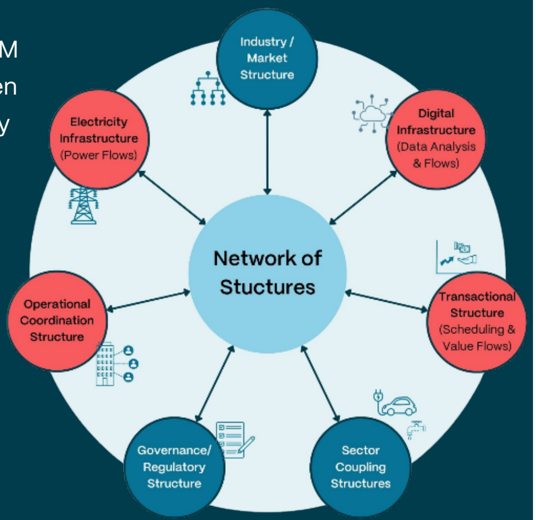
National regulatory authorities to reform regulatory frameworks to balance CAPEX/OPEX and TOTEX, ensuring that TSOs and DSOs are incentivised to invest in non-wire alternatives to unlock the true potential of the grid. This can be achieved by introducing performance/output-based regulations to incentivise them to pursue predefined goals and metrics, and a total cost approach that recognises the long-term benefits of non-wire alternatives.

Key Concepts G

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:



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

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

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

The Network of Structures paradigm [48], developed by Pacific Northwest National Laboratory (PNNL), provides an essential framework for the holistic analysis, mapping, and optimisation of current and future system structures.

8 Alternative DSO & TDC Models: Different structures impact visibility, coordination and complexity

As discussed earlier in this report, Australia's NEM is experiencing a scale of structural transformation unprecedented in the history of electricity systems. All vertical tiers/layers of the legacy system – bulk power, transmission and distribution – are simultaneously being impacted as conventional generation is largely replaced by weather-dependent VRE connected across the HV, MV and LV systems.

In this context, operational dynamics never previously experienced in a GW-scale power system must now be navigated as power flows become increasingly volatile and bidirectional. As the structural arrangements of the NEM were originally configured for comparatively stable, unidirectional operation these developments are ultimately transformative rather than peripheral or incremental. They directly impact the structural and operational underpinnings of one of Australia's largest, most complex and most critical systems which must now be provisioned for more flexible and interdependent whole-system operation.

This chapter applies formal Systems Architecture principles to evaluate three structural archetypes that have often been proposed as the context in which DSO and Transmission-Distribution Coordination (TDC) models may be deployed. Relevant legacy structural features of the existing power system are discussed to highlight why the inherited structural arrangements are increasingly ill suited for enabling Australia's high-CER/DER future. The discussion then focuses on assessing the advantages and disadvantages of the two most plausible structural archetypes in which DSO and TDC models may be deployed.

The diverse range of global and Australian sources that have informed Chapter 8 are provided in the Cyber-Physical Structures section of Appendix B: Key Topic Bibliography.

8.1 Three DSO & TDC structural archetypes

As noted earlier in Chapter 6, Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models are best understood as critical structural interventions that are required to enable a decarbonising, high-CER/DER power system to operate securely and efficiently. Although performing distinct functions, DSO and TDC models together with their enabling structures directly impact the pressing issues of whole-system visibility, operational coordination and system balancing.

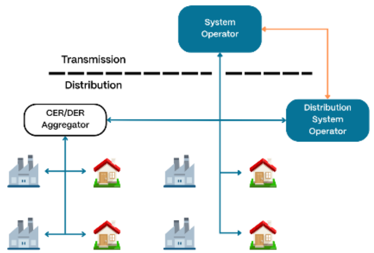
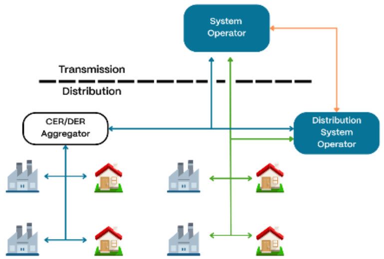
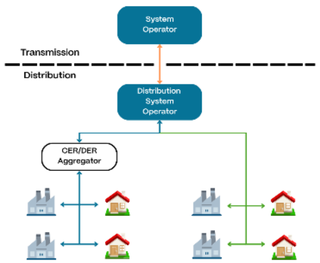
As the consideration of DSO models has evolved over the last 10-15 years, the discussion has often been shaped around a set of high-level structural options for how these formalised capabilities may function with the rest of the power system. While a range of different names have been used internationally, three structural archetypes have commonly been advanced for discussion.

Each of these structural models are briefly described in Table 12 below. As theoretical concepts, the three models have typically been advanced as a basis for comparative economic analyses, often in a manner that suggests they are all similarly credible technological options. This limitation appears to have remained unaddressed and been compounded by the absence of applications of Systems Engineering in the electric power sector coupled with an inadequate awareness of the specific structural constraints embedded in today's legacy grid arrangements.

However, these non-trivial constraints, inherited from the architectural arrangements of a unidirectional system, directly impact whole-system visibility, operational coordination and system balancing. They are a fundamental reason that structural analysis cannot be sidestepped if the NEM is to be made able to cost-effectively support the very different futures represented by AEMO's ISP scenarios, not least the high-CER/DER Step Change scenario.

It should also be noted that while there are three basic structural archetypes that have been advanced over the last decade, several different names have been employed in different jurisdictions. To assist with clarity, these three categories have been assigned a simple, accurate title that reflects the predominant, distinguishing features of each structural archetype, namely: Top-down, Multi-entity and Layered Coordination.

Table 12: Three structural archetypes that are commonly advanced in the context of exploring DSO and TDC models

Category	Conceptual Schema	High-level Description	Sources & Different Terms Used
Top-down		The System Operator (SO) of the bulk power system has responsibility to manage all participating resources that are connected across the transmission system and each related distribution system, including all CER/DER. The DSO role in this case is limited and is closer to that of a conventional DNSP than in any other category.	• **Total ISO** [49] • **Total TSO** [48], [49], [50], [51] • **ESO Coordinates** [53] • **Single Integrated Platform** [54], [55]
Multi-entity		The upstream SO and the relevant downstream DSO both have operational responsibilities for managing and/or influencing the operation of distribution-connected resources as do CER/DER aggregators. Enabling scalable operational coordination and market co-optimisation under this model requires significant additional cyber-physical and computational platform investments.	• **Hybrid Model** [48], [50], [51], [52], [54], [55] • **Coordinated DSO and ESO Procurement** [53]
Layered Coordination		The DSO has overall responsibility to manage the reliable and cost-optimised performance of the distribution system as an interdependent system layer, including network and non-network assets such as CER/DER. The DSO communicates aggregated data to the SO, and both entities actively manage the two-way interdependencies between the bulk power and distribution systems.	• **Total DSO** [48], [49], [50], [51], [52] • **Two-Step Tiered Platform** [54], [55] • **DSO Coordinates** [53]

8.2 Shortlisting the credible transformation options

In more recent years, the expanding complexity of navigating large-scale grid transformation has forced an increased focus on the critical role of structural analysis.[12] This is in a context where the combined impact of increasingly volatile and bidirectional operations is driving world-first challenges for managing a grid originally designed for comparatively stable, unidirectional operation.

In such a context where the operational requirements of a legacy system are changing quite fundamentally from their original design philosophy, while targeted treatments may assist for a time, enduring scalable solutions ultimately require structural interventions. This is an ironclad reality of how complex systems work as supported by the Foundational Sources outlined in Appendix A. In other words, a scalable, fit-for-purpose systems architecture to underpin formalised DSO and TDC models is essential to the security and cost-efficiency of Australia's power systems.

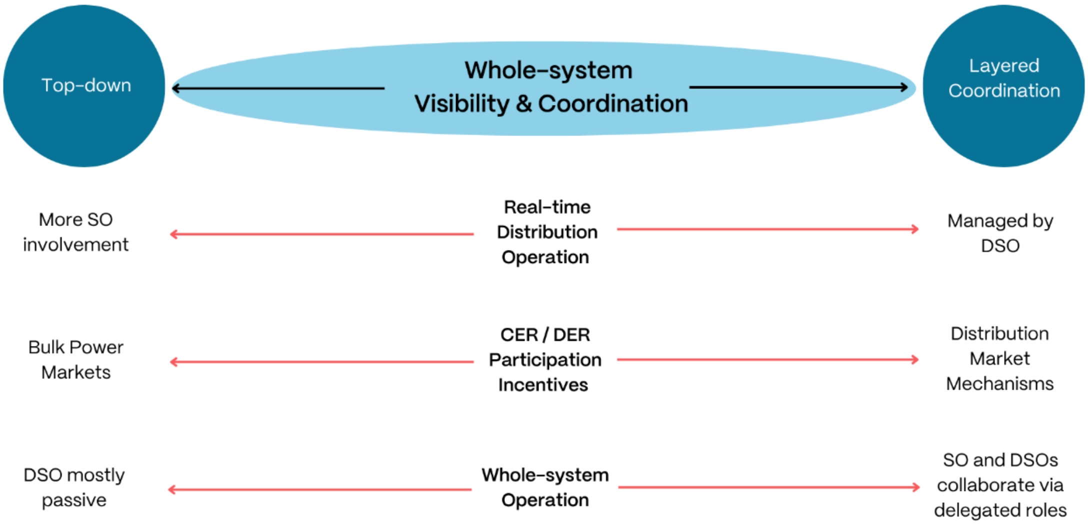


Figure 22: DSO and TDC structural models directly impact the ability to provide whole-system visibility and operational coordination. Image adapted from [51]

The maturing of structural analysis and a growing collective awareness of the limits of issue-in-isolation treatments has provided a more robust understanding of the three structural archetypes, and their ability to enable scalable whole-system visibility and coordination in a transforming grid. Following is a summary of what we now know.

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[12] 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. Refer also to Key Concepts N.

Top-down archetype

The Top-down category of structural models may have relevance for power systems that are projected to only host low levels of CER/DER deployment. This is because Top-down structures are ideal for a hierarchical, command-and-control approach to the management of a power system that is largely served by a finite number of large, upstream dispatchable resources.

By contrast, such models are ill-suited for enabling a power system transitioning from hundreds of upstream merchant resources to tens of millions of diverse resources connected across the end-to-end system. Given that DSO models are generally considered where large volumes of distribution-connected CER/DER are being deployed, there is no known deployment of a Top-down DSO model as a credible, long-term enabler of a high-CER/DER system. In this context, it is further noted that the inherited structural arrangements of legacy systems like the NEM fall under this general category which helps explain why the deep systems integration of millions of CER/DER is increasingly difficult.

Multi-entity archetype

The Multi-entity or blended/hybrid category of structural models are often initially appealing as they appear to offer a means for simplifying stakeholder complexities and disputes by retaining familiar aspects of the legacy structural arrangements. This may indeed be appropriate as a temporary waypoint or stepping stone in a wider process of transformation.

An unintended consequence of attempting to perpetuate a Multi-entity DSO model long-term in a high-CER/DER power system, however, involves a significant increase in the technological complexity and economic cost combined with elevated reliability and resilience risks. While several variants of the Multi-entity archetype have been proposed, these downsides are ultimately due to significant, non-scalable characteristics and constraints that are intrinsic to all Multi-entity DSO models. We discuss some of these unintended consequences later in Chapter 9.

Layered Coordination archetype

The Layered Coordination category of structural models provides a robust basis for solving the numerous legacy structural issues that impede whole-system visibility and the operational coordination of millions of diverse participating CER/DER. Based on formally established mathematical techniques, the model is widely employed in many complex sectors including aerospace, the internet and communications, cloud computing and autonomous transport. As an inherently scalable model, under a mature Layered Coordination DSO structure, the operator of each vertical tier/layer is responsible for its reliable and cost-efficient and only needs to deal with the tiers/layers immediately above and below.

As a foundational strategy for managing complexity in large, complex systems, layered structural models configure a highly complex system into semi-independent, logically structured tiers/layers, each of which provides services to the tier/layer above and uses services from the one below. 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. In the case of a transforming power system, it provides a structural framework for the operational coordination of edge resources such as CER/DER co-optimised with the more conventional bulk power resources.

Key Concepts H

Structure

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

Architecture

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

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

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

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

Scalability

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.

8.3 Interrogating non-scalable legacy structural constraints[13]

Like most GW-scale power systems in the developed world, the NEM evolved and matured throughout the 20th century in a context where:

- Almost all generation requirements were served by several hundred MW-scale merchant generation plant located upstream from customers
- Real power flows were unidirectional, end-users were largely passive receivers of electricity, and distribution networks largely provided one-way supply to consumers; and
- As customer demand was the major source of variability, the system operator (AEMO) dispatched upstream generation capacity in line with downstream customer demand.

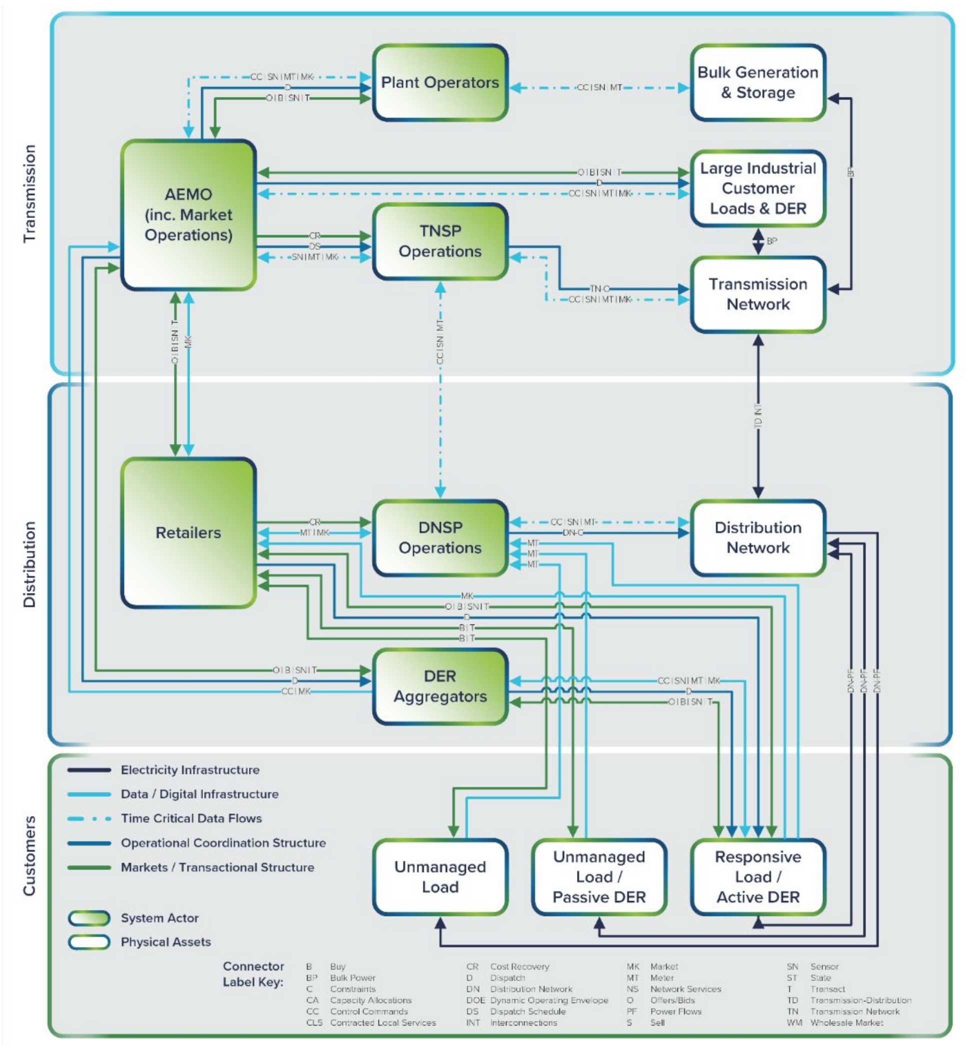

Figure 23: The as-built structural arrangements of the NEM were originally configured to enable the top-down management of a unidirectional power system[7]

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[13] This content is considered in more detail in Report 3 of this series (Sections 4.2.1 – 4.2.3). Detailed structural analysis of the three archetypes was also undertaken in the Stage 2 (Section 4) report.

These basic characteristics operated effectively for much of the last century. Unsurprisingly, the underpinning structural arrangements or 'architecture' of the NEM developed around enabling this model which are illustrated in Figure 23 above. A key benefit of this type of structural mapping is that the underlying architectural issues can be made explicit, non-scalable constraints identified and enduring solutions derived that mitigate the risk of future rework and stranded investments.[14]

For example, as the level of distribution-connected CER/DER grows exponentially as a proportion of the NEM generation fleet, Coordination Gaps, Hidden Couplings and Tier/Layer Bypassing embedded in legacy unidirectional structures will increasingly interfere with the operability of the system.

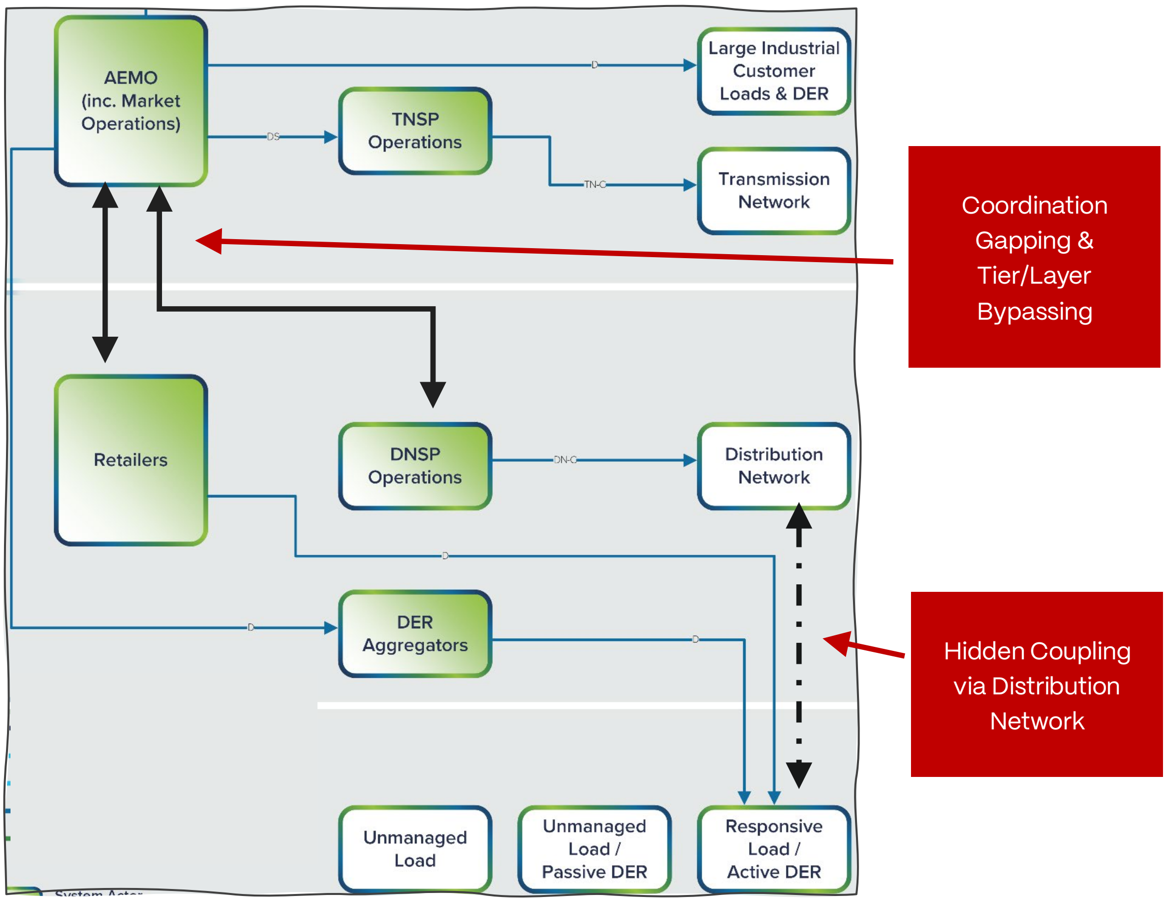

Figure 24: Architectural issues arising from the as-built structural arrangements of the NEM, in this case specific to the Operational Coordination and Transactional structures[7]

Perhaps once considered an area of academic interest, today critical operational coordination problems arising from Tier/Layer Bypassing, Coordination Gapping and Hidden Coupling are increasingly occurring in actual GW-scale power systems that host high levels of CER/DER. In addition, Latency Cascading, Computational Time & Cost Excursions and Back-end Integration Constraints have also been manifesting in various models of CER/DER management at scale.

[14] Refer to Key Concepts I for an outline of eight architectural issues that must be avoided.

Key Concepts I

Architectural Issues

Following are eight important structural issues that the Power Systems Architecture disciplines address that will otherwise negatively impact the operability and resilience of decarbonising power systems:

1. **Tier/Layer Bypassing:** The creation of information flows or coordination signals that 'leapfrog' a vertical tier/layer of the power system's operational hierarchy.
2. **Coordination Gapping:** An element of the power system does not receive an explicit flow of coordination signals from any higher tier/layer of the system and therefore operates in isolation.
3. **Hidden Coupling:** Two or more control entities with partial views of system state issue simultaneous but conflicting coordination signals to a CER/DER or component of the power system.
4. **Cluster Coupling:** Where CER/DER are addressed in groups that do not allow for separation of edge device commands by specific criterion: location, device type, device service provision, etc.
5. **Latency Cascading:** Creation of compounding latencies in information flows due to the serial routing of data through various computational systems, processes and organisations.
6. **Computational Time & Cost Excursions: Where massive data volumes, latencies and processing 'bottlenecks' occur, compounded by unresolved structural issues, optimisation engines risk hitting a computational 'time wall' where no amount of computing resource will be adequate to solve the optimisation problems in an acceptable time and at an efficient cost.**[15]
7. **Cybersecurity Structural Vulnerabilities:** Ill-informed and often unnecessary structural choices result in communication and routings that create non-cyber vulnerabilities to system penetration.
8. **Back-end Integration Constraints:** Multiple vertical silo structures found in many supply-chain organisations drive significant back-end integration costs, anti-resilience and are anti-extensible due to the coupling of applications in which where failure in one can ripple through to degrade others.

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

8.4 Considering the two most credible structural options[16]

Putting aside Top-down structural models due to Australia's high-CER/DER context, following is a brief overview of the Multi-entity DSO and Layered Coordination DSO models.

Multi-entity DSO models

As noted above, an attraction of the Multi-entity or blended/hybrid category of structural models is that they appear to offer a means for simplifying stakeholder complexities by retaining some familiar aspects of legacy Top-down structural arrangements with adaptations. They may also provide temporary waypoint or stepping stone in a wider process of transformation.

An unintended consequence of attempting to perpetuate a Multi-entity archetype long-term in a high-CER/DER power system, however, is a significant increase in the technological complexity, deployment and operational costs, and elevated reliability and resilience risks. This is because Multi-entity structural models suffer from lack of strong architecture as they are ultimately the product of a combination of ad hoc structural compromises.

Given the expanding complexity of a decarbonising grid, this runs the significant risk of creating numerous issues that progressively erode the security and economic efficiency of a high-CER/DER power system. Not dissimilar to the as-built structural arrangements, Tier/Layer Bypassing, Coordination Gapping and Hidden Coupling can emerge in the form of unexpected system behaviours as decarbonisation and CER/DER uptake advances. Due to the operational dynamics and feedback loops of a complex system, the resulting behaviours cannot be fully anticipated in advance of implementation and are difficult to resolve when they emerge. Hidden Coupling is one of the more serious of these consequences when its impacts materialise at scale.

The architectural concept of 'coupling' is the grouping of two or more elements in a way that makes them interdependent and/or causes them to act uniformly as a unit. Coupling may be intentionally applied, and systems theory provides an established body of knowledge concerning the types and degrees of beneficial coupling. The critical issue for power system transformation, however, is largely how unintended or unrecognised coupling can occur to the detriment of system behaviour and performance. Referred to as Hidden Coupling, it can occur in various ways such as physical and electrical arrangements, the relationships between separate control systems and/or the coupling of grid processes and functions.

Figure 25 Illustrates some examples of coupling in a power system that have been implemented. While these simple examples are easy to present diagrammatically, in practice modern power systems are so complex that hidden couplings can happen inadvertently and at much higher levels within system functions, processes and sub-systems than shown here.

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[16] The background to this content is considered in more detail in Report 3 of this series (Sections 4.2.1 – 4.2.3). Detailed structural analysis of the archetypes was also undertaken in the Stage 2 (Section 4) report.

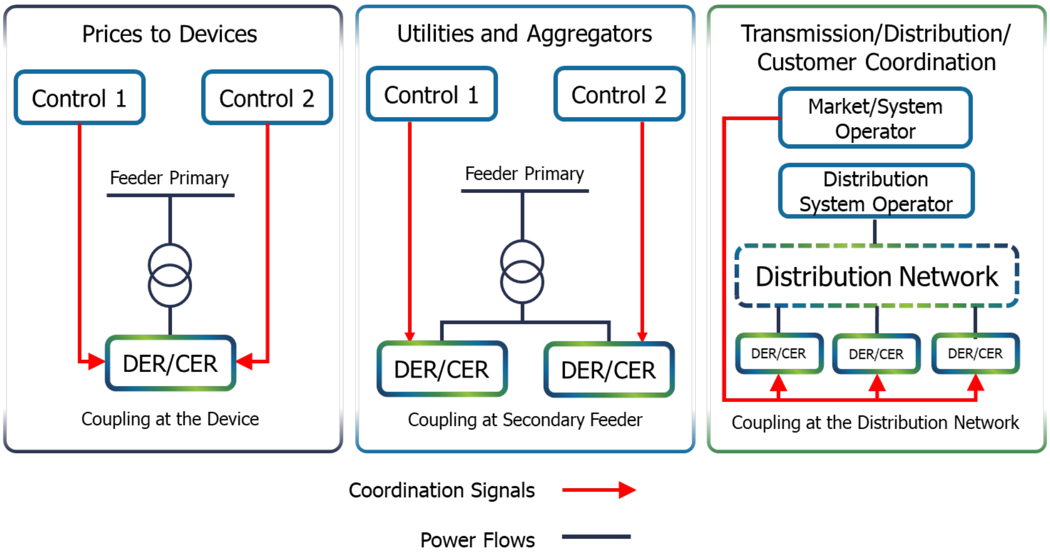

Figure 25: Different types of couplings which can result in problematic system behaviours where deployed at scale[5]

The rightmost diagram in Figure 25 illustrates the related problem of Tier/Layer Bypassing. In this case, operational coordination signals from the SO bypass the DNSP/DSO, which results in Hidden Coupling at the distribution grid level. This is problematic since the DNSP/DSO is ultimately responsible for distribution reliability whereas poorly coordinated actions can drive reliability issues, particularly as CER/DER volumes continue to grow.

In the Australian context it is important to note that the application of Dynamic Operating Envelopes (DOEs) does not resolve the potential Hidden Coupling problems or the related CER/DER dispatch issues. Rather, the existence of interpenetrated VPPs complicates the operation of the DOEs as it becomes necessary to create an extra layer of complexity in DOE dispatch to deal with the mappings from LV feeders >> CER/DER >> VPPs. In effect, the DOEs become coupled through the resulting ad hoc VPP-to-CER/DER mappings.

In addition, Coordination Gapping will occur where an entity is left out of the coordination structure [56], which is often, but not always, coincident with Tier/Layer Bypassing. It can also happen unrealised within supply chain entity processes and mechanisms, not just at the physical level. Finally, as illustrated in Figure 26, it can also occur laterally, where two devices, systems, or entities on the same system tier/layer should be included in the coordination framework, but one is left out. For example, within the distribution layer, a DERMS may coordinate with CER/DER for local network services, while the ADMS is running a fault isolation routine.

As noted below, with the Multi-entity DSO it is difficult or impossible to avoid Hidden Coupling problems. While several variants of this model have been proposed, this is ultimately due to the structural characteristics intrinsic to all Multi-entity DSO models. While the issues may arise when the model is initially implemented, it is more likely they will develop over time as decarbonisation and CER/DER uptake advance and the structure is adapted by various parties in an uncoordinated way due to lack of formal, unifying architectural principles.

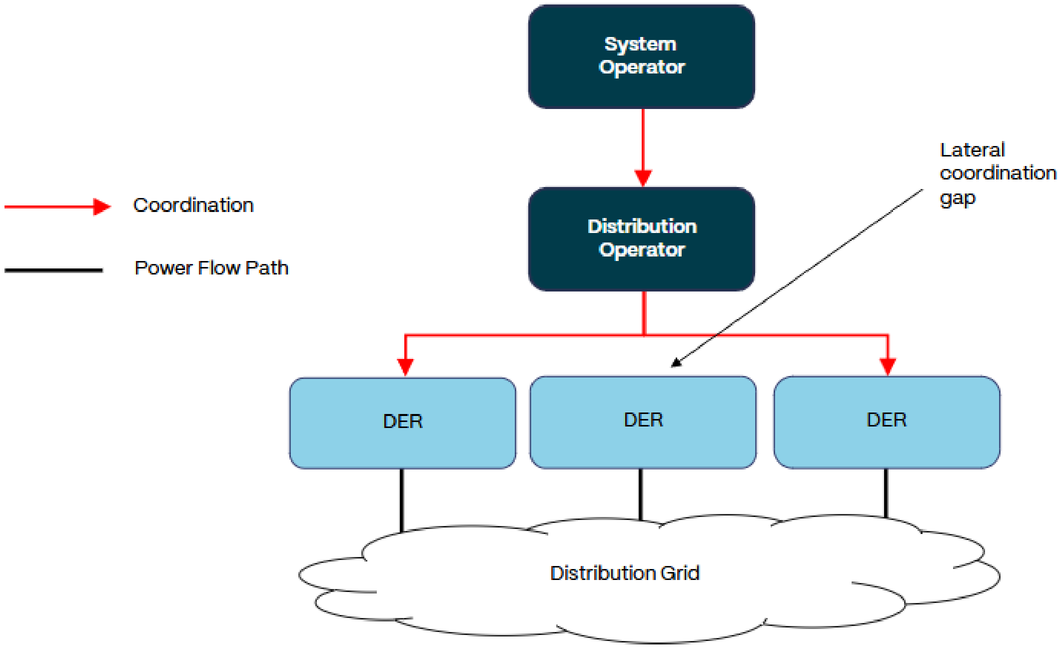

Figure 26: Coordination Gapping occurs where an entity is left out of the coordination structure

In short, a Multi-entity DSO model may be appropriate as a temporary stepping stone for advancing initial DSO and TDC functions in a wider process of grid transformation. There are credible reasons, however, to anticipate that seeking to perpetuate such a model for the long-term in a high-CER/DER context like the NEM will significantly increase technological complexity, economic costs and operational resilience risks. Significant cyber-physical and computational investments will be needed to enable scalable operational coordination and market co-optimisation, accompanied by material rework and investment stranding risks.

Layered Coordination DSO models

Decarbonising power systems like the NEM face growing levels of volatility and bidirectional power and information flows as they transition from hundreds of upstream resources to tens of millions connected across all tiers/layers of the grid. In this context, the time windows where 100% of instantaneous demand is served by distribution-connected resources are continuing to expand meaning that power flows behave in an increasingly 'tidal' manner over each 24-hour period.

The existence of layered structural models in operational systems in other industries 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. Based on formally established mathematical techniques, layered decomposition is widely employed in the aerospace sector, underpins key internet and communications protocols, is foundational to cloud computing and autonomous transport. It reduces coupling, increases resilience and enables scalability, making it a hallmark of modern complex engineered systems.

As a foundational strategy for managing complexity in large, complex systems, layered structural models configure a highly complex system into semi-independent, logically structured tiers/layers, each of which provides services to the tier/layer above and uses services from the one below. 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. In the case of a transforming power system, it provides a structural framework for the operational coordination of edge resources such as CER/DER co-optimised with the more conventional bulk power resources.

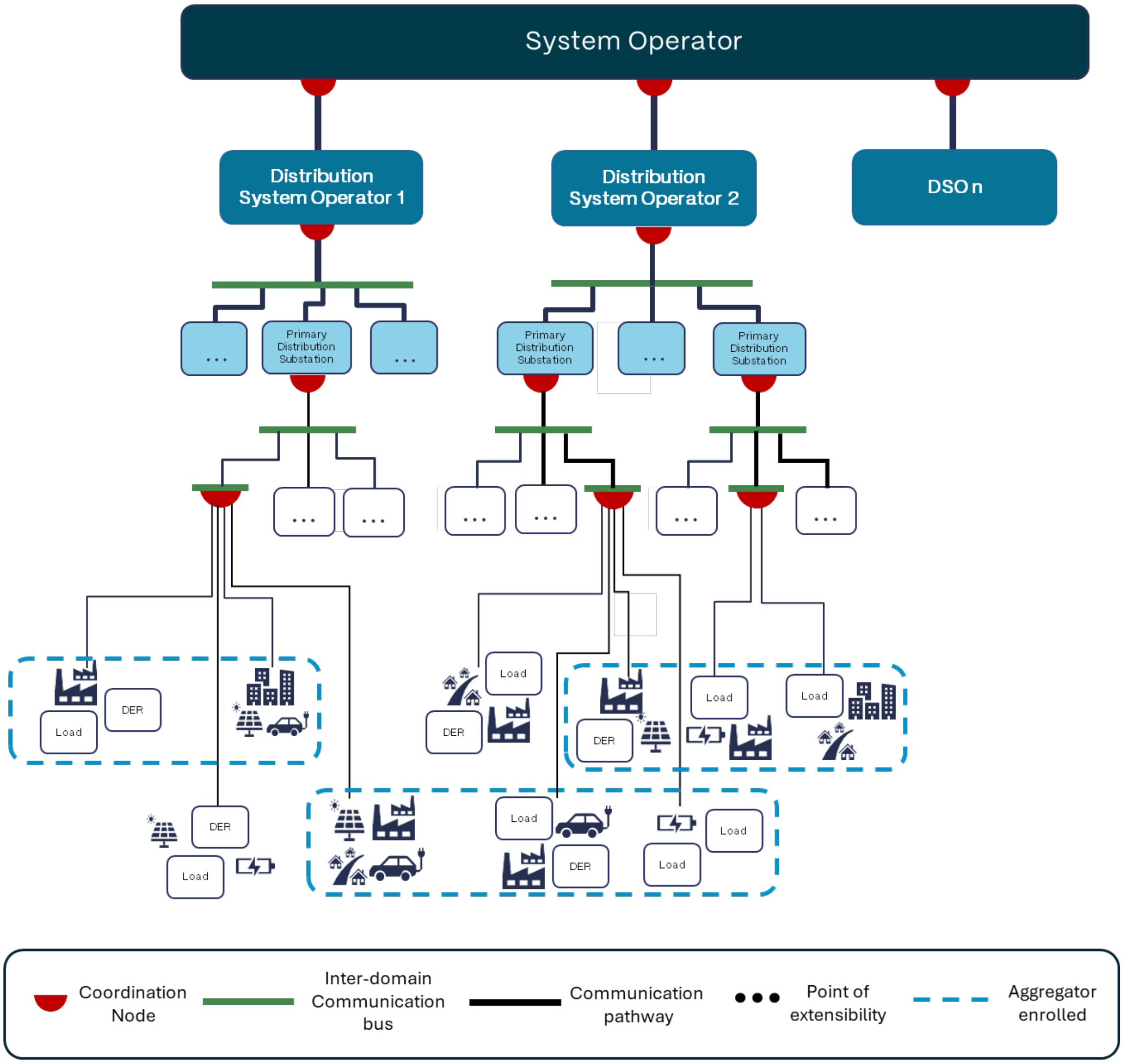

Figure 27: In a Layered Coordination structure, the operator for each tier/layer only needs visibility into and control of its interfaces with the tiers/layers above and below (i.e. at the coordination nodes)

As an inherently scalable and extensible model, key features of a mature Layered Coordination structural model include:

- The operator for each tier/layer is responsible for its reliable and cost-efficient performance together with its interfaces with the adjacent layers above and below.
- Each operator only needs to deal with, and have visibility into and control of, its interfaces with the adjacent tiers/layers above and below.
- Each tier/layer can trade services with those above and below via economic transactions at the interfaces.
- Each tier/layer may have specific objectives and constraints not common to the others, although all tiers/layers share responsibility for the functioning of the whole-system via formalised roles and accountabilities.
- As societal electrification advances, substantial national security and system resilience benefits accrue where each tier/layer is also enabled to smoothly island from the tier/layer above and operate autonomously during system-wide disturbances [57].

As noted above, layered decomposition is on formally established mathematical techniques relevant to Ultra Large Scale (ULS) systems. **However, complex mathematics are not required as the practical rules and structural forms have already been extracted from the math and can be applied directly to power system challenges.** This is a critical point as the solutions to the structural issues discussed above – including Hidden Coupling, Coordination Gapping and Tier/Layer Bypassing – may be derived from this empirical foundation.

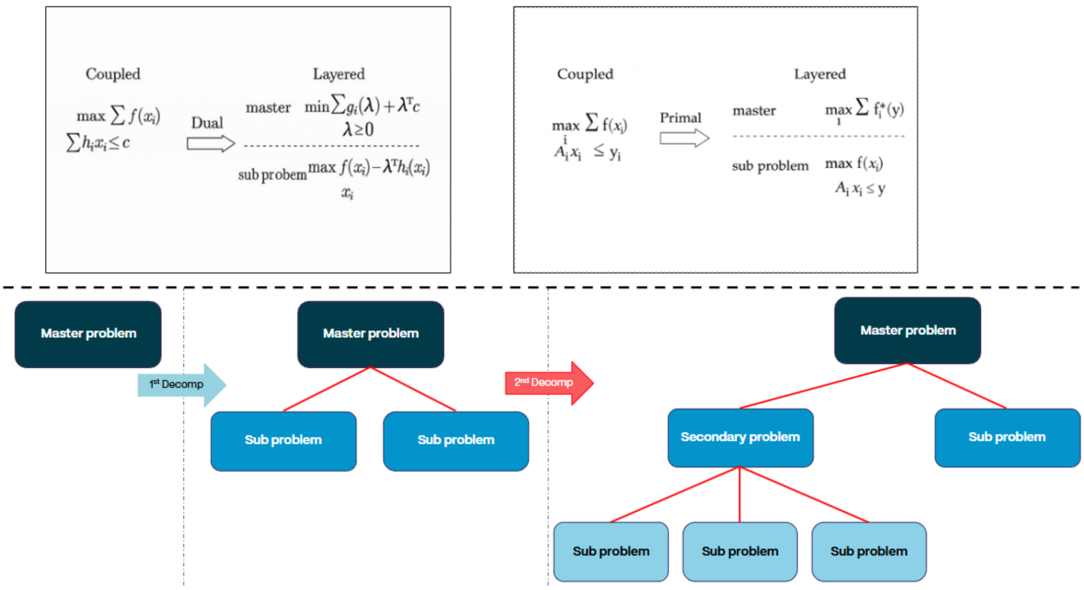

Figure 28: Layered Coordination structural models employ practical rules derived from the math to provide an inherently more scalable model for operating a decarbonising, high-CER/DER grid

For example, employing the universal principles derived from the mathematics of layered decomposition, Figure 28 above illustrates how a Layered Coordination structural model enables highly complex problems to be decomposed multiple times into sub-problems, which are then simultaneously solved to answer the original problem. Together with its breadth of intrinsic technological advantages, Layered Coordination structural models provide an inherently more reliable, cost-effective and scalable platform for enabling the transformation of the NEM in a manner that enables all plausible future scenarios.

8.5 Transitioning from legacy to future structural arrangements

A system is an interconnected set of components that are formally linked together by a set of structural and functional relationships to achieve specific purpose(s). The components of any system include those objects that are generally the most tangible, for example in a power system, the generators, poles and wires, transformers, CER/DER, institutional actors, regulatory processes, pricing models, etc.

What is not widely appreciated is that the underpinning structure of any system always has a disproportionate influence on the essential limits of what the system can reliably and efficiently perform. In other words, as the NEM experienced unprecedented transformation, the robust analysis of the future-fitness of the NEM's underpinning structures is not an optional or discretionary activity if the goal is a secure, cost-effective, decarbonised power system.

As noted earlier, the Multi-entity or blended/hybrid category of structural models are often appealing as they appear to offer a means for simplifying stakeholder complexities by retaining familiar aspects of the legacy structural arrangements. While this may be beneficial in the near term, perpetuating this model in the medium – longer term is likely to escalate technological complexity resulting in declining system resilience, increasing costs and reduced customer participation options.

Where a Multi-entity structural model is considered, the best approach may be to consider it as a temporary waypoint on the path to an eventual Layered Coordination model as part of a stepwise transition process. In this case, developing an intermediate Multi-entity structure en route to an enduring Layered Coordination structure will simplify design choices and support more targeted and efficient investments. Doing so will provide all stakeholders greater clarity about the integrated set of transition steps required, helping to significantly derisk the potential for overinvestment in specific steps which are inherently time limited.

Key Concepts J

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.

Ultra-Large-Scale (ULS) system

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

A ULS system also typically exhibits the following characteristics:

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

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

9 DSO Relationships: Functional relationships between the DSO and the wider power system

The previous chapter considered alternate structural archetypes that provide the context and enablers for how the DSO functions in relationship with the wider power system. This structural perspective is vital at both a 'macro' whole-system level and also when considering the many more 'micro' sub-system relationships. As noted, it is the underpinning system structure that has a disproportionate influence on the essential limits of what the system can reliably and efficiently do.

This chapter explores the functional relationships between a DSO and the various other entities involved in managing a decarbonising, high-CER/DER power system. Informed by the analysis of Section 8, this provides an indicative comparison of the operational complexity between the Multi-entity and Layered Coordination structural archetypes. The coordination relationships are then considered in more detail between the DSO and horizontal, upstream and downstream entities, again considering the comparative complexity of the Multi-entity and Layered Coordination structural archetypes. The chapter concludes by considering how the structural alternatives impact the ability of the DSO to provide the system operator visibility and predictability of CER/DER, enable enhanced operational coordination of millions of CER/DER and support well-integrated Transmission-Distribution Coordination.

9.1 Evaluating the complexity of DSO operational relationships

As noted throughout this report, DSO models are properly understood as a key structural intervention needed to enable a decarbonising, high-CER/DER power system. In fulfilling its core functions, a DSO performs a key coordination role which means that it is deeply interconnected with many different entities involved in the operation of increasingly distributed power systems.

Building on the earlier analysis, this chapter considers the two most credible DSO models with respect to the complexity of their horizontal, upstream and downstream functional relationships, as per Figure 29 together with an assessment of whole-system operational complexity. Consistent with the conclusions of Section 8, only the Multi-entity and Layered Coordination DSO structural archetypes are considered.

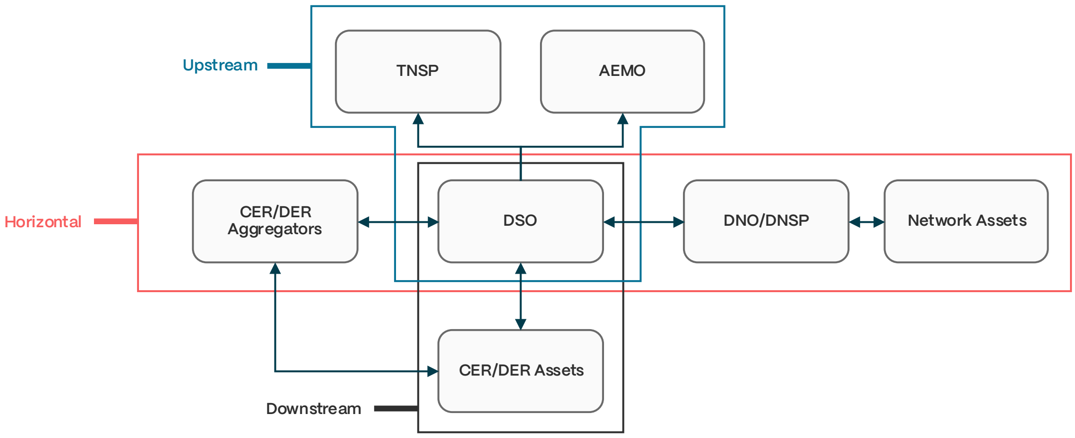

Figure 29: DSO horizontal, upstream and downstream functional relationships

As context for this analysis, under the Multi-entity structural archetype, CER/DER is largely dispatched by AEMO as the system operator (SO) within the local network limits provided by the DSO. In this case, the volume and granularity of cross-layer operational coordination is onerous, but continuity between legacy systems and processes is maintained to a certain degree. As noted earlier, where applied, this model is best considered as a transition point rather than a final destination.

By contrast, under the Layered Coordination structural archetype, both the SO and DSO operations are more clearly focused within their specific, well-defined operating zones, with more limited, aggregated and targeted cross-layer coordination being managed at the interfaces. While this is a departure from the more conventional top-down operational paradigms, the formalised nature of the layered relationships and interfaces helps make stepwise implementation both practical and resilient.

Table 13 below provides an indicative assessment of horizontal, upstream and downstream functional relationships relevant to several high-CER/DER system management needs informed by the architectural analysis previously undertaken [5], [7]. It is primarily aimed at supporting a more informed discussion of the trade-off choices arising from the consideration of alternate structural archetypes relevant to DSO design and implementation.

For the purposes of this analysis, key high-level architectural factors that have informed the comparative assessment of the resulting complexity of the different archetypes include:

- **Number of actors:** More actors will generally result in more interfaces, more contractual/operational alignments, more data flow complexity, and more bilateral or multilateral dependencies increasing required data exchange and complexity
- **Extent of cross-layer interactions:** Typically, alignment between operational roles and operating zone responsibilities will result in fewer coordination interfaces and less complexity. From a regulatory perspective, complexity also increases where responsibilities span regulatory domains or institutions with divergent mandates (e.g., state vs. federal or AEMO vs. DNSPs).
- **Visibility and control alignment:** Similar to the above, complexity decreases where an actor has dual responsibility for issuing control signals and measuring the impacts of those control signals within their respective operating zone.
- **Role and responsibility alignment:** Ad hoc arrangements create opportunities for misalignment of functions and Hidden Couplings while also causing fragmentation of responsibilities, placing key entities in operational conflict.
- **Ability to scale:** Coordination complexity increases non-linearly with more CER/DER, more service offerings, or more participating consumers. For time-sensitive coordination functions, structural arrangements between actors will exacerbate or reduce computational and communication overheads.
- **Data exchange/interoperability:** This key enabler is a cross-cutting architectural driver of complexity that is tightly coupled with all of the above.

The assignment of ratings has applied architectural judgement with respect to the above. It has not included a deep dive into detailed coordination regimes from a technical perspective. It should also be noted that the assessment does not address the change in scope or complexity of the function under different structural arrangements, only the coordination required to perform that function.

Sections 9.2 through 9.4 provide some of the architectural rationale taking an aggregated view of the cumulative outcomes across both the Multi-entity and Layered Coordination structural archetypes, with the indicative ratings used provided in

Table 13: Ratings used for evaluating the structural complexity of different DSO archetypes

Rating	DSO Coordination Complexity
1	Minimal
2	Moderate
3	Intensive[17]
4	Extensive[18]

In Section 9.5, a discussion on the whole-system implications for overall operability is provided assuming a mature DSO consistent with the two structural archetypes and including advanced operational integration between the DSO and the DNSP.

[17] Involves deep, frequent, and complex interactions between multiple systems/entities

[18] Coordination across many interdependent systems/entities where timing, operational data, and communication are critical and tightly coupled

Table 14: Indicative complexity rating of key DSO functions requiring cross-entity coordination

Functions requiring Coordination	Description	Functional Relationships	Cross-Entity Complexity	
			Multi-entity	Layered
CER/DER Scheduling, Dispatch & Operational Coordination	Without coordination, CER/DER dispatch risks conflicting with local and system-level needs, causing instability or inefficiencies. Aligning the SO, DSOs, aggregators, etc. ensures safe, reliable operation and prevents counterproductive signals that could overload assets, disrupt balancing or have sub-optimal economic outcomes.	Horizontal	3	2
		Upstream	4	1
		Downstream	3	3
CER/DER Forecasting, Visibility & Observability	Siloed forecasting limits whole-system awareness and increases risks of overload or imbalance. Coordinated data sharing across CER/DER, DSOs and SO enhances planning, reduces uncertainty, and enables secure integration of high CER/DER volumes.	Horizontal	4	2
		Upstream	3	2
		Downstream	2	3
Network Constraints Management (Transmission)	CER/DER can unintentionally distort transmission-level network utilisation. DSOs must coordinate with the SO and TNSP to ensure local actions don't breach transmission limits or disrupt flows. Coordination improves reliability and unlocks CER/DER flexibility.	Horizontal	3	2
		Upstream	4	2
		Downstream	2	2

Functions requiring Coordination	Description	Functional Relationships	Cross-Entity Complexity	
			Multi-entity	Layered
Network Constraints (Distribution)	Local constraint management without coordination can lead to overloading of distribution network assets or missed economic opportunities. DSOs must align with aggregators and market actors to prevent misjudging CER/DER impacts and compromising reliability.	Horizontal	3	4
		Upstream	2	2
		Downstream	2	3
Voltage Support (Local/Distribution)	Local voltage control by CER/DER must be coordinated to avoid overcorrection or instability. Without alignment across CER/DER and assets, voltage responses may conflict, risking poor quality or unsafe conditions.	Horizontal	3	2
		Upstream	2	1
		Downstream	2	2
Voltage Support (Transmission Level)	DSO operational decisions can affect transmission voltage at TDI. Without coordination, reactive power support can conflict with SO operations, risking voltage excursions or ineffective control.	Horizontal	2	2
		Upstream	3	2
		Downstream	2	2

Functions requiring Coordination	Description	Functional Relationships	Cross-Entity Complexity	
			Multi-entity	Layered
Frequency Regulation	Frequency is system-wide and requires coordinated response of CER/DER to prevent over-response or interference. DSO alignment with AEMO/TNSP ensures reliability and complements traditional reserves.	Horizontal	2	1
		Upstream	4	2
		Downstream	3	2
CER/DER Performance Standards	Non-uniform enforcement of CER/DER standards risks mass disconnections during faults. Coordination ensures CER/DER meet resilience expectations, preventing grid instability during disturbances.	Horizontal	3	2
		Upstream	3	1
		Downstream	2	4
CER/DER Emergency Overrides	Emergency overrides must be precisely coordinated. Acting in isolation can miss critical CER/DER or trigger conflicting responses. Joint execution ensures rapid, effective system protection.	Horizontal	3	1
		Upstream	4	2
		Downstream	3	4

Functions requiring Coordination	Description	Functional Relationships	Cross-Entity Complexity	
			Multi-entity	Layered
Bulk Power & Distribution Market Co-optimisation (Energy & Ancillary)	Without coordination, CER/DER providing services across markets risk double-counting or conflicting dispatch. Co-optimisation ensures CER/DER are used efficiently and reliably, avoiding inefficiencies and preserving local network stability.	Horizontal	4	2
		Upstream	3	2
		Downstream	2	2
CER/DER Cyber-security	Incomplete cybersecurity creates entry points for system-wide attacks. Coordinated standards and monitoring between the SO, DSOs and aggregators are essential to defend shared assets and prevent cascading failures.	Horizontal	3	2
		Upstream	2	1
		Downstream	2	2
System Restoration Support	CER and DER can both assist black start or islanding but only if actions are well coordinated. Without alignment, CER/DER may hinder restoration or operate unsafely. Coordinated plans ensure CER/DER support, not delay, recovery.	Horizontal	3	2
		Upstream	3	2
		Downstream	2	2

Key Concepts K

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.

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.

9.2 The 'horizontal' structural and functional relationships between the DSO and the DNSP and CER/DER Aggregators

The DSO's horizontal relationships with the other entities involved in co-managing power flows in the distribution network require structured coordination to ensure system reliability, efficiency and market access. In both the Multi-entity and Layered Coordination structural archetypes, the DSO provides a coordinating role across all distribution layer entities and assets to enable this as illustrated in Figure 30. The nature, complexity and frequency of these interactions will differ significantly, however, based on the structural arrangements for how the DSO interoperates with the wider system.

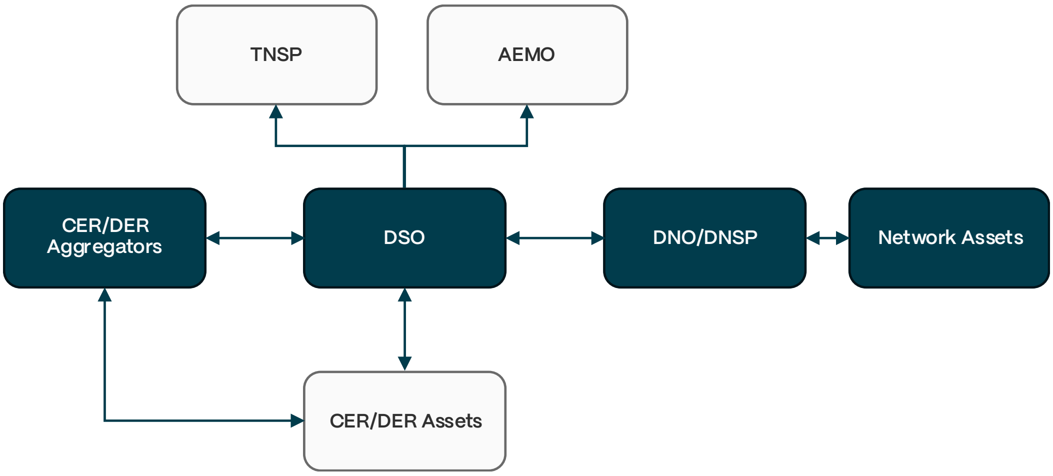

Figure 30: Horizontal relationships across the distribution layer

Indicatively, summing the above ratings shows a cumulative decrease in coordination complexity of 33% (36 to 24) from Multi-entity DSO to Layered Coordination DSO models for horizontal relationships. At a high-level, this can be explained by the level of autonomy that the Layered Coordination DSO has to manage its operating zone alongside other horizontal actors. By comparison, under the Multi-entity DSO structural arrangements, horizontal relationships are complicated by the DSO's interoperation with the upstream SO and partial visibility of all the actors within its operating zone, adding friction and complexity to the execution of the above functions. For example, under a Multi-entity archetype, the DSO may not have complete visibility of CER/DER aggregator intentions, complicating its ability to manage voltage levels.

Other function-specific observations relevant to these horizontal relationships include:

- **CER/DER Scheduling, Dispatch & Operational Coordination**: In the Multi-entity DSO model, the scheduling, dispatch, and operational coordination of CER/DER involves additional entities and interfaces when compared with the Layered Coordination DSO model which provides a cleaner, more efficient set of interfaces and function allocations. In either case, the DSO role would be carried out by the DNSP, with appropriate firewalls and regulatory boundaries. Concerns about neutrality and operational transparency are the same for both models and may be adequately addressed in both. In the Layered Coordination model, since the DSO negotiates with the SO for exchanges across the TDI, it can more easily harmonise procurement of services among CER/DER aggregators, other DNSPs and the SO to support both system stability and market responsiveness.

- **Bulk Power & Distribution Market Co-optimisation:** Under both models, the DSO must concurrently and jointly optimise bulk system and distribution system resources and needs. In the Multi-entity DSO model, this process requires a tighter operational coupling with the upstream SO and typically results in an emphasis on bulk power system needs. The Layered Coordination DSO provides a clearer separation of concerns and emphasises alignment of local needs with local resources through distribution-level markets. It can also support coordination with other DSOs in adjacent distribution systems in a regularised manner.
- **CER/DER Cyber-security coordination:** In the Multi-entity DSO model, cybersecurity responsibilities can be fragmented across network operations and market facilitation layers, risking vulnerabilities. Under a Layered Coordination DSO, the demarcation of responsibility for cyber-security is more defined, enabling consistent cybersecurity oversight across all horizontal actors—aggregators, DNSPs, and DER providers—ensuring unified threat detection, response, and compliance frameworks.

9.3 The 'upstream' structural and functional relationships between the DSO and the System Operator and the relevant TNSP

Upstream coordination focuses on how DSOs interact with the SO and relevant TNSP (i.e. the entities that manage the power flows in the bulk power system, which is 'upstream' of the distribution system) to ensure whole-system integrity, especially as CER/DER penetration contributes to operational volatility at the Transmission-Distribution Interface (TDI).

Under the Multi-entity structural archetype, the DSO may rely on existing DNSP relationships and legacy protocols to manage this interface, which may obscure real-time visibility and limit proactive operational alignment.

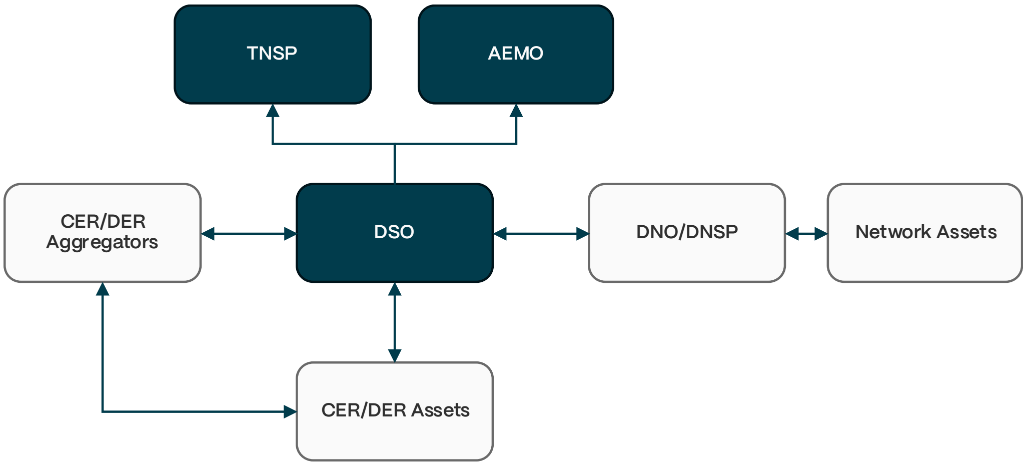

Figure 31: Upstream relationships with the system operator and TNSP

Indicatively, the above qualitative assessment reveals a decrease in DSO coordination complexity of 49% (37 to 19) from the Multi-entity to Layered Coordination DSO models for upstream relationships. This is primarily due to the separation and alignment of roles with respective operating zones where a more layered structure is applied. The reduced overlap moderates the need for granular coordination, while heightening the DSO's shared responsibility for system-wide balancing and security.

Other noteworthy function-specific observations relevant to the upstream relationships include:

- **Network Constraints Management (Transmission)**: Under the Multi-entity DSO model, the cumulative impacts from market scheduled and off-market CER/DER on the transmission system must be derived from a synthesis of operational data from numerous sources. Retrieving such data requires the SO to 'reach down' into the distribution operating zone and rely on lightly regulated commercial entities in aggregators to model CER/DER impacts on power flows for the transmission network. Under a Layered Coordination DSO model, the distribution operating zone behaves as a 'black-box' from the perspective of TNSPs and AEMO – meaning that a consolidated set of characteristics are provided to TNSPs and AEMO. This shields upstream actors from the inherent complexity within the distribution layer, while still providing the necessary operational variables for them to maintain system security. An example relevant operational variables to transmission network constraints is real-time and forecast dynamic grid equivalents at TDI for state estimation models.

- **CER/DER Forecasting, Visibility & Observability:** Under the Multi-entity DSO model, CER/DER visibility must come from a number of potentially entangled sources. In a Layered Coordination DSO, CER/DER data for a given distribution system are consolidated by the DSO, enabling standardised, high-resolution forecasting at points of TDI to be shared with upstream actors, improving planning accuracy and reducing the risks of imbalance or overload.
- **System Restoration Support**: Under the Multi-entity DSO model, fragmented roles can delay or misalign CER/DER operation for system restart. A Layered Coordination DSO provides a clear coordination point for restoration protocols involving CERs/DERs, enabling safe, timely, and integrated recovery processes aligned with AEMO and TNSPs energisation sequencing.

9.4 The 'downstream' structural and functional relationships between the DSO and individual CER/DER assets

Downstream relationships define how DSOs coordinate directly with individual FTM and BTM CERs/DERs, embedded networks, and microgrids to manage local network reliability and unlock CER/DER value (that is, the relationships with entities that manage power flows "downstream" of the distribution network system in the direction of individual customers). This may include emergency override controls for CER/DER with customer agents, or where the DSO has a direct contractual relationship with CER/DER owner.

Indicatively, the above assessment reveals an increase in DSO-internal operational coordination complexity of 15% (27 to 31) from Multi-entity DSO to Layered Coordination DSO models for downstream relationships. But this is at the cost of putting a larger burden on the SO under the Multi-entity DSO model where the SO orchestrates market scheduled CER/DER via aggregators. Under a layered arrangement, facilitation of market participation moves to the DSO, increasing the amount of downstream coordination required of the DSO, but with reduced overall system complexity and burden on the SO.

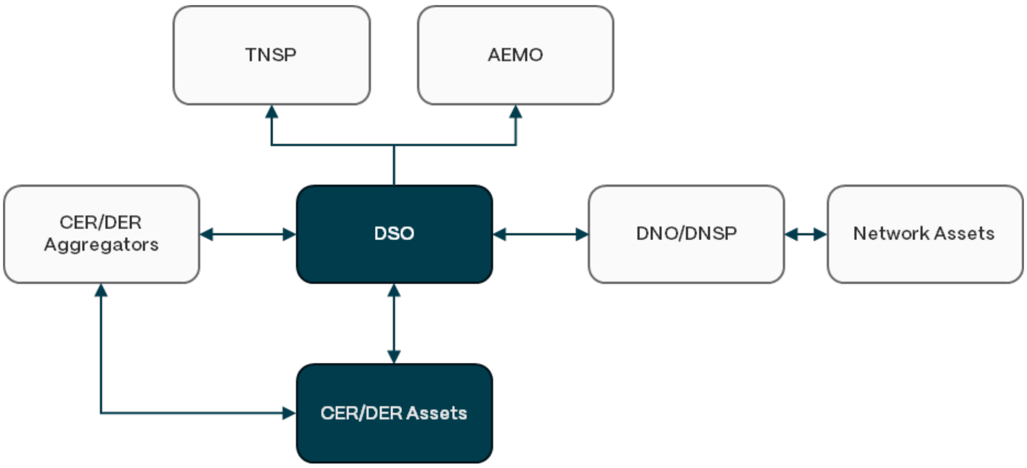

Figure 32: Downstream relationships with CER/DER assets

Other noteworthy function-specific observations for select functions relevant to the downstream relationships of the DSO are:

- **Voltage Support (Local/Distribution):** In a Multi-entity DSO model, local CER/DER-based voltage management must be procured via aggregators (which are dispatched by AEMO) or under bilateral arrangements, where permitted by the regulator. This creates friction in the DSO's ability to manage voltage levels by leveraging CER/DER in their own networks. They can also be operationally constrained by limited visibility of bulk power market participation mapped to specific circuits. Layered Coordination DSOs with consolidated responsibility for CER/DERs including their provision of ancillary services have increased network awareness, can actively orchestrate DER voltage responses through real-time platforms, improving power quality, and can more efficiently signal needed downstream responses for ancillary services.

- **CER/DER Performance Standards:** Where operational risks and mandated responsibilities are not well aligned, Multi-entity DSO models may result in inconsistent enforcement of standards across DSOs in ways that could trigger instability during faults. A Layered Coordination DSO is typically responsible and accountable for the operational implications of poor enforcement of CER/DER performance standards and are much more likely to maintain ongoing compliance through continuous monitoring and engagement with CER/DER operators, enhancing system resilience.
- **CER/DER Emergency Overrides:** In emergencies, fragmented coordination and control hierarchies can cause delayed or conflicting responses. For example, in a Multi-entity DSO an aggregator providing frequency support under minimum load conditions could be curtailed by the DNSP/DSO attempting to reduce DPV output. A Layered Coordination DSO is better placed to streamline, standardise, and centralise emergency override protocols, ensuring fast, coordinated actions across diverse CER/DER fleets and embedded systems.

9.5 How do DSO models enhance whole-system operability?

What is operability and why does it matter?

While understanding the structural and functional complexity of DSO relationships under different archetypes is important, it is secondary to the broader challenge of optimising whole-system operability. The power system functions as a unified, physics-based whole. Ultimately this requires that whole-system operability must be a key goal of all actors, especially as grids become increasingly interdependent operationally.

Whole-system operability is 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. It is also important to note that operability is a multidimensional system attribute, not a single metric. It 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).

How do the different DSO structural archetypes impact whole-system operability?

In this context, a key architectural principle is that coordination within a single operating zone tends to be simpler and more scalable than coordination across layers. This is because intra-layer coordination avoids the need to translate and reconcile between different operational systems and approaches used at different levels of the system. Concentrating coordination within clearly defined operating zones—where possible—can therefore simplify system-wide operations.

For example, Layered Coordination DSOs take on greater responsibility for coordinating with actors horizontally at the distribution level, which increases their intra-layer coordination load. However, this is offset by a significant reduction in the complexity, granularity and frequency of interactions between each DSO and upstream SO (AEMO) and TNSP. This is because whole-system operational objectives can be decomposed into sub-objectives for autonomous DSOs, simplifying net system-wide operability. It also supports clearer functional separation between SOs and DSOs. Cross-layer coordination is more aggregated, purpose-specific, and limited in scope. This reduces the cumulative operational burden on the SO and improves scalability. However, this shift also diverges from established operational norms and may present new implementation challenges.

By contrast, Multi-entity DSO models retain more top-down coordination, with the SO dispatching CER/DER via aggregators while relying on DSOs to provide local constraint information. While this may ease integration with legacy systems in the short term, it requires high volumes of detailed cross-layer data exchange and is interaction-intensive. Notably, proposals for Multi-entity DSO models often include an intermediary "platform" at the T-D interface, which would handle DER registration, operational coordination, and market functions. This introduces a new layer of institutional complexity, requiring the creation and maintenance of an entity separate from the DSOs. In contrast, the Layered Coordination DSO model avoids the need for such a platform through well-defined role allocation and clearer delineation of responsibilities.

9.6 How do DSO models impact Transmission-Distribution Coordination (TDC)?

What is TDC and why does it matter?

Transmission-Distribution Coordination (TDC) is 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 DSOs 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.

How do the different DSO structural archetypes impact TDC in practice?

As the bifurcation of transmission and distribution-connected resources continues, the physics of emerging power systems require much tighter coordination across the Transmission-Distribution Interface (TDI). This physics-based requirement, when considered alongside scalability, resilience, and organisational factors, is a key driver of architectural considerations and their implications for the assignment of roles and responsibilities.

In other words, the allocation of roles and responsibilities on either side of the TDI should follow from architectural consideration grounded in emerging trends and grid physics. The increasing centrality of TDC to system security and economic efficiency further emphasises this point.

Under both structural archetypes, the DSO has a responsibility to interact with the SO. Under the Multi-entity DSO model, other entities also interact with the SO and with the DSO, complicating the coordination problem and the interface issues for the SO. By contrast, under the Layered Coordination DSO model, each DSO interfaces with the SO and acts as the consolidation point for its distribution system with full responsibility for managing CER/DER impacts, local reliability, and market participation. The DSO manages the distribution system up to the TDI and the SO treats the DSO as a bounded entity, interacting at points of interface.

The latter arrangement significantly reduces ongoing coordination volume with the SO but increases the need for formalised coordination protocols and mutual trust. The DSO manages the dispatch of CER/DER for local objectives and coordinates with the SO to manage cross-boundary impacts. In this way, coordination is structured around well-defined service boundaries. The DSO may offer aggregated services such as flexibility to the SO, treating the TDI like a 'contractual port' where both parties become service providers for the counterparty. For example, the DSO signals to the SO any shortfall in the self-sufficiency of its service territory which the bulk power system can meet. The SO may signal to the DSO opportunities for economically efficient distribution level flexibility that relieves transmission-network congestion, allowing lower-cost generation to be dispatched and whole-system costs to be reduced.

In both structural arrangements, the DSO requires a step change in capability compared to legacy DNSPs and robust and interface definitions with a high level of redundancy.

9.7 How DSO models support enhanced CER/DER visibility and predictability for the System Operator?

What is visibility and why does it matter?

Visibility is 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.

Visibility relates closely to Observability which, as noted earlier, is 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 adjust generation or demand in response to system needs.

How do the different DSO structural archetypes impact visibility?

Working in conjunction with the relevant DNSP, a DSO can support enhanced CER/DER visibility by collecting, analysing and sharing the detailed distribution network data, CER/DER data, usage data, and weather data and forecasts in its service area, the CER/DER aggregators and individual owner/operators and the independent meter readers, to assemble real time grid state, actual and forecasted demand, CER/DER forecasted capacities and responses, and DOE limits.

Under the Multi-entity DSO model, the DSO, aggregators, large owner/operators and meter data providers would report to the SO separately, requiring the SO to handle many interfaces and process multiple heterogeneous data sets to assemble a view of each distribution system's capacities, demand, forecasts, and responses. This would require the SO to have to track dynamic mappings from circuits to CER/DER to aggregators to be able to assemble coherent views of distribution states and forecasts as per Figure 33 below. The SO would have to act as observer and predictor for each distribution system, using the multiple data sets it would get from the various distribution system sources. In addition, the DSO/DNSP and the aggregators would have to exchange data, leading to additional interfaces, latencies, and complexities.

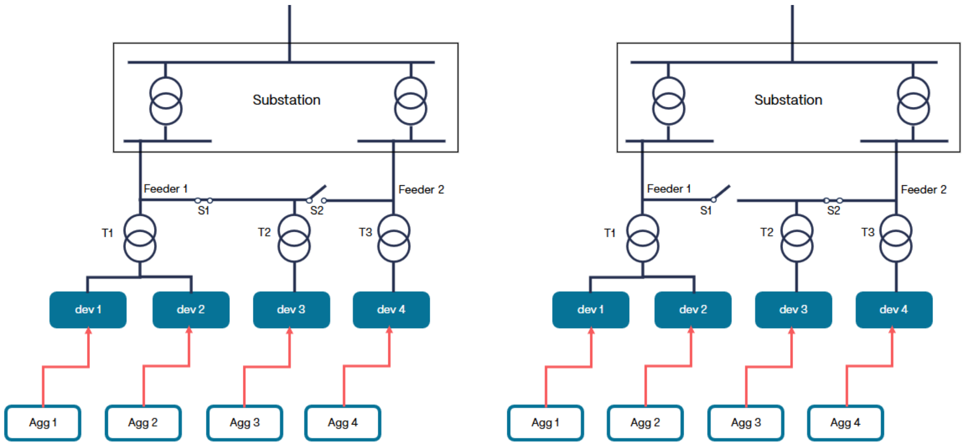

Figure 33: System Operator requires visibility of circuit switching, which can instantly change VPP-Grid Network Configurations

Under a Layered Coordination DSO, CER/DER aggregators, large owner/operators, meter data providers and DNSPs all report through the DSO. The individual DSO is responsible to assemble all relevant data for its distribution system and apply analytic transformations to enable a standardised information set representing the present and anticipated operational state to be provided to the SO at the relevant TDIs. In practice, each DSO fulfils the role it is best equipped to perform as the entity that overseas and manages its own distribution system and its relationship with the wider power system.

In this case, as each DSO is responsible for its own distribution service area and the SO only requires standardised interfaces and information exchanges with each of the individual DSOs. The SO benefits from uniform views of each distribution systems near real-time and forecast operation without the SO needing to assume a range of distribution level functions itself. From the huge volume of granular data that is unique to each distribution system, and inherently spatially and temporally dynamic as CER/DER aggregator relationships, network switching and distribution state vary, by employing advanced data analytics, the Layered Coordination DSO assembles and presents aggregated information to the SO through the TDC mechanisms.

9.8 How DSO models support the enhanced operational coordination of CER/DER scalable to futures such as AEMO's Step Change scenario?

What is Operational Coordination and why does it matter?

Operational coordination is one of the most critical functions of power system operations. It involves 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. For example, it includes the systematic operational alignment, across timescales from day-ahead to real-time operation, of the following:

- System Operator (SO) and DSOs.
- Generators, Energy Storage, Consumer Energy Resources (CER/DER), etc.
- Transmission and Distribution network assets.
- Market participants, CER/DER Aggregators, etc.
- 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 SO, 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.

How do the different DSO structural archetypes impact Operational Coordination?

The deployment of millions of distribution-connected energy resources has fundamentally impacted the structural dynamics of the grid. This has led to significant and expanding new challenges to operational coordination which a well-designed DSO can help address. This is because a DSO is ultimately a mechanism for solving the critical scaling issue by breaking up the coordination problem into coordinated subsets proximate to where clusters of CER/DER are sited. As such, a DSO can support more scalable operational coordination by translating the real time operational requirements from the SO into detailed Dynamic Operating Envelopes (DOEs), direct CER/DER activation, flexibility market dispatches, etc. in its service area.

In the Multi-entity DSO model, the SO must decompose and partition bulk commands for the DSO, and the various aggregators and individual CER/DER owners. This may also require the SO to have to track dynamic mappings from circuits to CER/DER to aggregators to be able to decompose the commands and work with the large number of interfaces that would be involved. At the distribution level, the DSO, DNSP, and CER/DER aggregators would have to sort out the command sets to be able to determine impact on distribution operation and reliability. The Multi-entity DSO model will help to some degree with scalability, but it ultimately imposes structural limits on the degree of scalability that can be achieved as CER/DER volumes continue to grow.

In the Layered Coordination DSO model, each DSO provides a single standard interface to the SO. The DSO handles disaggregation of SO dispatches to the DNSP, the CER/DER aggregators operating in its service area and the individually owned energy resources. The DSO handles balance for the distribution service area while interacting with the SO, and if necessary, the other DSOs. The DSO coordinates the actions of the CER/DER aggregators in its service area. A Layered Coordination DSO inherently supports scalability of data flows up and down the entire power delivery chain, distributed and layered coordination processes, and device control.

This layered structure can be extended down into the distribution system to any level and can also easily support distributed and co-optimised electricity markets involving the SO and the other DSOs. In the Layered Coordination DSO, distribution-level markets may iterate with the NEM and coordinate with peer DSOs under the layered decomposition structure. This can achieve the necessary co-optimisation in a fashion that requires only minimal changes to the NEM. This will substantially enhance whole-system operations and the impact of the growing scale of distribution-connected CER/DER on NEM operations as the coordination of all resources in each distribution area will be managed by its DSO.

10 Detailed DSO Functions: Exploring the core functions that DSOs are responsible to perform

While DSO models have been under consideration for over a decade, the concept is still maturing, and different jurisdictions tend to emphasise different aspects subject to their specific grid transformation context. As a result, while scores of relevant global reports exist, no authoritative or universally accepted set of DSO functions is known to exist.

Building on the content developed in Chapter 6, this chapter examines each of the five core functions of a DSO at a next level of detail. While a wide range of sources have informed this section, much of the content has been developed on a first principles basis as the published tabulation of DSO functions and subfunctions is limited. The operational independence of these five functions is then illustrated to highlight how each function leads, supports or benefits from the other functions and subfunctions.

The diverse range of global and Australian sources that have informed Chapter 10 are provided in the DSO Design Considerations and Distribution Market Mechanisms sections of Appendix B: Key Topic Bibliography.

10.1 High-level Definition and Functions

The following content provides the context for exploring the range of DSO functions in more detail. In the absence of a universally agreed framework, it has been informed by the problem definition and objectives examined in Sections 6.2 and 6.3 and calibrated against the multiple sources note above.

The findings should therefore be considered indicative and directional, with customisation to specific jurisdictional priorities being necessary.

High-level DSO Definition

A DSO Is 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 SO, 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.

In summary, a DSO is responsible for achieving a wider set of objectives than a conventional DNSP via the real-time coordination of the 'system' of network assets, flexible demand, customer-owned CER and large-scale DER.

Five Integrated DSO Functions[19]

While varying terminology is used across different jurisdictions, there appears to be a general convergence on five DSO functional responsibilities in a high-CER/DER context. These are:

1. **Active System Management:** Manage safe, reliable and efficient operation of the distribution system in a two-way power flow environment to ensure the continuous supply of electricity to, between and from customers. This involves the proactive identification and resolution of constraints, congestion management, optimised asset utilisation and enabling the scale participation of CER/DER and flexible loads. In includes actively managing the optimal combinations of distribution network assets, CER/DER and flexible loads in a non-discriminatory manner to provide beneficial services to the distribution system, the wider power system and both participating and non-participating customers.

2. **Distribution Market Mechanisms:** Employ 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.

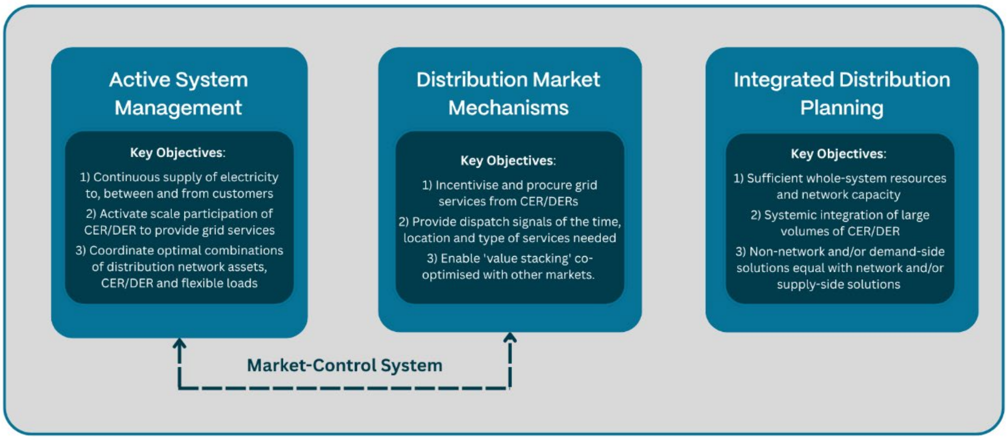

Figure 34: The market-control system relationship between Active System Management and Distribution Market Mechanisms

3. **Integrated Distribution Planning:** Perform long-term distribution system planning, in active collaboration with the relevant DNSP, upstream TNSP and the SO, as an integral part of whole-system planning. Ensure sufficient whole-system and distribution-level generation, storage, flexible resources and network infrastructure to serve all customers reliably, including the systems integration required to beneficially leverage large volumes of participating CER/DER and flexible loads. Both non-network and conventional network solutions receive equal, non-discriminatory consideration.

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[19] This distillation of core functions is derived from a meta-analysis of the global literature and informed by previous collaboration with Dr Lorenzo Kristov, Matthew McDonnel, Nikhil Balakumar and Dan Cross-Call.

4. **Advanced Data Analytics and Sharing:** Enable enhanced network visibility, real-time monitoring and rapid response to dynamic conditions, including fault prediction and network performance optimisation. Support improved real-time forecasting of load, generation and storage operational behaviours. Provide analytics to underpin the operation of flexibility markets by identifying opportunities for demand response and coordinating with market participants to optimise resource utilisation. Facilitate better understanding of customer behaviour and energy usage patterns to offer tailored services and engage customers mutually beneficial initiatives.

5. **Transmission-Distribution Coordination:** Actively collaborate with the SO and relevant transmission network to enable operational visibility, support relevant data exchanges, align operational and market interactions, and coordinate longer-term system planning. Key functions include low latency data transformations and exchange relevant to the joint management of frequency, voltage, congestion, energy flows, essential system services and supply-demand balancing.

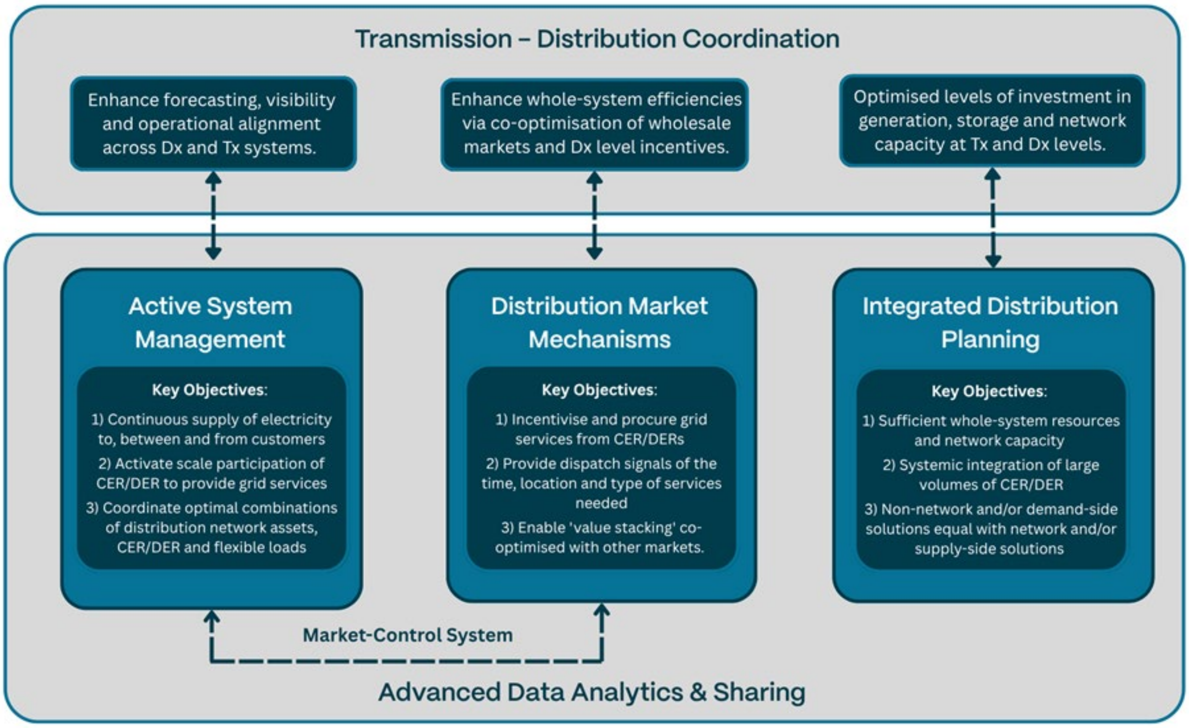


Figure 35: A high-level representation of the relationship between the five DSO Functions

Closely Interdependent Functions

While the above five functional areas are outlined individually, and each explored in additional detail below, it is important to recognise that they are rely on a high degree of operational interdependence with each other. For example, given that a key function of a DSO is to orchestrate privately owned resources, both the Active System Management and Distribution Market Mechanisms must be designed to function seamlessly together to provide an effective market-control system.

Each of these five functions are now discussed in some additional detail which, again, should be considered indicative and directional. Having considered each individually, their operational independence is then illustrated to highlight how each of the functions either leads, supports or benefits from the other functions to achieve different target outcomes.

10.2 Function 1: Active System Management

Core Function

Manage safe, reliable and efficient operation of the distribution system in a two-way power flow environment to ensure the continuous supply of electricity to, between and from customers. This involves the proactive identification and resolution of constraints, congestion management, optimised asset utilisation and enabling the scale participation of CER/DER and flexible loads. In includes actively managing the optimal combinations of distribution network assets, CER/DER and flexible loads in a non-discriminatory manner to provide beneficial services to the distribution system, the wider power system and both participating and non-participating customers.

Functional Objective

In collaboration with the DNSP, maintain safe, reliable and efficient real-time operation of the distribution system for the purposes of:

1. Ensuring continuous supply of electricity to, between and from customers
2. Enabling the scale participation of CER/DER and flexible loads to provide beneficial services to the distribution system and/or the wider power system, and
3. Actively manage the optimal combinations of distribution network assets, CER/DER and flexible loads in a non-discriminatory manner to achieve the above objectives.

Functional Activities

The supporting functional activities are generally recognised as key to enabling Active System Management are outlined below, broadly according to the sequence in which they may be developed, deployed and matured over time:

A. CER/DER Registration

B. System Security & Restart

C. Operational Visibility

D. Operational Forecasting

E. Distribution System Coordination

Table 15: Function 1 – Active System Management functional activities

Active System Management
A. CER/DER Registration
Determine, publish and maintain technical requirements for CER/DER connection and participation.
Analyse and publish emerging CER/DER hosting capacity opportunities and constraints.
Process CER/DER registration applications and related connection agreements (e.g. static, dynamic, etc).
Establish and maintain a register of all CER/DER assets by type and location.
B. System Security & Restart
Monitor availability of CER/DER in real-time relevant to system security requirements.
Risk manage and prepare for CER/DER curtailment requirements under low load conditions.
Enact emergency CER/DER curtailment arrangements as directed by AEMO under low load conditions
Risk manage and prepare for local system restart, whole-system black start and other major contingencies.
Enact local system restart or whole-system black start response as directed by AEMO.
C. Operational Visibility
Develop and maintain distribution network model to support power flow analysis, load forecasting, etc.
Perform real-time LV system monitoring to provide locational and temporal visibility across all network elements.
Conduct ongoing analysis to monitor system state across all network elements.
Aggregate and provide relevant operational data to AEMO and relevant TNSP.
Publish selective operational data and distribution system requirements to authorised third parties.

D. Operational Forecasting
Analyse short and medium-term trends in network loading to identify emerging congestion and constraints.
Forecast plausible range of near-term CER/DER operating behaviours and resulting network flows (pre-orchestration).
Analyse the quantum of CER/DER and flexibility services required to alleviate network constraints and support system optimisation.
Aggregate and provide relevant operational forecasting data to AEMO and relevant TNSP.
Receive and process near real-time and day ahead bulk power operational forecasting data from AEMO.
Publish selective forecasting data and distribution system requirements to authorised third parties.
E. Distribution System Coordination
Actively monitor dynamic network constraints and service requirements arising from switching activities.
Perform ongoing computation of Dynamic Operating Envelope (DOE) information and provide to CER/DER aggregators
Actively coordinate and optimise the operation of distribution network assets and flexible demand, CER and large-scale DER under the direct control of the DSO.
Publish additional requirements for CER/DER and flexibility services through Distribution Market Mechanisms (DMM).
Continuously collaborate with DNSP in real-time to manage congestion, bidirectional flows and support supply and demand alignment.
Continuously negotiate with AEMO in near real-time to determine power, service and value flows across the Transmission-Distribution Interface (TDI).

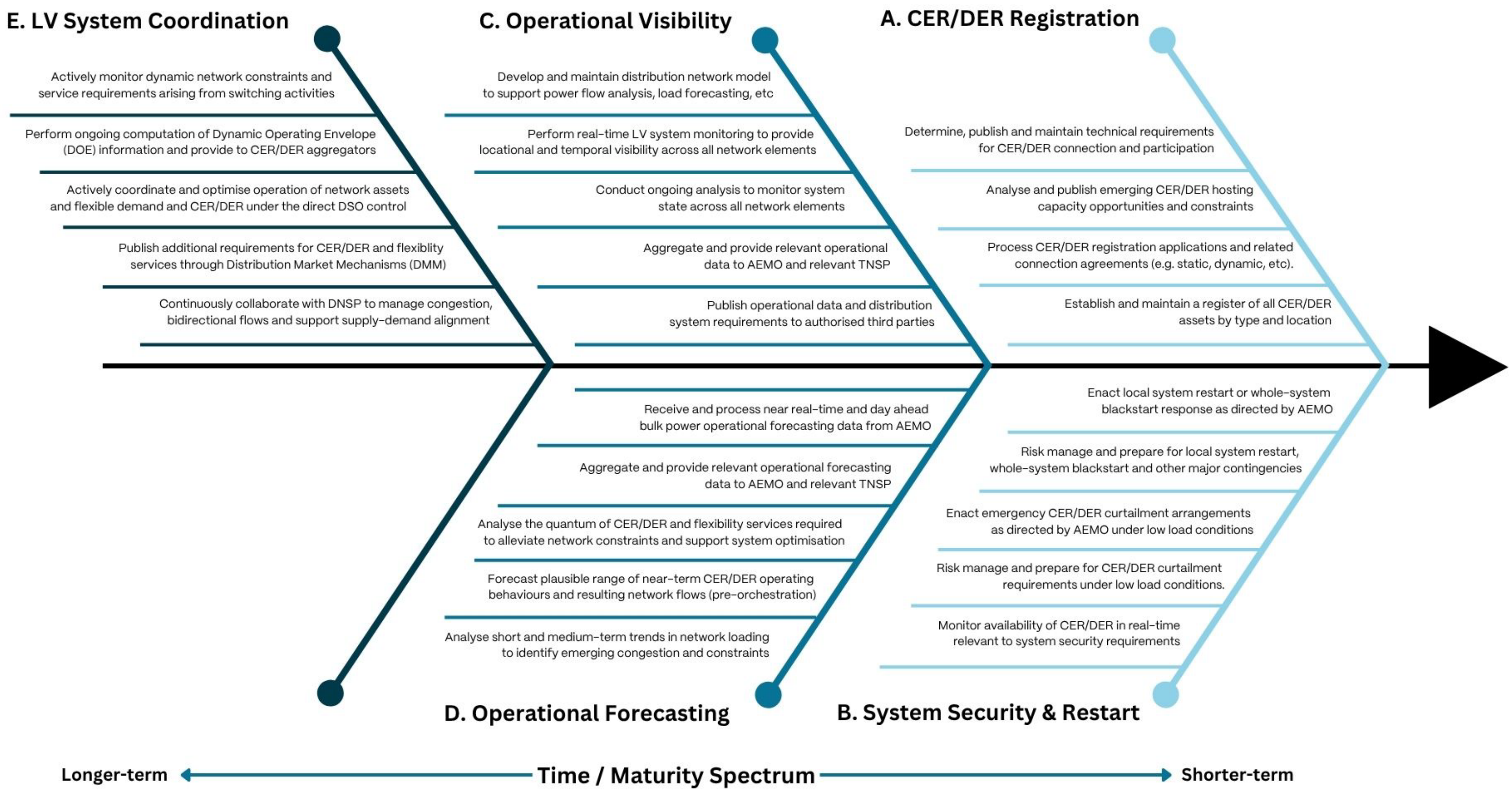


Figure 36: Function 1 – Active System Management functional activities

10.3 Function 2: Distribution Market Mechanisms

Core Function

Employ a wide 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.

Functional Objective:

Establish distribution-level market mechanisms that support scale participation of flexible loads and CER/DER by:

1. Incentivising and procuring beneficial grid services from CER/DER and flexible loads
2. Providing clear dispatch signals of the time, location and type of services required by the system; and
3. Enabling the 'value stacking' of services in a manner that is co-optimised with bulk power markets.

Functional Activities

The supporting functional activities are generally recognised as key to enabling Distribution Market Mechanisms are outlined below, broadly according to the sequence in which they may be developed, deployed and matured over time:

A. Basic Market/Tariff Mechanisms

B. Aggregator Registration

C. Advanced Market Mechanisms

D. Services Procurement & Dispatch

Other Discussion

The discussion of Distribution Market Mechanisms as one of a DSOs five core functions is deliberately broad and recognises a spectrum of incentive mechanisms that are likely to evolve and mature over time, from tariff-based incentives and bilateral contracts to more advanced digital markets.

As CER/DER volumes continue to increase in Australia, more advanced distribution-level markets can provide market-based dispatch signals for the specific services required, better achieving 'the right service – at the right time – at the right location'. This would enable transactions that are more scalable and lower friction, supporting more granular procurement of required system services, the value of which varies temporally and spatially. Where holistically designed, enhanced 'value stacking' of services co-optimised with the bulk power market is also more feasible.

Importantly, both the economically efficient procurement and technically secure orchestration of services from millions of CER/DER will ultimately require a more dynamic and well-integrated 'market-control system' than conventional tariff-based incentives are able to support. The market-control system of an electric power 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.

For example, Security Constrained Economic Dispatch (SCED) in bulk power markets is broadly familiar to many people in the electricity sector. SCED is a critical algorithmic component *within* the broader market-control system. Traditionally employed in bulk power markets, SCED translates market signals and reliability rules into physically feasible, cost-optimal dispatch of large transmission-connected energy resources.

As Australia's power systems decarbonise and become increasingly distributed, they also become more volatile and bidirectional, increasing operational dynamics and compressing operational timescales. This will require increasingly granular and targeted CER/DER incentivisation due to their value to the system being temporally and spatially variant. In this context, digital markets enable far more time and location-specific incentives which support more targeted recruitment high-value CER/DER, enhanced system cost efficiencies and reduced over-procurement risk of CER/DER services that the system ultimately does not require.

As noted above, the category of Distribution Market Mechanisms is intentionally broad and a comprehensive treatment is beyond the scope of this report. However, in support of the most informed discussion, a high-level survey of different approaches to advanced market mechanisms relevant to CER/DER participation and efficient incentivisation is provided in Appendix F.

Table 16: Function 2 – Distribution Market Mechanisms functional activities

Distribution Market Mechanisms
A. Basic Market/Tariff Mechanisms
Deploy cost-reflective and value-reflective tariff options (e.g. solar sponge tariffs, etc.).
Establish bilateral contracting, dispatch and settlement of CER/DER network services.
Establish bilateral reserve contracts for short and long-term emergency support of distribution system security.
Actively promote customer/societal awareness of the need for new models of electricity pricing as grids become more dynamic and participative.
B. Aggregator Registration
Register CER/DER aggregators and large aggregated facilities/precincts for market participation.
Confirm registered participants meet all market, prudential and operational requirements.
Confirm market-standard compliance of installation of aggregated CER/DER and orchestration mechanisms.
Register directly participating CER/DER and confirm site-level dynamic connection agreements.
C. Advanced Market Mechanisms
Define standard network services and market products (e.g. peak shaving, load shaping, voltage support, etc).
Develop and publish transparent, technology neutral valuation approach for all network services.
Develop and publish market-neutral processes for procurement, selection, dispatch, settlement and compensation.
Develop and deploy a market platform environment for publishing competitive tenders and receiving offers for network services.
Develop and deploy a market platform dispatch mechanisms (both direct and indirect) to support firmness of response.

D. Services Procurement & Dispatch
Identify locational/temporal network constraints and publish tenders for services (e.g. typically day-ahead to month-ahead).
Receive and evaluate competitive offers to select the winning bids required to meet sufficient, non-conflicting network requirements.
Notify successful providers ahead of time (e.g. day-ahead or intraday).
During the service window, send dispatch instructions via the market platform or APIs.
Manage metrology data acquisition, market clearing, reporting, funds clearing, compliance and dispute resolution.
Receive dispatch outcomes reports from aggregators and verify actual vs reported outcomes.

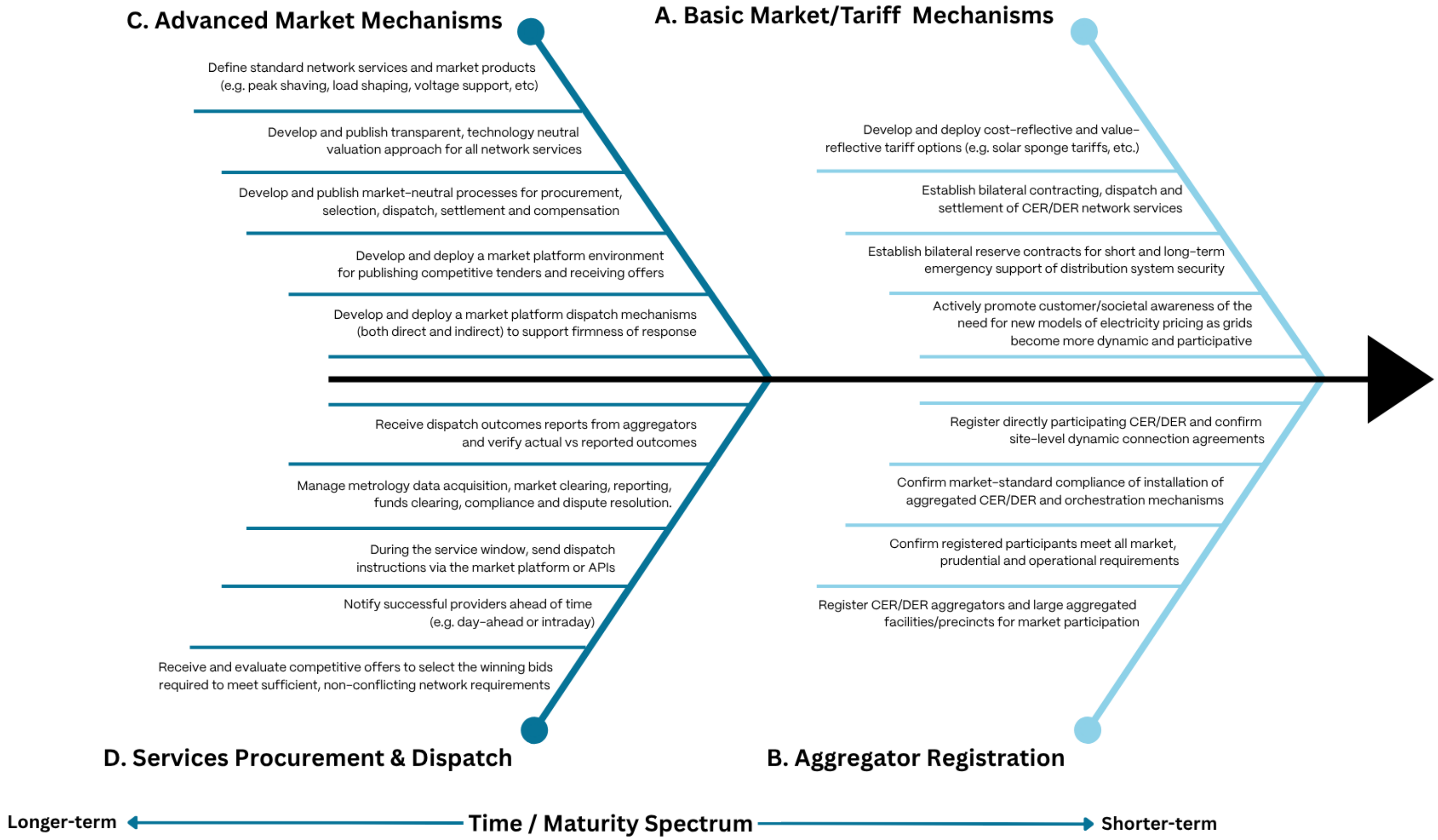


Figure 37: Distribution Market Mechanisms functional activities

10.4 Function 3: Integrated Distribution Planning

Core Function

Perform long-term distribution system planning, in active collaboration with the relevant DNSP, upstream TNSP and the SO, as an integral part of whole-system planning. Ensure sufficient whole-system and distribution-level generation, storage, flexible resources and network infrastructure to serve all customers reliably, including the systems integration required to beneficially leverage large volumes of participating CER/DER and flexible loads. Both non-network and conventional network solutions receive equal, non-discriminatory consideration.

Functional Objective

In active collaboration with the relevant DNSP, upstream TNSP and the SO, ensure:

1. Sufficient whole-system generation, storage, flexible resources and network infrastructure to serve all customers reliably
2. The systemic integration and ability to beneficially leverage large volumes of participating CER/DER and flexible loads, and
3. Both non-network and/or demand-side solutions and conventional network and/or supply-side solutions receive equal, non-discriminatory consideration.

Functional Activities

The supporting functional activities are generally recognised as key to enabling Integrated Distribution Planning are outlined below, broadly according to the sequence in which they may be developed, deployed and matured over time:

A. Future Scenario Analyses

B. Integrated Needs Analyses

C. Integrated Options Analyses

D. Integrated Solution Selection

Table 17: Function 3 – Integrated Distribution Planning functional activities

Integrated Distribution Planning
A. Future Scenario Analyses
Collaboratively explore long-term consumer technology trends and energy use scenarios with stakeholders and researchers.
Collaboratively explore long-term regional bulk power, transmission and distribution planning scenarios with AEMO and relevant TNSP.
Conduct long-term analysis of CER/DER deployment and EV adoption scenarios.
Conduct long-term analysis of distribution system loading and power flow scenarios.
B. Integrated Needs Analyses
Collaborate with the DNSP to develop probabilistic, locationally granular forecasting across the distribution system relevant to alternative scenarios.
Collaborate with AEMO and the relevant TNSP to analyse upstream system issues and opportunities arising from alternative distribution scenarios.
Collaborate with the DNSP to assess and shortlist medium and long-term distribution system needs under alternative scenarios.
Identify and publish emerging priority constraints and/or opportunities.
C. Integrated Options Analyses
Solicit technology-neutral solution options including conventional network, non-network and/or grid enhancing technologies.
Conduct initial screening of options (e.g. based on technical feasibility, regulatory compliance, market availability, time to implement, etc).
Employ multi-criteria analysis to shortlist best options (e.g. including reliability and resilience impacts, scalability and future-readiness, etc).
Undertake enhanced cost-benefit analysis to determine the deferment/avoidance value, including consideration of upstream system implications and costs.
Present shortlisted options through public consultation and/or customer panels and adjust based on stakeholder feedback.

D. Integrated Solution Selection
DSO and DNSP collaboratively select and formalise the preferred solution(s) proceeding to full business case development.
Engage with upstream TNSP and AEMO to maximise whole-system benefits which should also be outlined in the business case.
Translate selected options into executable projects with precise specifications, timing, and operational parameters.
Undertake detailed engineering design and analysis of system optimisation/outcomes.
Undertake procurement and contracting processes appropriate to the required solutions (i.e. conventional network, non-network and/or grid enhancing technologies).

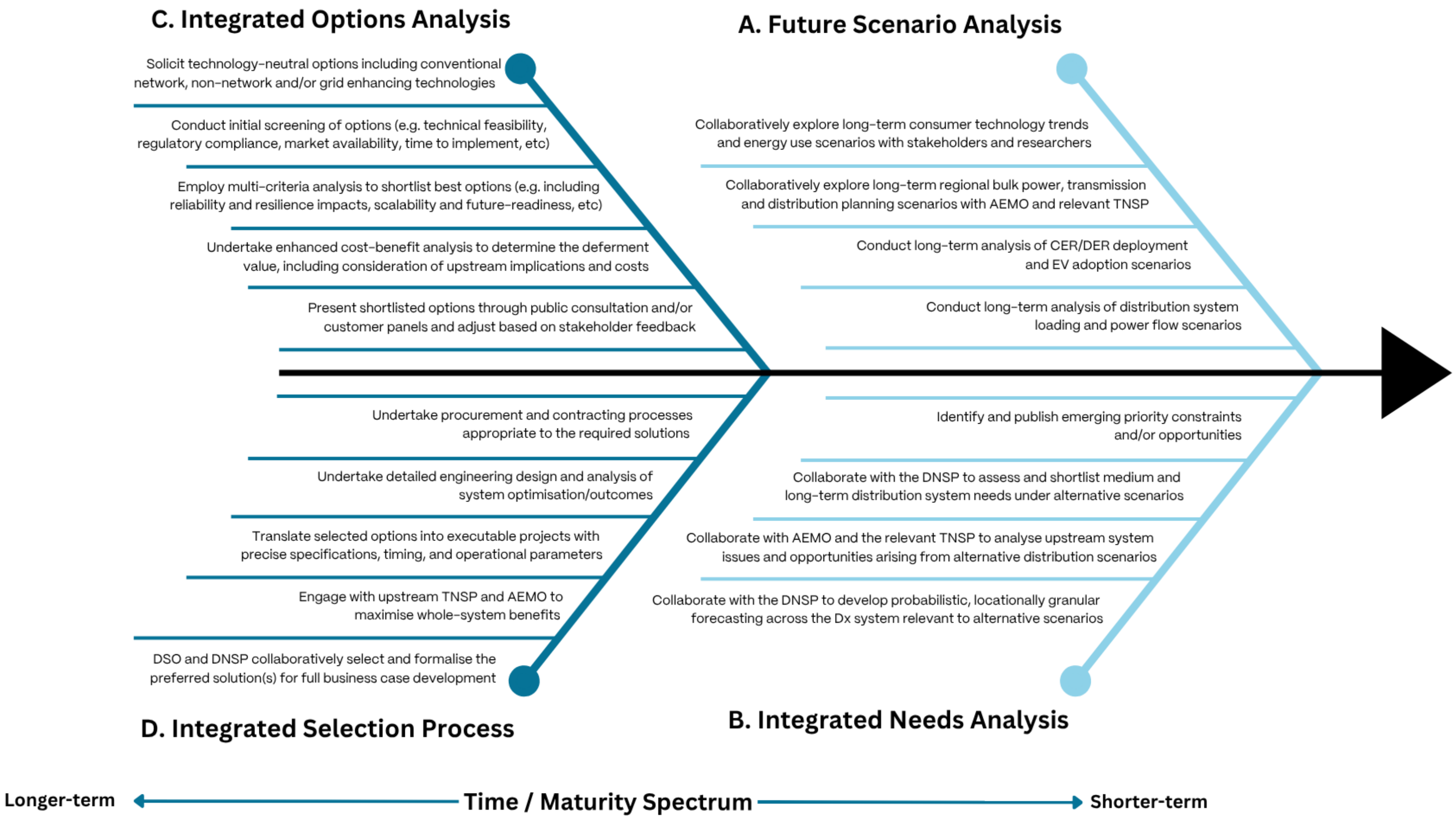


Figure 38: Function 3 – Integrated Distribution Planning functional activities

10.5 Function 4: Advanced Data Analytics & Sharing

Core Function

Enable enhanced network visibility, real-time monitoring and rapid response to dynamic conditions, including fault prediction and network performance optimisation. Support improved real-time forecasting of load, generation and storage operational behaviours. Provide analytics to underpin the operation of flexibility markets by identifying opportunities for demand response and coordinating with market participants to optimise resource utilisation. Facilitate better understanding of customer behaviour and energy usage patterns to offer tailored services and engage customers mutually beneficial initiatives.

Discussion

As noted earlier, a key focus of a DSO is the real-time coordination of the 'system' of network assets, flexible and inflexible demand, customer-owned CER and large-scale DER. A key objective is to deliver enhanced technical and economic outcomes not possible by managing network assets alone.

As power system operations become increasingly dynamic, performing this role requires a significantly expanded data analytics capability that underpins the three core DSO functions discussed above. Following are selective examples of the critical role of advanced data analytics:

- More accurate load forecasting: Leveraging big data from historical loads, weather data, CER/DER generation output, etc., supports enhanced forecasting both for short-term operations and long-term planning. For example, this may employ high-resolution weather data and machine learning at a *hyper-local level* down to individual feeders to create probabilistic demand/generation forecasts that guide real-time operational decisions.
- Voltage and power flow optimisation. By analysing data from smart transformers, capacitors, customer meters, etc., DSOs can perform Volt/VAR optimisation and dynamic reconfiguration to minimise losses and maintain power quality. Similarly, enhanced situational awareness of where CER/DER are connected and how they affect power flows, coupled with power flow analytics and hosting capacity calculations, enable potential congestion or voltage issues to be anticipated and proactively managed.
- Supporting flexibility and local markets: Data analytics underpin enhanced flexibility services in multiple ways, firstly by identifying when and where flexibility is needed by analysing load and CER/DER operational patterns to predict congestion. Similarly, data analytics underpins local market operations and dispatch algorithms. In a significantly more temporally and spatially dynamic operating environment, this allows the necessary services to be sourced in a targeted and cost-efficient manner.
- Enabling customer participation: As power systems decarbonise and decentralise, as neutral facilitators DSOs play a key role in enabling the scale participation of customers. Data transparency and access is a key activity involving open data platforms that enable the sharing of key datasets with the customers, developers and third-party solution providers.

In addition to the above selective examples, advanced data analytics plays a foundational role in enabling whole-system operational visibility, coordination and data exchange through Transmission-Distribution Coordination (TDC) as considered below.

10.6 Function 5: Transmission-Distribution Coordination

Core Function

Actively collaborate with the SO and relevant transmission network to enable operational visibility, support relevant data exchanges, align operational and market interactions, and coordinate longer-term system planning. Key functions include low latency data transformations and exchange relevant to the joint management of frequency, voltage, congestion, energy flows, essential system services and supply-demand balancing.

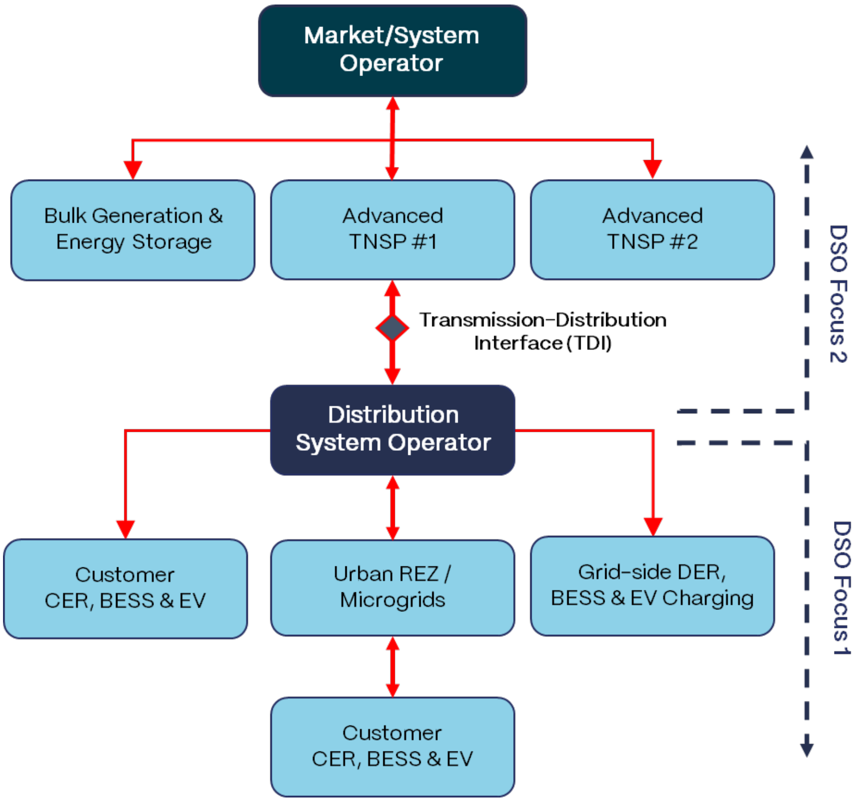


Figure 39: DSO has a dual downstream and upstream operational focus

Discussion

Whereas a conventional DNSP had a primary downstream focus on the distribution network, a DSO has dual focus: downstream on the active management of a high-CER/DER distribution system and upstream on its two-way interoperation with the bulk power system, as illustrated in Figure 39 above.

The topic of Transmission-Distribution Coordination (TDC) is explored in more detail in Report 5 of this series [133]. However, as the power system become more volatile and bidirectional, a key functional activity of the DSO is providing the SO enhanced operational visibility of the growing volumes of distribution-connected energy resources. This will also underpin the development of enhanced operational coordination of these resources to support of system balancing.

Given the millions of CER/DER devices connected to many distribution systems, data analytics and transformation for sharing with the SO and other authorised supply chain actors is key enabler of the TDC function.

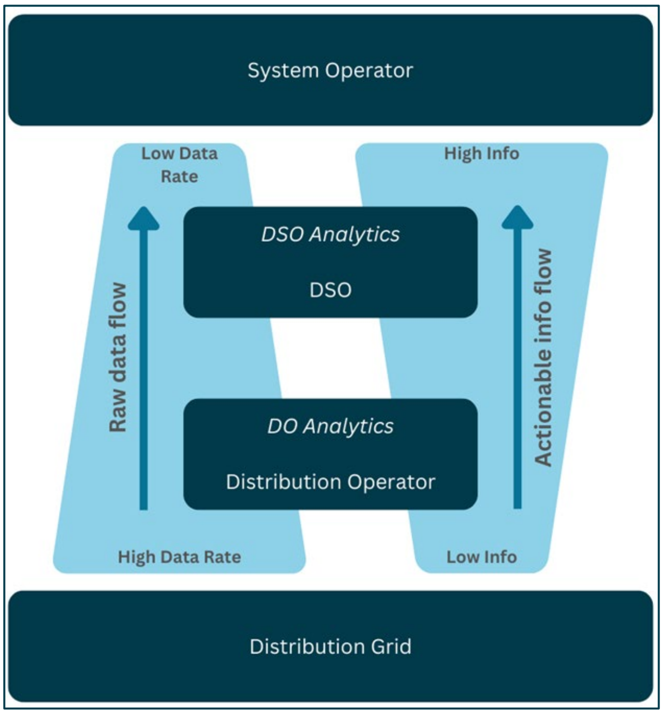


Figure 40: Data rates and information extraction relationships

Data transformations reduce the data exchange volumes while extracting and providing the required actionable information. This principle can be used to guide the design of multi-stage analytics, distributed data storage and communications in complex engineered systems such as the power system. This leads to the concept of a sequence, stack, or hierarchy of data transformations as an information funnel – as we move through a processing chain, extracted information should increase at each stage, while data volume decreases.

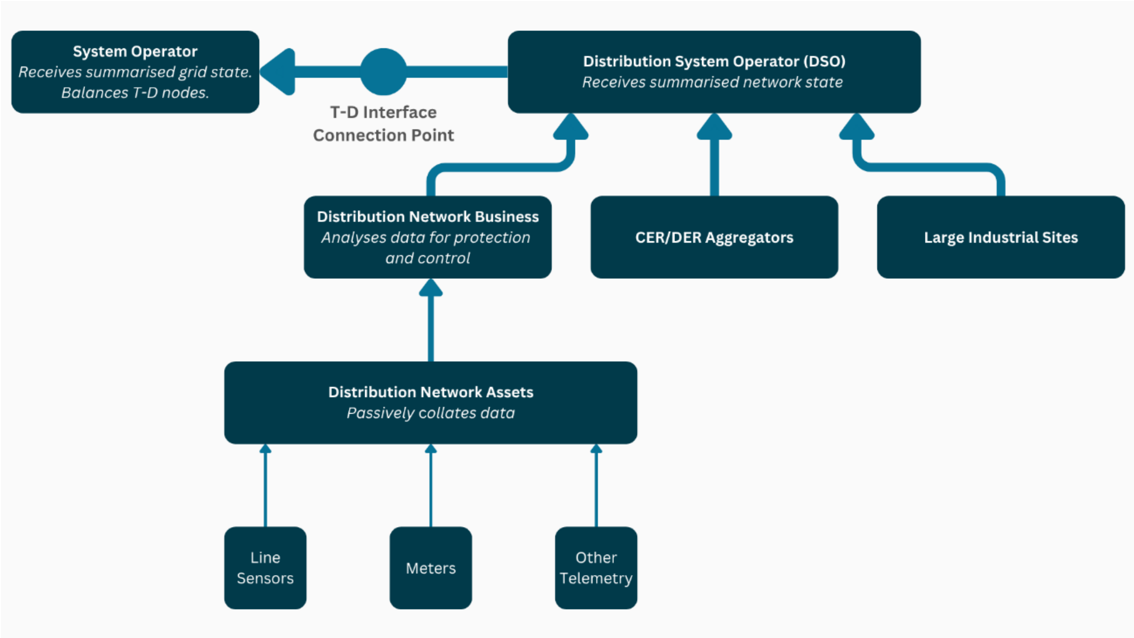


Figure 41: Example upward dataflows and data transformations

As an illustration of how this would work for operational data, consider Figure 41 above. Working from upstream from the bottom of the diagram:

1. The distribution network generates data from line sensors, meters, and related devices and systems. This occurs at different levels, from the low voltage network up to the high voltage and sub-transmission levels.

2. The DNSP analyses the data streams for its own purposes of protection and control and summarises the grid state which is provided to the DSO.

3. The DSO analyses the data from the DNPS and other sources (including DER aggregators) for the purpose of fulfilling its operational responsibilities.

4. The DSO also summarises the critical information which is provided to the SO across the Transmission-Distribution Interface (TDI).

5. The SO uses the information for the purpose of fulfilling its operational responsibilities

As a decarbonising power system like the NEM becomes more volatile and bidirectional, it must also become more flexible and interdependent end-to-end. In this context, Figure 42 below highlights why formalised, consistent data transformations are essential when viewed from a whole-system perspective. Simply put, as the system moves from hundreds to millions of participating resources, providing inadequately transformed data to the SO is neither effective or scalable.

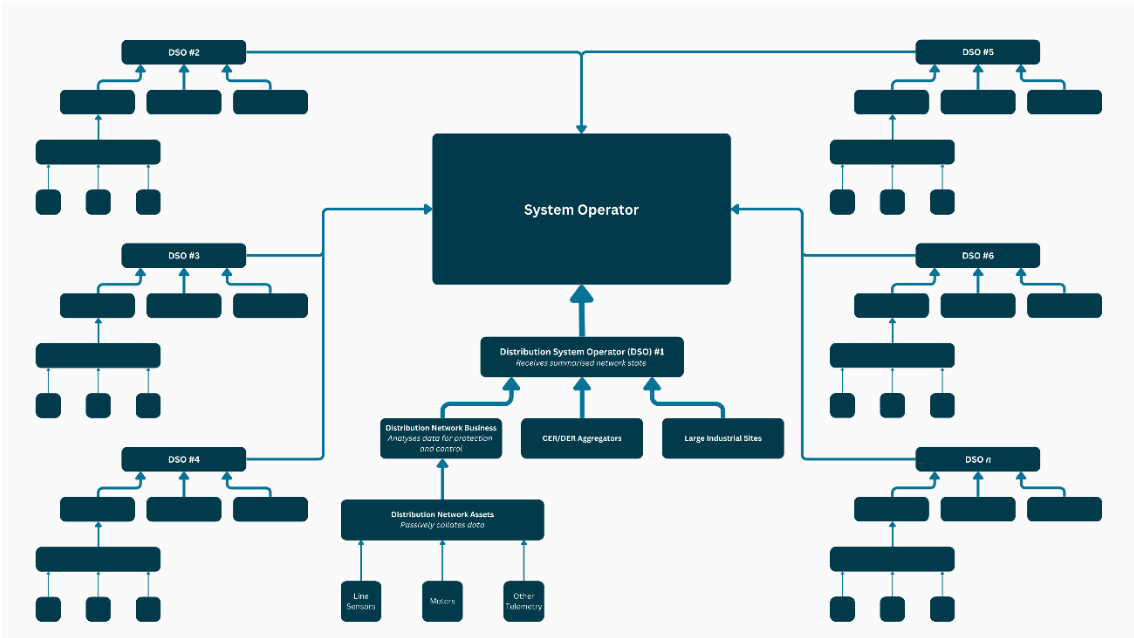


Figure 42: Dataflows viewed from a whole-system perspective, highlighting the critical need for established data transformation approaches

10.7 The interdependence of the five core functions

As noted earlier, while the above five core and enabling/supporting functional areas are outlined individually, they are all dependent on a high degree of operational interdependence with each other.

Table 18 below provides a high-level illustration of how the five functions play different roles to lead, support, enable and /or benefit from the performance of the other functions for various example outcomes to be achieved.

Table 18: Short-medium term examples of how the individual DSO functions lead, support and/or benefit from the other functions

Example Target Outcomes	Description	Active System Management	Distribution Market Mechanisms	Integrated Distribution Planning	Advanced Data Analytics & Sharing	Transmission-Distribution Coordination
Short - Medium Term						
Operational distribution visibility and forecasting enhanced	Advanced data acquisition, analytics, observability and forecasting across low-voltage network enables enhanced near real-time operational decision-making.	1. Functional Lead	4. Beneficiary	4. Beneficiary	3. Underpinning Enabler	2. Functional Support
More efficient management of two-way power flows	Operational issues arising from variable, two-way power flows between loads, CER/DER and the distribution network are pre-emptively managed.	1. Functional Lead	2. Functional Support	4. Beneficiary	3. Underpinning Enabler	4. Beneficiary
Distribution congestion and constraints mitigated	Emerging local grid constraints are proactively managed to maintain security of supply and support enhanced asset utilisation.	1. Functional Lead	2. Functional Support	4. Beneficiary	3. Underpinning Enabler	4. Beneficiary
Operational efficiencies from coordination of network assets, flexible loads and CER/DER	Continuously monitoring and beneficially orchestrating network assets, flexible loads and CER/DER provide potential cost savings and enhanced asset utilisation.	1. Functional Lead	2. Functional Support	4. Beneficiary	3. Underpinning Enabler	4. Beneficiary

Example Target Outcomes	Description	Active System Management	Distribution Market Mechanisms	Integrated Distribution Planning	Advanced Data Analytics & Sharing	Transmission-Distribution Coordination
Short - Medium Term (Cont')						
Beneficial participation levels of flexible loads and CER/DER increased	Participation levels of flexible loads and CER/DER orchestration expands with enhanced customer benefits through advanced tariffs.	2. Functional Support	1. Functional Lead	4. Beneficiary	3. Underpinning Enabler	4. Beneficiary
Firm responsiveness of participating flexible loads and CER/DER increased	Firmness of response from participating flexible loads and CER/DER is enhanced through end-to-end automation and supported by advanced tariffs.	1. Functional Lead	1. Functional Lead	4. Beneficiary	3. Underpinning Enabler	4. Beneficiary
Enhanced distribution planning under uncertainty	Scenario-based analysis, probabilistic tools and enhanced analytics supports planning under high levels of uncertainty relevant to a more participative system.	4. Beneficiary	4. Beneficiary	1. Functional Lead	3. Underpinning Enabler	2. Functional Support
Cost savings via expanded options to traditional network augmentation	Expanded range of options for deferring or avoiding network augmentation through the use of non-wires alternatives.	4. Beneficiary	4. Beneficiary	1. Functional Lead	3. Underpinning Enabler	5. N/A

Table 19: Medium-long term examples of how the individual DSO functions lead, support and/or benefit from the other functions

Example Target Outcomes	Description	Active System Management	Distribution Market Mechanisms	Integrated Distribution Planning	Advanced Data Analytics & Sharing	Transmission-Distribution Coordination
Medium – Long Term						
Enhanced whole-system management of constraints, congestion and minimum loads	During bulk power and transmission system constraint, congestion and/or minimum operational demand events, the DSO provides a range of flexibility services beneficial to whole-system operations.	1. Functional Lead	2. Functional Support	4. Beneficiary	3. Underpinning Enabler	1. Functional Lead
Enhanced operational efficiencies through multi-level coordination and system balancing	As the overall proportion of energy resources that are connected to the distribution network grows, the DSO plays an increasing and ongoing role in managing local supply-demand balance to deliver both local and whole-system benefits.	1. Functional Lead	2. Functional Support	4. Beneficiary	3. Underpinning Enabler	1. Functional Lead
Enhanced whole-system reliability and resilience	In active coordination with the System Operator, the DSO is capable of adaptively supporting whole-system operations and providing beneficial services in support of reliability and resilience outcomes.	1. Functional Lead	2. Functional Support	4. Beneficiary	3. Underpinning Enabler	1. Functional Lead

Example Target Outcomes	Description	Active System Management	Distribution Market Mechanisms	Integrated Distribution Planning	Advanced Data Analytics & Sharing	Transmission-Distribution Coordination
Medium - Long Term						
Beneficial participation of flexible loads and CER/DER maximised	Flexible load and CER/DER scale participation is maximised through the establishment of low friction distribution-level markets enabling access to the full 'value stack' of local grid services co-optimised with bulk power markets.	2. Functional Support	1. Functional Lead	4. Beneficiary	3. Underpinning Enabler	2. Functional Support
Enhanced whole-system investment efficiency	Align long-term system planning, sector couplings and active coordination between the transmission and distribution systems to deliver cost stabilisation through enhanced investment efficiency.	2. Functional Support	2. Functional Support	1. Functional Lead	3. Underpinning Enabler	1. Functional Lead
Accelerated whole-system decarbonisation	Align near-term operations, long-term system planning, sector couplings and active coordination between the transmission and distribution systems to support accelerated decarbonisation outcomes.	1. Functional Lead	2. Functional Support	1. Functional Lead	3. Underpinning Enabler	1. Functional Lead

Key Concepts L

Market Mechanism

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

Market-Control System

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

Value Stacking

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

Co-optimisation

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

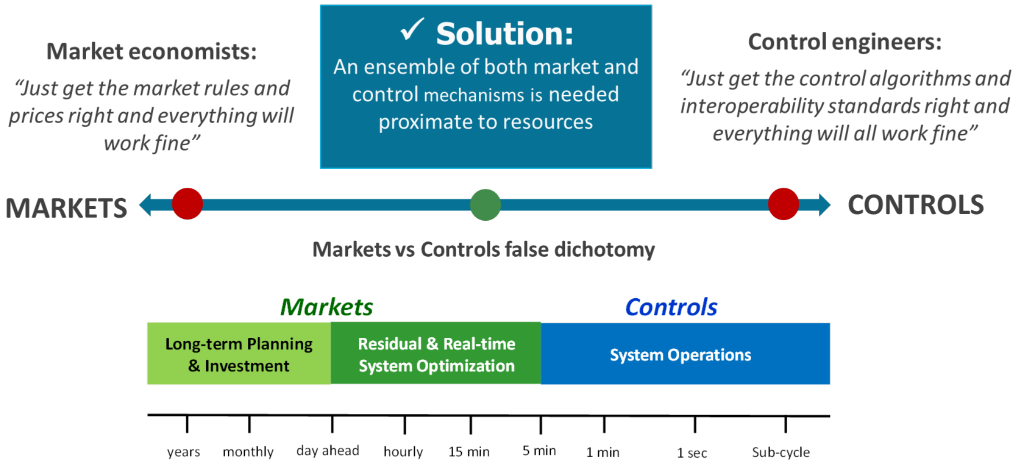


Figure 43: Market-Control System relationship relevant to operational coordination[20]

[20] Image: Paul De Martini (Adapted)

10.8 Objective, scalable and future-ready assignment of DSO and TDC roles, responsibilities and systemic interfaces

Modern power systems consist of a web of seven distinct, overlaid structures, several of which dynamically influence each other on a hours-minutes-microseconds basis. Accurately described as a Network of Structures[21], many of the structures span the various tiers/layers of the electricity supply chain including bulk power, transmission and distribution systems, energy retailers, aggregators and customers.

Accordingly, the secure and efficient operation of GW-scale power systems depends on an expansive set of relationships and interdependencies across numerous functions, entities, structures, system boundaries, interfaces and hand-off points. As decarbonising power systems become increasingly volatile and bidirectional, this inherent complexity grows and additional capabilities such as DSO and TDC models are required.

Given the deeply interconnected role of DSO and TDC models in future system operations, the assignment of related roles and responsibilities, and their relationships with DNSPs, CER/DER aggregators, etc., must be underpinned by formal structural and behavioural analyses if unintended consequences and sub-optimal outcomes are to be avoided. While explored in more detail in Report 3 [5] of this series, if the aim is to progressively ready the NEM for more deeply decarbonised, flexible and whole-system operation, due diligence requires a structurally informed approach to interrogating all functional relationships, feedback loops and precise hand-off points between systems and entities. While at a high-level this may not immediately appear necessary, in the context of a transforming ultra complex system like the NEM, it is a critical part of:

- Avoiding the unintentional propagation of the several architectural issues that directly impact power system security, stability and efficiency.[22]
- Enabling the objective, evidence-based and defensible assignment of future roles and responsibilities in a manner that minimises the risk of requiring significant future rework and re-assignment of roles.

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

1. Mapping of the most plausible phases through which essential new capabilities such as Distribution System Operator (DSO) and Transmission-Distribution Coordination (TDC) models will need to evolve and mature as distribution-connected energy resources continue to grow as a proportion of net system resources.
2. Detailed analysis of the as-built structures, entity relationships, interfaces, hand-offs and data flows embedded across the legacy power system.

[21] Refer to Key Concepts G.

[22] Refer to Report 3, Sections 4.2.1 – 4.2.3 for more detail.

3. Interrogation of the most credible options for how these structural and functional relationships, interfaces and hand-off points between systems and entities may need to be changed to enable secure and efficient operation in the longer term, supported by high fidelity dynamic behaviour and scalability analyses.

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

To illustrate further, Figure 44 below provides one credible view of how the NEM's legacy structures, interfaces and hand-off points between entities, systems and subsystems will need to change to enable high-CER/DER futures even broadly similar to AEMO's Step Change scenario [9]. Stakeholder perspectives, preferences and the consideration of individual use cases are all important inputs to the wider process of considering future roles and responsibilities. However, in the context of such a complex and functionally interdependent system, they are not sufficient for providing a credible, systemic basis for the detailed assignment of roles and responsibilities.

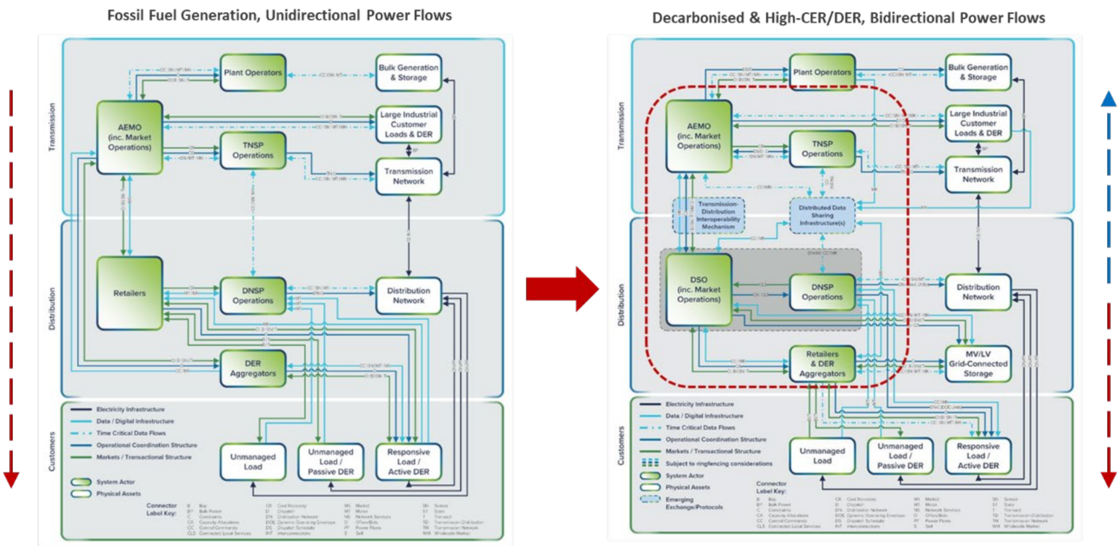


Figure 44: One credible view of how the NEM's legacy structures will need to change to enable high-CER/DER futures similar to AEMO's Step Change scenario[134]

Where the more subjective considerations are not underpinned by more objective structural analyses, the risk of unintended consequences and cost excursions is significantly elevated. By contrast, the targeted application of System Architecture disciplines and tools such as Model-Based Systems Engineering (MBSE) enables a far more holistic and stepwise view of the system's transformation, including how key roles and responsibilities will need to evolve over time. Critically, this also enables much higher resolution analyses of changing power system structures, the multi-entity relationships and neessary data flows – in the current, future, and transitionary states.

Key Concepts M

Component

A generic term for the uniquely identifiable elements, building blocks, organisations, devices and applications which are related together by a structure to enable the purposes of the system to be achieved.

The term also includes mechanisms intrinsic to the functioning of the system that are both tangible and intangible, such as policy instruments, regulatory mechanisms, rate or tariff structures, etc.

Capability

The ability to perform certain actions or achieve specific outcomes.

Function

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

Role

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

Responsibility

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

As illustrated in Figure 45 below, the seven-step process developed by Dr Jeffrey Taft, former Chief Architect at Pacific Northwest National Laboratory (PNNL)[59], commences by outlining an integrated set of desired DSO and TDC capabilities as outlined in both this report and Report 5 of this series [133].

Having identified the desired capabilities, the distinct and non-overlapping functions needed to implement each of the desired capabilities are then distilled. Each individual function may then be allocated to the most relevant cluster of functions, and each cluster of functions is then assigned to only one formal role. While each role may be assigned to only one entity, an entity may be assigned more than one role. The result of applying this stepwise approach is that roles and responsibilities are assigned in a structurally informed manner that automatically avoids conflicts, duplications and ambiguities

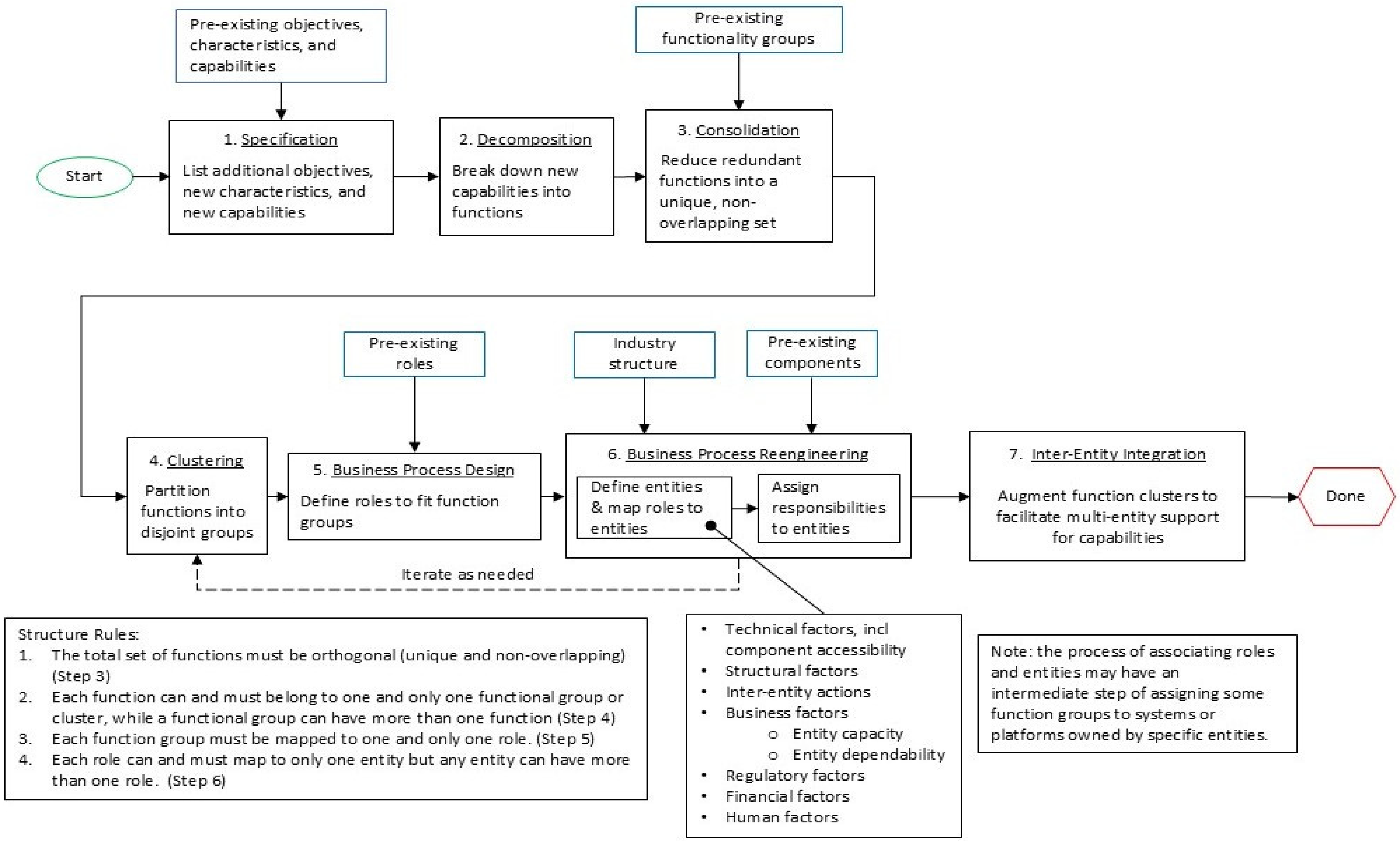


Figure 45: Structurally informed process for the assignment of roles and responsibilities[59]

11 DSO Governance: Ensuring neutrality and trust

A DSO is uniquely responsible for achieving its objectives via the real-time coordination of the 'system' of network assets, flexible and inflexible demand, customer-owned CER and large-scale DER. By comparison, a conventional DNSP achieves its key objectives of enabling safe, reliable and efficient power delivery to consumers primarily via the management of network assets in a unidirectional context. Transparency, neutrality and trust are, therefore, essential requirements for the DSO, with this trusted neutrality particularly extending to the consistent and verifiable equal treatment of network and non-network assets and their incentivisation.

While a comprehensive review of DSO governance, regulatory and financial considerations is beyond the scope of this report, this chapter provides initial perspectives on how different jurisdictions are approaching these matters to ensure operational neutrality and stakeholder trust. It does so by summarising different approaches to distinguishing DSO and DNSP equivalent roles across structural, governance and financial arrangements. Two alternative approaches from the United Kingdom are provided for illustration. In a context where theoretical options and diverse opinions abound, the chapter concludes by providing observations that demonstrate how the targeted application of architectural and physics-based considerations helps differentiate the governance options that have the greatest practical relevance from those that are ultimately implausible.

11.1 Structural Separation

DNSP and DSO Roles	
United Kingdom [49], [61]	• Ofgem requires at least a formally ring-fenced separation of a DSO underpinned by a formal Operational Agreement with its DNO counterpart and an Independent Supervisory Board. • While this avoids mandated legal unbundling, as in the case of Scottish and Southern Energy Networks (SSEN), it also allows other businesses to adopt a more comprehensive structural separation, as in the case of UK Power Networks (UKPN).
European Union [40], [41]	• Conventional 'passive' DSOs are broadly equivalent to what would be called a DNSP in Australia. • While Active DSOs are still at an early stage, similarities with the approach taken by Ofgem appear to be considered credible by European regulators.
United States [52], [62]	• In many states, DNSP functions are embedded within vertically integrated utilities. • In California and New York state, regulators assign DSO-like functions to existing utilities through planning mandates and regulatory oversight.

Regulatory Safeguards	
United Kingdom [61], [63]	• Ofgem enforces internal functional separation, transparency, and incentive-based regulation. • Independent bodies now manage planning and market roles, reducing conflict risks without requiring full DNO/DSO unbundling.
European Union [40]	• EU law mandates unbundling DSO activities from supply activities, market-based procurement of flexibility, and transparency obligations. • DSOs must act neutrally, are often subject to branding and compliance rules, and are barred from owning generation or storage assets except under strict conditions.
United States [52], [62]	• State regulators enforce performance-based regulation, planning requirements and conflict-of-interest rules. • Utilities must competitively procure DER solutions and are restricted from owning them directly in many cases. • Formal role definitions and reporting obligations are used to ensure neutrality within the integrated structure.

11.2 Governance Separation

Corporate Governance	
United Kingdom [49], [64]	• Internal functional separation involves a single accountable executive, a clearly defined DSO team and formal hand-offs between DSO/DNO staff. • Oversight includes external advisory panels.
European Union [65]	• Emerging best practices similarly emphasise internal separation, executive-level accountability, and alignment of leadership incentives, though legal unbundling remains the base regulatory safeguard.
Operational Governance	
United Kingdom [63]	• Governance frameworks developed under the Open Networks project define TSO-DSO coordination. • New roles including the National Energy System Operator (NESO), the Flexibility Market Facilitator and Regional System Planners have also been established • Formal operational agreements define authority and conflict resolution mechanisms between the respective entities.

European Union [66]	• TSO-DSO coordination frameworks are formalised and updated through EU DSO Entity and ENTSO-E collaboration. • Initiatives include "traffic light" DER activation protocols and joint procedures for redispatch and balancing
Data Governance	
United Kingdom [67]	• Meter data is handled by the independent Data Communications Company (DCC), preventing DNOs from accessing customer-level information directly.
European Union [68]	• Governance mandates privacy protection and controlled sharing of smart meter data, while promoting access to anonymised datasets for innovation.

11.3 Financial Mechanisms

Cost Recovery	
United Kingdom [63]	• DSO costs are included in DNO revenue allowances under RIIO-ED2, covering IT, monitoring, and flexibility procurement. • No separate billing is required; funding is treated as part of core monopoly service.
European Union [69]	• DSOs recover costs through approved tariffs. • In some member states, TOTEX regulation enables CAPEX/OPEX neutrality, encouraging cost-effective use of flexibility over infrastructure expansion.
Performance Incentives	
United Kingdom [70]	• RIIO-ED2 links part of DNO revenue to DSO performance on flexibility, visibility, and customer outcomes. • Performance incentives allow in the order of 50% of operational cost savings delivered by the DSO to be retained which provides a substantial organisational motivation and significant customer benefits.
European Union [69]	• Some member states apply output-based incentives under TOTEX models, linking revenue to service quality, efficiency, and innovation targets.

11.4 DSO Governance Models are Still Maturing

Given the global leadership that the United Kingdom has demonstrated with the design and deployment of DSO models, the different degrees of structural separation that Ofgem has accommodated, with a minimum requirement of formal ring-fencing, are instructive. Quoting perspectives of the two main approaches at some length is of value.

Scottish & Southern Energy Networks (SSEN): Ring Fencing

Under the heading 'Further evidence is needed on the case for DSO-DNO separation', NERA Consulting for SSEN notes the following in favour of a ring-fenced approach [61]:

> *Specifically looking at DNO and DSO separation, Burger et al. (2019) do not recommend separation of the two roles due to the complexities of such a move in distribution, although they do recognise the need for adequate incentive regulation and a degree of independence between DNOs and DSOs. Specifically, they argue that distribution utilities should not be allowed to own DERs, given evidence that DER ownership is "best left exclusively to non-monopoly actors". They argue that allowing monopoly participation in competitive activities has negative impacts and will likely result in inefficient utilisation of DER capacity.*
>
> *Overall, Burger et al. (2019) point towards the need for stronger separation between DNOs/DSOs and any competitive actors but stop short of recommending specific unbundling of DNOs and DSOs.*
>
> *The above review of the literature suggests that evidence from the academic literature on the benefits of DNO-DSO unbundling is limited, and the one which does exist does not support the need for separation. Also, most of the literature on distribution unbundling focuses on unbundling generation and retail from distribution, and – unlike transmission where there is a reasonably clear consensus that some level of separation is needed – the literature shows a much lesser case for distribution unbundling.*
>
> *Finally, much of the existing literature on distribution unbundling is also dated, so does not consider the ongoing changes in the industry and the evolving role of the DNO due to decarbonisation, decentralisation and digitalisation. As such, to inform Ofgem and BEIS's decision on potential future separation, further evidence is needed.*

NERA's concluding observations state:

> *In our report, we undertake a quantitative analysis of the costs associated with DSO separation. We estimate a range for the costs for each DSO governance model (ring-fencing, legal unbundling, ownership unbundling and ESO amalgamation), as well as for different scopes of the DSO (Narrow, Wider and Widest). Our results show significant costs of separation, and the costs of separation rising with both the level of business separation and larger scope of the DSO.*
>
> *Comparatively the benefits of separation are difficult to quantify and are far more uncertain. Therefore, we provide a more qualitative assessment of the potential benefits supported by economic theory. In distribution, we assess that the main potential benefit of separation to be the avoidance of both the existence and perception of an asset ownership bias, although this effect is likely to be small, no more than 1 to 2 per cent of avoidable expenditure. However, the extent to which this benefit would be realised depends on both the degree of separation and scope of the*

DSO. A greater degree of separation and a wider scope for the DSO means this bias is more likely to be avoided. However, greater separation and a wider scope is associated with higher separation costs. We also find that other benefits that have been identified to support the case for separation at the transmission level are not applicable in distribution, including for example avoiding distortions to competition in competitive procurement of networks.

UK Power Networks (UKPN): Structural Separation

Under the heading 'Building trust through transparency', UKPN notes the following in favour of a structurally separated approach [71]:

DSO Net benefits (to 2040): High confidence NPV benefits: £560-670m Total including wider system PV benefits: The DSO will be responsible for planning our Net Zero future system and establishing markets for flexibility and access products that can create more network capacity at lower cost, whilst meeting the evolving needs of our customers. To create trust in our ability to operate market functions independently of our network business our customers expect a high degree of transparency in how our DSO will operate.

At present, our DSO-related activities are conducted from several areas in our business. This approach has served us well to date, enabling a clear focus internally for innovation in flexibility services and new connection products, whilst also gaining good feedback from stakeholders, customers, and flexibility service providers. However, in development of our DSO Strategy for RIIO-ED2 we have undertaken further extensive stakeholder engagement and worked through an operating model design process. Our conclusion from undertaking this work is that there are several challenges in continuing with the current model in which DSO functionality is embedded in the DNO business.

Whilst transparency delivered through clear processes and data publication will go some way to providing confidence, it will not address the perceived conflict of interest inherent in any model in which the DSO is ultimately governed by the DNO. It will also result in Directors who hold accountabilities for both DSO and DNO outcomes, leading to reduced transparency in decision making, and potentially raising questions over how the best outcomes for customers have been achieved if all decision makers in the process have dual responsibilities.

Our experience pushing ahead with our DSO development has shown us that delivering a fully-fledged DSO operation will be a transformative change challenge, and we believe that any model based on incremental evolution 'in the line' will not create the focus, commercial mind-set, customer centricity, and step change in ambition required to succeed. It will also fail to confront instances where processes are not clear and grey areas in decision making exist.

Having considered the costs and benefits of a range of operating model options, and informed our thinking through a rigorous design process, we have concluded that to be successful a DSO must be established at least as a fully ring-fenced entity. Given that stakeholders are telling us that delivering transparency is critical to achieving the benefits of the DSO, it is clear that the minimal incremental costs of full legal separation are both warranted and appropriate, and the feedback we have received since the publication of our July submission has reinforced this view. We know that our strategy has generated a lot of discussion in the industry with "traditionalists" suggesting that we are not serious or that "it can't be done." Our operating model work has not only helped us to understand specifically how a legally separate DSO could function; it has reinforced our confidence that it can be done, and we will set the bar for the industry.

We are therefore setting out what we believe to be the UK's first clearly defined operating model of how a legally separate DSO could work in the best interests of customers. Our operating model for the beginning of RIIO-ED2 is based on the following key foundational actions:

1. *Key organisational changes to create an agile, transparent, DSO business unit within UK Power Networks on day 1 of RIIO-ED2 with clear accountabilities, set-up as a separate legal entity within UK Power Networks Group with appropriate governance and controls.*
2. *Development and publication of a DSO:DNO Operational Agreement (modelled on the SO-TO Code) setting out key interactions and encompassing our transparent process across all roles and how they are governed.*
3. *An independent DSO Supervisory Board, which will provide assurance of our compliance with the DSO:DNO Operational Agreement, represent the views of our customers and stakeholders, and ensure that customers get the best-value solutions. The independent DSO Supervisory Board will review and approve key DSO investment decisions to provide extra assurance that the best-value solutions for all customers are taken forward.*

This clear separation between DSO and DNO business units significantly exceeds Ofgem's baseline expectations for transparency. We believe that establishing a legally separate DSO will foster confidence in our decision making, thus stimulating greater engagement and competition, and the clear accountabilities and incentives on individuals will lead us to maximise the benefits of our investments in DSO capabilities.

This separation has enabled us to develop clear accountabilities for the DSO and DNO across all DSO roles – for instance in how decisions are made for network development (with the DSO accountable for the cost of network expansion, and the DNO accountable for reliability and delivery efficiency), how flexibility service dispatch decisions are made in operational timeframes, and how Distribution Market Operations functions can be carried out via a partnership with an independently owned platform provider.

11.5 Summary Insights

DSO models are still evolving and maturing and so are their governance models. While the global experience provides no universal blueprint, several consistent principles emerge as follows:

- **Expanding dynamic complexity.** Firstly, a key distinction between managing a transmission network and managing most Australian distribution networks is the order of magnitude greater number of nodes and end points, with the latter typically being in the many millions. This complexity only continues to expand as both temporal and locational dynamics and computational loads grow with the scale deployment of distribution-connected CER/DER.
- **Intrinsic physics-based relationships.** In recognising key distinctions between the roles of a conventional DNSP and a DSO as highlighted in Section 6.4, it is important to note that an intrinsic physics-based relationship exists between them. This is because both are focused on the operational behaviours and outcomes of a particular distribution system which has its own unique physical topology, operational dynamics and levels of CER/DER participation.
- **Cyber-physical realities and localised optimisation informs options.** Due to the intrinsic physics-based relationship between the DNSP and DSO, and the expanding complexity of managing each distribution system's idiosyncrasies, the functional interdependence between the DSNP and DSO cannot ultimately be separated. Considered from the perspective of cyber-physical and computational scalability, the priority of localised bottom-up optimisation (within a global coordination framework), the dynamic complexities and real-time trade-offs faced by each individual DSO, and all distribution systems in aggregate, is poorly suited to being effectively managed by one centralised entity or platform.
- **Neutrality, transparency and trust essential.** The DSO must actively coordinate the 'system' of network assets, flexible demand, customer-owned CER and large-scale DER to fulfil its obligations. Transparency, neutrality and trust are, therefore, essential requirements for the DSO. This neutrality particularly extends to the consistent and verifiable equal treatment of network and non-network assets and their incentivisation and procurement.
- **Varied models of structural separation.** From a governance perspective, full structural separation may be a credible and beneficial option, as in the case of UKPN. However, it may not be essential where robust ring-fencing mechanisms and enforcement are in place, as in the case of SSEN.
- **Policy, regulatory and innovation context is vital.** Given the breadth of matters involved in the successful deployment of DSO models, a wider strategic policy, regulatory and innovation context is critical to provide the necessary coherence, incentives and funding needed to enable such significant future-facing capability (see Section 7). As noted earlier, in the UK this wider 'innovation ecosystem' has also involved the development of various new entities and adjacencies such as the National Energy System Operator (NESO), the Flexibility Market Facilitator and Regional System Planners.
- **No known deployment of iDSO models.** Finally, while discussion of so-called Independent DSO (iDSO) models has occurred from time to time, ostensibly due to concerns about the lack of neutrality and conflicts of interests, such a model is not known to have been deployed in any global jurisdiction.

12 DSO Benefits: The societal and whole-system benefits DSO deployments are already delivering

DSO implementations across various jurisdictions are increasingly demonstrating benefits that contribute to supporting the Future Customer& Societal Objectives explored in Report 1 [3] and mitigating the impact of Systemic Issues & Transformation Risks examined in Report 3 [5]. This chapter collates a range of benefits against the most relevant categories derived by the prior reports.

12.1 Supporting Future Customer & Societal Objectives

Electricity systems exist to serve individuals, families, businesses, institutions and whole societies. Individually and collectively, humans provide the fundamental reason our power system exists and the priorities it must serve.

In the context of global power system transformations, Report 1 [3] in this series explored the following set of eight future customer and societal objectives that emerged from the Australian and global literature. These provide the structure for mapping a range of benefits related to DSO deployment that relate to objectives as identified.

Figure 46: Eight future customer and societal objectives identified in Report 1[3]

Table 20: Practical examples of how DSO models support achievement of the future customer and societal objectives

Supporting Future Customer & Societal Objectives – Practical Examples
Dependable
• UKPN's RIIO-ED2 business plan targets >90% coverage of LV substations with remote monitoring and automation capabilities. These benefits include: 2x faster fault restoration, ~30% reduction in unplanned outage minutes, £400 million in deferred reinforcement cost [70]. • The UK's National Grid ESO Distributed ReStart demonstrated the feasibility of distributed black start via DERs, coordinated through DSO-level control frameworks. This validated new roles for DSOs in whole-system restoration following system-wide outages [72]. • As of 2023, France's Enedis operates over 750,000 remotely controllable MV/LV substations. This has enabled outcomes including up to 50% reduction in outage durations in targeted regions, improved fault detection and remote isolation capabilities [73].
Affordable
• UK's SSEN's RIIO-ED2 DSO Implementation business plan outlines DSO-enabled investments in automation and flexibility that reduce network reinforcement needs. Notable outcomes include UK's Optimised customer DER and low-carbon tech connections leading to lower long-term system costs via active network management [74]. • United States: Pacific Northwest National Laboratory – DSO+T Transactive Market Study Simulations in a Texas-sized grid region showed a 9–15% reduction in system peak load, $3.3–5.0 billion annual system cost savings, and 10–16% lower bills for all customer classes [75]. • Germany's BNetzA and BMWK Local Flexibility Markets frameworks show potential to avoid significant grid expansion investments by efficiently dispatching DER for congestion relief [76].
Sustainable
• UKPN's 2024 DSO Benefits Report identifies the DSO function as central to enabling Net Zero through proactive DER integration, automated flexibility dispatch, and avoided reinforcement. UKPN frames DSOs as essential to scaling low-carbon technologies on constrained networks [77].

• United States' Pacific Northwest National Laboratory's 2022 DSO+T Study showed DSO coordination allows flexible EV charging and DER dispatch to reduce curtailment and carbon intensity, while maintaining cost and reliability targets [78]. • ENA's Delivering Decarbonisation Through DSO deliverable outlines how DSOs unlock large-scale electrification of heat and transport by removing hosting constraints and supporting network-wide visibility and dynamic control. DSO functionality is positioned as a structural enabler for net-zero delivery [79]. • European Union's 2024 "Eurelectric – The Future of DSOs Report" describes DSOs as climate-critical entities, facilitating localised flexibility, distributed renewable integration, and real-time operations core to achieving EU Green Deal goals and 2050 carbon neutrality [80].
Equitable
• UK's Ofgem's RIIO-ED2 DSO Fair Procurement and Incentives Framework mandates transparent and inclusive procurement processes for flexibility services. Metrics include stakeholder satisfaction, fairness of access, and equitable cost recovery [81]. • European Union's JRC / E.DSO Neutral Market Facilitation Model emphasise DSOs as neutral market enablers. Reports outline the need for their harmonised flexibility platforms, non-discriminatory DER access, and equal treatment in data services across EU jurisdictions [82] [83].
Empowering
• Europe's E.DSO's Best Practices for DSOs Enhancing Customer Empowerment includes Belgium's Fluvius 'Databoost' dashboard, which provides households with detailed, real-time usage insights and carbon tracking [84]. • United Kingdom's Northern Powergrid Community DSO trial of "cellular" DSO structures allows local communities to assume graduated operational roles. These range from passive monitoring to active asset dispatch. Designed to maximise local flexibility, improve grid integration of community-owned assets, and increase energy sovereignty [85].
Expandable
• European Union's E.DSO outlines how DSOs manage the exponential rollout of public and private EV charging by enabling smart grid integration, mitigating local congestion, and supporting spatial planning [86]. • France's Enedis uses grid intelligence tools to manage EV integration, estimating that cumulative investment in EV-related upgrades will remain under 10% of total CAPEX to 2035, provided coordination is maintained [87].

- European Union's ENTSO-E emphasises DSOs' critical role in enabling flexibility through smart charging. Forecasts show DSO-level coordination is essential for aligning EV charging with renewable generation and maintaining grid stability [88]. - European Union's E.DSO's FLOW project identifies the functional roles DSOs play in vehicle-grid integration, especially under Fit-for-55. It emphasises user-centric, interoperable charging that aligns with grid capacity [89].	
Adaptable	
- Europe's CIRED's conference synthesises dozens of peer-reviewed papers highlighting how DSOs across Europe are adapting to emerging customer-centric services, new business models (e.g. platform-based DSOs), and regulatory innovation (e.g. sandboxing for flexibility) [90]. - Europe's Eurelectric's 2024 DSO Digital Maturity survey of 31 DSOs in 21 countries finds strong evidence of DSOs' institutional adaptability to digital transformation and regulatory evolution [91].	
Beneficial	
- United Kingdom's Ofgem's DSO Incentive links financial rewards/penalties to stakeholder satisfaction and Independent Performance Panel assessment. This mechanism ties operational quality to social accountability [92]. - United Kingdom's Electricity North West's 2025 "Social DSO" Strategy embeds social value into DSO governance and investment decisions. It includes stakeholder co-design, distributional fairness metrics, and commitments to just transition [93]. - European Union's E.DSO's 2024 Financing Mechanisms Report outlines regulatory tools and financial structures that allow DSOs to deliver public-good infrastructure while remaining investable. It emphasises predictable cost recovery and risk-mitigated capital attraction [94]. - United Kingdom's SSEN's 2025 DSO Governance and Transparency Measures has established an independent advisory board, published decision protocols, and committed to operational transparency to promote investor confidence and public legitimacy [95].	

1. Delivery of DSO Benefits

We have delivered benefits for customers and the wider system in 2023/24 and laid the foundations for future years. Our activities went above and beyond the incentive requirements and our business plan commitments to respond to customer needs. We have quantified benefits prudently and robustly in line with the HM Treasury Green Book, with expert external validation (see p.6). Below is a summary of the key benefits and outputs of our 2023/24 activities.

£199m benefits realised during 2023/24 and **£1,038m** forecast during RIIO-ED2, including wider system benefits

Benefits to consumers

£91m benefits in 2023/24 by using flexibility to deliver capacity, saving the cost of distribution network reinforcement

£410m benefits during RIIO-ED2

Benefits to the ESO and wider system

£205m wider system benefits during RIIO-ED2 due to more low carbon generation connecting sooner via Technical Limits and MW Dispatch

Better decision-making *through day-ahead and intra-day data exchange with the ESO on DER availability*

Benefits to distributed energy resources

£106m benefits in 2023/24 by using flexible connections, saving customers the cost of distribution and transmission network reinforcement

£277m benefits during RIIO-ED2

4GW capacity unlocked over RIIO-ED2 through Technical Limits

1.5GW capacity unlocked over RIIO-ED2 through MW Dispatch

89% reduction in curtailment in 2023/24, enabling generators to generate for longer

Benefits to local authorities

Easier to develop and share local decarbonisation plans due to our tailor-made tools, data and support

Benefits to flexibility providers

>1.5GW flexibility contracts awarded in 2023/24

7.8GWh flexibility dispatched in 2023/24, building confidence in the market

Environmental benefits

£2m benefits in 2023/24 due to 7,397 tonnes of carbon emissions avoided by reduced curtailment of low carbon generation

£146m benefits during RIIO-ED2 due to 487,643 tonnes of carbon emissions avoided by a) reduced curtailment of low carbon generation and b) more low carbon generation connecting sooner via Technical Limits and MW Dispatch

Monitoring our performance

We track benefits through a robust economic model that connects our outputs to the benefits described in this section by applying Green Book principles (see p.6-8 for further detail) and is regularly updated. We have defined a set of KPIs which we will publish monthly from 2024/25, including the DSO Outturn Performance Metrics. Our March 2024 performance is available here

DSO Outturn Performance Metrics

Performance Metric	Flexibility Market Testing	Secondary Network Visibility	Curtailment Efficiency
Performance 2023/24	97.1% of the capacity we added this year was through flexibility	96.7% forecast accuracy of substation utilisation on the secondary network	>99% network availability for sites with flexible connections
What is demonstrates	Effective use of flexibility to deliver timely and cost-effective network capacity	Good understanding of capacity needs on the low voltage network, to plan interventions that are necessary and efficient	Skilful use of data, technology and flexibility to improve network access for customers

The DSO Incentive Governance Document set an expectation that all DSOs would regularly report on the three key metrics above. We understand Ofgem's concerns over the ability of some licensees to reliably report on these metrics. We have taken these obligations seriously; we have published our 2023/24 performance against all three DSO metrics and are confident in the accuracy of our data.

1. The data presented here is based on the methodologies set by Ofgem in their request for information from licensees at the end of 2023.

2 DSO Performance Panel Report 2023/24

Figure 47: Example of DSO benefits reported by UK Power Networks (UKPN)[51]

12.2 Mitigating Systemic Issues & Transformation Risks

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

Systemic Issues typically surface when the cumulative impact of numerous emerging trends intersect with the systems legacy structural arrangements and constraints. Report 3 [5] of this series identified fifteen Systemic Issues broadly relevant to the development of DSO and TDC models. The following section maps a range of selective examples of how DSO models help address the impact of many Systemic Issues.

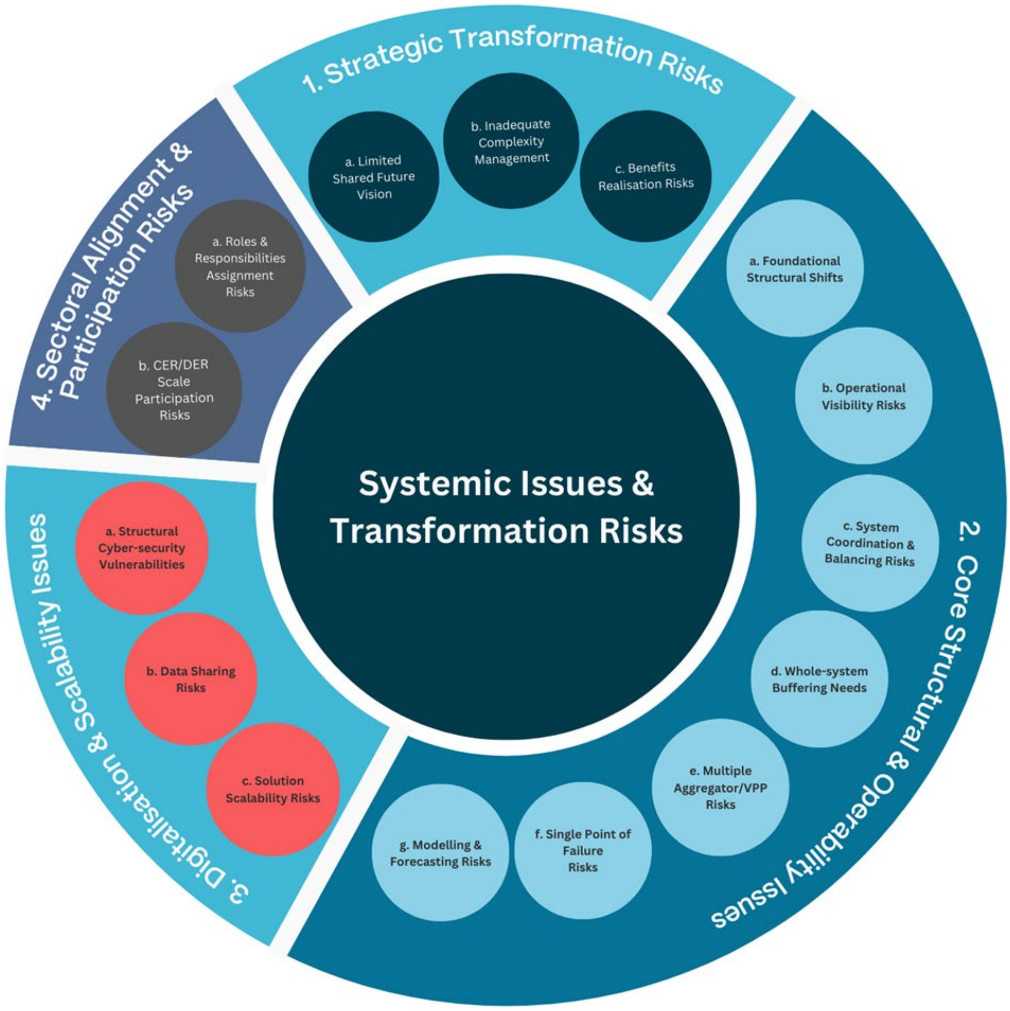


Figure 48: Systemic Issues and Transformation Risks identified in Report 3[5]

Table 21: Selective examples of how DSO models help address the impact of Systemic Issues & Transformation Risks.

Mitigating Systemic Issues & Transformation Risks – Practical Examples
Limited Shared Future Vision
• European Union's 2025 DSO Entity Technical Vision establishes a unified framework and common language for DSOs, aligning distributed infrastructure planning, data interoperability, and flexibility markets to support a cohesive energy transition vision [65]. • United Kingdom's National Grid ESO "Enabling the DSO Transition" describes a coordinated framework for ESO-DSO role clarity, scenario alignment, and collaborative planning to unify system vision across operational layers [96]. • European Union's ENTSO-E & EU DSO Entity 2025 Joint Roadmap for Future-Proof Grids presents joint targets across TSOs and DSOs on regulatory harmonisation, procurement frameworks, technology adoption, and investment visibility with the aim of building a collective system roadmap [43]. • United Kingdom's SSEN's 2024 DSO Capabilities Roadmap features an Open Data Portal with full-network asset visibility and structured stakeholder engagement planning for investment transparency [97].
Inadequate Complexity Management
• European Union's E.DSO Complexity Management Framework requires system-of-systems planning tools for its proposed integration LV/MV, DER, EVs, storage, and the use of digital twins and scenario simulations to validate system responses under varying conditions. It also emphasises governance methods that ensure interoperability and cross-domain coordination [98]. • United Kingdom's SSEN and Northern Powergrid Digital Twin Pilot trialled high-fidelity digital twins of MV networks incorporating DER and flexibility assets. Outcomes included predictive congestion analysis, accelerated scenario testing for rare events, optimisation of network reinforcement decisions, and demonstrated scalable planning complexity reduction [99].
Benefits Realisation Risks
• UKPN's DSO Benefits Quantification Methodology developed a "theory of change" framework to link DSO activities to system-wide benefits. Several DSO service areas were modelled with measurable outputs including avoided reinforcement, lower carbon, and service quality. The methodology is independently assured and designed to avoid benefit overlap [100].

• United Kingdom's Electricity North West created a Collaborative DSO Benefit Tracking realisation framework that aligns with Ofgem and ENA DSO guidance. Benefits are disaggregated by stakeholder group and outcome category (economic, social, environmental), and tracked through a structured KPI system [101]. • United Kingdom's ENA / DNV-GL: DSO Implementation Plan presents a structured rollout plan identifying timelines, interdependencies, and cumulative system benefits across flexibility, grid visibility, and customer value chains. It promotes coordinated implementation across all DNOs [102].
Foundational Structural Shifts
• Europe's CurrENT's Innovative Grid Tech Deployment guide identifies that expanding traditional grids alone isn't scalable. DSOs implementing smart, innovative distribution network technologies like dynamic line ratings and automation can reduce conventional expansion cost savings through architectural efficiency and structural modernisation [103]. • Studies from Swiss DSOs demonstrate that LV DERMS platforms enable bidirectional flow management and voltage stability in LV/MV networks without full system rebuild. This adaptability forms a modern grid architecture through existing DSO-led digital upgrades [104]. • Europe Union's DSO Entity & ENTSO-E Technopedia Collaboration catalogues smart grid and grid-tech use cases across DSOs and builds shared structural knowledge. This supports harmonised deployment of future-ready grid components across jurisdictions [105]. • United Kingdom's National Grid ESO / ENA Open Networks DSO Vision introduced a new DSO operational layer recognising the need for active, bidirectional distribution coordination. It sets the foundation for structural shifts through layered planning, control, and interoperation with TSOs [96].
Operational Visibility Risks
• United Kingdom's National Grid ESO & ENA Open Networks defined "operational visibility" as real-time DER MW/MVAr reporting across transmission and distribution. A roadmap specified use-cases including fault coordination, balancing, forecasting, resilience, and market access. ESO estimates significant financial benefits from improved DER visibility alone [106], [107]. • UKPN's DSO Operations and Daily Operational Plan outlines how the DSO Operations team actively monitors and dispatches DER from dedicated control rooms. A publicly available Daily Operational Plan provides DER customers with visibility into network constraints, curtailment events, and outage schedules, supporting coordination and situational awareness [108], [109].

- Europe's DSO Entity & ENTSO-E signed a Declaration of Intent to develop an EU-wide electricity grid Digital Twin. The platform aims to enhance observability, forecasting, scenario simulations, and operational coordination across TSOs and DSOs. It is expected to become a critical enabler of layered DER visibility and reliability [110].
- United Kingdom's Smart Energy Network Digital in Pilot implemented a distribution network Digital Twin including DER export limits and voltage control. Results showed DER curtailment reduction of 56% under real-world data uncertainties, validating tangible visibility and control benefits within DSO-aligned operations [111].

System Coordination & Balancing Risks

- Europe's ATTEST & BRIDGE EU projects proposed five scalable TSO-DSO coordination schemes that range from basic technical data exchange to co-optimised markets. These models are designed to integrate DERs into system balancing with DSO-managed local control supporting overall grid stability [112], [113].
- UKPN's Day-Ahead Flexibility Market cleared 4.4 GWh of DER flexibility in 2023 via a DSO-led day-ahead platform. This involved more than 100,000 assets and demonstrated scalable coordination between distributed assets and bulk system needs, delivering significant financial benefits [114].
- United States' PNNL DSO+T Transactive Study simulated DSO-layered transactive energy coordination in a Texas-scale system. It found 9–15% peak load reduction, $3.3–5 billion in annual benefits, and enhanced balancing capacity through decentralised, demand-side participation [75].

Whole-system Buffering Needs

- UKPN's DSO tenders have contracted ≈2.1 GW of flexible capacity, ~40 % of which is battery energy storage. Assets are dispatched for voltage management, thermal constraint relief, and local reserve, providing sub-second buffering that defers traditional reinforcement and supports system balancing [114].
- United States' Con Edison's Brooklyn-Queens Demand Management 52 MWh battery, operated under DSO-style local control, deferred a US $1 billion substation upgrade and supplies fast-response capacity for area load spikes. This demonstrates storage-as-buffer integrated into distribution operations [115].

Multiple Aggregator / VPP Risks

- UKPN's Day-Ahead Flexibility Market enables DER assets aggregated into VPPs, to participate in day-ahead flexibility auctions. This platform co-ordinates multiple aggregators, avoids dispatch conflicts, and delivers £91 million in system-wide consumer benefits, demonstrating efficient multi-player market design [114].
- Cyprus's Electricity Authority deployed a holistic demand-response cooperation framework, reducing systemic risk from conflicting DER dispatch [116].

Single Point of Failure Risks
• California's Calistoga Resiliency Center's 293 MWh hybrid hydrogen and battery microgrid provides up to 48 hours of autonomous power. Designed to "island" during Public Safety Power Shutoffs, it secures critical infrastructure (e.g. medical, emergency services) and removes reliance on central grid assets, demonstrating modular system resilience [117].
Modelling & Forecasting Risks
• UKPN deployed a DSO-integrated forecasting tool to predict short-term load, DER generation, congestion, and outages. Used in operational control rooms to inform dispatch and flexibility procurement, this system reduces reliance on static legacy models [118]. • European Union's ENTSO-E and EU DSO Entity's Grid Digital Twin is under development to support forecasting, simulation, and visibility. The initiative is jointly led by TSO and DSO bodies to ensure layered modelling is continuously updated to reflect evolving DER and system complexity [110]. • United Kingdom's SSEN's DSO Capabilities Roadmap commits to 100% network visibility and real-time data availability for forecasting and planning. The Open Data Portal supports agile modelling and enhances alignment between operational states and forecast outputs [97]. • European Union's Horizon DSO4DT Project is an initiative to deploy scalable Digital Twins across DSOs, supporting adaptive forecasting and grid operation. It is being designed to reflect real-time DER impacts and market dynamics [119]. • United Kingdom's Smart Energy Network Digital Twin Demonstrator project showed that DSO-integrated Digital Twins reduced DER curtailment by 56% by improving real-time visibility and scenario forecasting [111].
Structural Cyber-security Vulnerabilities
• European Union's Network Code on Cyber-Security co-authored by ENTSO-E and the EU DSO Entity imposes standardised, multi-layered cyber-security requirements on DSOs. Scope includes grid protection, procurement standards, crisis governance, and structural cyber resilience, addressing both digital and non-digital attack vectors [120]. • European Union's ENCS & EU DSO Entity MoU on Cyber-Security Best Practices memorandum formalised joint development of cyber-security regulation and standards tailored to the distribution layer. Focus areas include structural controls (ISO-like segmentation), supply-chain defence, and best practice sharing, enhancing DSO-level systemic cyber resilience [121].

• United Kingdom's Ofgem and NIS Regulations on DSO Cyber Reporting Requirements designates DSOs as Operators of Essential Services. They must implement multi-dimensional cyber defence, incident exercise protocols, and structural risk assessments across DSO responsibilities including flexibility markets and DER coordination [122]. • European Union's ENISA, E.DSO, EE-ISAC, and ENCS jointly hosted a forum for addressing structural attack vectors in power systems, including distribution automation, DERMS, and microgrid vulnerabilities. The event convened DSO security experts to form a multi-layered defence posture at the DSO level [123].
Data Sharing Risks
• United Kingdom's UKPN and SPEN launched open data portals offering hundreds of network datasets (real-time and historical) on assets, DER, constraints, and flex usage. These portals use standardisation frameworks to manage privacy/security risk and enable cross-sector innovation. Four other DNOs adopted shared platform practices under UK-regulatory guidance [124], [125]. • European Union's OneNet and ENTSO-E's CIM/CGMES profiles and interoperability standards support scalable data exchange across TSO-DSO ecosystems. OneNet published guidelines to align data models and ENTSO-E recommends standardised grid-model exchanges. These efforts reduce integration risk in multi-actor data environments [45]. • European Union's DESAP Joint TSO-DSO Data Governance Report proposes clear governance for cross-organisation data architecture, defining ownership, exchange protocols, standard interfaces, and observability models for TSO-DSO integration, reducing hidden constraints and enabling scalable data ecosystems [126].
Solution Scalability Risks
• France's Enedis CIRM Pilot on Local Flexibility via Automation trial demonstrated that flexibility services can alleviate voltage and thermal constraints at the distribution level, enabling scalable DER integration without reinforcing lines. Scaling recommendations included digital sensor rollouts and standardised communication, demonstrating DSO-aligned operational expansion [127]. • Europe's CurrENT's DSO Deployment Guide addresses scalability risks of innovative grid tech (e.g., dynamic line ratings, modular sensors). The guide advocates peer-shared technical assurance, anticipatory investment, and harmonised procurement for reducing duplicated risk across DSOs and smoothing mass deployment [103].

Roles & Responsibilities Assignment Risks
• United Kingdom's National Grid Electricity Distribution established a separate DSO directorate with clearly delineated responsibilities from the DNO, governed by formal segregation measures and conflict-of-interest controls. This structure aligns with Ofgem's three DSO roles, planning, operation, and market development, ensuring roles are dynamically assigned and transparent [128]. • United Kingdom's SPEN's DNO-DSO Operating Framework specifies the boundaries and interactions between DNO and DSO personnel for each assigned DSO role and activity. The clarity supports operational efficiency, neutral market facilitation, and stakeholder confidence in aligned responsibilities [129]. • United Kingdom's Electricity North West's DSO-DNO Governance Framework formalised executive accountability, internal separation, independent stakeholder panels, and publication of decision protocols, clearly segregating DSO decision-making from traditional infrastructure-focused DNO activities [53]. • European Union's ENTSO-E and EU DSO Entity's TSO-DSO Data Management and Role Definition reports established common terminology, role clarity, and interface use cases (balancing, planning, flexibility), enabling concrete assignment of responsibilities across operators, reducing ambiguities and ensuring systemic alignment [130].
CER/DER Scale Participation Risks
• UKPN's DSO-led platform enabled DER assets (BESS, PV, EV chargers) to participate in a national-scale day-ahead flexibility auction. This large-scale orchestration with automated dispatch ensures mass participation is operationally feasible and economically viable [114]. • United States' Pacific Northwest National Laboratory's DSO+T Transactive Market Study simulated DSO coordination models showing scalable DER participation can meaningfully reduce peak load and deliver significant annual financial value. It showed mass DER orchestration through DSO architecture yields measurable system benefits [131]. • Canada's Alectra's DER pilot coordinated community-scale BESS and EV participation via its DSO-inspired framework. Results showed sustained temporal dispatch (>12 months), high aggregator engagement rates, and operational stability [132].

Key Concepts N

Structural Analysis

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

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

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

Structural Intervention

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

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

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

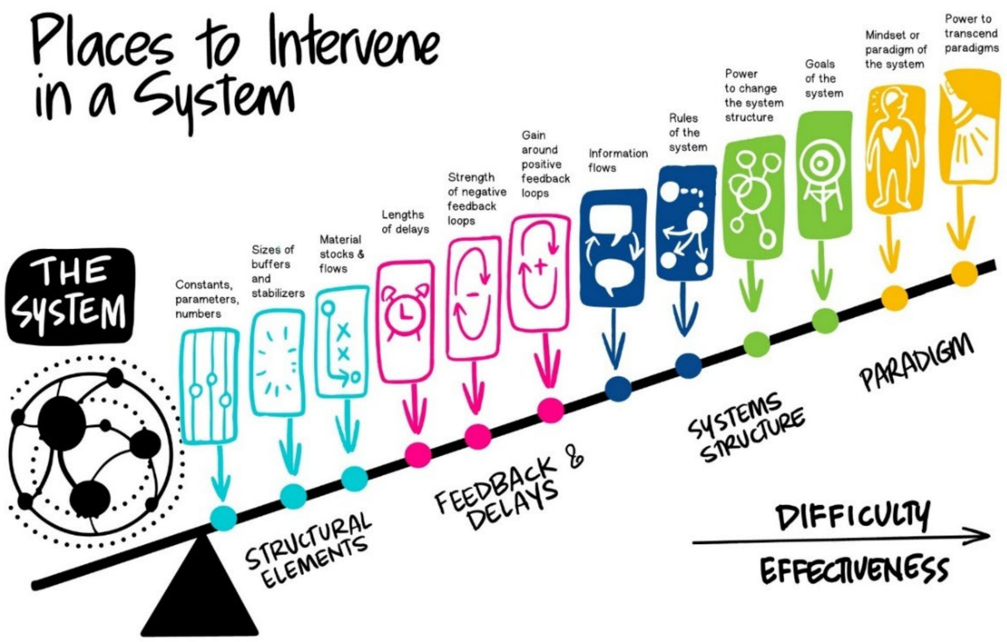
These interventions may include network reinforcement and reconfiguration, deployment of advanced digital infrastructure, implementation of new control and protection schemes, and policy and market redesign to maintain reliability, resilience, and economic efficiency in the evolving energy ecosystem.

13 Recommended Priority Actions

Australia's large scale power systems are transforming from a unidirectional past involving hundreds of large generation plant to a more dynamic and bidirectional future involving tens of millions of diverse energy resources participating across all vertical tiers/layers of the grid.

Many of the challenges faced in preparing existing legacy power systems for a deeply decarbonised and increasingly distributed future are not unique to the NEM. However, the world-leading pace and scale of Australia's grid transformation will require new ways of conceptualising the nature of the challenges we face and how to best address them.

For example, informed by the field of transition design, it is noteworthy that a primary model of change in the power sector has traditionally focused on addressing elements, often in an issue-in-isolation manner. As Figure 49 below highlights, while focusing on structural elements in relative isolation may be entirely appropriate in a steady-state system, this is less effective where a system is experiencing profound change. In such a case, it becomes essential to reconceptualise dominant paradigms and address critical issues with the system structure which are no longer fit-for-purpose.



Adapted from Donella Meadows

Figure 49: The field of transition design highlights the need to reconceptualise key paradigms and address system structures that are no longer fit-for-purpose

13.1 PRIORITY 1: Recognise that 21st century distribution systems are becoming renewable energy zones that will self-supply >50 – 150% of local demand.

Given Australia's world-leading levels of DPV, the NEM already has whole regions that experience close to 100% of instantaneous demand being served by distribution-connected CER/DER on sunny, low load days. Later the same evening, these same regions are almost 100% supplied by the centralised system. This is now resulting in a 24-hour operational profile that is essentially 'tidal' – and the transformation still has a very long way yet to go! For example, by 2035 AEMO's Step Change scenario [9] anticipates DPV capacity reaching approximately ~55GW/70TWh, meaning that the NEM will regularly experience time windows where most supply is flowing 'upstream' from the distribution system.

In a legacy context where the dominant models of change primarily focus on enhancements to individual elements, honestly confronting the emerging scale of change and its practical implications is key to ensuring a fit-for-purpose approach. For example, attempting to develop DSO models in a manner that is, perhaps implicitly, largely based on extrapolations from the legacy models of the past significantly elevates the risk of sub-optimal outcomes, operational disruption and expensive rework. By contrast, where a more realistic and future-facing approach is applied, the DSO models developed can still be implemented in a stepwise manner as CER/DER volumes increase but will be significantly more adaptive, scalable and future-ready by design.

13.2 PRIORITY 2: Reconceptualise the 21st century transmission-distribution relationship as intrinsically bidirectional, collaborative and mutual-beneficial.

This scale of transformation described above is anticipated to only increase as time passes. For example, AEMO's Step Change scenario [9] anticipates that by 2050 NEM operations will be predominantly bidirectional with ~115GW/100TWh capacity provided by DPV, representing a further fourfold increase on Australia's already world-leading levels in 2025. In this case, enabling transmission-distribution relationships to function in an intrinsically bidirectional, collaborative and mutual-beneficial manner will be key to future-proofing the NEM.

Once again, allowing the practical implications of the scenarios we regularly discuss to inform our DSO and TDC design considerations will enable significant efficiencies, mitigate the need for subsequent rework and potentially unlock significant economic value much earlier. Addressing these matters holistically will enable a more flexible and interdependent power system end-to-end that can anticipate, adapt to and manage variability and volatility of supply and demand across all relevant time scales. As GW-scale power systems like the NEM become increasingly volatile and bidirectional, this will be essential to operational visibility, coordination and the instantaneous balancing of supply and demand.

13.3 PRIORITY 3: Recognise that DSO & TDC models are transformational enablers, not simply enhancements to the legacy grid structures.

Providing end-to-end visibility, predictability and operational coordination of millions of energy resources located across the system is extremely difficult because of the structural constraints embedded in the legacy systems architecture of the NEM. Therefore, comprehending the intrinsic relationship between the design of DSO and TDC models, and the criticality of their wider structural relationships, illustrates why considering them, even implicitly, as an enhancement to or 'patch' on the 20th century power system is vastly inadequate. By contrast, both DSO and TDC models are properly understood as key enablers required to 'cross the chasm' illustrated by Figure 50 below.

Similar to the above, addressing these matters holistically will enable a more flexible and interdependent power system that can anticipate, adapt to and manage variability and volatility of supply and demand across all relevant time scales. Unlocking the whole-system value of millions of resources will maximise societal benefits, customer savings and equitable outcomes. Regardless of the DSO or TDC model designs adopted, this cannot ultimately be achieved without the necessary targeted structural interventions critical to their operation.

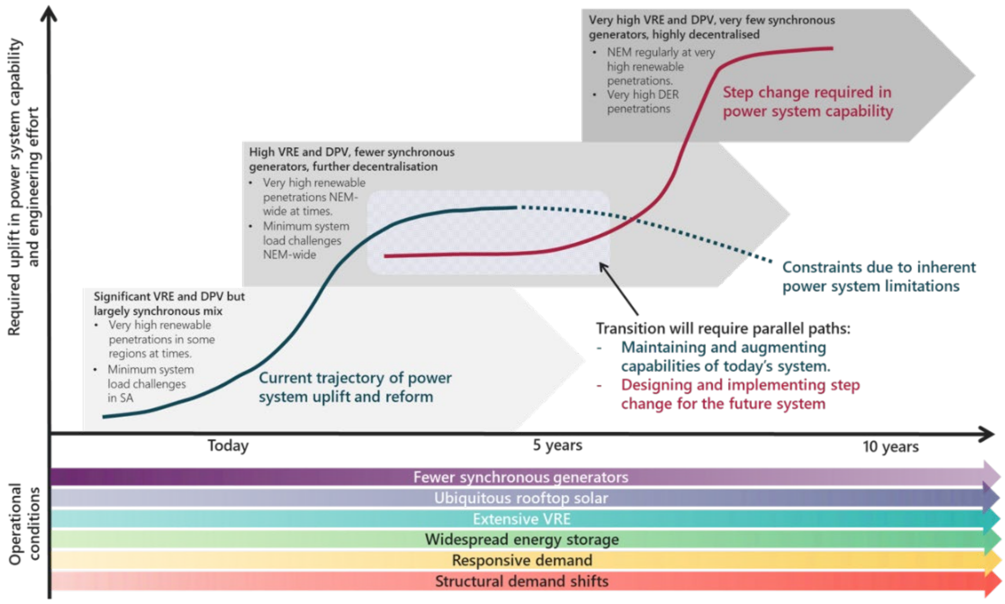


Figure 50: DSO and TDC models are key enablers for 'crossing the chasm' between two distinct parallel paths of capability [135]

13.4 PRIORITY 4: Recognise that activities focused on 'keeping the lights on' and 'creating the future power system' are equally necessary and require parallel paths of focus and effort.

While the previous considerations may sound reasonable in theory, they are often quickly dismissed as impractical. Most commonly, this is due to there being only one path of transformational activity. Given that the immediate issues of 'keeping the lights on' will always take precedence, a practical outcome is that most change initiatives remain disproportionately focused on the nearer term. Most also largely assume a model of extrapolating from the established legacy arrangements into the future. While this may be entirely appropriate in a comparatively steady-state environment, it is largely incapable of effectively responding to large structural transformations.

Consistent with transition design theory and practice, navigating large structural transformations requires at least two simultaneous paths of focus and effort. Path 1 is the most familiar; it is where the necessary enhancements to the existing system continue to be made to enable it to keep operating in the near to medium term. While not always well understood, a further purpose of Path 1 is to 'buy time' to address the more complex structural issues that impede longer-term solutions. Given the scale of system change to which DSO and TDC models respond, Path 2 provides the context, processes and time in which all of the relevant matters may be collaboratively interrogated and scalable solutions developed. Further high-value benefits of establishing parallel paths of activity include enabling several time horizons to be kept in focus and relevant learnings can be actively shared between the respective participants to the advantage of both paths.

13.5 PRIORITY 5: Accept that in times of profound transformation, there is no textbook, no perfect knowledge and no single entity with all the answers.

A further challenge a times of profound transformation is that few if any established sources of knowledge exist to seamlessly guide the way to enduring solutions. This is particularly unsettling in a century old sector providing an essential service, where many recurring activities are performed with algorithmic certainty and near perfect knowledge.

An additional benefit of the parallel path approach outlined above is that is provides the environment for intensive shared learning, trial and error, and accelerated convergence on the most credible DSO and TDC design options. In addition, System Architecture tools provide a valuable means for 'taming' the structural complexity of transforming power systems by providing multiple points of view on key systemic issues. This enables enhanced multi-stakeholder collaboration to identify critical issues and shortlist the most credible solutions, underpinned by a shared, trusted and evidence-based analytic framework.

13.6 PRIORITY 6: Build sector-wide capacity for identifying and addressing structural constraints in addition to upgrading components and targeted enhancements.

Although GW-scale power systems are some of humanity's most complex systems, Systems Engineering and related disciplines developed over recent decades have not been widely applied in what was a comparatively steady state environment.

As these capabilities are now increasingly required, multi-stakeholder processes for mapping and documenting the 'as built' and plausible future structural arrangements of the NEM delivers tangible benefits and also enable the upskilling of industry participants. A further benefit is that it enables the diverse entities working in different segments of the NEM to acquire a better comprehension of how their segment interfaces with the rest of the system.

13.7 PRIORITY 7: Establish a strategic and collaborative program of Systems Architecture development to underpin DSO, TDC and related NCERR initiatives

Given the structural context that underpins the development of DSO and TDC models, a prerequisite to forward progress is a shared architectural vision. Fragmentation and conflicting assumptions about the future end-state, and especially between the alternate structural archetypes discussed in Chapter 8, risks stalling operationalisation of scalable solutions. Stakeholders must collectively agree on the long-term architectural trajectory, recognising this as a dynamic but directional path.

The application of Model-Based Systems Engineering (MBSE) tools also provides a powerful complement that enables:

- Visual and functional mapping of system configurations
- Simulation of different roles, functions and system interface relationships
- Clearly defined structural configurations that may evolve over different time-horizons
- Evaluate performance and scalability dimensions of alternate structural configurations.

Such approaches can bring rigour, traceability and collaborative insight to what would otherwise be fragmented and ad hoc reform.

13.8 PRIORITY 8: Advance DSO & TDC designs as interdependent structural enablers

DSO and TDC model development and implementation should be treated as co-evolving constructs, not parallel or independent streams. TDC is the operational and structural 'connective tissue' that enable multiple DSOs to effectively interface with the SO and related markets. Conversely, emerging DSO capabilities form the observability and execution layer utilising the TDC for joint system operation. Recognising this interdependence is essential for coherent policy design, regulatory reform, and technical architecture development.

13.9 PRIORITY 9: Formalise DSO & TDC roles using a structurally informed approach

To operationalise the core functions of both DSO and TDC models, a structurally informed process is needed to assign specific roles and responsibilities in a manner that is cognisant of operational interdependencies over various time-horizons. A rigorous, evidence-based methodology for functional role assignment should be employed together the appropriate tools for shared understanding and codesign as discussed in Section 10.9.

13.10 PRIORITY 10: Distinguish between transitional and enduring DSO & TDC structures and functions

A critical design challenge lies in distinguishing which DSO and TDC structures and functions are transitional – required to temporarily bridge current constraints – and which are enduring. A 'lease regrets' approach should be applied that focuses on scalable, modular investments that enable future evolution and adaptation.

An advantage of this approach is that it avoids forcing premature convergence on role assignments and/or embedding of systems or particular technologies in a manner that is difficult or impossible to reverse. Identifying and avoiding over-investment in technology and/or structural options that will not efficiently scale is key preserving future optionality and avoiding stranded investments.

14 Conclusion

Australia's power systems are undergoing an unprecedented structural transformation, driven by accelerating decarbonisation and the explosive growth of CER/DER. The recommendations derived from this analysis underscore the need to rethink key aspects of the 21st century power system as a foundation for developing future-facing capabilities like DSO and TDC models. Doing so is neither academic nor abstract: achieving secure, affordable and sustainable electricity for the longer-term will depend on it.

A core imperative involves recognising that the scale of change is transformative, not incremental. Distribution networks are evolving into dynamic renewable energy zones (Priority 1), fundamentally altering the conventional unidirectional flow of power to create an increasingly bidirectional system requiring collaborative transmission-distribution relationships (Priority 2). Attempting to manage this through piecemeal enhancements to legacy systems is a path to suboptimal outcomes, disruption, and costly rework. Instead, DSO and TDC models must be understood as essential transformational enablers (Priority 3), designed from the outset for long-term scalability and extensibility.

Successfully navigating this profound transformation demands parallel paths of effort: diligently maintaining current operations ('keeping the lights on') while simultaneously and proactively 'co-creating the future power system' (Priority 4). This acknowledges the inherent uncertainty; there is no perfect blueprint, requiring a sector-wide commitment to intensive shared learning, trial and error, and collaborative problem-solving (Priority 5). Building capacity to identify and address structural constraints, moving beyond simply upgrading components, is paramount (Priority 6).

Establishing a shared, strategic vision through collaborative Systems Architecture development, and utilising tools like Model-Based Systems Engineering (MBSE), is a foundational prerequisite (Priority 7). This provides the essential framework to rigorously design DSO and TDC roles as deeply *interdependent enablers* (Priority 8), with responsibilities formally assigned using a structurally informed approach that is cognisant of evolving system needs (Priority 9). Crucially, a 'least regrets' strategy must distinguish between transitional solutions and enduring, scalable structures and functions, preserving future optionality and avoiding stranded investments (Priority 10).

Ultimately, embracing these priorities holistically is vital to unlock the immense societal value of millions of CER/DER, creating a flexible, interdependent, and resilient power system capable of managing volatility across all timescales, maximising customer benefits, and securing Australia's clean energy future.

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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)
- United States Department of Energy, Office of Electricity (DOE)

Individuals

- Dr Thomas Brinsmead
- Pablo Campillos
- Paul De Martini
- Prof. Lynne Kiesling
- Dr Lorenzo Kristov
- Rama Ganguli
- 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: Key Topic Bibliography

Following is a range of sources that have particularly informed the thinking of the development team on several key topics addressed in this report, namely:

- DSO Design Considerations
- Interdependent Power Systems
- Flexible Power Systems
- Distribution Market Mechanisms
- Cyber-Physical Structures

B1 DSO Design Considerations

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Appendix C: 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.

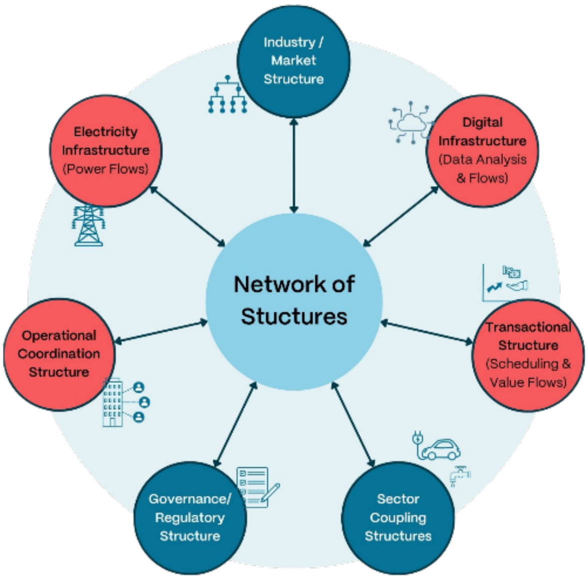
Visibility	The degree to which information on energy resource characteristics and operational status is available to the System Operator, Distribution System Operator (DSO), and other authorised third parties. Examples include real-time or near real-time information on electrical demand, generation output, 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.

Appendix D: 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:

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



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

Network of Structures – Seven Power System Structures
1. Electricity Infrastructure (Power Flows)
Infrastructures and subsystems that provide for the generation and physical movement of electricity across the end-to-end Power System, including Generation Plant, Transmission Networks, Distribution Networks, Substations, Embedded Networks, Microgrids and diverse Energy Resources. While historically designed for unidirectional operational, today Electricity Infrastructure increasingly experiences bi-directional Power Flows, especially in the Distribution Networks. A sample of conventional and emerging examples include: • Power Flows from the Bulk Power System through the Transmission Networks to Bulk Supply Points (BSP).

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

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

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

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

3. Transactional Structure

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

A sample of conventional and emerging examples include:

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

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

4. Operational Coordination Structure

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

A sample of conventional and emerging examples include:

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

5. Industry / Market Structure

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

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

6. Governance / Regulatory Structure

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

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

7. Sector Coupling Structures

As decarbonisation advances, the proactive management of Interfaces between the Power System and other sectors becomes an increasingly critical part of enabling a more flexible and adaptive Grid. Examples of various sector couplings include:

- Electricity and gas sectors;
- Electricity and industrial processes;
- Electricity and transport;

- Electricity and building services;
- Electricity and water systems;
- Power system and ICT technologies; and,
- Electricity and the emerging Green Hydrogen sector.

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

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

A common mistake is that a focus on 'digital architecture' is the primary or singular focus of architectural disciplines when applied to Power System transformation. While digital architecture is indeed vital, a power system is a cyber-physical system, not simply a digital system – as is illustrated by the seven overlaid structures which constitute its architecture as illustrated by the Network of Structures model. This is critical to the holistic consideration of transformation options as all seven structures have a significant influence on each other, four of which are dynamically inter-dependent on a hours-to-milliseconds basis (i.e. electricity infrastructure, operational coordination structure and transactional structure).

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

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

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

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

Appendix F: Distribution-level Markets

The discussion of Distribution Market Mechanisms as one of a DSOs five core functions is deliberately broad and recognises a spectrum of incentive mechanisms that are likely to evolve and mature over time, from tariff-based incentives and bilateral contracts to more advanced digital markets.

As CER/DER volumes continue to increase in Australia, more advanced distribution-level markets can provide market-based dispatch signals for the specific services required, better achieving 'the right service – at the right time – at the right location'. This would enable transactions that are more scalable and lower friction, supporting more granular procurement of required system services, the value of which varies temporally and spatially. Where holistically designed, enhanced 'value stacking' of services co-optimised with the bulk power market is also more feasible.

Importantly, both the economically-efficient procurement and technically-secure orchestration of services from millions of CER/DER will ultimately require a more dynamic and well-integrated 'market-control system' than conventional tariff-based incentives are able to support. The market-control system of an electric power 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.

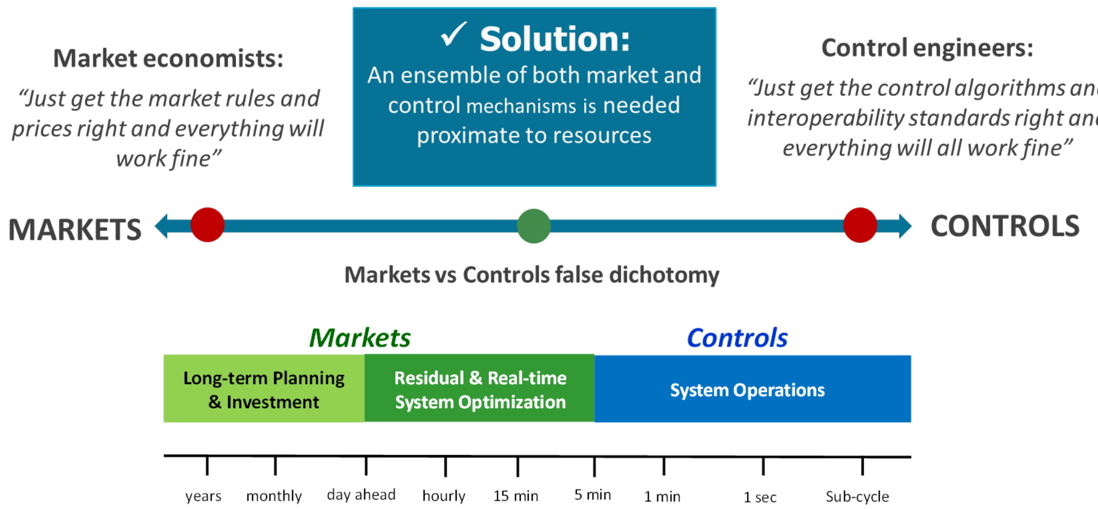


Figure 51: Market-Control System relationship relevant to operational coordination[23]

[23] Image: Paul De Martini (Adapted)

For example, Security Constrained Economic Dispatch (SCED) in bulk power markets is broadly familiar to many people in the electricity sector. SCED is a critical algorithmic component within the broader market-control system. Traditionally employed in bulk power markets, SCED translates market signals and reliability rules into physically feasible, cost-optimal dispatch of large transmission-connected energy resources.

As Australia's power systems decarbonise and become increasingly distributed, they also become more volatile and bidirectional, increasing operational dynamics and compressing operational timescales. This will require increasingly granular and targeted CER/DER incentivisation due to their value to the system being temporally and spatially variant. In this context, digital markets enable far more time and location-specific incentives which support more targeted recruitment high-value CER/DER, enhanced system cost efficiencies and reduced over-procurement risk of CER/DER services that the system ultimately does not require.

As noted above, the category of Distribution Market Mechanisms is intentionally broad and a comprehensive treatment is beyond the scope of this report. However, in support of the most informed discussion, an indicative survey of different approaches to advanced market mechanisms relevant to CER/DER participation and efficient incentivisation is provided below. It covers the following emerging types of distribution level markets:

- Visibility-Only Frameworks.
- Bilateral / Platform-Based Flexibility Markets.
- Layered Distribution Markets.
- Centralised Real-Time Distribution Markets.
- Peer-to-Peer & Community Markets

Visibility-Only Frameworks	

Functional Roles	• **Distribution System Operator (DSO):**
	  ○ Passive network management (no local market).
	  ○ Ensures network limits via static or dynamic constraints.
	• **System Operator (SO):**
	  ○ Sole market operator (wholesale market dispatch).
	  ○ CER/DER mostly unscheduled (passive) or indirectly represented via retailer/aggregator forecasts.
	• **CER/DER Aggregators:**
	  ○ Optional, may aggregate CER/DER as a voluntary scheduled resource in wholesale market (if allowed), but no separate DSO-run market.

Co-Optimisation Mechanism	• No dedicated distribution market. • CER/DER impacts are indirectly handled by improved forecasting and static/dynamic operating envelopes. • SO's wholesale dispatch includes better visibility of CER/DER but does not actively optimise distribution constraints. • Any needed distribution constraint management is via 'off-market' DSO actions (curtailments, connection agreements).
Services Supported	• Primarily energy via existing wholesale market (if CER/DER participates through aggregators) • Limited network support (DSO may impose limits or emergency curtailment, not market-based) • Few ancillary services from CER/DER except via aggregator in SO's markets (e.g. CER/DER in frequency regulation via an aggregator).
Pros	• **Simple:** Minimal changes to legacy market structure – leverages existing wholesale market. • **Low implementation complexity:** Focuses on better data (forecasts, network visibility) rather than new market mechanisms. • **Avoids local price volatility:** For consumers, prices remain uniform wholesale/retail rates).

Cons	• **Inefficient CER/DER utilisation:** No price signals for local constraints -> CER/DER value to the system (e.g. relieving distribution congestion) is not monetised. • **Congestion management gaps:** DSO relies on blunt tools (curtailment or static limits) since congestion can only be managed off-market, which likely misses optimal dispatch. • **Limited CER/DER incentives:** Earnings only from wholesale participation (if any) and retail tariffs, so many CER/DER remain passive. • **Forecast reliance:** Accuracy of CER/DER forecasts is critical; errors can affect wholesale dispatch and reliability.
Examples	• Australia (NEM) current state: o CER/DER mostly non-scheduled o New rule requires retailers to provide forecasts of price-responsive CER/DER to SO. o Distribution constraints handled via static export limits or Dynamic Operating Envelopes (DOEs) off-market. • UNITED KINGDOM status quo: o No formal local markets. o DSOs manage constraints by network upgrades or occasional flex contracts. o CER/DER can join national markets (e.g. ancillary services) via aggregators. • United States (various states): o CER/DER largely integrated via net-metering or demand response programs. o No separate distribution market, but some ISOs improving CER/DER visibility in forecasts.

Bilateral / Platform-Based Flexibility Markets	

Functional Roles	• **Distribution System Operator (DSO):**
	  ○ Active procurement of flexibility from CER/DER to manage local network needs.
	  ○ Runs tenders or uses an online platform to contract CER/DER, often via aggregators, for specific services (e.g. load reduction on a constrained feeder).
	  ○ May provide market-based dispatch signals for required services.
	• **System Operator (SO):**
	  ○ Continues to run wholesale and system-level ancillary markets separately.
	• **Aggregators/Flex Providers:**
	  ○ Participate in DSO's flexibility tenders or platform auctions, offering CER/DER capacity for local constraint management.
	  ○ May also separately bid CER/DER into wholesale markets or other services, within contractual limits.

Co-Optimisation Mechanism	• **Decoupled markets:**
	  ○ DSO procures CER/DER flexibility in advance or in intraday to solve distribution constraints (like a 'mini-market' for local congestion).
	  ○ This is parallel to, but not integrated with, the wholesale market.
	  ○ Coordination is via contract conditions and 'primacy rules' – e.g. if a CER/DER has committed to a DSO service, it may have to refrain from conflicting wholesale bids.
	• **Co-optimisation largely left to the aggregator:**
	  ○ They decide which market's opportunity to pursue at a given time, since the DSO's local calls might override or coincide with wholesale dispatch.
	  ○ Some platforms attempt basic coordination (e.g. informing SO of DSO activations).

Services Supported	• **Network support / congestion management (primary focus):** ○ CER/DER paid to alter generation/consumption to relieve specific distribution constraints.

	• **Energy:** ○ Not usually traded in these local mechanisms (energy still settled via retail/wholesale), except as implied by reduced consumption or export when providing flexibility. • **Ancillary services:** ○ DSO flexibility contracts can include voltage control or resilience services. ○ Frequency response remains procured by SO (though CER/DER providing DSO services might also offer into SO ancillary markets at other times).
Pros	• **Targets local issues:** ○ Efficiently addresses distribution constraints at lower cost than building network – DSO can defer upgrades by contracting CER/DER flexibility. • **Quick to implement:** ○ Leverages bilateral contracts or simple platforms; many pilots show DSOs can set these up under existing regulations (as an extension of demand response programs). • **Customisable:** ○ Contracts can be tailored (location-specific, time-specific) to DSO needs; platform auctions allow price discovery of local flex value (reveals locational value). • **Learning path:** ○ Builds DSO operational experience with CER/DER and informs eventual market evolution.
Cons	• **Fragmented/coarse optimisation:** ○ Since distribution and transmission markets are separate, no global optimum is achieved. ○ CER/DER might be dispatched for local needs even if not optimal for the overall system (or vice versa). ○ SO and DSO instructions could conflict, requiring complex primacy rules to resolve conflicts. • **Potential for low liquidity:** ○ Each DSO's flex market is limited to specific locations and times, often yielding low participation. This can lead to insufficient competition or higher costs for flexibility.

	• **Coordination burden on aggregators:**
	  ○ Aggregators must navigate multiple markets (wholesale, DSO tenders, possibly capacity markets), deciding where to commit CER/DER – increasing complexity and transaction costs.
	• **Governance and fairness:**
	  ○ DSO-operated markets raise questions of neutrality (DSO must fairly dispatch CER/DER, including those owned by third parties or by the DSO's affiliates).
	  ○ Double compensation risks if CER/DER earn wholesale and DSO payments for same action must be managed.

Real-World Examples	• **United Kingdom:**
	  ○ All UK DSOs run tenders via platforms (e.g. Piclo Flex) to procure local constraint management (peak shaving) from CER/DER.
	  ○ For example, UK Power Networks' and Western Power Distribution's flexibility auctions for constrained zones.
	• **Europe:**
	  ○ Platforms like NODES (Nordic) and GOPACS (Netherlands) facilitate DSO-SO coordination: CER/DER offer flexibility that DSOs can buy to relieve grid constraints, with SO informed to avoid counter-actions.
	• **Australia:**
	  ○ Several distribution utilities (Ausgrid, Energex, etc.) have bilateral contracts or trials for CER/DER network support (non-wires alternatives).
	  ○ For example, Ausgrid's Project Edith compared contracts vs. dynamic tariffs vs. markets for local support (2023) and used a platform to dispatch community batteries and demand response for feeder congestion.
	• **United States:**
	  ○ Utilities in some states (e.g. New York REV initiative) procure CER/DER via 'non-wires solution' contracts to defer upgrades, essentially bilateral flexibility procurement.

<table>
<tr><th colspan="2">Layered Distribution Markets</th></tr>
<tr><td>Functional Roles</td><td>

Distribution System Operator (DSO) or Distribution Market Operator (DMO):

Local real-time market for CER/DER may be run by the DSO, DMO or an independent entity.
The DMO could also be the DSO if it takes on market operation.
The responsible entity collects bids/offers from CER/DER aggregators and optimises the distribution-level dispatch, accounting for local network constraints.

System Operator (SO):

Runs the transmission-level wholesale market in parallel. Coordinates with DMO through iterative information exchange.

Aggregators:

Submit bids to the DMO (instead of directly to the SO) for distribution-connected resources.
They effectively participate in a two-tier market, interacting with the DMO for local dispatch and indirectly with the SO via the DMO's coordination.

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<tr><td>Co-Optimisation Mechanism</td><td>

Two-layer iterative optimisation:

The DMO clears a distribution market (solving for the optimal dispatch of participating CER/DER within the distribution network limits).
The SO clears the transmission wholesale market.
The SO and DMO exchange information. For example, the DMO provides the net injection/withdrawal from its distribution area to the SO. The SO provides locational prices or constraints to the DMO. The SO and DMO iterate to converge on a consistent solution.

This iterative market coupling co-optimises across layers:

It aims to yield the same outcome as a fully integrated optimisation if convergence is achieved.
In practice, a few rounds of DMO-SO communication (similar to multiple runs of clearing or 'pre-dispatch' rounds) might be used.

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	○ Settlement can be designed with a uniform wholesale price (e.g. paying CER/DER at the SO's regional price in one model) or potentially include some differentiation by distribution region.
Services Supported	• Energy: ○ Yes. CER/DER can buy/sell energy through the distribution market, which then reflects into the overall dispatch. ○ The total system energy dispatch is co-optimised, so local generation can substitute for central generation if economic. • Congestion management: ○ Yes. The DMO's optimisation includes distribution network constraints, ensuring CER/DER dispatch respects thermal/voltage limits. ○ Congestion is managed through market signals (if local prices are used) or via the dispatch quantities in the iterative process. • Ancillary services: ○ Potentially. CER/DER can provide services like voltage support or fast response as products in the distribution market, and these can be coordinated with SO's needs (some models allow the DMO to aggregate CER/DER ancillary bids up to the SO). ○ Frequency regulation is still scheduled by the SO, but CER/DER may participate via the DMO as proxies. • Overall, supports multi-service CER/DER: ○ One resource may offer energy and local network support via its bids, with the DMO deciding the optimal use.
Pros	• Co-optimisation of CER/DER with grid: ○ Achieves a more efficient dispatch than separate markets – the iteration means distribution constraints and CER/DER costs are reflected into the wholesale outcome. ○ This reduces conflicts and captures the full value of CER/DER flexibility across the system. • Uses existing hierarchies: ○ By keeping two layers (SO and DMO) but coordinating them, this model can align with existing responsibilities. ○ The SO and DSO each optimise their layer and share data, which may be institutionally easier than creating one unified operator.

	• **Scalability:**
	  ○ Solving two smaller problems (each DMO optimises its area, SO optimises top-level) can be computationally more credible/viable than one giant centralised optimisation with thousands of nodes.
	  ○ It can also be deployed gradually (one region at a time adopting a DMO market).
	• **Local price signals (optional):**
	  ○ If implemented with some form of local pricing or shadow prices for constraints, CER/DER get clear signals of where and when their flexibility is most valuable, guiding investment to high-value locations (though Design B in one example settled at wholesale price only, the concept could incorporate shadow prices paid via separate mechanism).

	• **New roles and governance:**
	  ○ Introduction of a DMO raises institutional questions – e.g. should the DSO operate the market (potential conflict of interest if it also owns assets) or an independent body?
	  ○ Defining DSO vs DMO vs SO responsibilities and regulatory oversight is non-trivial.
	• **Many CER/DER are still out-of-market:**
	  ○ In practice, not all CER/DER submit bids (small devices might remain passive) and unscheduled CER/DER may still cause constraints.
	  ○ As noted in trials, complementary measures like Dynamic Operating Envelopes or emergency curtailment schemes may still be needed for residual congestion.
	• **Settlement and pricing design:**
	  ○ If using uniform wholesale prices for settlement, the model doesn't provide locational economic signals to CER/DER (beyond the risk of being constrained off).
	  ○ Conversely, introducing locational prices adds complexity and may face stakeholder resistance (e.g. exposure of consumers to variable local prices).
	• **Coordination failure edge-cases:**
	  ○ If SO and DMO objectives diverge (e.g. a CER/DER is very valuable for national balancing but causes local network issues), any misalignment or failure to converge could lead to suboptimal dispatch or reliance on fallback rules (like curtailing CER/DER out-of-market).
	• Clear rule sets are needed for such scenarios.

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<td>Real-World Examples</td>
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- European SO-DSO coordination pilots:
  - Projects like CoordiNet, InteGrid, and SmartNet in the EU have tested market architectures where DSOs run local markets for flexibility and coordinate with the SO. E.g. Spain's CoordiNet pilot created a DSO market for CER/DER providing local congestion relief and system balancing, using iterative clearing between SO and DSO platforms.
- Australia:
  - Project EDGE (AEMO, AusNet Services, Mondo) trialled a 'decentralised market' for CER/DER. A DMO (AEMO in this case) and DSO used a common platform to dispatch aggregated CER/DER for both wholesale services and local network services.
  - The approach involved iterative dispatch: CER/DER received both wholesale price signals and dynamic network signals, and the aggregator decided on offers; however, full centralised co-optimisation was not implemented (aggregators effectively performed the coordination).
  - The trial highlighted benefits (e.g. network constraint management at scale) but also complexity in communication and the need for data hubs.
- United Kingdom:
  - Cornwall Local Energy Market – A trial by Centrica in Cornwall enabled CER/DER to participate in a local flexibility platform that served both the regional DNO (Western Power Distribution) and the SO (National Grid ESO).
  - The platform attempted a layered approach, allowing CER/DER to be scheduled for either DNO constraint management or SO balancing services through a coordinated auction.
- United States:
  - NYISO DSP Concept – As part of New York's REV initiative, utilities acting as Distributed System Platforms (DSPs) were envisioned to interface with the NYISO wholesale market.
  - The DSP would secure local CER/DER for distribution needs and present their aggregated capabilities to the NYISO – an iterative coordination concept. This is still in developmental stages.

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<table>
<tr><th colspan="2">Centralised Real-Time Distribution Markets</th></tr>
<tr><td>Functional Roles</td><td>Combined SO/DMO (or Integrated Market Operator):
A single entity (or tightly integrated system) operates a unified market that dispatches both transmission- and distribution-connected resources in one optimisation.
This could be an expanded role for the SO (covering distribution constraints in its dispatch engine) or a new organisation jointly operated by SO+DSOs.
The key is a common platform handling all dispatch decisions.
Distribution System Operator:
Provides detailed network data, real-time constraints, and operational coordination, but does not run a separate market.
The DSO ensures its network model is integrated into the market's algorithms and may execute physical control actions as instructed by the central market.
Aggregators/DER:
Submit bids/offers directly into the central market system (similar to how large generators do), potentially at the node or zone level.
CER/DER are visible to the market operator just like any other resource, albeit with some telemetry and aggregation considerations at the distribution level.</td></tr>
<tr><td>Co-Optimisation Mechanism</td><td>Single optimisation, full co-optimisation:
All resources, from large power plants to rooftop solar or flexible loads (via aggregators), are dispatched through one unified real-time market clearing that considers the entire network (transmission and distribution).
The market optimisation (often a security-constrained economic dispatch) explicitly includes distribution network constraints (line limits, voltage constraints, etc.) as well as transmission constraints.
As a result, the solution inherently co-optimises CER/DER with conventional generation in one step – there is no need for iterative coordination because conflicts are resolved within the single optimisation run.</td></tr>
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	• **Locational pricing is typically used:** o The market computes locational marginal prices (LMPs) or some form of nodal prices at distribution nodes to clear supply and demand given network constraints. o CER/DER would be settled at their local price, reflecting both transmission and distribution constraints. This provides granular economic signals but is a significant departure from uniform retail pricing. (Some variants propose simpler zonal or 'area' prices as an intermediate step.) Ancillary services (frequency, voltage) can be co-optimised in the same market clearing as well.
Services Supported	• **Energy:** o Yes, fully integrated. CER/DER can sell energy into the market and be centrally dispatched. o Their output directly substitutes for other generation if cheaper (subject to network limits). o Surplus local generation will cause local price depression relative to system price, incentivising either export if network allows or curtailment if not. • **Congestion management:** o Inherent. Distribution constraints are part of the dispatch, so if a line is congested, the market will constrain/offload CER/DER and produce a price difference (higher downstream, lower upstream) to reflect it. o This internalises congestion management economically rather than through out-of-market actions. • **Ancillary services:** o Both transmission-level (e.g. frequency regulation, reserves) and distribution-level (voltage control, reactive power support) services can be procured from CER/DER in the same framework. o The market can include constraints or separate products for these services and clear them alongside energy (true co-optimisation of energy and ancillary). For example, a battery could be scheduled for both energy and a fraction of its capacity for frequency response if needed, based on price signals.

	• **Customer/prosumer services:**
	  ○ Allows advanced prosumers to fully valorise their flexibility – potentially providing simultaneous services (energy + ancillary) with proper remuneration.
	  ○ May enable local energy trading implicitly via nodal price differences (neighbours would have incentive to trade at a price between their respective LMPs, effectively achieved through the market if not directly peer-to-peer).

Pros	• **Maximum economic efficiency:**
	  ○ In theory, this yields the globally optimal dispatch – all relevant constraints and resources are considered together.
	  ○ No need for imperfect heuristics or separate mechanisms; CER/DER are used exactly when and where they provide net benefit to the system.
	• **No conflict or double counting:**
	  ○ A single decision platform means CER/DER won't be asked by a DSO and SO at cross-purposes – the market clearing inherently decides the best allocation of a CER/DER (e.g. whether it should reduce output to relieve local congestion or increase output to support system energy, based on comparative value). Theoretically this avoids the complicated coordination rules needed in siloed models.
	• **Transparent price signals:**
	  ○ Local marginal prices provide clear signals of locational value. Investors in CER/DER or flexible load see where the grid is congested (price separation) and can respond by locating or operating assets accordingly.
	  ○ Over time, this should guide efficient CER/DER investment and siting (a benefit noted in studies of locational pricing).
	• **Integrated services:**
	  ○ Easier to incorporate new services (such as for resilience or power quality services) into one market optimisation rather than maintaining multiple procurement processes.
	  ○ It also enables stacked value for CER/DER: a resource can earn from energy and ancillary simultaneously in one market, improving its economics.

	• **Simplified market interface:** ◦ From the aggregator/participant perspective, there is one interface – one market to bid into, one set of rules – rather than juggling separate SO and DSO programs.
Cons	• **Integrity of market-control system impacted** ◦ Separating or diminishing the direct relationship between market/incentive functions and physics-based grid management fundamentally undermines the integrity of the market-control system. • **Extreme complexity and computational demands:** ◦ Modelling an entire distribution system (potentially tens of thousands of nodes) in a real-time market dispatch engine is computationally intense and potentially implausible due to inherent cyber-physical constraints. ◦ The power flow in low-voltage networks is nonlinear (especially with AC power flow and voltage control), which is harder to incorporate into standard market solvers. ◦ Approximations or distribution grid simplifications might be needed, potentially reducing optimality. ◦ Ensuring the market clears in a timely manner (e.g. every 5 minutes) with so many variables is a challenge. • **Data and visibility:** ◦ This model requires the SO and DSO to have full network observability and detailed, validated network models down to the low-voltage level. ◦ It also needs real-time telemetry or state estimation for CER/DER and distribution equipment. ◦ The investment in IT/OT infrastructure is substantial. • **Market governance and structure:** ◦ A fundamental shift in roles – possibly making the SO (or a new entity) the operator of all levels of dispatch. ◦ Jurisdictional questions arise (who governs distribution markets – national regulator, local regulator?). ◦ DSOs will likely resist ceding operational control. There are also market power concerns: at a granular node level, a single large set of DERs may have local monopoly power during congestion.

	○ Mitigating abuse (market power monitoring) becomes more complex at the micro level. • **Impact on retail and consumers:** ○ Exposing customers to nodal prices can lead to high volatility and geographic disparities in energy costs. This may face public and political pushback. ○ Alternative approaches (e.g. having aggregators buffer consumers from volatility, or only large customers face nodal prices) add complexity. • **Transition path:** ○ Hard to implement. Likely requires a staged approach (e.g. start with a subset of resources or use clearing prices for CER/DER that shadow nodal costs without being fully nodal in retail). ○ Implementation costs and change management are very high.
Real-World Examples	• **Theoretical/Academic proposals** – Several studies and regulatory consultations have considered full network co-optimisation. E.g., Cambridge Energy Policy Associates (CEPA) Design C for Australia's NEM is a 'Centralised market with local prices' model: a combined TMO/DMO optimises dispatch across transmission and distribution with nodal (local) pricing for settlements. The U.S. DOE's Transactive Energy frameworks and Pacific Northwest National Lab (PNNL) trials have simulated transactive coordination that approximates this model via price signals. • **Open Energy Networks** – Single Integrated Platform (SIP) – In Australia, the 2019 Open Energy Networks project studied a 'Single Integrated Platform' where AEMO would extend its systems to dispatch CER/DER taking distribution constraints into account. This is conceptually equivalent to a centralised model. It was deemed high benefit but also high complexity. • **No large-scale real-time implementation yet** – To date, no country operates a full nodal market down to the LV distribution level. However, pilot programs have tested pieces: e.g. Project Symphony (Western Australia) demonstrated integrated dispatch of CER/DER via a DMO platform (AEMO) linked with the DSO's network constraints in real time. That pilot showed the feasibility of sending dispatch instructions from a central market platform to CER/DER aggregators for energy and contingency services within a distribution network.

	• **Other Examples:** Some U.S. ISOs (e.g. CAISO, NYISO) allow aggregated CER/DER to participate in wholesale markets, which is a step toward this model (with the ISO managing their dispatch). Distribution factors are handled via static constraints currently, but future enhancements may move closer to fully dynamic integration.

<table>
<tr><th colspan="2">Peer-to-Peer & Community Markets</th></tr>
<tr><td>Functional Roles</td><td>

Peer participants (prosumers and consumers):

Directly trade energy with each other or within a community via a platform.
There is no central ‘market operator’ optimising dispatch; the platform matches bids and offers from participants, or a smart contract system facilitates transactions.

Distribution System Operator (DSO):

Generally passive in the trading mechanism – the DSO’s grid is used as a platform for energy exchange, but the DSO may not actively control trades.
The DSO may set constraints or tariffs for network use (to ensure limits are respected and costs recovered).

Aggregator or Community Manager:

In some models, a community energy manager, retailer, or blockchain-based system acts as a facilitator to handle settlements, metering, and possibly enforce limits.
They are not optimising the whole system but ensuring participants’ transactions are executed and maybe providing an interface with the wider market (e.g. buying/selling any net surplus or deficit from the wholesale market on behalf of the community).

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<tr><td>Co-Optimisation Mechanism</td><td>

Decentralised trading with limited grid integration:

Participants in a P2P market submit offers to sell excess CER/DER generation (or reduce load) and bids to buy energy, typically at the community level.
A platform matches these trades based on price preferences, often prioritising local consumption of local generation. This reduces reliance on the wholesale market for those participants up to the volume traded locally.
Any imbalance between local generation and demand is met by (or exported to) the main grid at prevailing wholesale/retail prices – this is how it interfaces with the conventional market.

Co-optimisation with the broader system is minimal:

The P2P platform usually does not account for transmission conditions or system-wide needs.

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	○ Some advanced concepts use transactive energy signals to iteratively adjust peer trading prices in response to grid conditions (a form of hierarchical P2P that attempts to converge with system equilibrium), but most real implementations have simpler rules. ○ Network constraints in P2P are either ignored or handled via static limits – e.g. the platform may bar trades that exceed a feeder's limit or rely on the DSO to manage violations separately.
Services Supported	• Energy trading: ○ This model is explicitly designed for energy transactions at the distribution edge. ○ Neighbours or community members can buy excess solar or share energy within microgrids. ○ This can improve local self-consumption and provide choice in sourcing (e.g. buy from local solar instead of the utility). • Congestion management: ○ Not inherently addressed, unless the platform includes rules for it. These schemes often assume the trade volumes are small enough or localised enough that they won't violate network constraints, or they operate within a microgrid with known limits. ○ Some research proposes integrating network fees or constraint signals into the matchmaking so that if a line is congested, trades that worsen it become more expensive, thereby indirectly controlling flows. • Ancillary services: ○ Generally, not a focus of P2P markets. Participants are transacting energy for mutual benefit, not explicitly providing frequency or voltage support (especially since there's no central dispatcher). ○ In principle, a community could collectively provide a service (e.g. a microgrid providing demand response to the grid), but that usually requires an aggregator coordinating them outside of the P2P mechanism. • Customer enablement: ○ This model ranks high on customer-centricity. It supports community goals (e.g. a town using its local renewable generation first) and allows consumers to actively choose how their energy is sourced or used, potentially boosting engagement and innovation (such as blockchain use for energy transactions).

Pros	• **Empowers consumers and communities:** o P2P trading gives prosumers control over their energy and can lower bills by maximising usage of local low-cost generation. o It also fosters community investment in renewables, as members see direct benefits from local energy sharing. • **Flexible and innovative:** o These schemes often leverage modern IT (blockchains, smart apps) and can be deployed relatively quickly on a small scale. o They allow experimentation with dynamic pricing and novel business models (e.g. community coins for energy). • **Reduced losses and infrastructure stress (potentially):** o By incentivising local consumption of generation, P2P can reduce energy flows over long distances, potentially lowering losses and deferring upgrades if generation and load are better balanced locally. • **Social and environmental benefits:** o Communities may use P2P to achieve higher renewables usage or to help vulnerable consumers via local tariffs. o The transparency and perceived fairness of trading among neighbours can improve public acceptance of CER/DER projects. • **Gradual integration:** o P2P markets can run in parallel with existing markets (just adjusting how retail transactions occur) without needing a full system overhaul, as long as basic regulations (netting, settlement) are adapted.
Cons	• **Limited grid coordination:** o Because these markets largely ignore broader grid optimisation, they can lead to suboptimal outcomes from a system perspective. For example, many participants might export at times of a regional surplus just because there are local buyers, exacerbating upstream congestion or over-generation issues. o Without co-optimisation, the local trades might conflict with what the main grid needs (hence some analysts consider P2P incomplete if not integrated).

	• Network cost recovery & fairness: ○ If neighbours trade energy freely, how do we charge for the use of the wires? P2P models often struggle with incorporating fair network tariffs. ○ Participants could avoid paying their share of network costs (if, say, they reduce their net consumption but still rely on the grid infrastructure), shifting costs to others. ○ Regulators often require that P2P trades at least pay some distribution use fee, which can complicate the pricing and reduce the attractiveness of the trades. • Scaling and reliability: ○ P2P works in small communities or microgrids, but at larger scale it becomes chaotic without a coordinator. ○ Price discovery in a fully decentralised setting could be inefficient or unstable. Ensuring reliability is tricky – the platform must prevent deals that imperil network security, which essentially reintroduces some central control or at least monitoring. • Regulatory barriers: ○ In many jurisdictions, direct energy trading between consumers is not allowed under existing retail market rules. Implementing P2P often requires regulatory sandboxes or special permission. ○ Questions arise about supplier of record, balancing responsibility (who covers deviations if a peer seller under-delivers?), and consumer protection (if a neighbour doesn't deliver power, the lights must stay on via the normal supplier). • Technological maturity: ○ While numerous pilots exist, true peer-to-peer trading with automated smart contracts is still emerging. ○ Integration with smart home systems, reliable measurement for settlement, and cybersecurity are all challenges to resolve as these platforms scale.
Real-World Examples	• Brooklyn Microgrid (USA): ○ An iconic pilot in New York where residents with solar panels traded excess energy with their neighbours using a blockchain platform.

	o This community-driven project demonstrated the concept of local energy trading, though it remained disconnected from the NYISO wholesale market (trades occurred virtually with adjustments via the retailer). • Power Ledger trials (Australia, Asia): o Power Ledger's blockchain-based P2P trading platform has been trialled in communities in Western Australia, Thailand, and elsewhere. o Participants trade solar energy within a strata or neighbourhood, with the platform handling peer transactions. o These trials required a layer of retailer/utility involvement to handle settlement and ensure the grid supply as needed. • Energy Local (UK): o A community energy club model, not pure peer-to-peer but similar spirit: households in a village form a club to buy power from a local renewable generator at a rate better than the export tariff but lower than normal retail. o A coordinating supplier manages the interface with the grid. This increases local renewable usage and savings for participants. • ILEX and Vandebron (Netherlands): o Vandebron allows consumers to choose a specific local producer to buy from (a form of virtual P2P). o The InteGrid EU project tested a local trading platform in Portugal, combining P2P trading with DSO signals (a transactive energy demo). • Transactive Energy pilots: o Pacific Northwest Demo (USA) and AEP Ohio's experiment used transactive signals (dynamic prices) between homes and the utility. o While not open P2P trading, they share principles of decentralised decision-making and can be seen as a path toward more integrated peer-based coordination with grid signals.