Overview of G-PST Power Systems Architecture – Stage 2

IRED 2022, Adelaide

CONTEXT: Identifying and applying global best practice methodologies for 'taming' the structural complexity of grid transformations

- Stage 1 of this project reviewed various approaches employed globally for evaluating how the underpinning structures of GW-scale power systems may need to change to enable deep decarbonisation toward a NZE future.
- The Stage 1 report surveyed over twenty global initiatives and approaches. It also provided an Action Plan for implementing best practice learnings in Australia. The report and a short explainer video are both linked right.
- Stage 2 is currently undertaking an accelerated exploration of the 'as built' Reference Architectures (similar to prototypes) of the NEM and applying the formal tools to explore what may be required to enable grid futures similar to that illustrated by AEMO's 'Step Change' scenario.
- The project benefits from engagement with diverse Australian stakeholders and the International Expert Panel (IEP) with representatives from the United States, European Union and United Kingdom (refer slide 8).

Download Stage 1 report

Report Overview Video (12 min)

CONTEXT: The project occurs in parallel with a building consensus on the plausibility of AEMO's Step Change 2050 scenario

9x Grid-scale wind and solar

5x Distributed solar PV

3x Dispatchable firming capacity

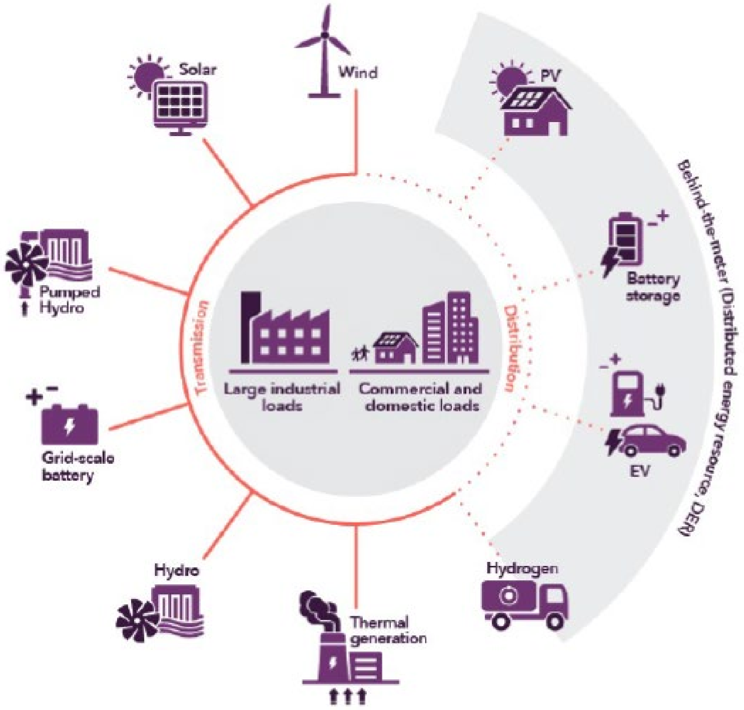


Image: AEMO Integrated System Plan (2022)

CONTEXT: The project benefits from engagement with diverse Australian stakeholders and the following International Expert Panel (IEP)

Prof. Jose Pablo Chaves Avila

Deputy Director at Instituto de Investigación Tecnológica (EU)

Paul De Martini

Executive Director, Pacific Energy Institute (US)

Prof. Lynne Kiesling

Research Director, Institute for Regulatory Law & Economics, University of Colorado-Denver (US)

Dr Jeffrey Hardy

Senior Research Fellow at Imperial College London (UK)

Dr Lorenzo Kristov

Power Markets & System Architecture Expert (USA)

Phil Lawton

Energy Systems Catapult (UK)

Dr Ron Melton

Director, Pacific Northwest National Labs Smart Grid Demonstration Project (USA)

Francis Mosley

Senior Innovation and Systems Engineer at Ofgem (UK)

Dr Seemita Pal

Senior Research Engineer, Pacific Northwest National Labs (USA)

Dr Jeffrey Taft

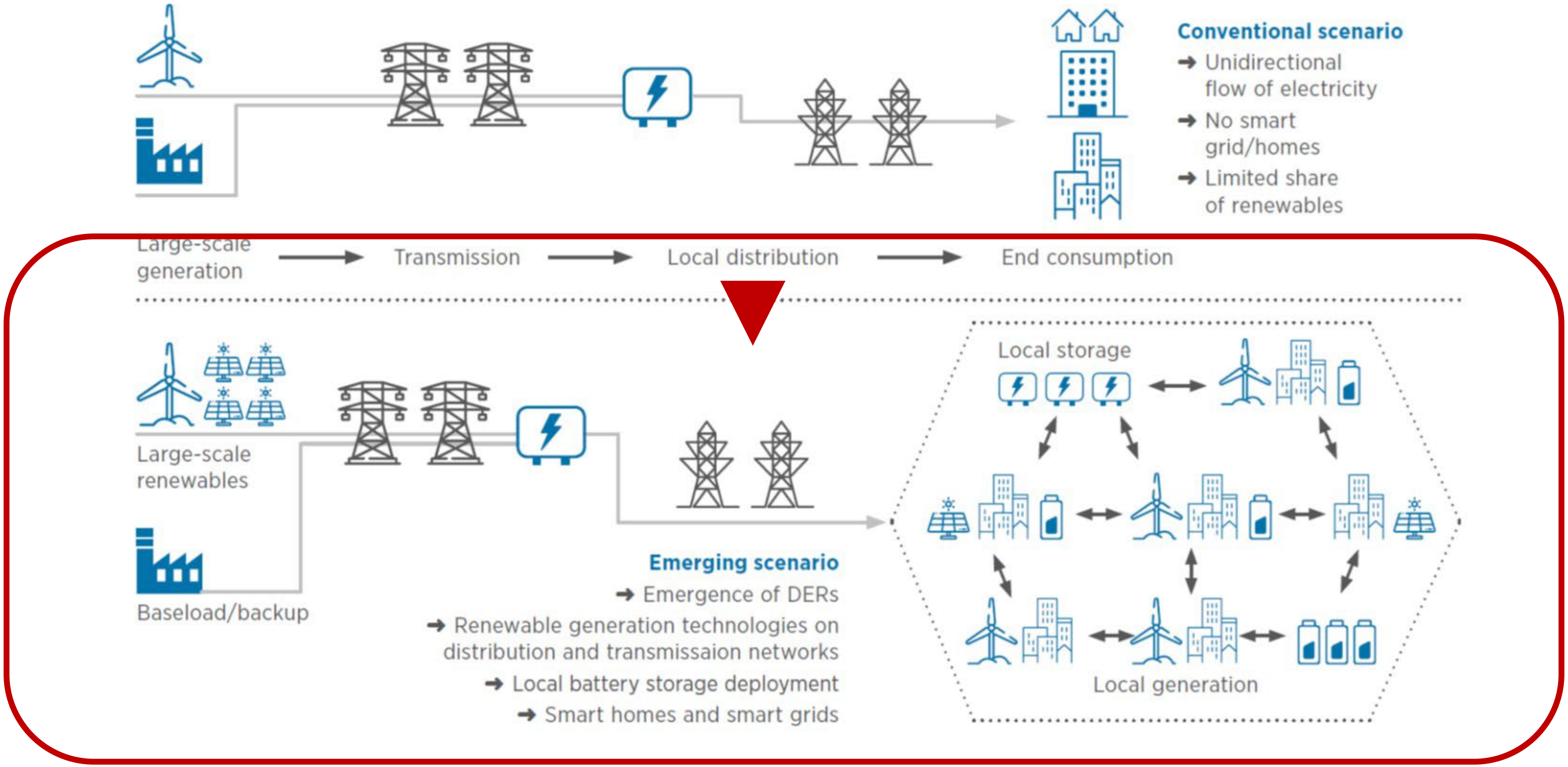
Former Chief Architect, Pacific Northwest National Laboratory (USA)

Thought Experiment…

Imagine 'zooming out' to consider the whole-system implications of deep decarbonisation…

(i.e. in particular, how future power systems will function 'end-to-end' as deeply interdependent and adaptive systems)

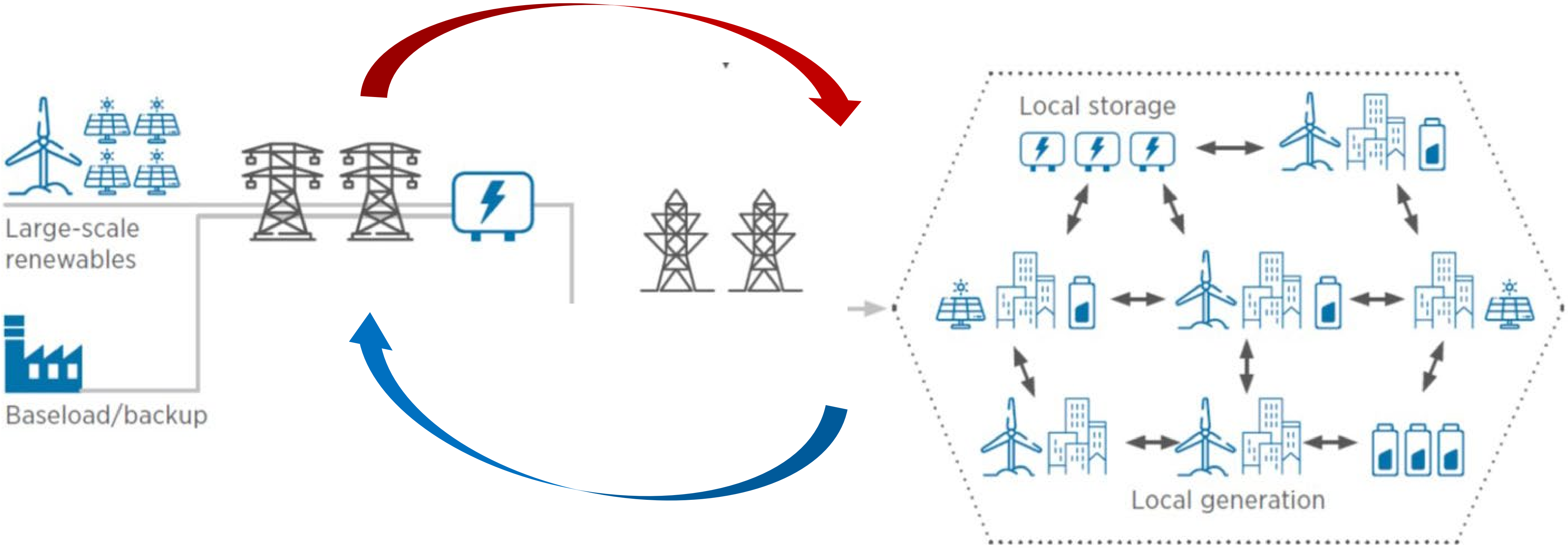
Australia's grid is rapidly transforming…



Australia's grid is rapidly transforming…

+ One of the world's fastest transitions away from coal-fired synchronous generation
+ Largely replaced by highly variable IBR generation (both centralised and decentralised)
+ Involves a transition from hundreds to tens of millions of participating resources, a growing proportion being privately owned
+ Supply and demand balancing and the provision of ESS far more challenging
+ Increasing time windows where >80% of instantaneous demand is served by DPV located at the polar opposite end of the system from its original design
+ System flexibility / balancing services must increasingly come from the customer (nee 'demand') end of the system

In other words…



21st century power systems will increasingly require bulk energy, transmission and distribution systems – and deep demand-side flexibility – to **function holistically** to enable reliable and efficient operation.

Image: IRENA System Operation Collection (2020)

Advanced ‘Operational Coordination’ models are key to enabling a system transitioning from hundreds to tens of millions of resources

The financial value of DER / BESS services vary significantly by time, location and the extent to which they are co-optimised across the ‘vertical’ layers of the power system (i.e. bulk power, Tx, Dx).

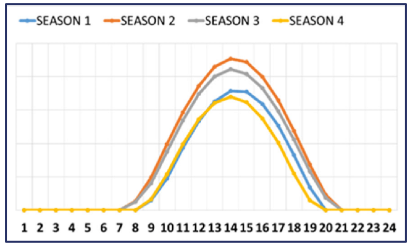
This is because the actual benefits provided to the power system by DER / BESS will be determined by what the power system needs at a given time and layer / location, which varies dynamically.

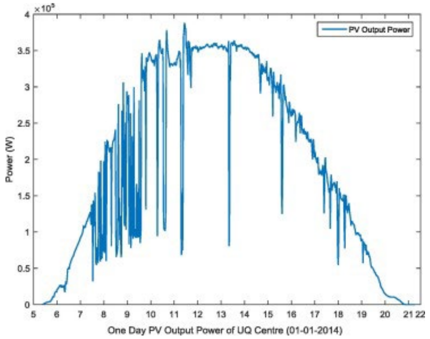
Advanced Operational Coordination models are key to maximising the customer / system / financial value of DER / BESS services as they enable the dynamic provision of:

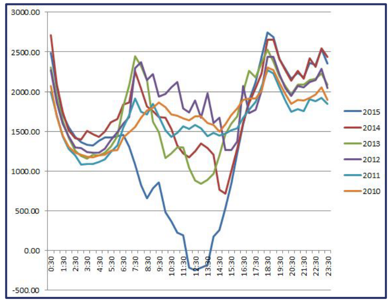
- ✓ the right physics-based service (energy, power, essential system services);
- ✓ at the right time (days, hours, minutes, seconds, microseconds); and,
- ✓ at the right layer / location (bulk power, Tx system, Dx system, Dx feeder).

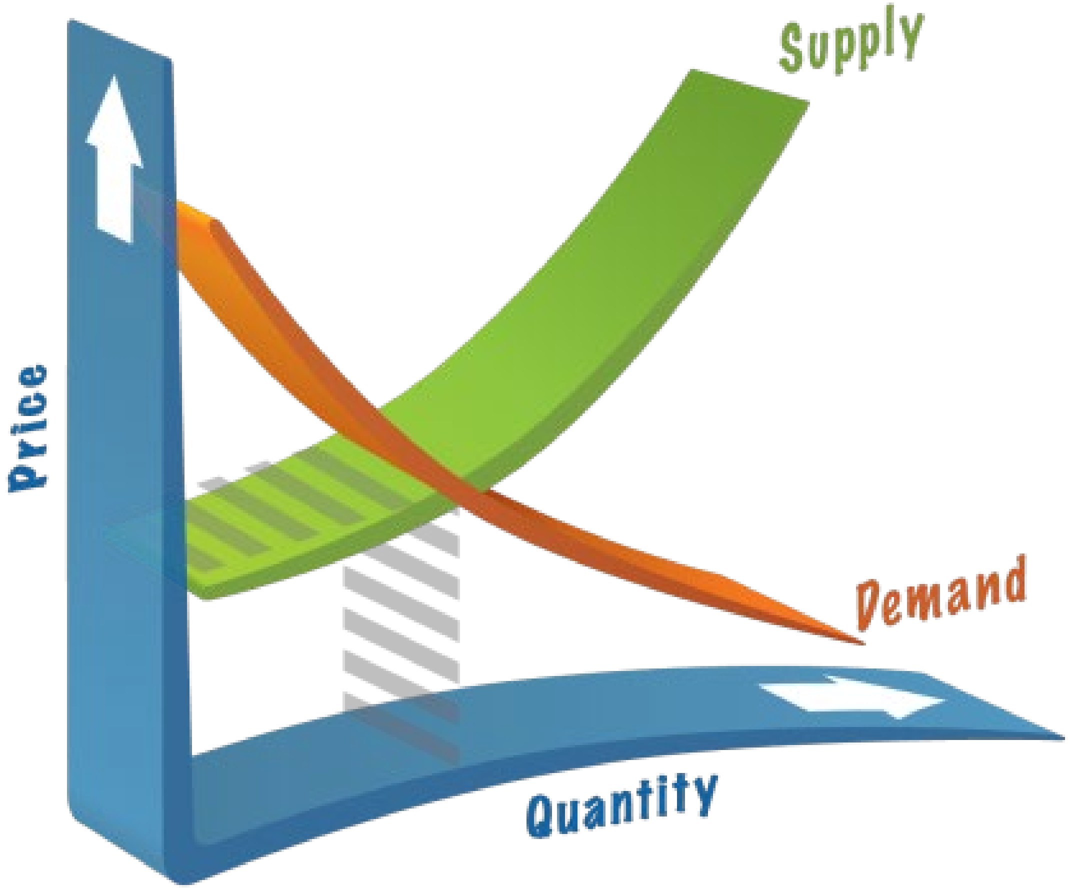
Ultimately, the stronger the correlation between specific power system needs and the dynamic provision of DER / BESS services, the stronger the potential quantum of financial benefits that can be shared with participating customers.

‘Keeping the lights on’ in a much more dynamic power system requires instantaneous balancing of supply and demand…





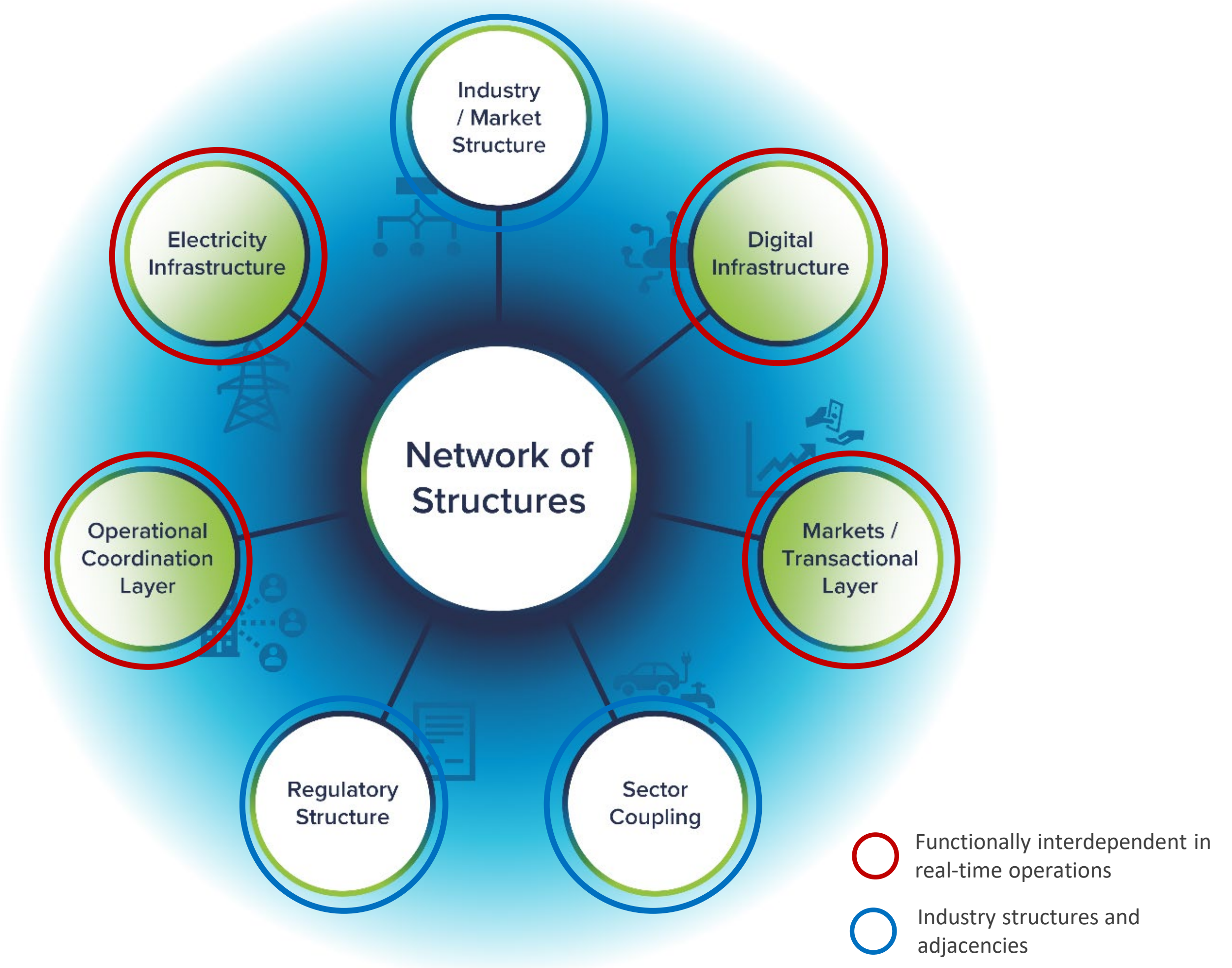




Volatility from both VRE generation and customer demand must be kept **‘in balance’ every millisecond**, not just on average during the year.

Advanced ‘Operational Coordination’ is critical for the end-to-end power system to operate holistically (and efficiently)

Modern power systems are a massively complex* ‘Network of Structures’



Systems Architecture disciplines are critical for ‘taming’ this complexity to develop robust models of Operational Coordination for the 21st century power system

CSIRO and AEMO have recognised that Systems Architecture is "central and foundational" to enabling Australia's grid transformation

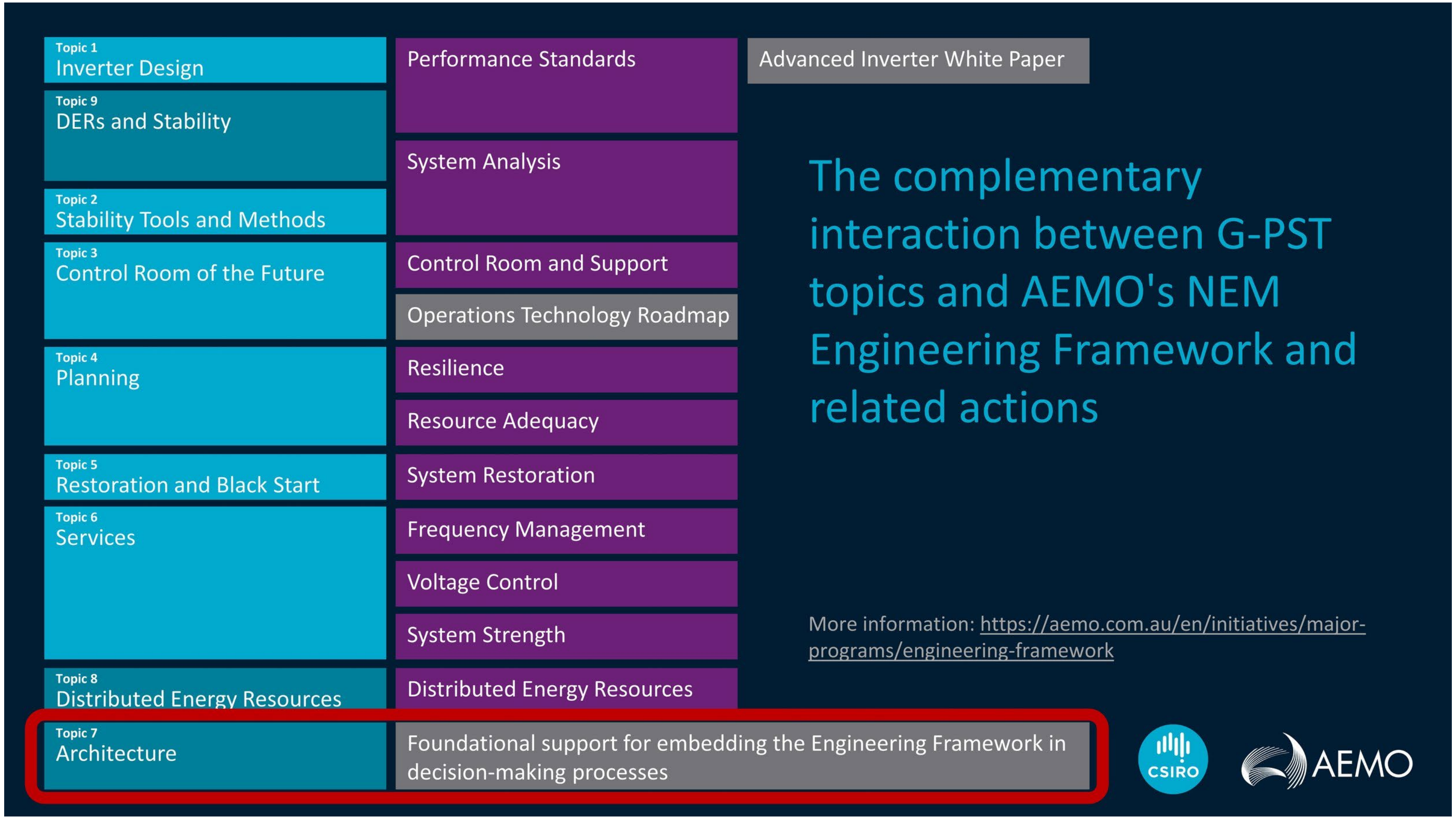


Image: Australian research leadership in the Global Power System Transformation, CSIRO & AEMO (March 2022)

Advanced 'Operational Coordination' will require both Markets and Controls across various layers of the system

Market economists:

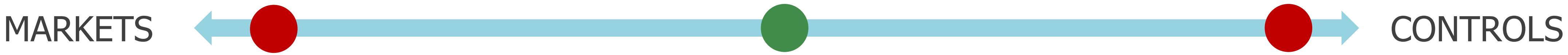
"Just get the market rules and prices right and everything will work fine"

✓ Solution:

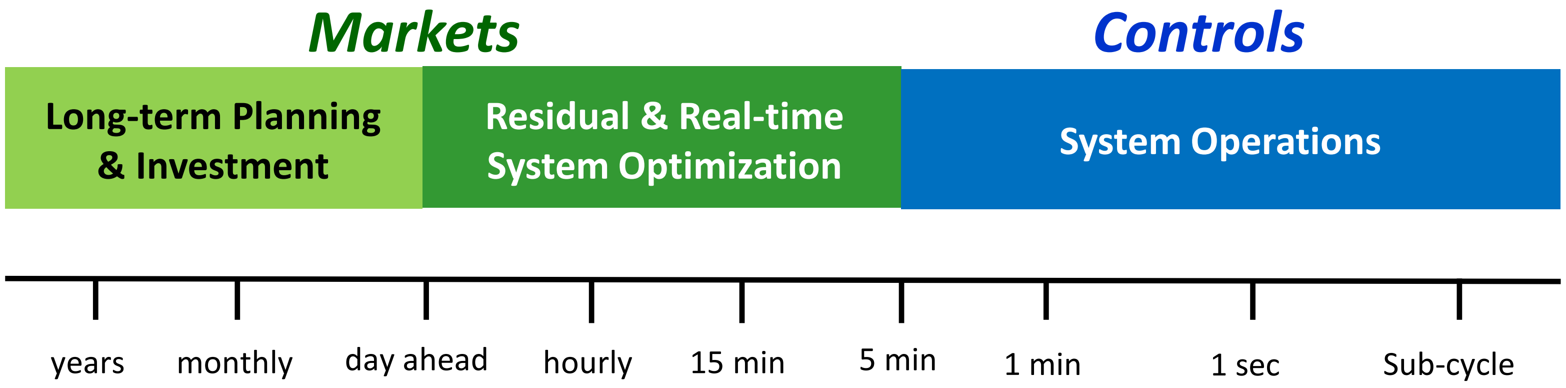
An ensemble of both market and control features is required

Control engineers:

"Just get the control algorithms and interoperability standards right and everything will all work fine"

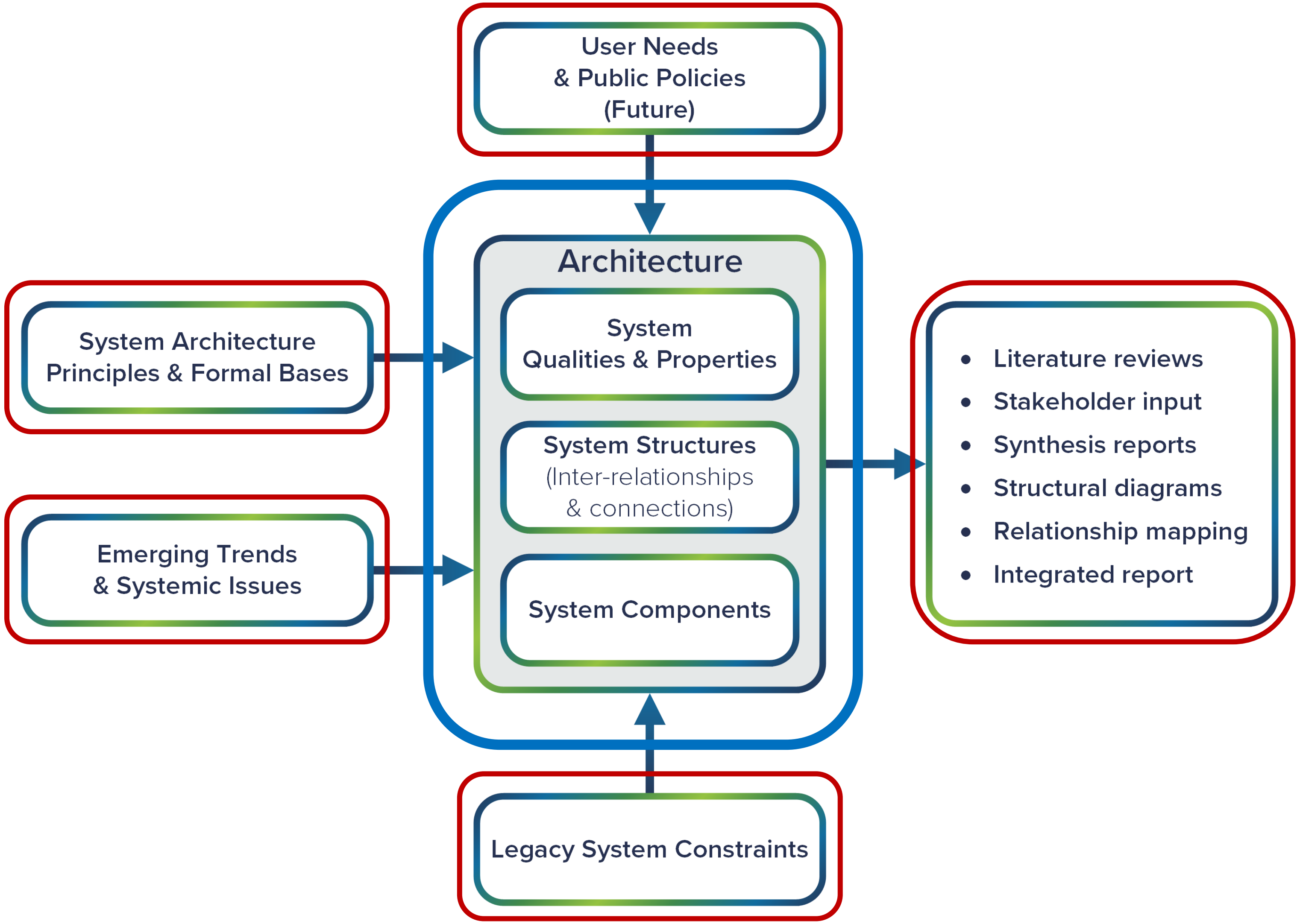


Markets vs Controls false dichotomy



Content adapted from Newport Consulting and Pacific Northwest National Lab.

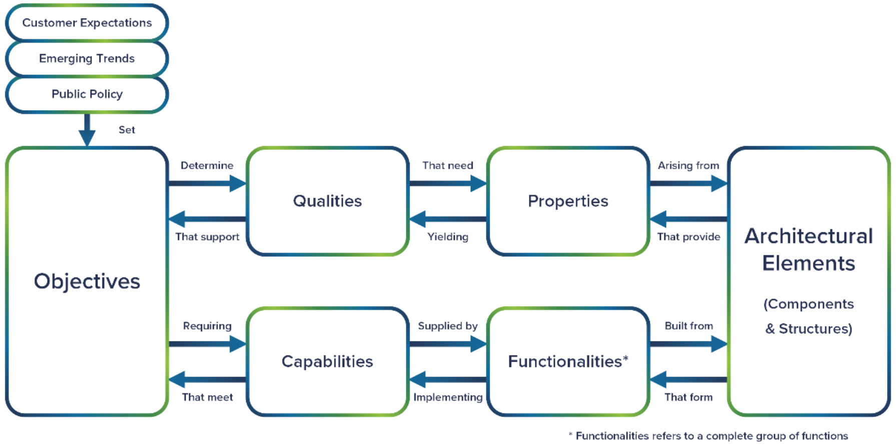
Architecture Development Process



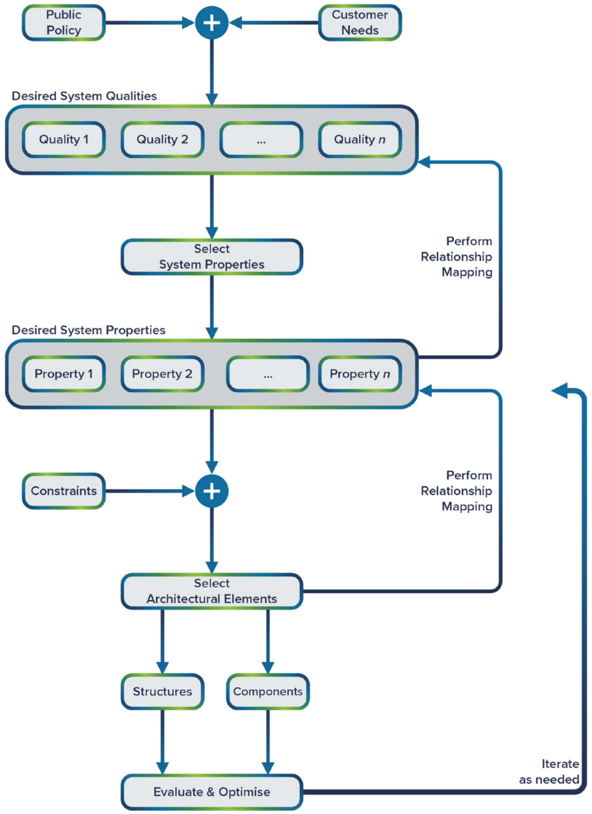
STRATEGEN

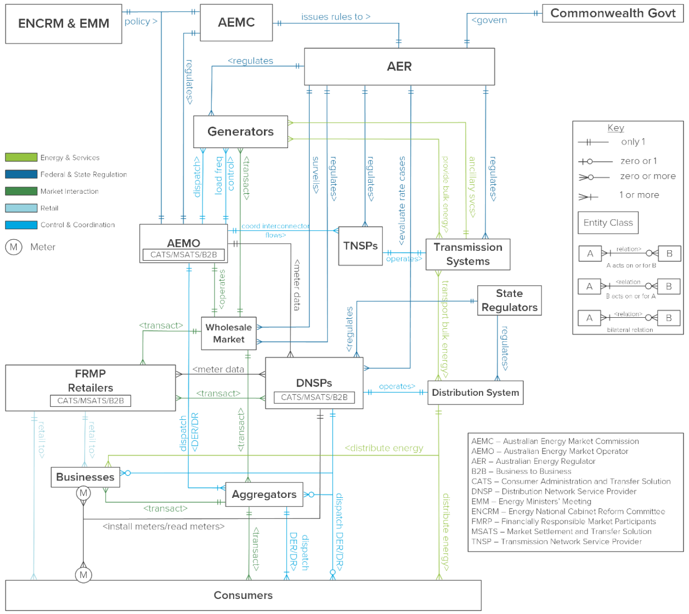
Example Systems Architecture Processes, Resources & ER Mapping* under development

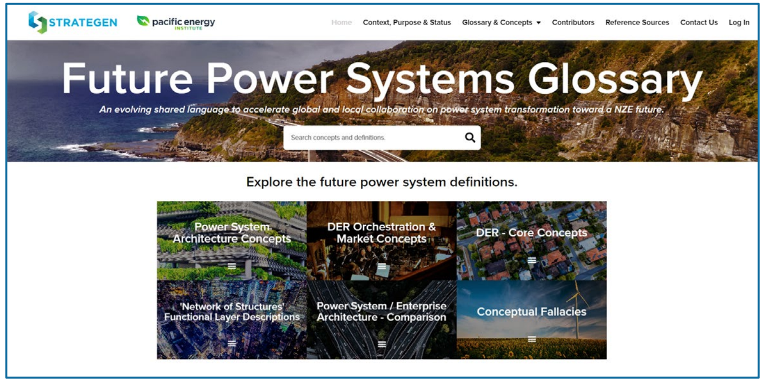
Power System Architecture Concepts Loop



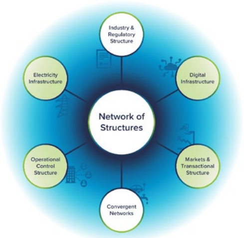
Qualities-Properties-Components Relationships Diagram

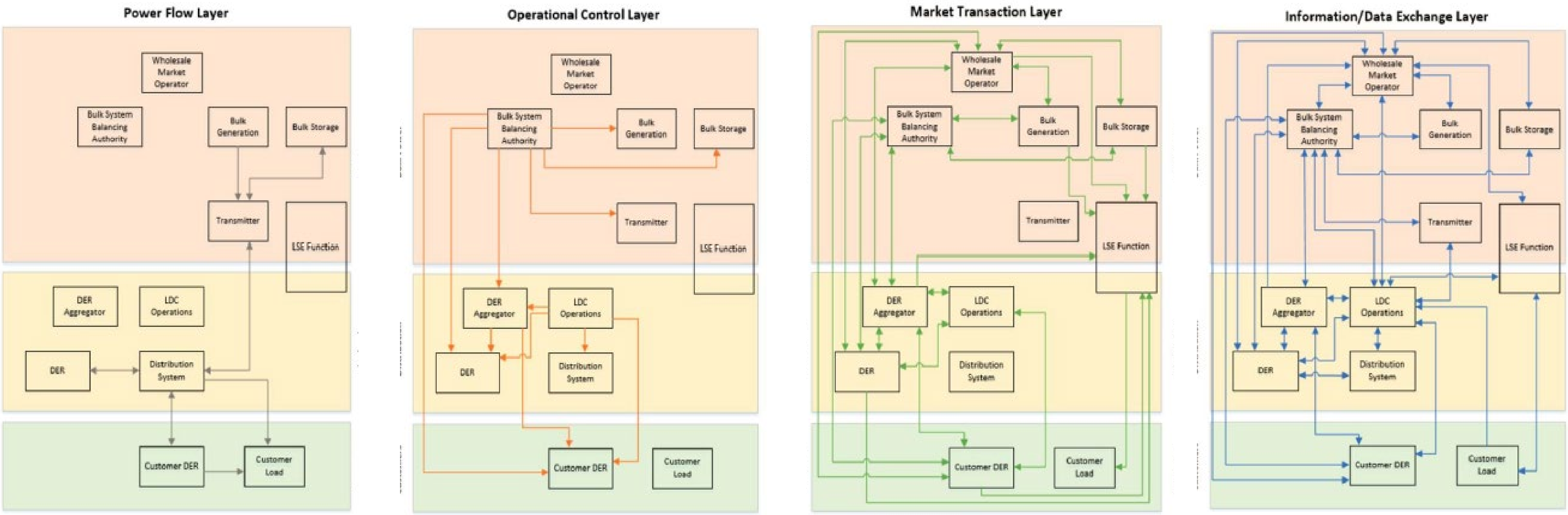






The ‘Network of Structures’ approach enables us to map and interrogate the ‘as-built’ structures and make choices about the future architecture



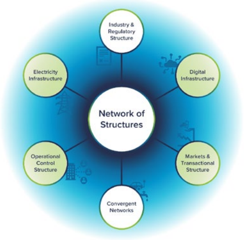


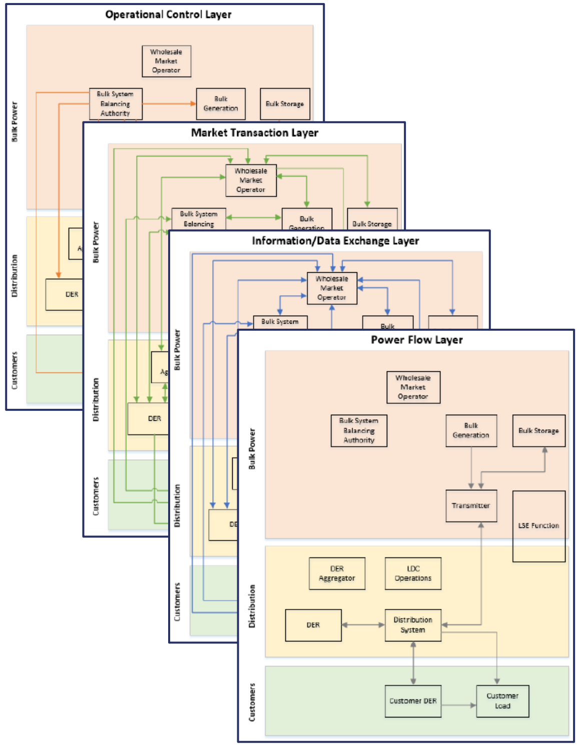
Important: In most jurisdictions that face large scale grid transformation, one of the first realisations is that no single or agreed set of ‘whole-of-system’ structural diagrams of all layers of the ‘as-built’ grid exists.

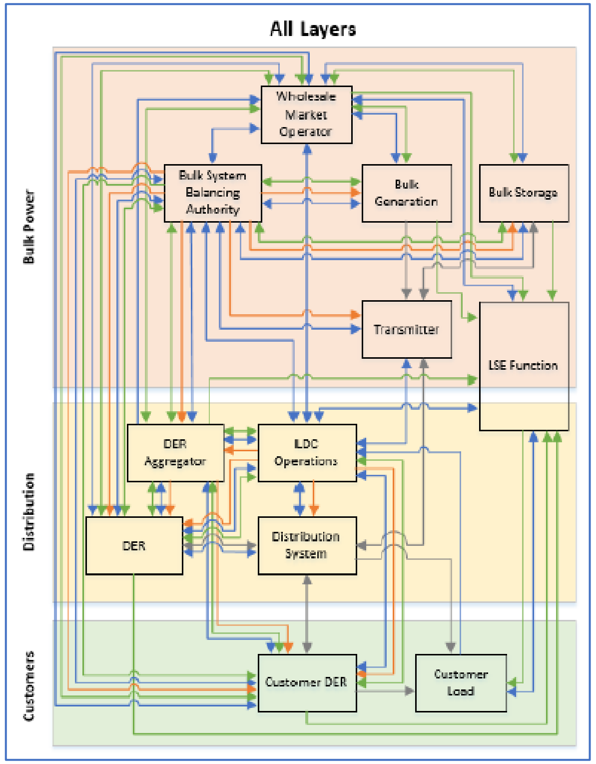
STRATEGEN

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

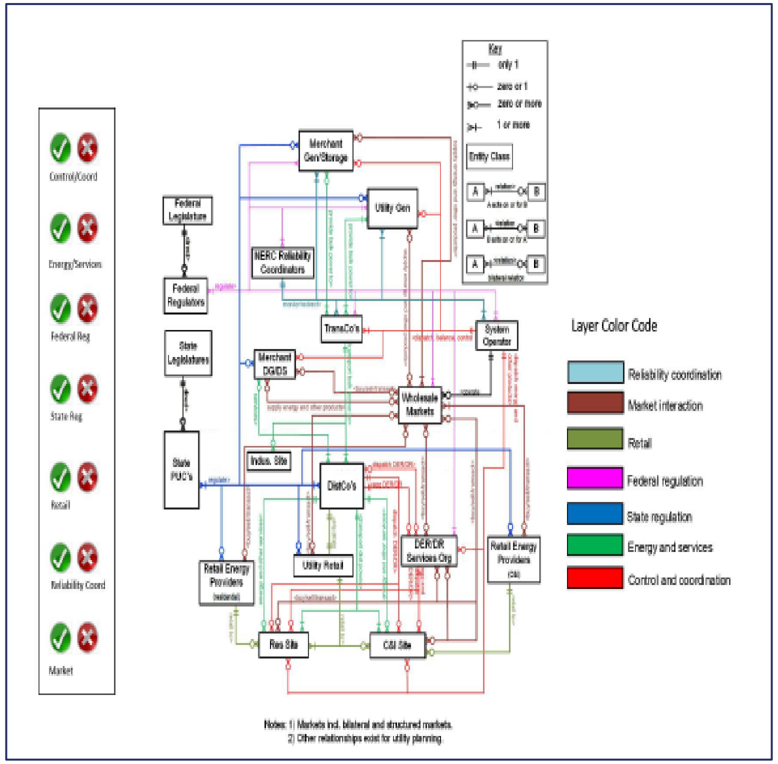
The 'Network of Structures' approach enables us to map and interrogate the 'as-built' structures and make choices about the future architecture







4 x Interdepended 'Functional' Layers

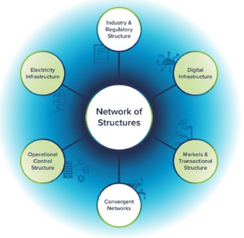


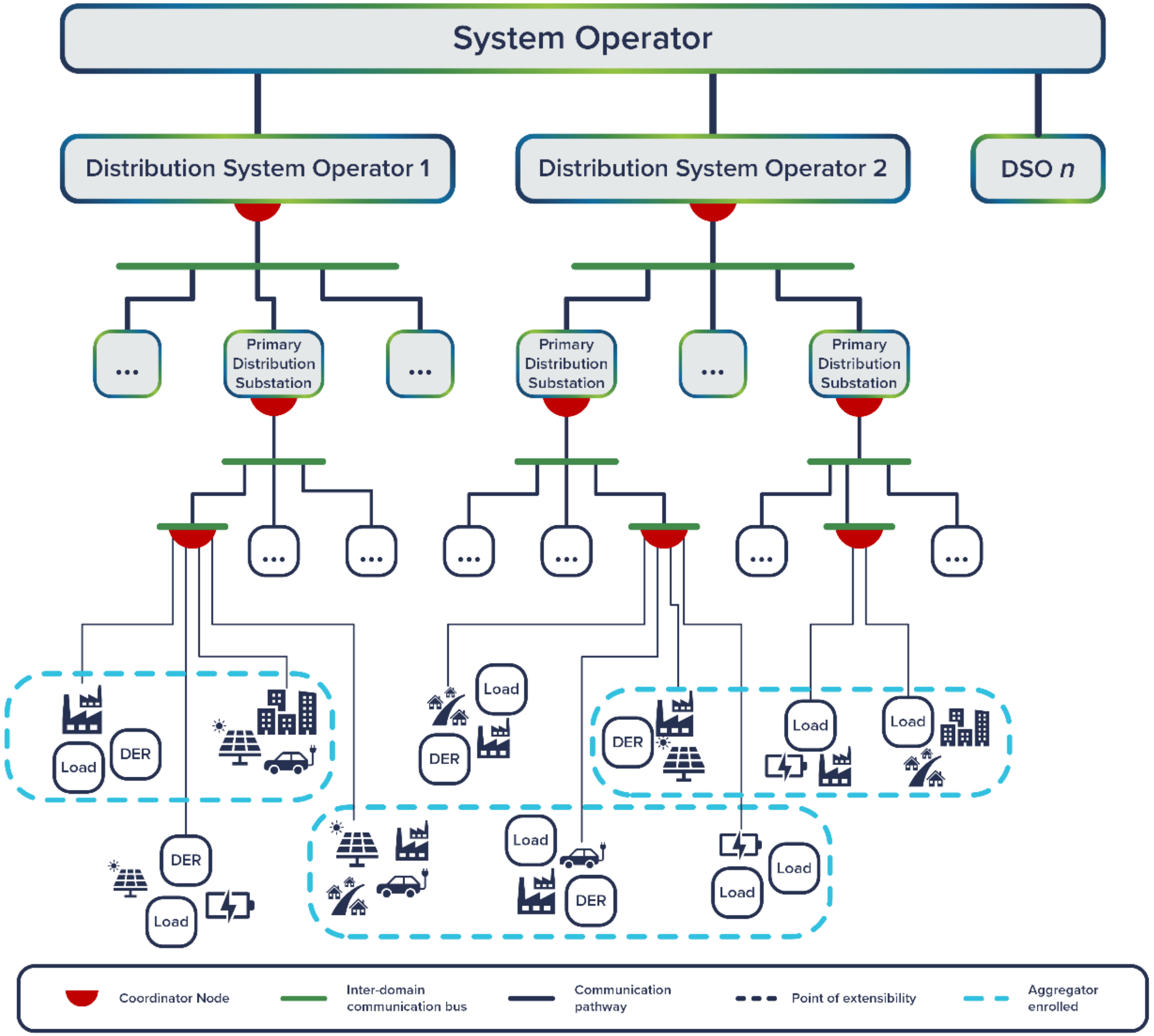
Industry & Regulatory Relationships

The above illustrates the four 'Functional Layers' of a modern power system overlaid as inter-dependent structures plus the industry and regulatory structures. This pre-existing complexity requires fit-for-purpose tools to decompose, 'tame' and simplify as the basis for future enhancements and stakeholder collaboration.

Images: Development of a Transmission-Distribution Interoperability Framework, prepared by ICF for the Independent Electricity System Operator, Ontario, Canada (2020) and Pacific Northwest National Lab (2021)

This is critical for making structural choices that can scale from hundreds to tens of millions of participating resources





Power Systems Architecture provides formal methodologies for examining:

- New System Functions such as Distribution System Operator (DSO) models, the evolving roles of the TNSP/TSO and Transmission-Distribution Interface (TDI) designs.
- How sectoral Roles & Responsibilities may need to evolve for optimal management of the power system in a future similar to AEMO's Step Change scenario.
- The detailed analysis of Operational Coordination models that the power system will require as it moves toward millions of participating resources.

Image: Strategen Consulting (2022)

Power Systems Architecture – Core 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. Fit-for-purpose tools are required to interrogate end-to-end structural weaknesses and stress-test potential changes and impacts while still in concept stage.
4. The future is uncertain, so providing greater optionality and future-resilience (not less) is a characteristic of fit-for-purpose tools.
5. The aim is to identify the minimum structural changes required for the existing power system to be future-ready for the scale of change unfolding.

* Feiler et al, Ultra-Large-Scale Systems: The Software Challenge of the Future, Carnegie Mellon, Software Engineering Institute, 2006

Power Systems Architecture – Key Benefits

1. Develop scalable, end-to-end Operational Coordination models for a power system that involves tens of millions of diverse and dynamic energy resources.

2. Identify hidden legacy structural issues that create cyber-security weaknesses.

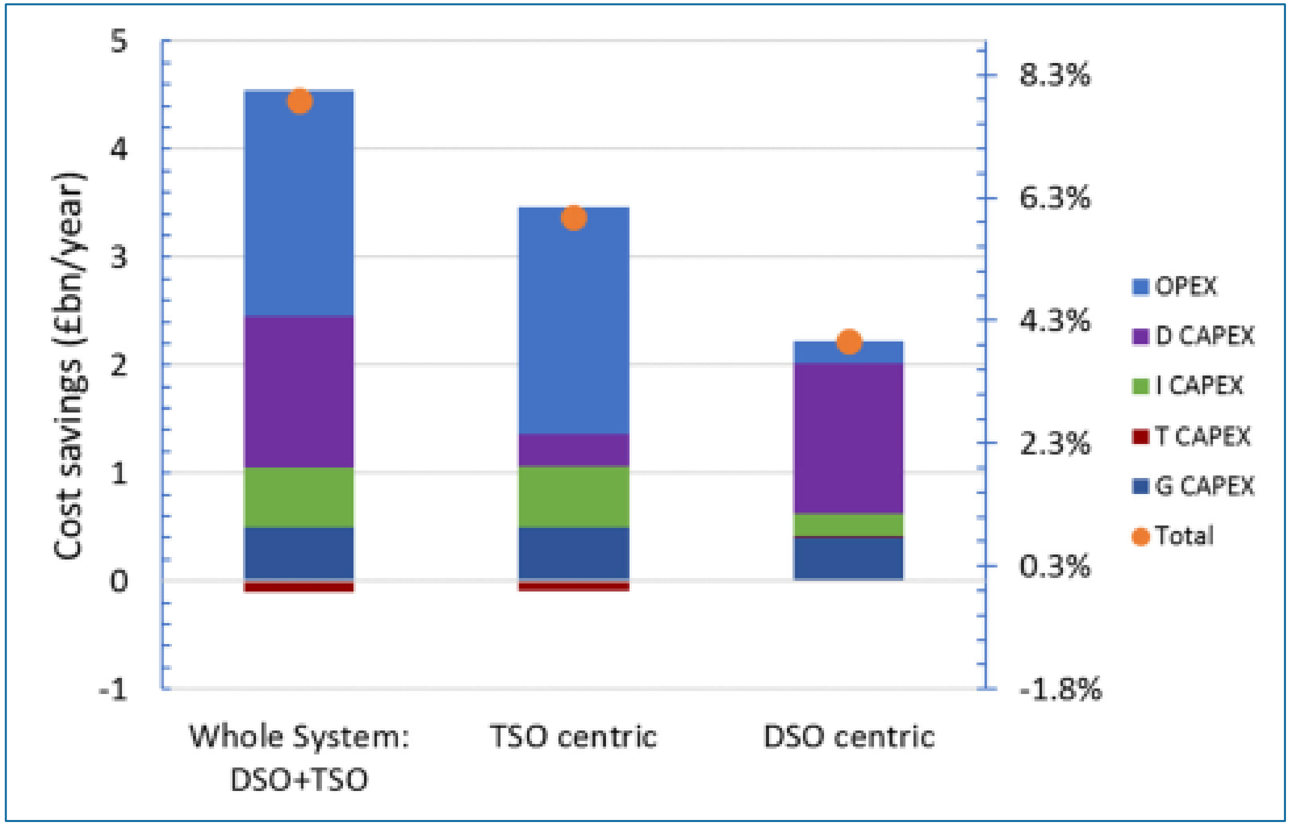
3. Provide a evidence-based methodology to analyse Australia's many technology trials to derive and convergence on universal and transferable learnings.

4. Without building anything further, stress-test the future mass-scalability of solutions beyond pilot volumes to tens of millions of participating resources

5. Identify early where short – medium term transition decisions may unintentionally propagate systemic complexity and fragility in the longer term.

These are key to Australia realising a whole-system optimisation premium in transforming its complex power systems: 'achieving more from less'

Power Systems Architecture – Optimisation Premium



Potential benefits of improved transmission and distribution control interface

Imperial College London (ICL) estimated the Optimisation Premium of whole-system-based coordination of demand-side flexibility in the UK to be in the order of 8.3% TOTEX annually.

Annual Savings

- DSO-centric approach AUD $3.9bn
- TSO-centric approach AUD $6.1bn
- Whole-system approach AUD $8.0bn

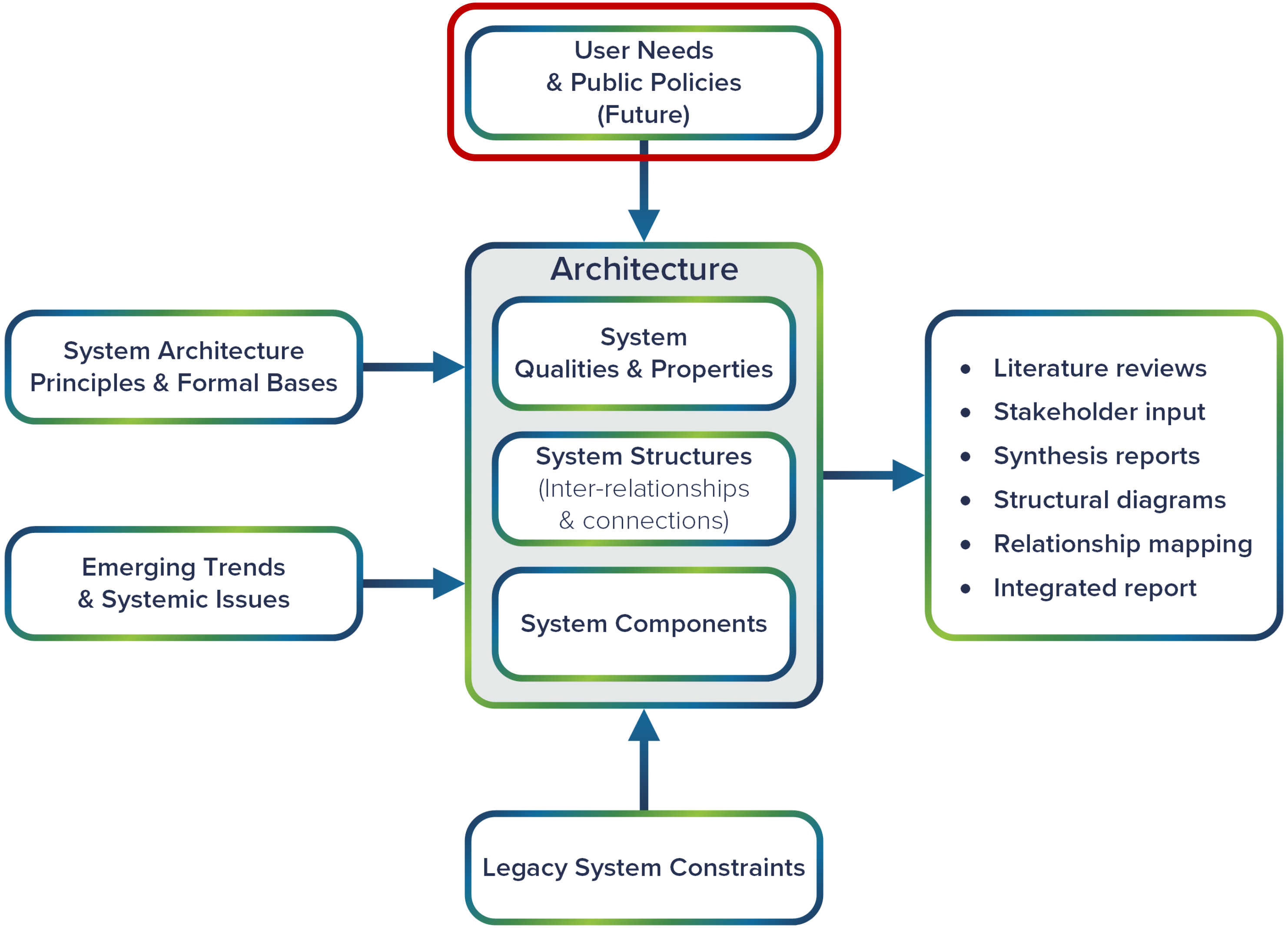
Strbac et al, Cost-Effective Decarbonization in a Decentralized Market: The Benefits of Using Flexible Technologies and Resources, IEEE Power & Energy Magazine, 2019

Thank You!

Appendix A: Customer & Societal expectations of future power systems

Early insights from Global & Australian literature review

Architecture Development Process



We require many things from our Power Systems: 8 x Key Objectives*

1. Dependable:
   Safe, secure, adequate, reliable and resilient
2. Affordable:
   Efficient and cost-effective
3. Sustainable:
   Enables 2030 and 2050 decarbonisation goals
4. Equitable:
   Broad accessibility of benefits and the fair sharing of costs
5. Empowering:
   Advances customer and community agency, optionality, and customisation
6. Expandable:
   Enables electrification of transport, building services and industrial processes
7. Adaptable:
   Flexible and adaptive to change, including technological, regulatory and business model innovation
8. Beneficial:
   Socially trusted, public good/benefits, commercially investable and financeable

* Source: Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

1. Dependable

+ Key Features: Safe, secure, adequate, reliable and resilient
+ Example Considerations:
  - Importance of continuity of supply continues to increase as lifestyles, homes, businesses, industry and transport become more electrified, automated and digitised
  - Opportunities arising from for improved reliability, resilience, and the time taken to restore services
  - New challenges and vulnerabilities, i.e. cyber-security including customer data privacy and protection
  - System resilience in the context of extreme weather events

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

2. Affordable

+ Key Features: Efficient and cost-effective
+ Example Considerations:
  - Utilisation of existing transmission and distribution
  - Efficient investment in utility-scale infrastructure
  - Tightly coupled with emerging features such as automation, demand-side flexibility, cost-reflective tariffs, unbundling of energy services, and energy efficiency
  - Customer’s perception of value and alignment with the costs they incur
  - Competition and cooperation across the supply chain

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

3. Sustainable

+ Key Features: Enables 2030 and 2050 decarbonisation goals
+ Example Considerations:
  - Customers increasing sense of shared responsibility for decarbonisation goals
  - Energy systems design, construction, operation and decommissioning
  - Energy efficiency (plant and equipment) and energy productivity (value gained from using a unit of energy)
  - Clear, transparent and accountable reporting on sustainability performance

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

4. Equitable

- Key Features: Broad accessibility of benefits and the fair sharing of costs
- Example Considerations:
  - Equitable distribution of benefits, ensuring vulnerable customers do not incur a disproportionate share of the costs of operating the system
  - Fit-for-purpose Consumer Protections
  - Minimising complexity for customers
  - Provision of relevant information to assess offerings relevant customer circumstances
  - Fair access to services and platforms

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

5. Empowering

+ Key Features: Advances customer and community agency, optionality, and customisation
+ Example Considerations:
    - Respecting the diversity of customer types and aspriations
    - Human-centred design and continuous feedback from customers
    - Enabling and empowering informed choice
    - Simple and intuitive platforms that enable customers to:
        - Chose whether to respond to energy 'events'
        - Understand key data for decision making
        - Capture and input household/business preferences, routines and expectations
    - Customers can easily compare offerings across competing providers and platforms
    - Availability of simple no-frills arrangements

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

6. Expandable

+ Key Features: Enables electrification of transport, building services and industrial processes
+ Example Considerations:
  - Promote load flexibility for supply and demand balancing
  - Temporal and spatial load diversification
  - Strategic integration of energy storage across all levels of the power system
  - Mutually beneficial customer offerings that support the operation of the power system
  - Operational scalability

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

7. Adaptable

+ Key Features: Flexible and adaptive to change, including technological, regulatory and business model innovation

+ Example Considerations:
  - Enable a diverse range of innovative business models, products, platforms and services while maintaining the security and stability of the system
  - Enable customer churn to encourage competition
  - ‘No regrets’ decisions that enable the power system to be resilient to broad range of plausible futures
  - Staged implementation of reforms to the power system that consider the long-term effects on optionality

Source: DRAFT Customer & Societal Objectives for 21st Century Power Systems, Strategen (2022)

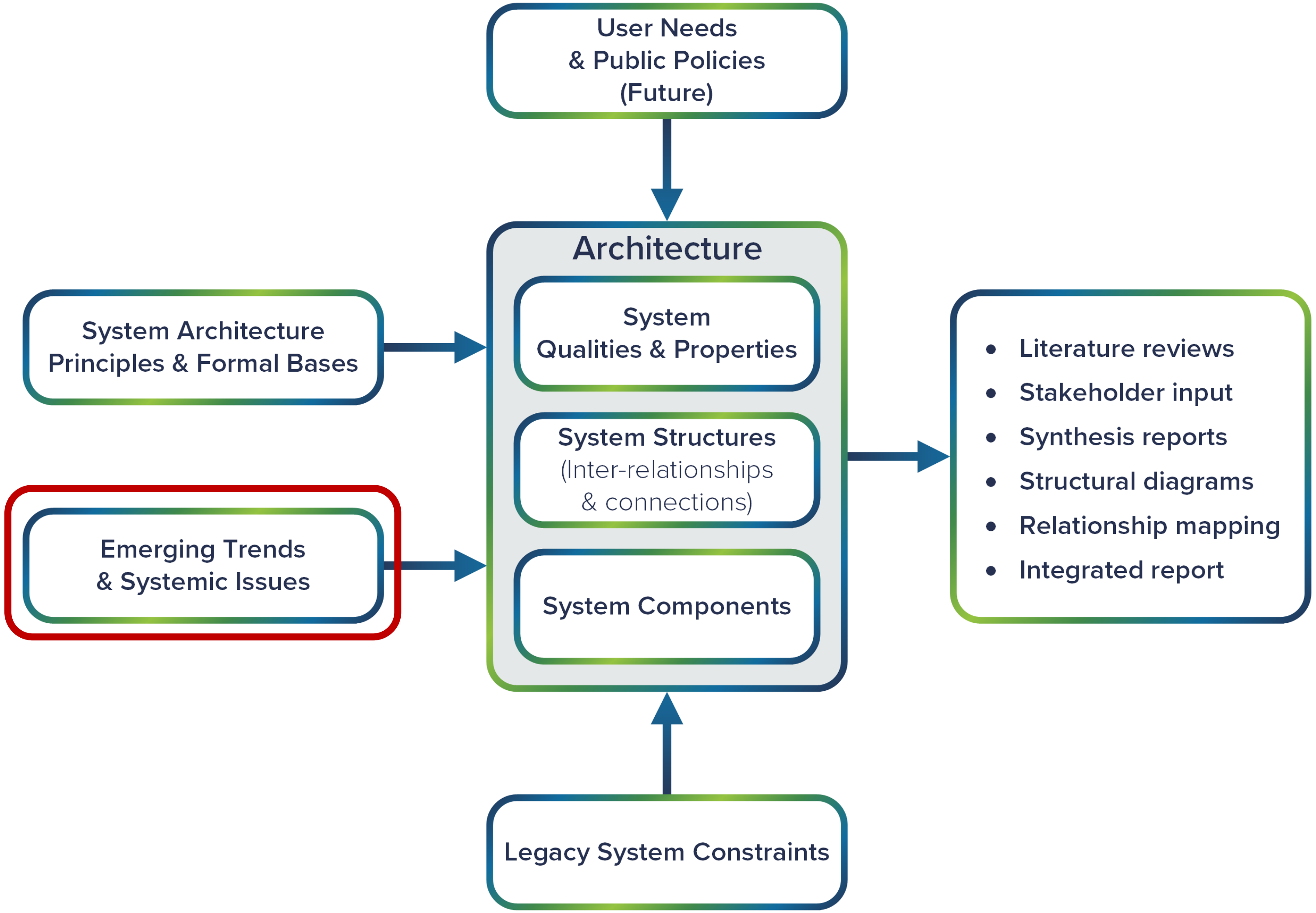
8. Beneficial

+ Key Features: Socially trusted, public good/benefits, commercially investable and financeable
+ Example Considerations:
  - Manage concerns around loss of control, data security, privacy and disruption to daily routines
  - Build trust by emphasising customer agency in the design of platforms and systems
  - Promote the societal good that comes from enrolling assets in programs that support the efficient operations
  - Reflect customer voice, concerns, and lived experience in customer facing product and service offerings

Appendix B: Emerging Trends impacting future power systems

Early insights from Global & Australian literature review

Architecture Development Process



Emerging Trends

Definition

"Drivers of change that may significantly influence the evolution of the power system over the next decade and beyond.

"These drivers present challenges and impediments and/or new opportunities and potentialities that are either probable or plausible (not simply possible).

"While on occasion they may be endogenous, they are typically exogenous and include the impacts of evolving Customer & Societal expectations of future power systems."

Focus Areas

2.1. Power System Structure

2.2. Operating Context

2.3. Generation Diversification

2.4. Load / Demand

2.5. Control Dynamics

2.6. Data & Communications

2.7. System Planning

2.8. Operational Forecasting, Management & Coordination

2.9. Business & Market

2.10. Network Convergence / Sector Coupling

Following are two examples of the sub-topics that are emerging from the analysis…

2.1 Power System Structure

2.1.1. The power system is transitioning from hundreds to tens of millions of participating energy resources

2.1.2. Participating energy resource types are becoming more varied, their operating characteristics more diverse and their locations more ubiquitous

2.1.3. The traditional 'supply-side / demand-side' bifurcation of the power system is eroding

2.1.4. Variable Renewable Energy (VRE) deployment at both HV and LV levels of the system is increasing volatility that can propagate in either direction

2.1.5. The scale deployment of energy storage connected to both Tx and Dx systems is accelerating and has the potential to be 'game changing' if systemically integrated

2.1.6. Essential System Services (ESS) will increasingly need to be provided by non-traditional sources connected to both the Tx and Dx systems

2.1.7. System flexibility and firming services will increasingly to be provided by non-traditional sources connected to both the Tx and Dx systems

2.1.8. While all layers of the power system are becoming more dynamically interdependent, the System Operator, Tx and Dx control rooms each have only partial visibility

2.1.9. There is growing recognition of the need for formal power system Roles & Responsibilities to evolve but a lack of clarity on longer-term requirements

2.1.10. There is some awareness of the structural constraints inherent to the legacy power system but limited discipline expertise for holistically addressing them

2.5 Management & Control

2.5.1. The power system is experiencing faster system dynamics and decreasing latency tolerance

2.5.2. The time windows in which the power system must operate with >100% of instantaneous demand being served by VRE are increasing in frequency and duration

2.5.3. System stability and optimisation risks increase where hidden feedbacks, cross-couplings and tier-bypassing exist in legacy power system structures

2.5.4. Co-ordination and co-optimisation of energy resources across several layers of the power system is becoming vastly more complex

2.5.5. System restoration and black start arrangements are becoming significantly more complex

2.5.6. Limited distribution system visibility, state estimation and controllability present increasingly significantly challenges at the whole-system level

2.5.7. The number and scale of new actors exerting control on the power system without fully appreciating the systemic implications is significantly expanding

2.5.8. The number and complexity of new control functions is growing significantly, especially at the distribution level

2.5.9. Power system computational loads are growing exponentially and computational ‘time wall’ risks are increasing

2.5.10. There is a growing need for scalable mass-deployment of Dynamic Operating Envelopes (DOE) to manage DPV export to the distribution system

2.6 Data & Communications

2.6.1. Operational, market and customer data volumes and variety are growing exponentially

2.6.2. Power system, market and customer data are required by an expanding number of entities

2.6.3. The cyber-security of systems and datasets is becoming increasingly prominent

2.6.4. Inadequate access rights to important operational data is becoming more problematic as the DPV fleet expands

2.6.5. Legacy system architectural and communications routing structures contain vulnerabilities that elevate cyber-security risks

2.6.6. Legacy system architectural and communications routing risk exacerbating latency cascading as the number of endpoints and data volumes expand

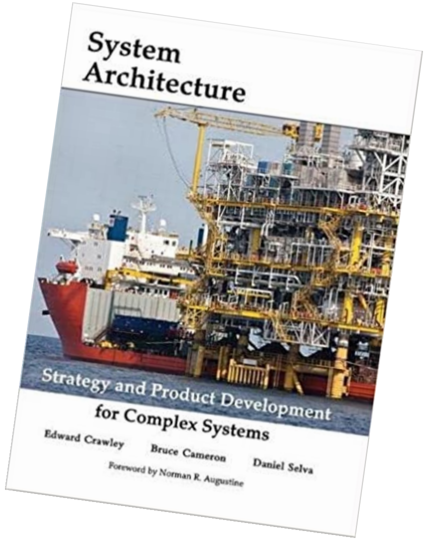
2.6.7. Technology and communications standards risk being impeded due to being developed in the absence of an agreed, future-ready systems architecture

2.6.8. Current interoperability standards development may be superseded as global consumer technology standards transition from a utility-focused to consumer-focused orientation

Appendix C: Key Concepts / Definitions

What is a "System"?

"A system is not the sum of its parts, but the product of the interactions of those parts"*



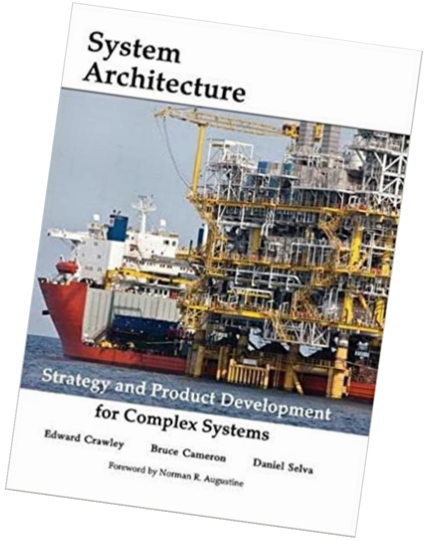
The 'emergent' characteristics of a functional system are the beneficial outcomes that are produced by the interactions of all its parts (i.e. being linked together by its underpinning structures).

'Emergency' is also a systems word with the same root. It's what emerges from a changing system where its legacy structures (which are key to how the parts interact) receive inadequate or only subjective consideration.

* Original quote attributed to Russell Ackhoff

What is "Complexity"?

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



"Complexity is driven into systems by 'asking more' of them: more function, more performance, more robustness, and more flexibility..."

"...It is also driven into systems by asking systems to work together and interconnect" (think BESS, EVs, smart inverters, etc. at scale)

What is "Power Systems Architecture"?

Power Systems Architecture is a generic term for an integrated set of disciplines that enable the strategic transformation of legacy power systems to better meet changing policy and customer expectations together with their physics-based implications.

While many traditional models of change focus on discrete parts or components, the PSA discipline enables a holistic view of the entire power system over 5, 10 and 20-year time horizons. Recognising that the legacy power system is an extremely complex 'Network of Structures', the PSA disciplines uniquely provide:

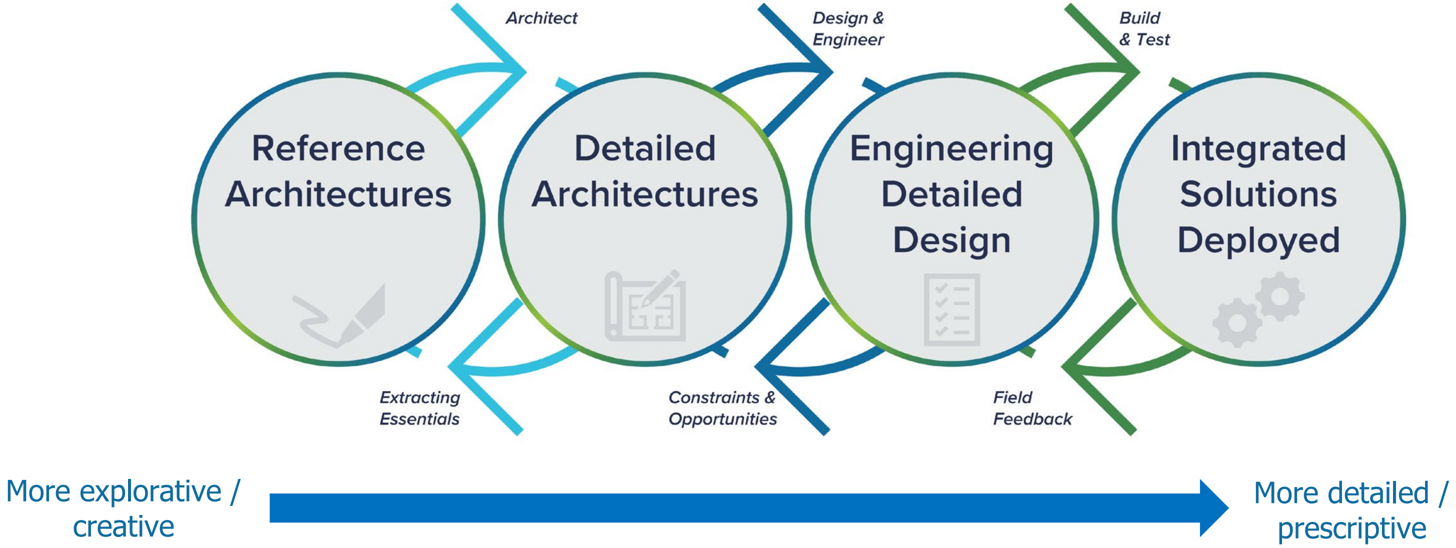
1. Whole-of-system insight that enables diverse stakeholders to collaboratively interrogate and map current, emerging and future power system priorities, objectives and functions informed by a range of plausible future scenarios;
2. Evidence-based tools to navigate, analyse and shortlist key transformational options through the combined application of Systems Architecture, Network Theory, Control Theory and Software Engineering complemented by Strategic Foresight and Energy Economics disciplines; and;
3. Future-resilient decision making enabled by surfacing hidden structural constraints early that may otherwise drive future issues such as computational constraints, latency cascading and cyber-security vulnerabilities, which provides assurance that new investments are scalable and extensible under all plausible futures.

Most importantly, PSA expands rather than limits optionality. It enables architectural decision making based on agreed principles, objective methodologies and detailed structural analysis. It gives priority to extensive collaboration with diverse stakeholders and subject matter experts throughout to enhance trust, ensure high levels of alignment and support social license for change.

What is a "Reference Architecture"?

+ A Reference Architecture process provides an initial integrated and credible set of documents and structural diagrams that capture the essence of the relationships, linkages and interdependencies embodied in a complex system. These underpinning structures are foundational to the efficient, reliable and resilient operation of any complex system which, by definition, involves large numbers of entities, technologies and sub-systems.

+ The collaborative development of a Reference Architecture representing the system in its 'as built' state is the essential precedent to considering the plausible options for future architectural structures. The Reference Architecture phase, therefore, functions as the first major loop of architectural development and 'community of practice' formation and is foundational to later Detailed Architecture and Engineering Detailed Design phases.



+ As illustrated above, the architecting process moves from the more explorative and creative Reference Architecture development toward later phases that are increasingly detailed and prescriptive definitions of future structures and solutions. In the case of power system transformation, the Reference Architecture phase provides a 'lower stakes' context for diverse and often conflicted stakeholders to initially explore and develop a shared appreciation of how the underlying structures of the system may need to evolve if customer and societal expectations are to be cost-efficiently met.

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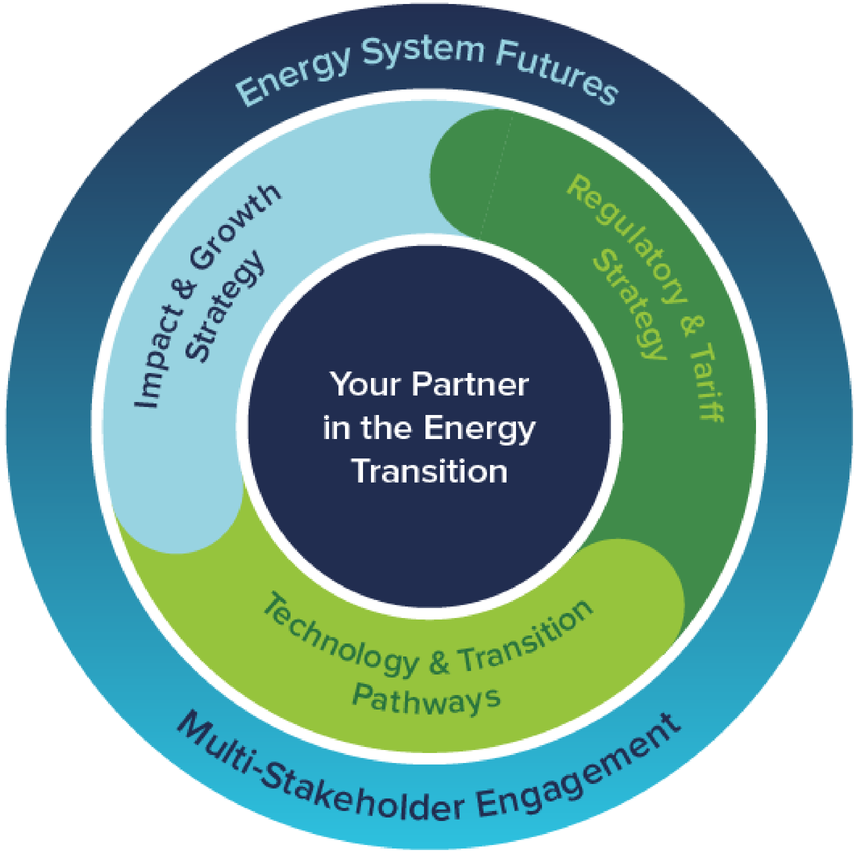

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Strategen is a globally-connected firm with unique expertise in accelerating whole-of-system transitions to a low carbon and human-centred energy future.

Strategen enables and accelerates whole-of-system transformation in the electricity and green hydrogen sectors. For well over a decade, we have played key roles in policy, regulatory, technology and market innovation in the United States, Australia and Europe.

Founded in 2005, Strategen has developed a unique and world-leading team of experts focused on the technologies, economics, market design and social license. With core expertise in the deep system and market integration of Variable Renewable Energy (VRE), Distributed Energy Resources (DER), Energy Storage and Green Hydrogen, we bring strategic futures and whole-system perspectives to everything we do.

Strategen's clients are leaders of the global energy transition. They include public and private utilities, system and market operators, state and federal government agencies, international development banks and a wide range of commercial enterprises.

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MARK PATERSON

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Lead Systems Architect

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.

Working with strategic clients, Mark leverages his experience leading several national energy system transformation projects and technology innovation firsts. At CSIRO, Australia's national science agency, he chaired the Future Grid Forum and directed the Electricity Network Transformation Roadmap program. At Horizon Power and Energex he led technology innovations for deploying new energy technologies in large meshed networks, regional microgrids and remote off-grid applications.

Internationally, he is a Fellow of the Pacific Energy Institute (PEI), contributing author for the IEEE Power & Energy Society, an invited Associate of the US Department of Energy's GridWise Architecture Council (GWAC) and an expert contributor to Asia-Pacific Economic Cooperation (APEC) grid resilience activities.

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