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Towards a Resilient Net-Zero National Electricity Grid: A Systems-of-Systems Engineering Perspective





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Overview

- Context - Evolution of the grid
- Systems and systems of systems engineering
- An SE view of resilience
- Insights
- Conclusion

Context



Initial Local Electricity Networks

- Electricity networks commenced with a single power station serving a group of consumers.
 - Simple and easy to control
 - But no redundancy

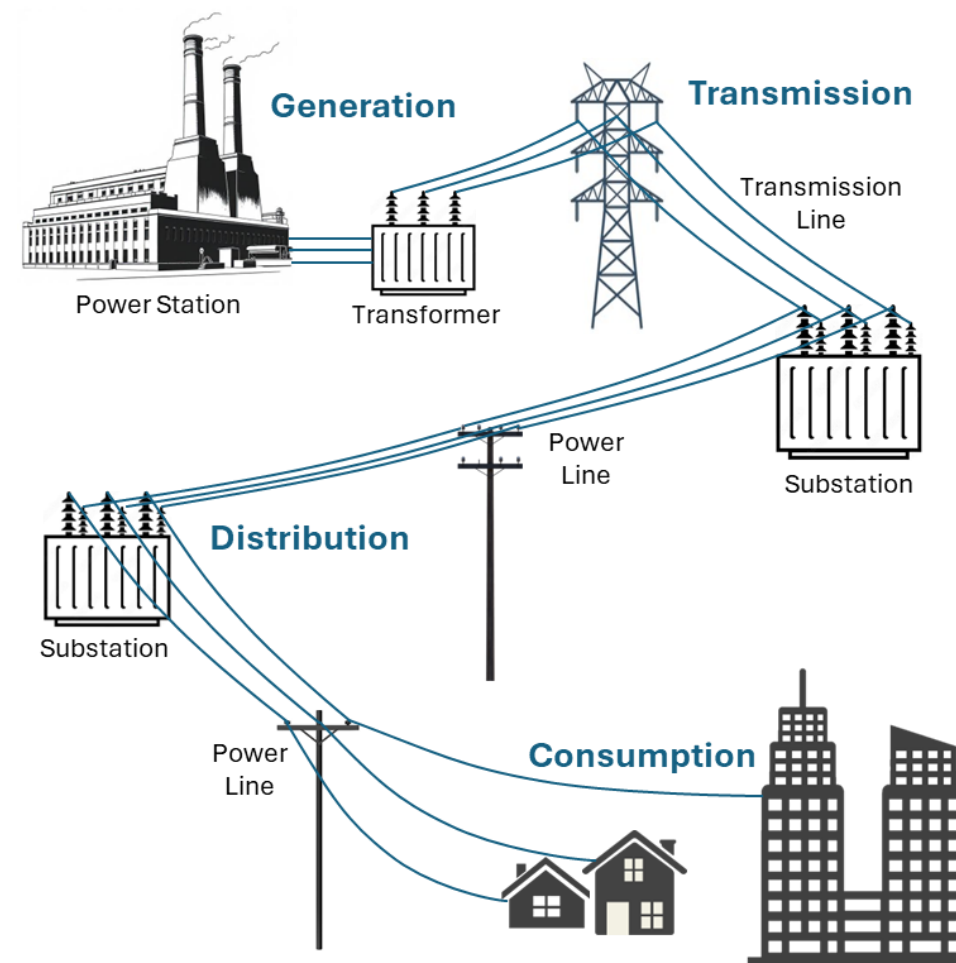
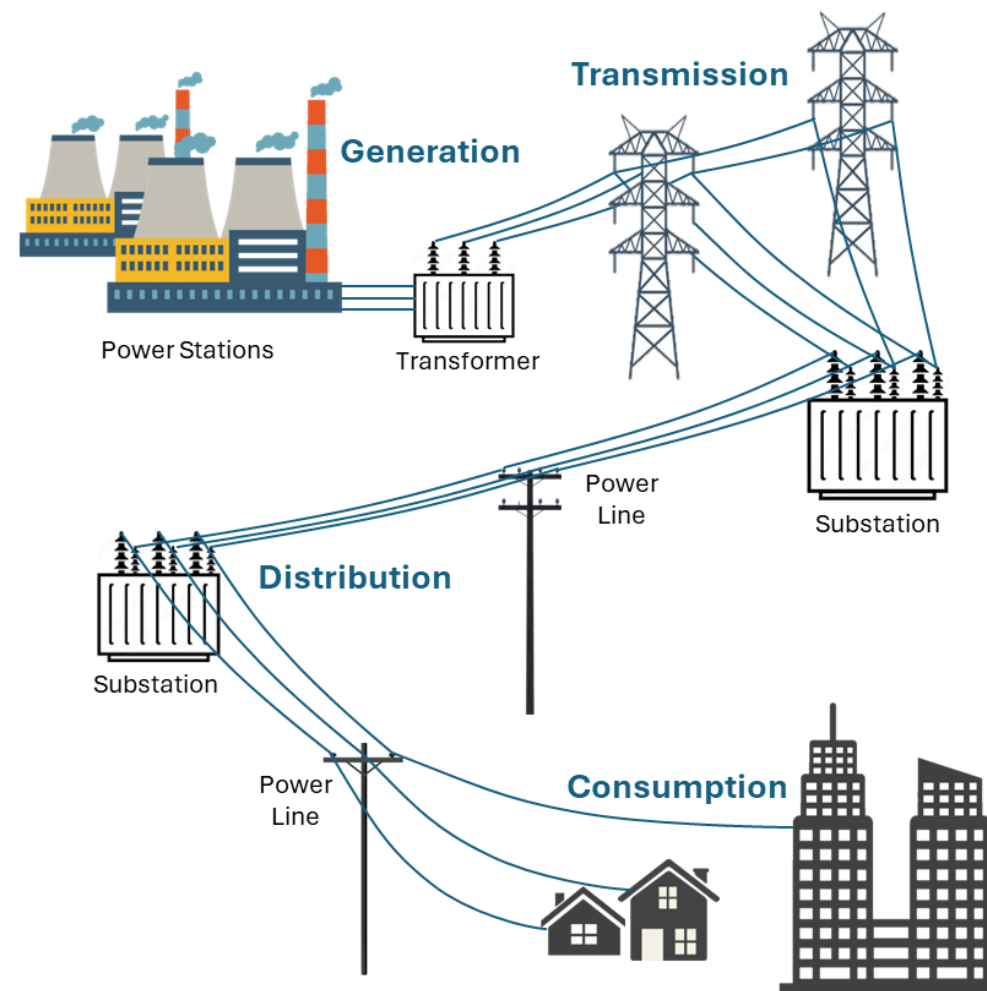


Diagram of an electricity grid with a single generator

Evolution to State Owned Island Networks

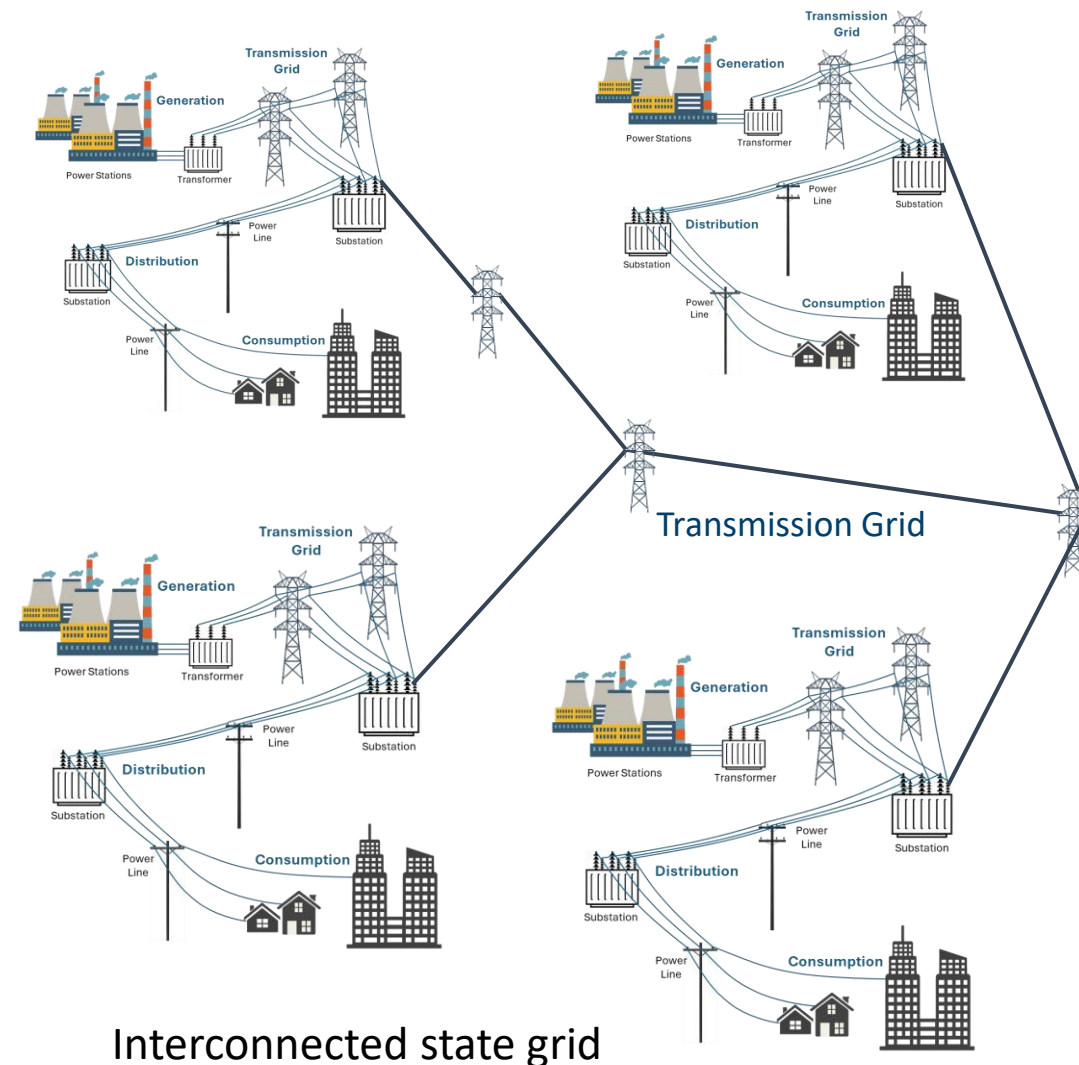
- Evolved into State owned or controlled networks
 - Multiple generators and redundant transmission infrastructure
 - Central planning and operations management
 - Designed to meet network quality needs: resilience, system strength
 - Low technical and commercial risk



Picture of a state grid with multiple generators and redundant distribution

Interconnection of State Island Grids

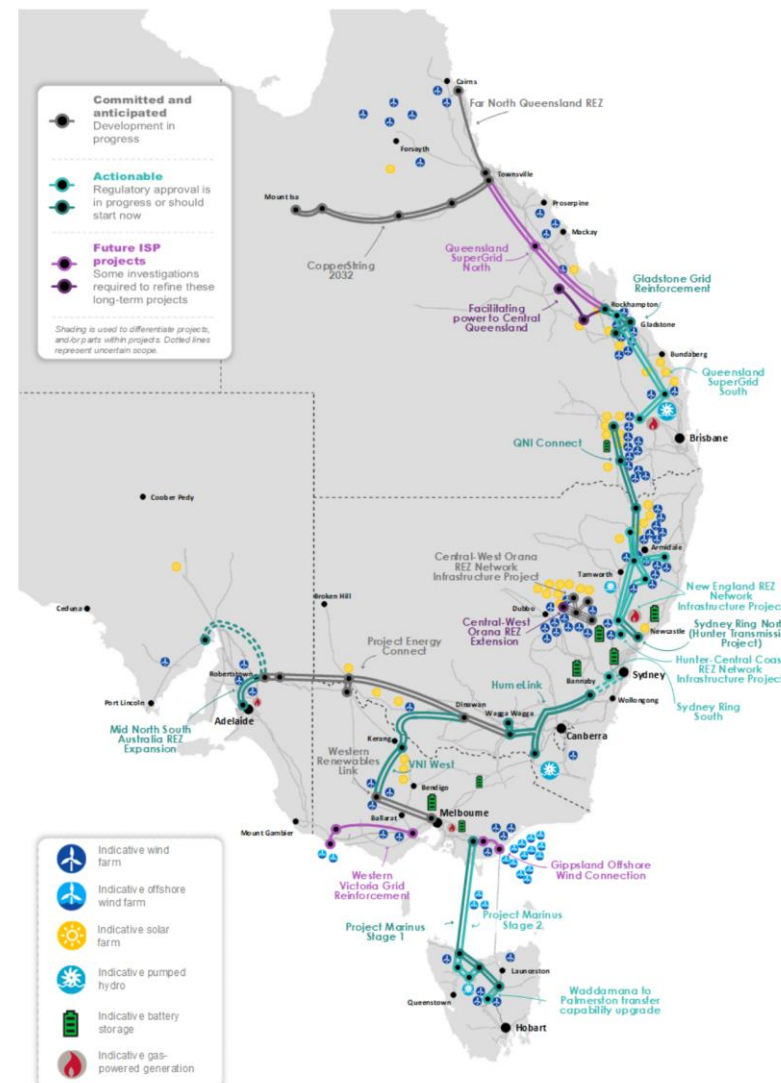
- Interconnection
 - State-based island grids Interconnected
 - Increased generation and transmission diversity
 - Reduced need for local reserve capacity
 - Improved overall efficiency
 - Retention of State-based central planning and operational control



Interconnected state grid

Move to a Privatised National Electricity Market

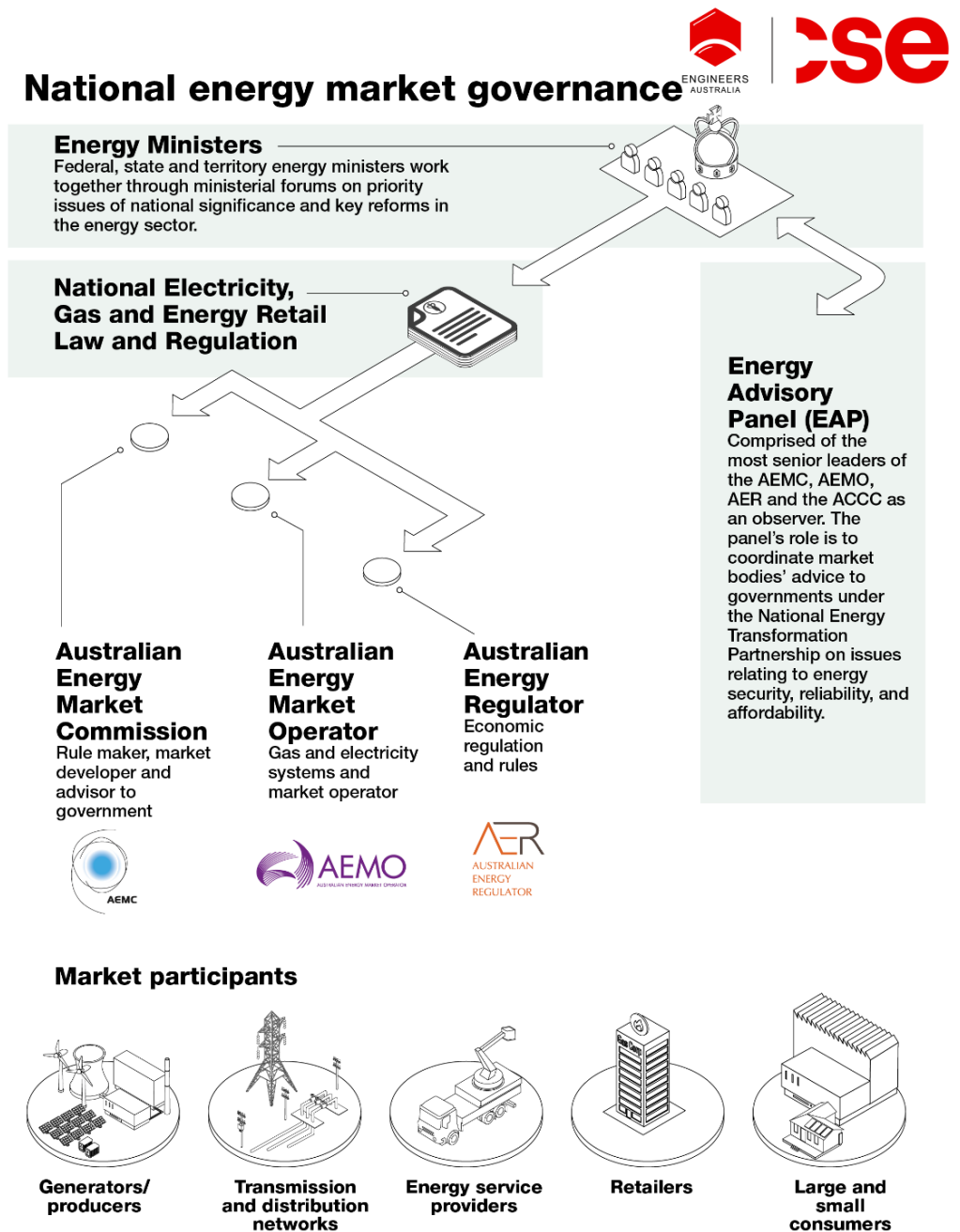
- Privatisation of State assets
- Advent of the National Electricity Market in 1998
- Introduction of substantial renewable energy
- Central Energy Market Regulation
- Increasingly strong central Energy Market Management



NEM grid (AEMO Integrated System Plan 2025)

The National Electricity Market

- End-to-end distance of more than 5,000 kms with 40,000 kilometres of high voltage transmission lines.
- 181TWh of electricity traded (FY 23/24) worth \$17bn
- Serves 23 m people
- Many players
 - Multiple jurisdictions
 - > 600 participants
 - > 300 generators
- Provides a mechanism for privately funded components to provide components on a commercial basis
- Central operational management strengthening over time
- Central planning with some authority to insist on network services and capacity provision but new generation dependant on market response or government intervention.



Challenges of Interconnected Grids¹

- The efficiency gains from better utilization of available generation and transmission capacity reduce local reserve capacity and redundancy - can introduce fragility
- Potential for cascading failure that cannot occur with island grids
 - e.g. Iberian Peninsular blackout
- Island grids were designed around centralised baseload power generation; not all components well suited to the needs of large-scale grids

Systems and SoS Engineering



Contemporary Systems Engineering

- *Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.”*

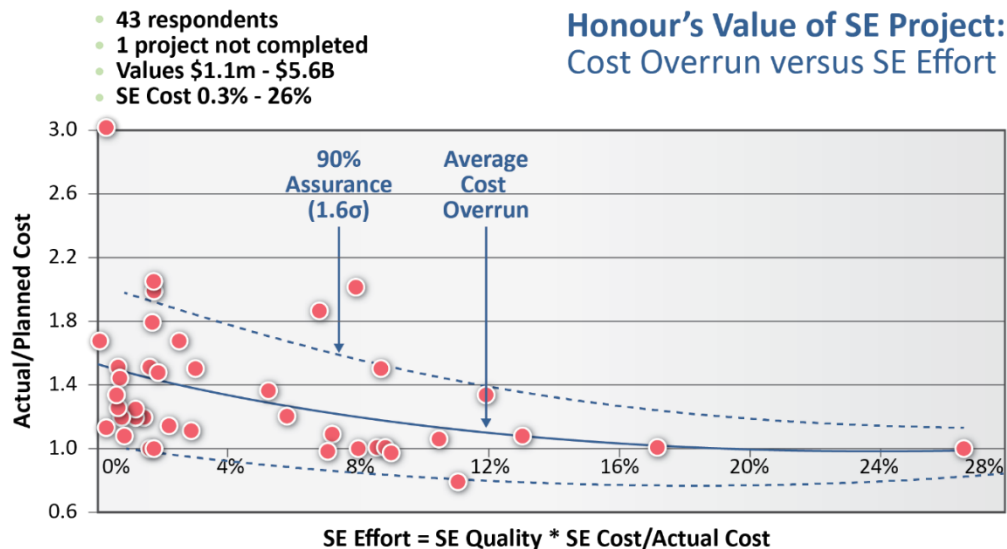
(Latest INCOSE definition in Sillitto et al., 2019)

- SE is a well-established **design practice** that deals with complex system developments
 - Standards
 - Processes
 - Guidebooks
 - Knowledge sources
 - Tools
 - Methods and Techniques
- That have been honed over decades by **practitioners**
- SE practice draws on a broad set of **competencies**
- Increasingly applied in **energy and construction** projects

The Return on Investment of Systems Engineering

- Expenditure on quality SE effort is highly correlated with project success

Table 2. Correlation of SE Capability Elements with Project Success
(adapted from Elm & Goldenson, 2012).



Driver	Correlation
Total deployed SE	+0.49 → Very strong positive
Project planning	+0.46 → Very strong positive
Requirements development and management	+0.44 → Very strong positive
Verification	+0.43 → Very strong positive
Product architecture	+0.41 → Very strong positive
Configuration management	+0.38 → Strong positive
Trade studies	+0.38 → Strong positive
Project monitoring and control	+0.38 → Strong positive
Product integration	+0.33 → Strong positive
Validation	+0.33 → Strong positive
Risk management	+0.21 → Moderate positive
Integrated product team realization	+0.18 → Weak positive

- Bottom line: Investing in **SE will save you money and drive project success!**

Systems of Systems and SoS Engineering

- A **System of Systems** is a collection of independent systems, integrated into a larger system that delivers unique capabilities¹
 - The independent Constituent Systems (CS) collaborate to produce global behaviour that they cannot produce alone.
- “**System of systems engineering (SoSE)** is a set of developing approaches, processes, tools, and methods for designing, re-designing and deploying solutions to system-of-systems challenges”²
- SoSE draws on traditional SE and embraces social-technical systems approaches and complexity theory

1. INCOSE, 2018
2. Wikipedia, 2025

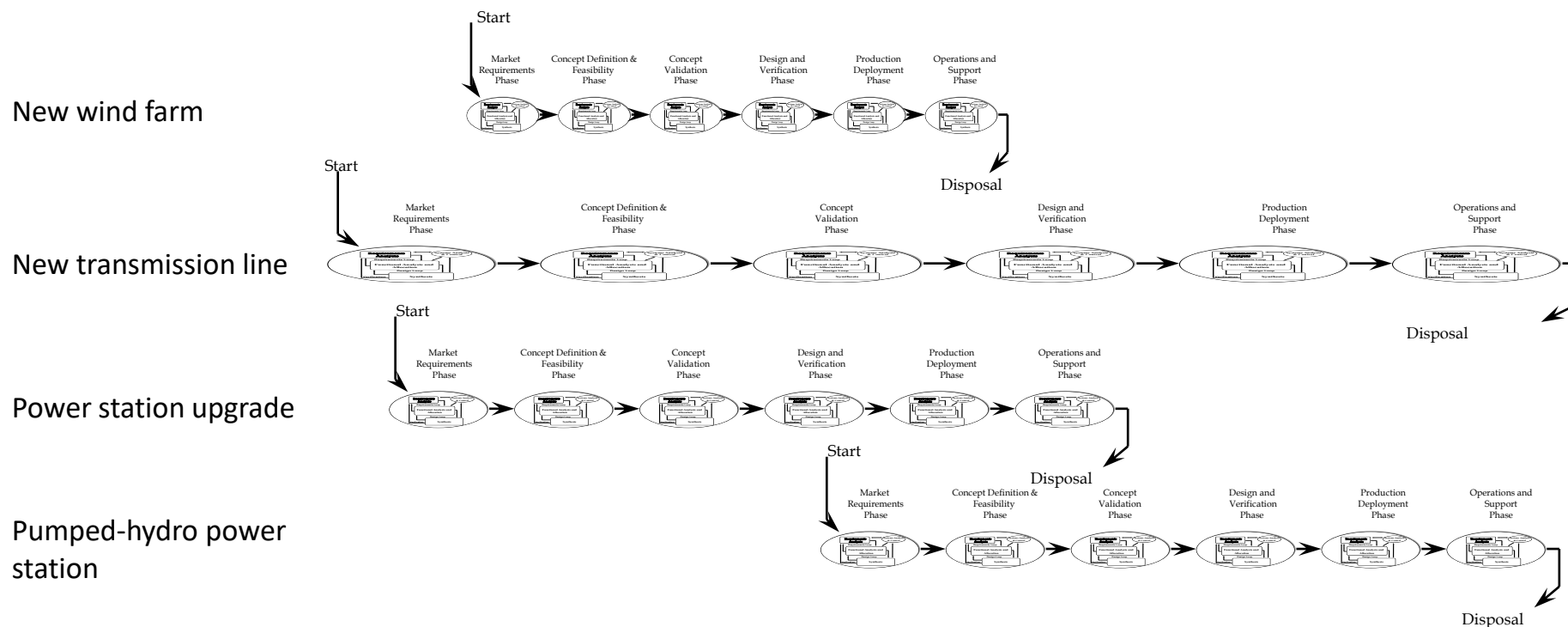
Where do we find SoS?

- **Transportation** - air traffic management, the European rail network, integrated ground transportation, cargo transport, highway management, and space systems
- **Energy** - National electricity generation and distribution, smart grids, smart houses, and integrated production/consumption
- **Health Care** - regional facilities management, emergency services, and personal health management
- **Natural Resource Management** - global environment, regional water resources, forestry, and recreational resources
- **Disaster Response** - responses to disaster events including forest fires, floods, and terrorist attacks
- **Consumer Products** - integrated entertainment and household product integration
- **Business** - banking and finance



What do these types of SoS have in common?

- Infrastructure SoS are enduring and do not follow a normal project life cycle
- Independently controlled and managed constituent systems that are often in competition
- Constituent systems seek their own goals which may not be fully aligned with the SoS goals
- Asynchronous evolution of constituent systems



SoS Exhibit a Variety of Types of Governance¹

- **Directed SoS** are centrally managed during long-term operation. The constituent systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.
[Theatre air defence](#)
- **Acknowledged SoS** have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches.
[International Banking](#)
- In **Collaborative SoS** the component systems interact more or less voluntarily to fulfill agreed upon central purposes.
[The Internet](#)
- **Virtual SoS** lack a central management authority and a centrally agreed upon purpose for the system-of-systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain it.
[Natural environment](#)
- **Discovered SoS** completely unplanned and unpredicted SoS that become apparent after they come into existence.
[Impromptu pub group](#)

1. (ISO/IEC/IEEE 21841:2019)

SoSE is a Recognised Subdiscipline of SE

- SoSE has:
 - A coherent set of socio-technical theoretical foundations and success principles
 - A set of SoSE approaches that can cover a range of SoS interventions
 - ISO/IET/IEEE Standardisation
 - Burgeoning Digital Engineering approaches
 - A wide range of SoSE Analytical Approaches
 - A SoSE Navigator – for designing bespoke SoSE methodologies
- A major consideration of SoSE is **resilience**

A Systems / SoS Engineering View of Resilience



System Resilience

- “Resilience ... refers to the ability of a system to resist, absorb, accommodate to, and recover from the effects of a hazard in a timely and efficient manner” AEMO(2020)
- INCOSE Resilient Systems Working Group (IRSWG) recommends the inclusion of the ability of a system to take action before the encounter with a threat event; this is called the **proactive resilience** (Willett, 2020).
- Simply stated, resilience is the ability to **adapt to changing conditions** and withstand and rapidly recover from disruption” (DHS, 2018).

Scope of Electricity Grid Resilience

- Resilience encompasses reliability, survivability, robustness, systems strength, restoration time, etc.
- Resilience engineering involves balancing the different aspects of resilience
- Resilience enhancement covers two phases (Dersin, 2024):
 - Resilience-oriented design and planning
 - Resilience-oriented operations

Improving Resilience (1)

- Design and planning means

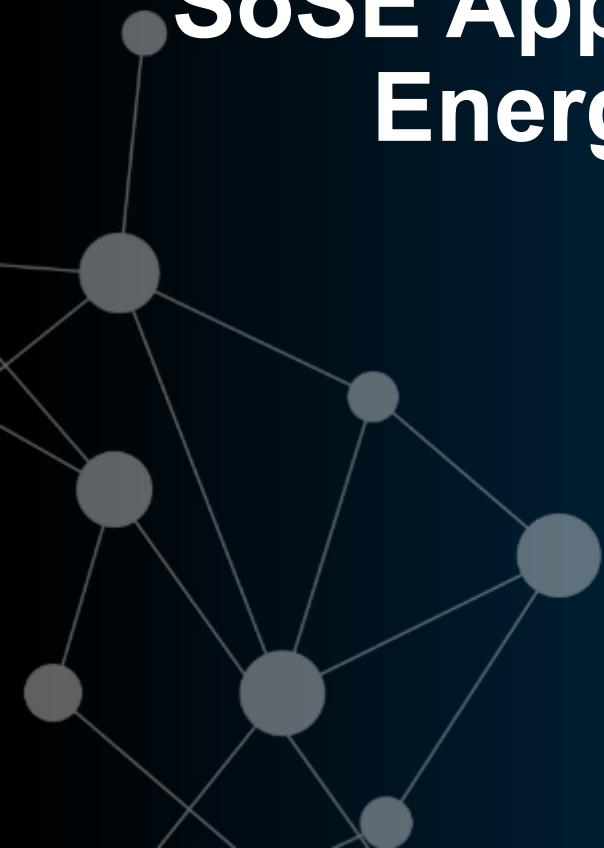
Design and Planning Means to Enhance Resilience	Description of SE Resilience Activity
Adaptive response	Design system to react appropriately to a specific situation to limit consequences and avoid unnecessary degradation of system capability.
Agility	Enable system to adapt to deliver required capability in unpredictable evolving conditions. (The antithesis of a system delivered against a rigid specification written years before delivery.)
Anticipation	Enable the system to establish awareness of potential adversities and identify how best to deal with them prior to the adversity stressing the system.
Disaggregation	Disperse system functions or elements across multiple system elements.
Evolution and Transformation	Enable the system to address changes in needs and adversities over time and enable consequential changes to the behaviour and topology to suit.
Fault Tolerance	Design the system to operate in the presence of flaws and during substantial element failures.
Graceful Degradation	Design the system to limit the propagation of instability or damage within the system and enable the system to transition to a state that provides a useful level of capability.
Prepare	Develop courses of action that address anticipated adversities.
Prevent	Deter and preclude the realisation of the adversities.
Re-architect	Modify the system architecture for enhanced resilience.
Robustness	Enable system elements to withstand adverse and unforeseen events or consequences of human errors without being damaged.
Situational Awareness	Design the system to enable the perception of system elements in their environment to inform the design and implementation of the systems to pre-emptively address risks and potential hazards as they are identified.
Understand	Develop and maintain useful representations of system capabilities, the system environment and the potential for degradation due to adversity.

Improving Resilience (2)

- Operational means

Operational Means to Enhance Resilience	Description of SE Resilience Activity
Adaptive response	Operate system to react appropriately to a specific situation to limit consequences and avoid unnecessary degradation of system capability.
Anticipation	Enable the system to establish awareness of potential adversities and identify how best to deal with them prior to the adversity stressing the system.
Graceful Degradation	Operate system to limit the propagation of instability or damage within the system and enable the system to transition to a state that provides useful levels of capability.
Situational Awareness	Maintain a dynamic perception of system elements in their environment and understand potential hazards.
Understand	Employ real-time representations of system capabilities and the system environment to facilitate operational resilience.

Insights from taking a SoSE Approach to the Energy Transition



Classifying the NEM Grid

- NEM grid is a complex enterprise SoS
 - In operation it can be categorized a **Directed SoS** with AEMO providing highly-effective operational management
- The NEM SoS is continually evolving
- AEMO makes plans for the evolution to a net-zero grid (AEMO, 2024)
 - AEMO has **limited power to implement** such plans – mostly up to the market
 - Hence, the development and evolution of the NEM spans from **Virtual to Collaborative SoS** with occasional Directed approaches
 - Making this explicit, helps stakeholders appreciate the root cause of impediments to the realisation of AEMO's Optimal Development Path (AEMO, 2024)

Insights on Benefits of SoSE for Grid Transition

- Understanding of the NEM Grid
- **Robustness and resilience evaluation and improvement**
- Whole-of-Systems Analysis
- Systems Intelligence
- Decision-Making optimisation
- Design across multiple, disaggregated systems and timeframes
- Improved coordination between disparate subsystems
- Risk and safety management
- Efficiency and performance enhancement
- Systems complexity reduction
- Consideration of environmental impact and sustainability
- Application of automation and AI integration and optimisation
- Real-time operational optimisation strategies

Conclusions



Conclusion

- NEM is a complex SoS – many sources of complexity
 - Operation is managed by AEMO under a complex regulatory framework delivered by AER
 - The future NEM is planned by AEMO but is implemented by a host of market players
- Grid resilience is an emergent property of the grid and can only be engineered at the whole-of-system level
- SoSE provides an appropriate socio-technical approach for transitioning to the future NEM
 - SoSE provides the understanding, insights, tools, and techniques to better achieve a resilient grid in a dynamically changing environment

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Questions and comments



STEPHEN COOK



MARK UNEWISSE



MATTHEW WYLIE

A close-up of a hand with fingers spread, reaching upwards. The background is a blurred crowd of people, with several other hands raised in the air, suggesting a lively event or a Q&A session.

Q & A

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