

Systems Architecture:

*21st Century Tools for 'Taming'
the Massive Complexity of
Electric Grid Transformation*

Mark Paterson
June 2023



Energy Catalyst

Acknowledgments

This paper was authored by Mark Paterson, Pacific Energy Institute Fellow and Managing Director of Energy Catalyst.

Valuable contributions and insights have been provided by Dr Jeffrey Taft, Paul De Martini, Dr Lorenzo Kristov and Dr Ron Melton. The Pacific Energy Institute Fellows are also acknowledged for their collaboration on the ideas that have informed this paper.

<https://pacificenergyinstitute.org/>

Disclaimer

The views and opinions of the authors expressed herein do not necessarily state or reflect those of the Pacific Energy Institute's Fellows and Advisory Board, or their respective organizations.





An unprecedented scale and pace of change

Australia is experiencing one of the fastest power system transformations on the planet and provides a window on the future for many jurisdictions.

It also illustrates the need for shared, evidence-based methodologies for enhancing multi-stakeholder collaboration and 'taming' of deep complexity.

Australia's power systems are being rapidly reshaped by the combined impact of the '4 x Ds' – decarbonisation, digitisation, democratisation and decentralisation. Accelerated by a complex range of societal, technological, economic and commercial shifts, many of these drivers of change are outside the direct control of the sector's traditional regulatory and governance mechanisms.

In this context, the Australian Energy Market Operator (AEMO) has noted that by 2025, the nation's power systems must be capable of operating reliably during periods where 100% of instantaneous demand is served by variable sources [\[1\]](#).

Compared with 2021 levels, AEMO's 'Step Change' scenario plausibly anticipates that Australia's National Electricity Market (NEM) will ultimately need to accommodate:

- **9x Centralised VRE:** A nine-fold increase in the installed capacity of utility-scale wind and solar VRE generation (from 15GW to 140GW);
- **5x Distributed DER/CER:** Almost a five-fold increase in the installed capacity of distributed energy resources, much of which is customer owned (from 15GW to 70GW);
- **3x Dispatchable Firming Capacity:** A three-fold increase in installed firming capacity that can respond to a dispatch signal; and,
- **99% Electric Vehicles:** Almost the entire passenger vehicle fleet electrified [\[2\]](#).

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

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

All these nearer and longer-term dimensions represent a transformative scale and pace of change. In recognising this, AEMO's Engineering Framework – Initial Roadmap noted:

“Traditional, legacy approaches will need to be maintained in the near term, but inherent structural limitations will eventually constrain the pace of transition. Parallel to this, it is critical that designing a step change in power system capability starts today, due to:

- *The extent of work and collaboration required across many areas, including technical engineering, planning, and regulatory reform.*
- *The pace of change underway and the asymmetric risk to consumers of disorderly, constrained and inefficient transition.*
- *The risks if timely action is not taken and system operators do not have the tools to securely and reliably manage new operational conditions as they emerge.”* [3]

Today, many challenges that span the traditional boundaries of bulk power, transmission and distribution systems are already emerging. For example, as rooftop solar PV becomes near ubiquitous, a range of new forecasting, visibility, controllability and minimum demand management issues require whole-system collaboration to address.

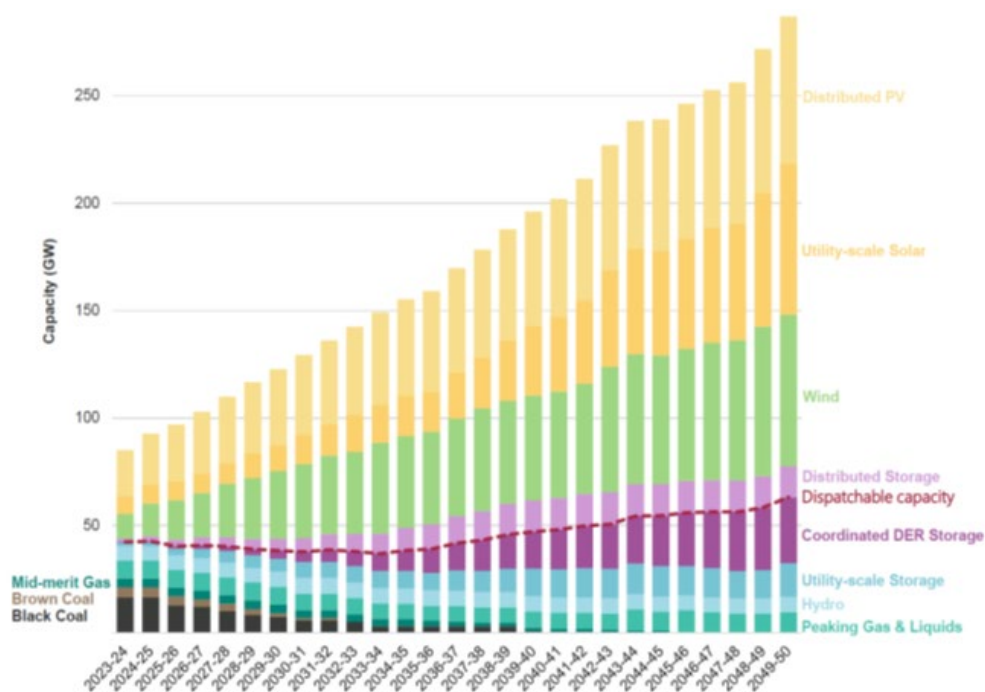


Figure 1: AEMO Step Change scenario [4]

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

[4] Image: Integrated System Plan, AEMO, 2022

Benefiting from the experience of other ultra-complex sectors

Modern power systems are highly complex cyber-physical-economic systems. They are arguably the largest and most complex ‘machines’ ever created by humanity and formally defined as Ultra Large-Scale (ULS) complex systems [5].

With these critical systems in profound transformation, it is vital to recognise that what has been referred to as ‘the power system’ (singular) is an overlay of seven inter-dependent structures which evolved gradually during the 20th century.

This web of overlaid structures includes the: (1) electricity infrastructure; (2) digital infrastructure; (3) operational coordination layer; (4) markets / transactional layer; (5) industry / market structure; (6) regulatory structure; and (7) sector couplings. Importantly, like an intricate tapestry, changes to one structure will typically impact the functioning of the other structures - in both intended and unintended ways.

“A system is complex if it has many interrelated, interconnected, or interwoven entities and relationships”

Crawley, et al

A further complication is that different segments of the power system – bulk power, transmission, distribution, energy retail, DER/CER aggregation, etc. – lack a shared ‘systems’ methodology for developing integrated solutions. This makes the holistic evaluation of alternative architectural models for the future grid, including Distribution System Operator (DSO) and Transmission–Distribution Interface (TDI) models, difficult if not impossible to objectively analyse and shortlist.

Like the modernising aerospace sector before it, a decarbonising power sector is now experiencing unprecedented new levels of complexity that exceed many of our traditional tools and navigational approaches. In such a context, formal Systems Architecture-based tools become essential for taming complexity and enhancing collaboration.

[5] Feiler et al, Ultra-Large-Scale Systems: The Software Challenge of the Future, Software Engineering Institute, 2006



Drivers of expanding power system complexity

The power systems that developed throughout the 20th century and served society well functioned in a historical context that was characterised by:

- Almost all generation served by a fleet of centralised and dispatchable MW-scale plant connected to the transmission system;
- Comparatively slow, incremental technological change;
- Steady load growth correlated with economic growth;
- End-users as relatively passive consumers;
- Negligible incumbent risk of 'product substitution' at scale.

By contrast, as decarbonisation goals are pursued around the world, this historical context is eroding. In Australia this transformation is being accelerated by:

- Declining levels of synchronous generation which is being progressively replaced by centralised and decentralised Inverter Based Resources (IBR);
- Accelerating growth in utility-scale wind and solar Variable Renewable Energy (VRE) generation;
- World-leading adoption of residential Customer Energy Resources (CER) and massive growth potential for Electric Vehicle (EV) charging;
- Emerging and increasingly frequent periods where VRE and DER/CER output drives minimum and negative regional demand; and,
- The increasing frequency of time windows where 100% of instantaneous demand is served by centralised and decentralised VRE.

As MIT's Crawley et al note, however, as such new requirements emerge, an unintended consequence of requiring greater functionality from any legacy system is that the operational complexity of the system will escalate further [\[6\]](#).

EXAMPLE: Operational Coordination for the 21st Century

A critical question that requires shared ‘systems’ methodologies and tools to address is: “How will our deeply decarbonised GW-scale grids be ‘Operationally Coordinated’?”

In the Australian context, this will involve **whole-system coordination** of one of the world’s longest power systems, as it transitions:

- From hundreds of large, dispatchable, synchronous machines to **tens of millions** of **diverse and highly dynamic resources**...
- Which are **ubiquitous** across **all vertical layers** of the grid, and blind to our historical bulk power, Tx and Dx boundaries...
- In a context where grid security will need increasing levels of **flexibility, balancing** and **ancillary services** from what we once called the ‘**demand-side**’ of the system, and...
- All of which must be Operationally Coordinated in a manner that **instantaneously balances** supply and demand **every millisecond** of the year.

This is a challenge that spans bulk power, transmission, distribution and DER/CER aggregation. It requires a shared systems methodology and tools for developing integrated solutions that benefit all.

Given the inseparable cyber-physical-economic nature of the power system, close ‘market-control’ alignment is required to incentivise and activate service provision in a reliable and mutually reinforcing manner (across timescales of days to milliseconds).

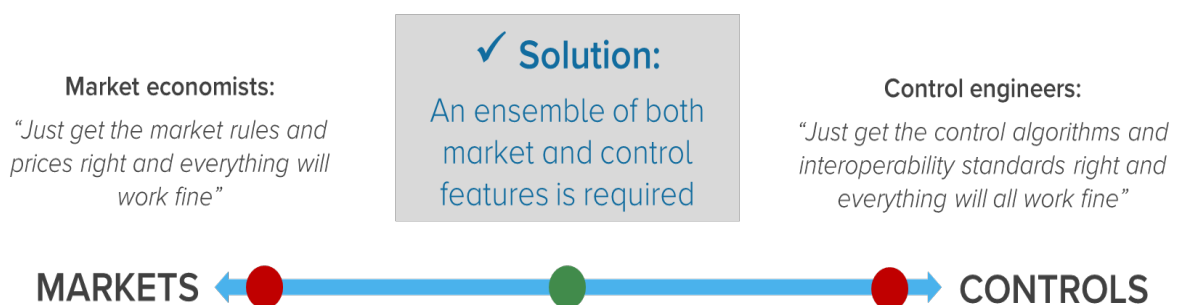


Figure 2: The ‘markets vs controls’ false dichotomy [7]

A critical 'toolkit' for taming grid complexity

In this transformational context, Australia's national science agency CSIRO together with AEMO have spearheaded the nation's contribution to the Global Power System Transformation (G-PST) initiative.

Under the G-PST initiative, Strategen Consulting and the Energy Catalyst team conducted a meta-analysis of the numerous global approaches to navigating and 'taming' this scale of systemic complexity [\[8\]](#).

As a universal insight, what became clear was that as more volatile decarbonised power systems emerge:

Bulk power, transmission and distribution systems – together with deep demand-side flexibility – will need to function far more holistically together to enable reliable and efficient grid operation.

As noted earlier, rather than a continuation of the comparatively slow, incremental change of the 20th century, AEMO recognises that significant structural and capability uplifts are required to enable an orderly transition.

Importantly, while the transition includes the addition of new technologies, this alone is not sufficient. This is because the underpinning structures of any legacy system – how all the individual technologies and actors are formally linked together – always has a disproportionate impact on what the system can reliably and cost-efficiently achieve. In other words, the readiness of any systems underpinning structures or 'architecture' is itself a critical enabler of transformation.

[8] Power Systems Architecture, Strategen Consulting (2021)



Given the unparalleled cyber-physical and transactional complexity of modern power systems, the ability to analyse and intelligently adapt the grid’s underpinning structures becomes essential. And as these structures traditional power system segments – bulk power, transmission, distribution, retail, etc. – the need for ‘neutral’ evidence-based tools to collectively navigate deep complexity becomes clear.

For this reason, the G-PST Stage 1 Executive Summary Report noted that application of Power Systems Architecture [9] disciplines were “central and foundational” to the overall program of work underpinning and enabling Australia’s power system transformation.

The underpinning structures of any complex system – how all the elements and actors are formally linked together – has a disproportionate impact on what the system can safely, reliably, and cost-efficiently do.

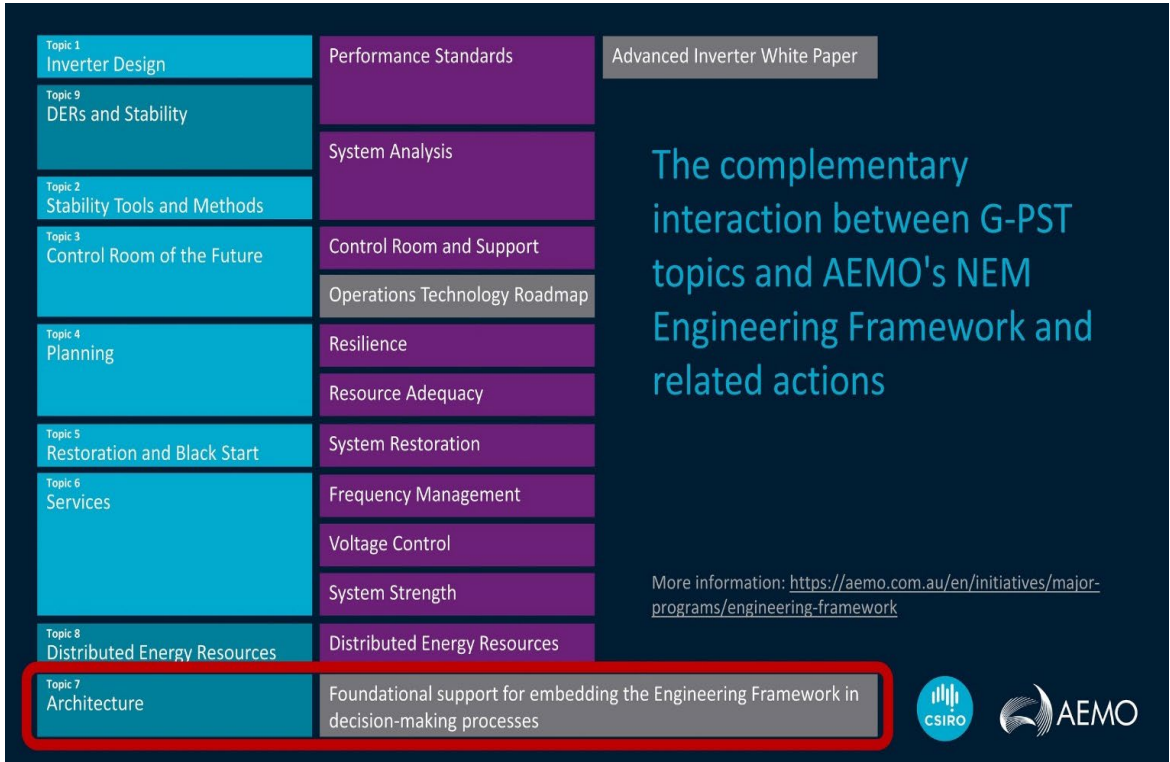


Figure 3: G-PST Stage 1 identified Power System Architecture as foundational to the other activities [10]

[9] The term Power Systems Architecture used in Australia is virtually synonymous with the term Grid Architecture which is more commonly used in the United States.
[10] Image: Executive Summary Report for Australia’s Global Power System Transformation Research Roadmap, CSIRO & AEMO, 2022 (emphasis added)

Empowering multi-stakeholder collaboration on complex grid transformation

As noted earlier, what we know as ‘the power system’ is a complex web of seven distinct but inter-dependent structures. In the Australian context, several significant issues are already emerging that impact these legacy structures and risk propagating instability both up and downstream.

Such unparalleled levels of complexity will only continue to expand as power systems decarbonise and become more dynamic and volatile.

In this context, the global power sector is recognising the need for an expanded ‘toolkit’, including formal methodologies in systems-level analysis, for guiding the transformation of our power systems.

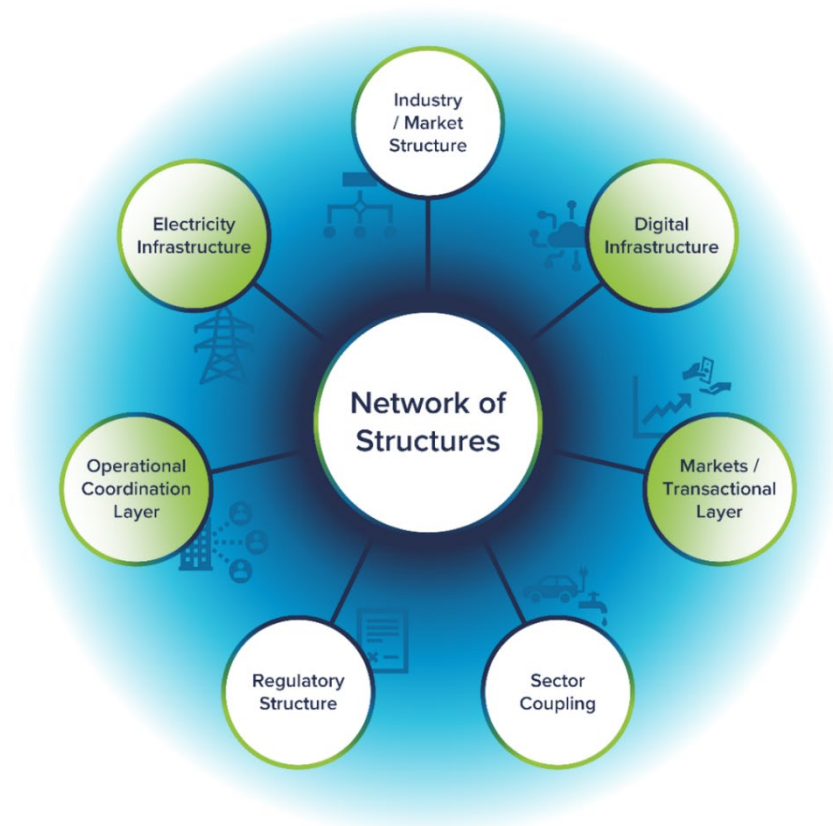


Figure 4: Modern power systems are a multi-structure network of deeply inter-dependent structures [\[11\]](#).

[11] Image: Adapted from Grid Architecture 2, Pacific Northwest National Laboratory, 2016

In this context, the 'Network of Structures' paradigm, developed by Pacific Northwest National Laboratory (PNNL), provides a powerful means to surface and decompose the hidden complexity that underpins every GW-scale power system.

Importantly, rather than making this more complex, it enables diverse stakeholders – both technical and non-technical – to have more objective, focused and efficient engagement on the available change options. Conversely, the lack a shared 'systems' methodology will often result in less efficient and more subjective debates which exacerbate complexity and fail to gain traction.

Practically, stakeholders are supported in the application of basic Power Systems Architecture (PSA) tools to collectively gain valuable new insights. This may involve a diverse range of end-user customers together with System Operator, transmission, distribution, DER/CER aggregation, technology vendors, regulatory representatives.

PSA enables a diverse range of stakeholders, including customer representatives, market and regulatory bodies, T&D networks, energy retailers, DER aggregators and technology vendors to collaborate in a more objective, focused and efficient manner

'Under the hood', the PSA discipline is informed by the multi-year work of PNNL funded by the United States Department of Energy. It brings together Systems Architecture, Network Theory, Control Theory and Software Engineering for application to changing power systems, supported by Strategic Foresight and Energy Economics disciplines.

Applied to the Network of Structures paradigm, these integrated disciplines enable robust structural analysis of both the legacy system and its most plausible future needs. By identifying the minimal structural changes required to deliver the maximum future system functionality, PSA disciplines are key to enabling the secure and least-cost transformation of global power systems.

Summary – Rationale & Benefits

Australia is experiencing one of the world's fastest grid transformations. New challenges that span the traditional boundaries of bulk power, transmission and distribution are already emerging that require whole-system collaboration and a shared set of tools to address.

While the context will vary by location, following is a summary of the key rationale for applying Power Systems Architecture tools and the targeted benefits relevant to any jurisdiction.

Key Rationale

1. Every complex system has an **underpinning structure** or 'architecture' that **disproportionately impacts** what the system can efficiently and reliably do.
2. Power systems were already ultra complex in the 20th Century and are now becoming **orders of magnitude** more **volatile, dynamic and complex**.
3. To support **decision-making under uncertainty**, there is a need for analytical tools that deliver greater **optionality and resilience** to different future outcomes.
4. Fit-for-purpose tools are required to **'tame' complexity**, identify embedded **structural constraints** and cost-effectively **'stress test' proposed changes** while they are still on paper.
5. An objective, evidence-based methodology provides a **shared set of 'neutral' tools** that stakeholders across the supply chain can learn and collaboratively apply to **solve complex problems faster**.



Target Benefits

1. Develop advanced **Operational Coordination models** that are scalable to a future power system involving **tens of millions** of diverse and dynamic participating energy resources.
2. Identify early where short and medium-term decisions may unintentionally propagate **systemic complexity, fragility** and/or **cyber-security vulnerabilities** in the longer term.
3. Markedly **reduce the complexity, contention** and **cycle-time** of multi-stakeholder engagement on complex structural questions and trade-offs in a manner that enhances **outcome quality and buy-in**.
4. Beyond pilot-scale demonstrations, develop architectural models for the future grid, including **Distribution System Operator (DSO)** and **Transmission-Distribution Interface (TDI)** models, that are capable of scaling to support whole-system integration and coordination.
5. As the grid decarbonises, deliver a **whole-system optimisation premium** that provides customers and society potential savings **worth \$-billions** not otherwise be visible or achievable.

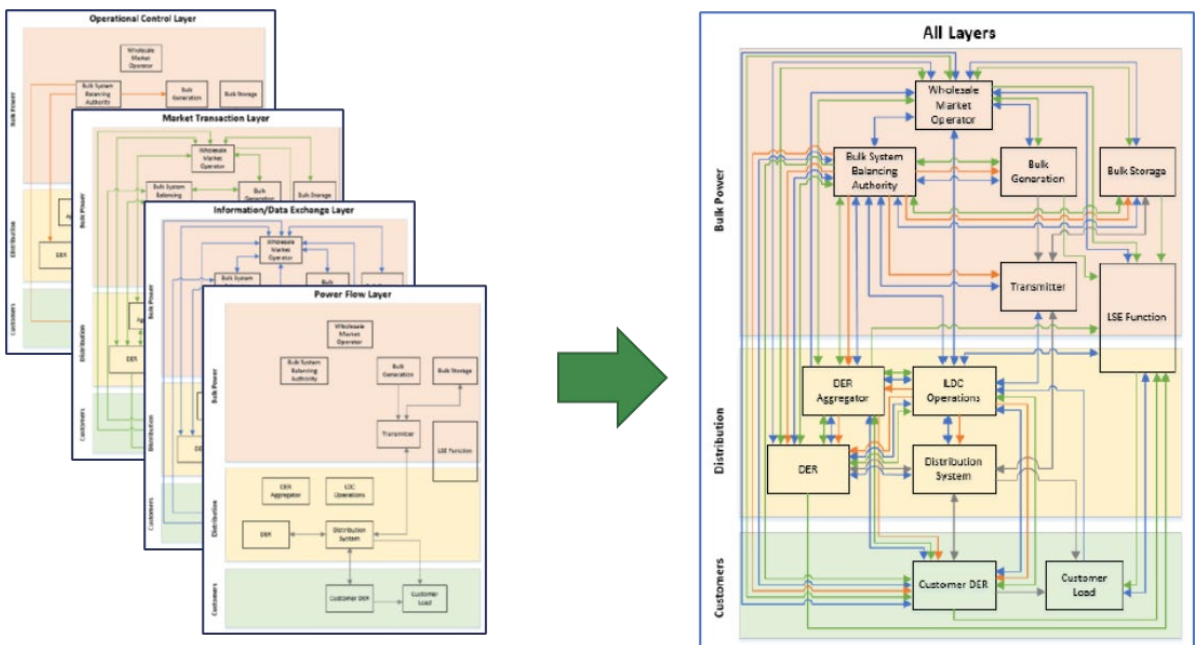


Figure 5: Systems Architecture disciplines provide essential tools for collaboratively identifying the minimum set of structural changes required to provision a power system for maximum future resilience [12].

Conclusion

An enormous range of new technology, regulatory, market and other initiatives will be required to enable the deep decarbonisation of our legacy power systems.

In the context of a once-in-a-century scale of change, Power Systems Architecture disciplines provide an entirely new level of strategic insight for navigating the transformation. As highlighted in an internationally co-authored 2022 report [13], these formal methodologies are key to addressing many critical issues now confronting the sector, including:

- Evidence-based evaluation of competing architectural models for the future grid to ensure resilience, efficiency and scalability;
- Alternative Distribution System Operator (DSO) configurations;
- Transmission–Distribution Interface (TDI) models;
- Future-ready configurations of Roles & Responsibilities and related system interfaces spanning the end-to-end power system; and,
- Deploying ‘Operational Coordination’ models capable of scaling to securely and efficiently support tens of millions of participating energy resources.

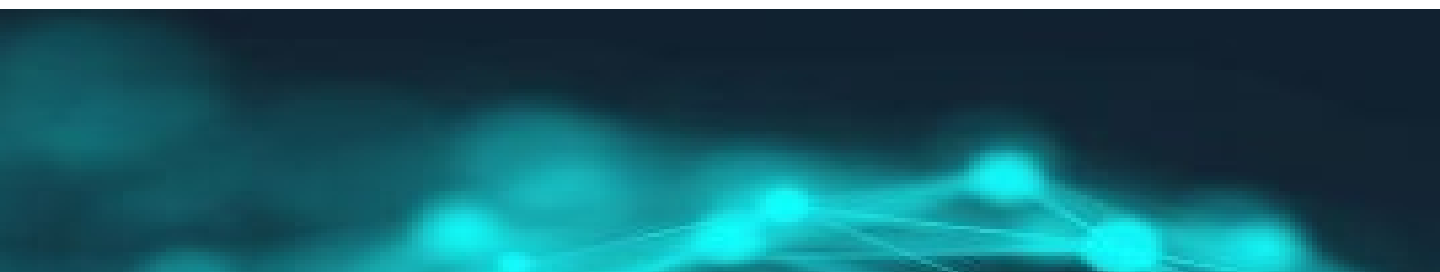
All these issues involve significant architectural dimensions, meaning that in the absence of the right tools, progress can be piecemeal and slow. Supported by Systems Architecture-based methodologies, however, inherent complexity becomes more tractable, and the consideration of design options and trade-offs more rigorous, evidence-based and objective.

When any complex legacy system experiences disruptive change, the ‘match fitness’ of its underpinning structures is a critical factor in its continued future relevance [14][15]. Appreciated in many other sectors, this is now increasingly recognised in the global power sector as it undergoes its own unprecedented transformation.

[13] Transmission & Distribution Grid Modernization to Mitigate Impacts from and Adapt to Climate Change, IEEE Power & Energy Society, 2022

[14] E. Crawley, B. Cameron & D. Selva, System Architecture: Strategy and Product Development for Complex Systems, Pearson, 2016

[15] Grid Architecture 2, Pacific Northwest National Laboratory





The Author



Mark Paterson is a Fellow of the Pacific Energy Institute. He is also Managing Director and Lead Systems Architect at Energy Catalyst. Informed by the key lessons derived from the successful navigation of sectoral disruptions, Energy Catalyst's unique approach brings together strategic futures, systems thinking, multi-stakeholder engagement and transition design.

Leveraging an unparalleled national and global network, Energy Catalyst works with an International Expert Panel of respected leaders from the United States, United Kingdom, European Union and Australia who collaborate on the application of advanced methodologies and the early detection of emerging trends.

Mark's theoretically robust but pragmatic approach is grounded in applied technology origins and Engineering, Business and Master of Enterprise qualifications. He has been formally trained in Systems Architecture & Engineering disciplines at the Massachusetts Institute of Technology (MIT), Strategic Foresighting methodologies developed by Europe's EDHEC and Power Systems Architecture methodologies developed through the US Department of Energy's Grid Modernisation Laboratory Consortia.

In addition to his work with the Pacific Energy Institute, Mark is a contributing author for the IEEE Power & Energy Society and an invited Associate of the US Department of Energy's GridWise Architecture Council (GWAC). He has also been an expert contributor to Asia-Pacific Economic Cooperation (APEC) grid resilience activities.



Energy Catalyst

Email: mpaterson@energycatalyst.au

Mobile: +61 459 841 006

References

- [1] Inputs, Assumptions & Scenarios Report, AEMO, 2021
- [2] Engineering Roadmap to 100% Renewables, AEMO, 2022
- [3] NEM Engineering Framework – Initial Roadmap, AEMO, 2021
- [4] Image: Integrated System Plan, AEMO, 2022
- [5] Feiler et al, Ultra-Large-Scale Systems: The Software Challenge of the Future, Software Engineering Institute, 2006
- [6] E. Crawley, B. Cameron & D. Selva, System Architecture: Strategy and Product Development for Complex Systems, Pearson, 2016
- [7] Image: Adapted from Paul De Martini and Dr Jeffrey Taft
- [8] Power Systems Architecture, Strategen Consulting (2021)
- [9] The term Power Systems Architecture used in Australia is virtually synonymous with the term Grid Architecture which is more commonly used in the United States.
- [10] Image: Executive Summary Report for Australia's Global Power System Transformation Research Roadmap, CSIRO & AEMO, 2022 (emphasis added)
- [11] Image: Adapted from Grid Architecture 2, Pacific Northwest National Laboratory, 2016
- [12] Images: Development of a Transmission-Distribution Interoperability Framework, prepared by ICF for the Independent Electricity System Operator, Ontario, Canada (2020)
- [13] Transmission & Distribution Grid Modernization to Mitigate Impacts from and Adapt to Climate Change, IEEE Power & Energy Society, 2022
- [14] E. Crawley, B. Cameron & D. Selva, System Architecture: Strategy and Product Development for Complex Systems, Pearson, 2016
- [15] Grid Architecture 2, Pacific Northwest National Laboratory, 2016



pacific energy
INSTITUTE