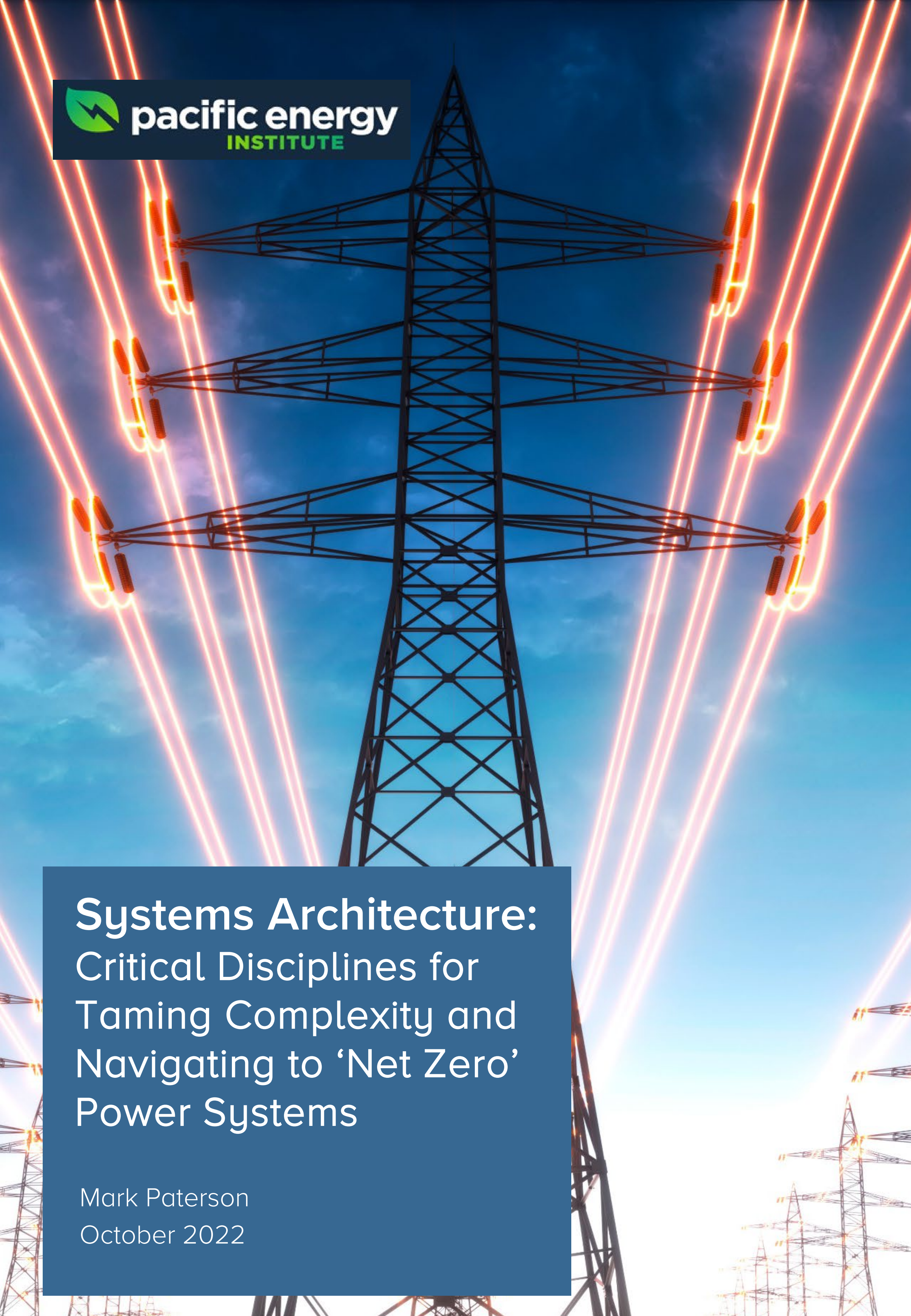


pacific energy INSTITUTE

Systems Architecture: Critical Disciplines for Taming Complexity and Navigating to 'Net Zero' Power Systems

Mark Paterson

October 2022

Acknowledgments

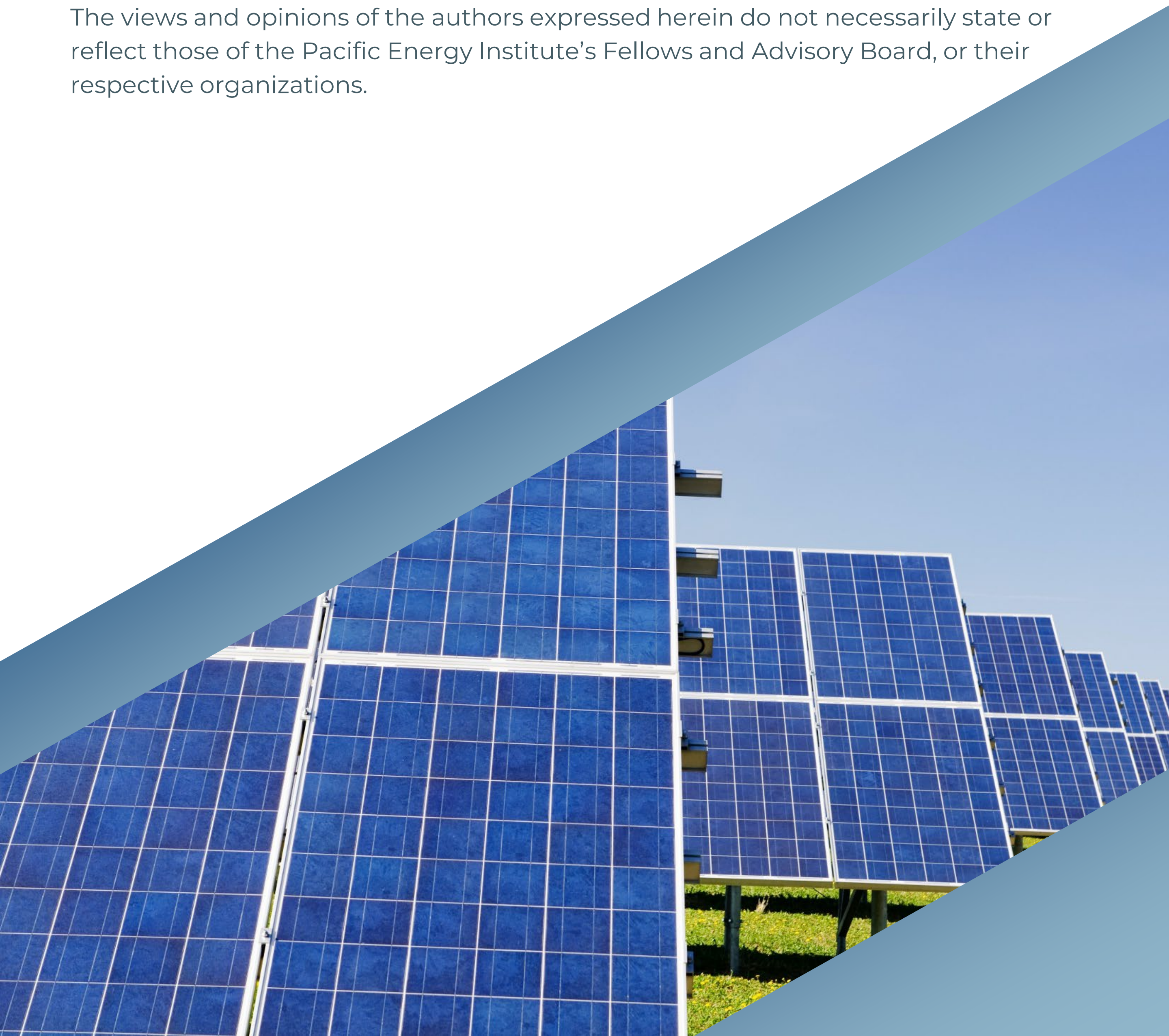
This paper was authored by Mark Paterson, Pacific Energy Institute Fellow and Managing Director Australia Pacific, Strategen Consulting.

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.



Once-in-a-century scale 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' deep complexity.

Australia's power systems are being rapidly reshaped by he combined impact of the '4 x Ds' – decarbonisation, digitisation, democratisation and decentralisation. This is being accelerated by a complex range of societal, technological, economic and commercial shifts, many of which transcend the reach of traditional power sector regulatory and governance mechanisms.

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 need to accommodate:

- **9x Centralised VRE:** A nine-fold increase in the installed capacity of utility-scale wind and solar VRE generation (from 15GW to 140GW);
- **5x Distributed VRE:** Almost a five-fold increase in the installed capacity of distributed solar VRE / DER generation (from 15GW to 70GW); and,
- **3x Dispatchable Firming Capacity:** A three-fold increase in installed firming capacity that can respond to a dispatch signal [2].

[1] https://aemo.com.au/en/newsroom/news-updates/the-view-from-the-control-room
[2] https://www.aemo.com.au/newsroom/media-release/nem-prepares-for-step-change

In recognition of the sheer pace and scale of change now confronting Australia's power systems, AEMO's Engineering Framework – Initial Roadmap notes:

> *"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]

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

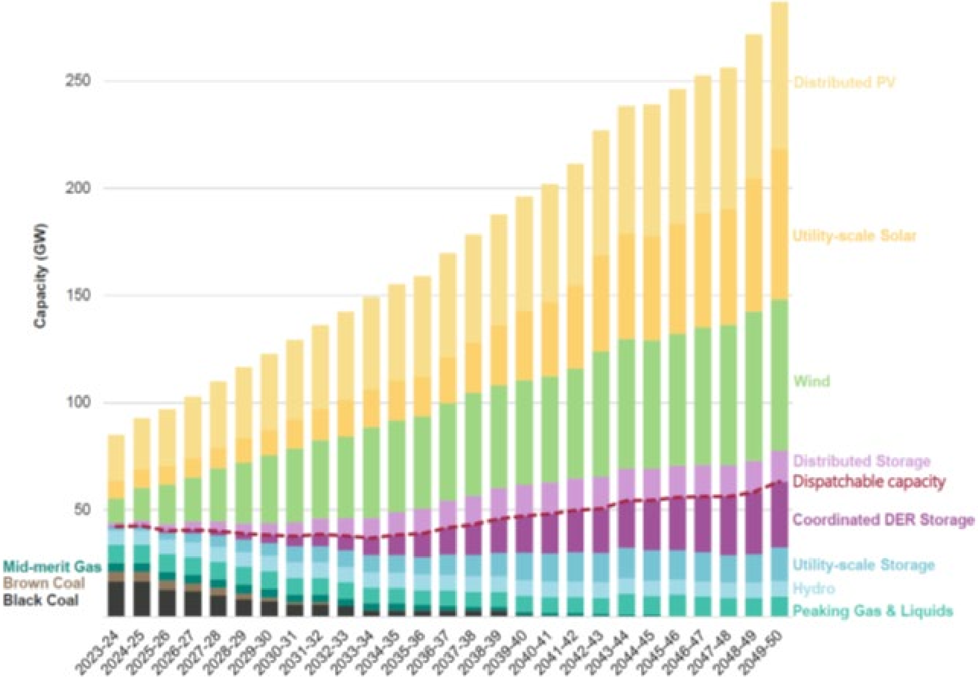


Figure 1: AEMO Step Change scenario [4]

[3] NEM Engineering Framework – Initial Roadmap, AEMO, 2021
[4] Image: Integrated System Plan, AEMO, 2022

Confronting Unparalleled Complexity

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 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 (plural) which evolved gradually during the 20th century.

This web of overlaid structures include 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 further complication is that different segments of the power sector – bulk power, transmission, distribution, energy retailers, DER aggregators – lack a shared 'systems' methodology for developing integrated solutions that benefit all. And as MIT's Crawley et al note, additional complexity is unavoidably driven into a legacy system as more and more functionality and interoperability are required of it [6]. This is exacerbated where there is no shared approach to addressing the underpinning cyber-physical-transactional structures of what is an already complex system.

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.

[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

Drivers of the Expanding Complexity

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

> *"A system is complex if it has many interrelated, interconnected, or interwoven entities and relationships"*
>
> Crawley, et al

- 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 Distributed Energy Resources (DER) and massive growth potential for Electric Vehicle (EV) charging;
- Emerging and increasingly frequent periods where VRE/ DER 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.

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 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).

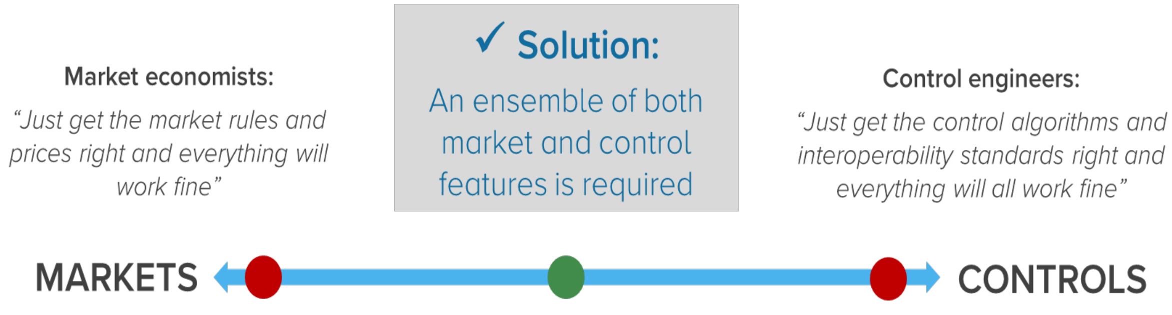


Figure 2: The 'markets vs controls' false dichotomy [7]

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

A Critical 'Toolkit' for Taming Grid Complexity

In this wider 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 this initiative, Strategen Consulting undertook a detailed analysis of the wide range of global approaches to navigating this level of systemic complexity [8].

At a high level, what became clear was that as more dynamic power systems emerge:

> *Bulk energy, transmission and distribution systems – together with deep demand-side flexibility – will need to function holistically to enable reliable and efficient operation.*

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

Importantly, however, this includes but is far more than simply adding new technologies and individual initiatives. This is because the underpinning structures of any complex system – that is, how all the elements and actors are formally linked together as an integrated system – always has a disproportionate impact on what the system can safely, reliably, and cost-efficiently do.

[8] The Strategen G-PST Power Systems Architecture (2021) report and overview video are provided here: https://www.strategen.com/gpst-psa-report

Given the unparalleled cyber-physical-transactional complexity of modern power systems, the ability to analyse and intelligently adapt the grid's structural complexity becomes essential. Given these underpinning structures essentially transcend traditional power system segments, the need for 'neutral', evidence-based systems tools for efficient collaboration and 'taming' complexity becomes clear.

> *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.*

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.

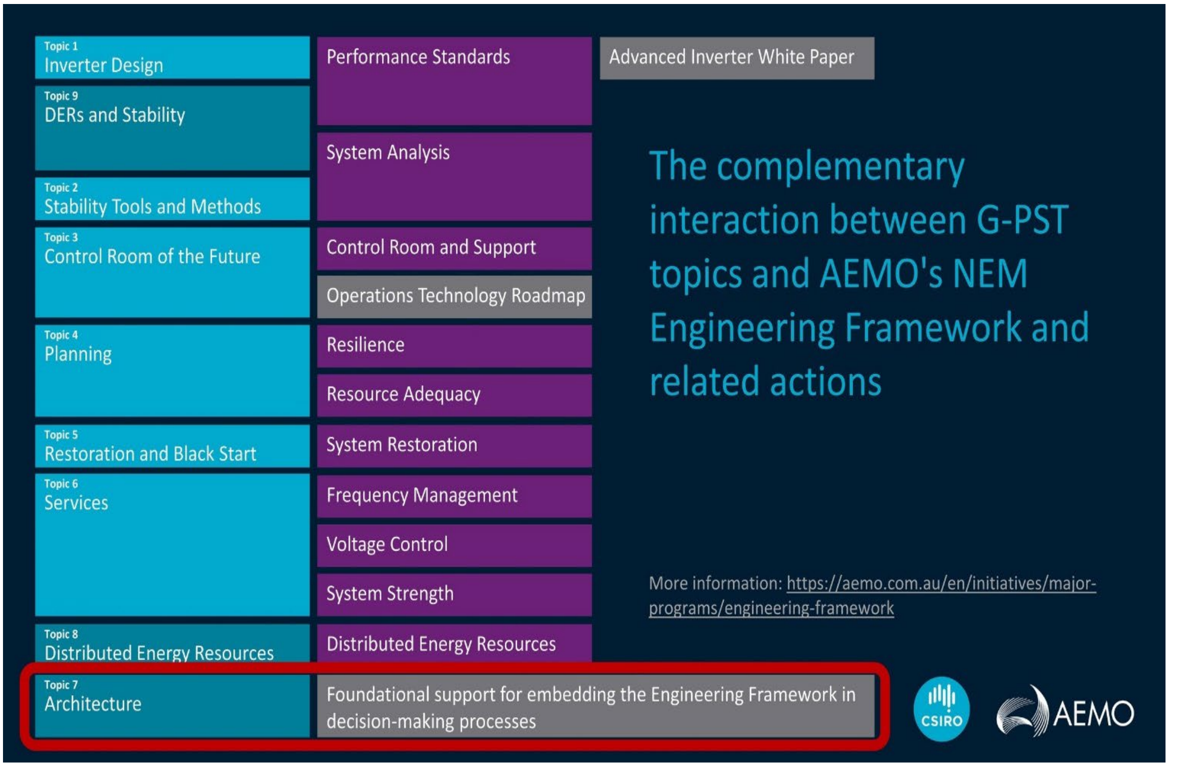
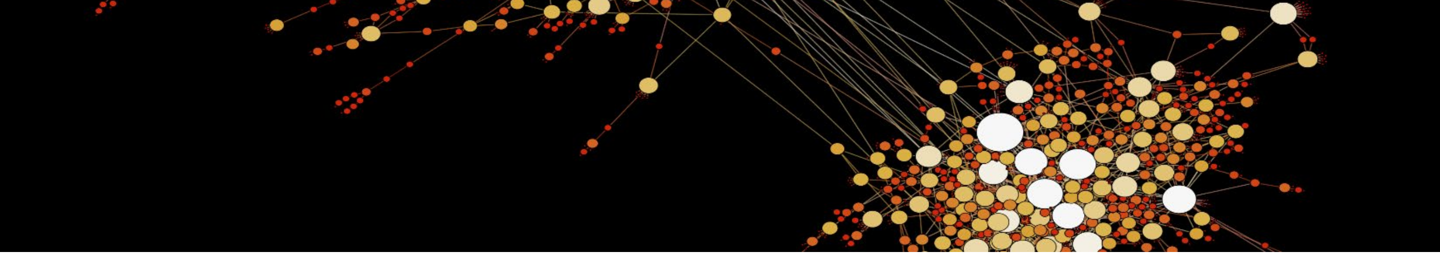


Figure 3: G-PST Stage 1 identified Power System Architecture as foundational to the other activities [10]

[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

Ultra-complex challenges are good for our humility – they remind us of our very human limitations. And this is precisely why it is imperative to build new human capital in applying even basic systems methodologies and tools to support the orderly transformation of our power systems.

As noted earlier, what we know as 'the power system' is a network of seven distinct but inter-dependent structures. In the Australian context, several significant issues are already emerging that are impacting these structures, spanning several industry segments and risk propagating instability both up and downstream.

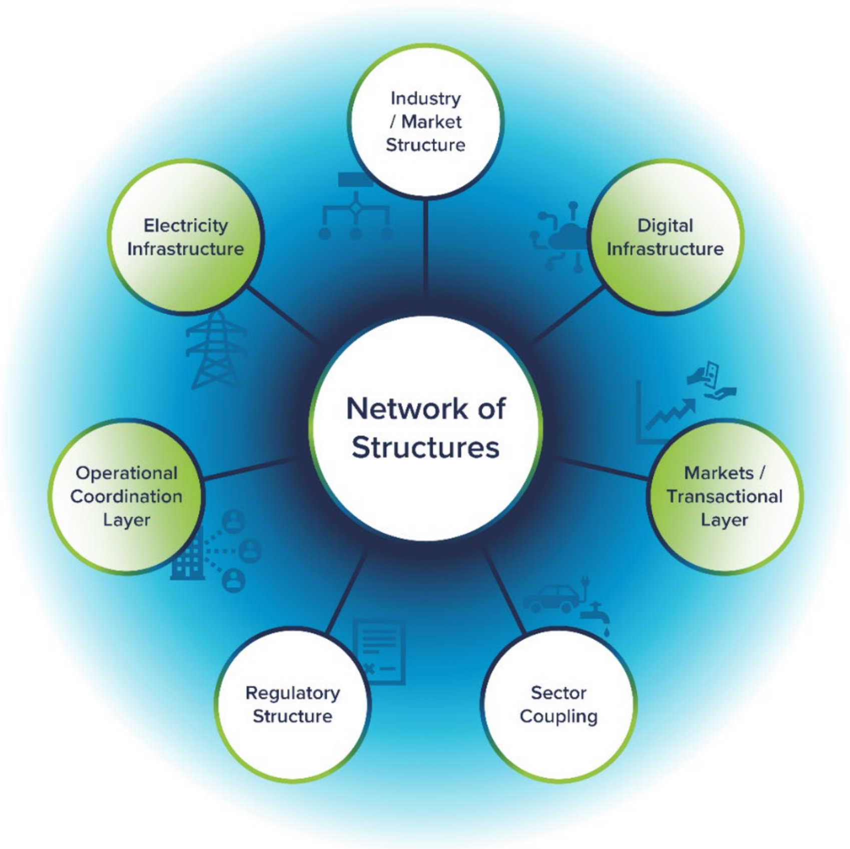


Figure 4: Modern power systems are a multi-structure network of deeply inter-dependent structures [11].

[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 any 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.

> *A diverse range of end-user customers together with System Operator, transmission, distribution, DER aggregation, technology vendors, regulatory representatives are supported in objective, focused and efficient engagement on change options*

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 aggregation, technology vendors, regulatory representatives.

'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-of-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 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 involving a few thousand participants, validate the integrated solution sets capable of scaling to serve many millions of participants without building anything further.

5. As the grid decarbonises, identify opportunities to deliver a whole-system optimisation premium that provides customers and society potential savings worth $-billions not otherwise be visible or achievable.

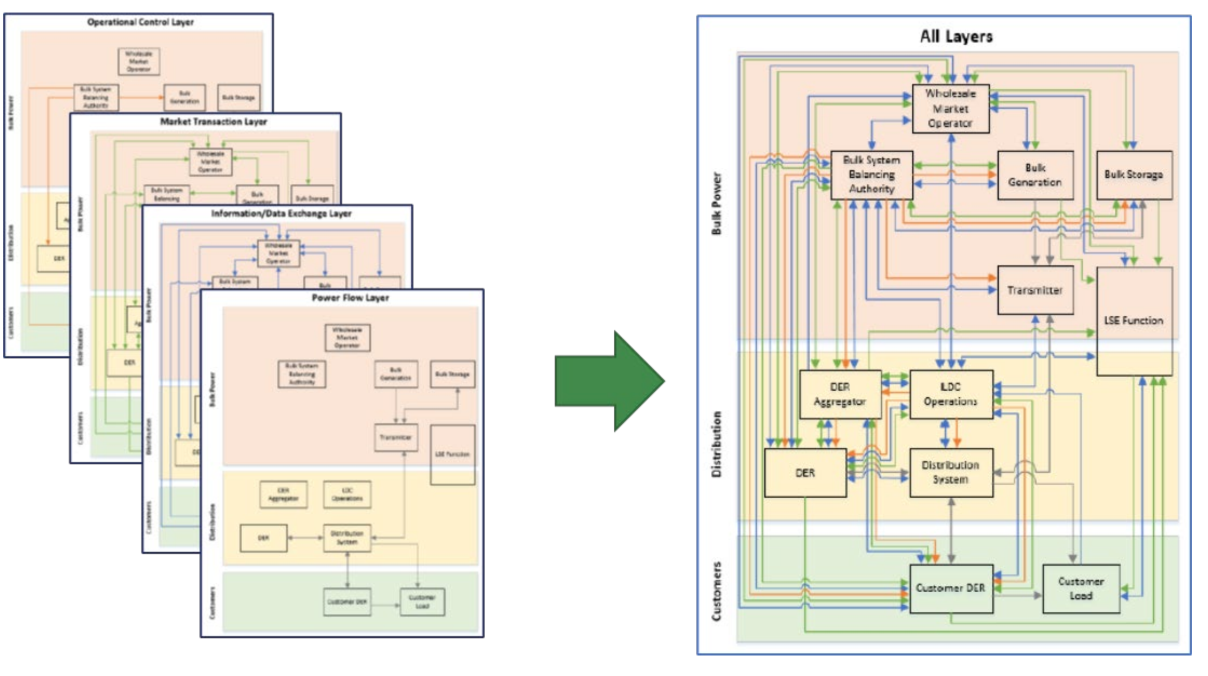


Figure 5: Systems Architecture disciplines provide essential tools for collaboratively identifying the minimum set of structural changes required to provision a power system for maximum future resilience [12].

[12] Images: Development of a Transmission-Distribution Interoperability Framework, prepared by ICF for the Independent Electricity System Operator, Ontario, Canada (2020)

Conclusion

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

In the context of a once-in-a-century scale of change, Power Systems Architecture disciplines provide new levels of strategic insight for navigating an uncertain future. As illustrated in a recent internationally co-authored IEEE report [12], such methodologies will be essential for objectively addressing many threshold issues in a future-resilient manner, including:

- Distribution System Operator (DSO) model designs and extensibility;
- Transmission–Distribution Interface design;
- Consideration and assignment of future roles and responsibilities across the full power system; and,
- How the 'Operational Coordination' of the power system will occur as it transition from hundreds to tens of millions of participating energy resources.

This is because the underpinning structures of any complex system always have a disproportionate influence on what the system can safely, reliably, and cost-efficiently do.

Ultimately, when a power system is experiencing profound change, ensuring its underpinning structures are 'match fit' for future needs is key to delivering secure and least cost outcomes for society [13][14].

For more information on Power Systems Architecture refer to:

https://www.strategen.com/gpst-psa-report

[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

The Author

Mark Paterson is a Fellow of the Pacific Energy Institute. He is also Managing Director, Australia Pacific and Lead Systems Architect at Strategen Consulting.

Mark is a globally-connected energy system transformation leader with over 25-years of experience in technology strategy, power systems architecture and thermal and fluid systems. He is known for his expertise in leading the collective navigation of complex and contested issues, systems thinking and the co-design of transformation pathways that build social licence and deliver future-resilient outcomes.

Mark's theoretically robust but pragmatic approach is grounded in applied technology origins and Engineering, Business and Master of Enterprise qualifications. He has been formally trained in Systems Architecture & Engineering disciplines at Massachusetts Institute of Technology (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.

Email: mpaterson@strategen.com

Mobile: +61 459 841 006

References

[1] https://aemo.com.au/en/newsroom/news-updates/the-view-from-the-control-room

[2] https://www.aemo.com.au/newsroom/media-release/nem-prepares-for-step-change

[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] The Strategen G-PST Power Systems Architecture (2021) report and overview video are provided here: https://www.strategen.com/gpst-psa-report

[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