

How System Engineering Can Derisk the Energy Transition

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Overview

- Context for decarbonisation
- Complex Energy Decarbonisation (CED) systems
- CED system modelling & analysis
- Examples of austere DE approach to CED Systems
- Electricity grids in energy transition
- A Systems / SoS Engineering view of grid resilience
- Conclusion



Sourced from SANY



Context

- Challenge of Climate Change
- Australia has mandated for Net-Zero greenhouse gas emissions by 2050
- This will require a major investment
 - Estimated at \$100s of billion up to \$7 Trillion ¹
 - i.e. 10% of GDP for next 25 years
- Large and growing number of CED projects
 - Ranging from \$10s of millions to \$10s of billions
- Projects often undertaken
 - With limited whole-of-system understanding
 - Using overly optimistic assumptions
 - With a focus on subsidies




¹ Net-Zero Australia, 2023

Opportunity for Systems Engineering (SE)

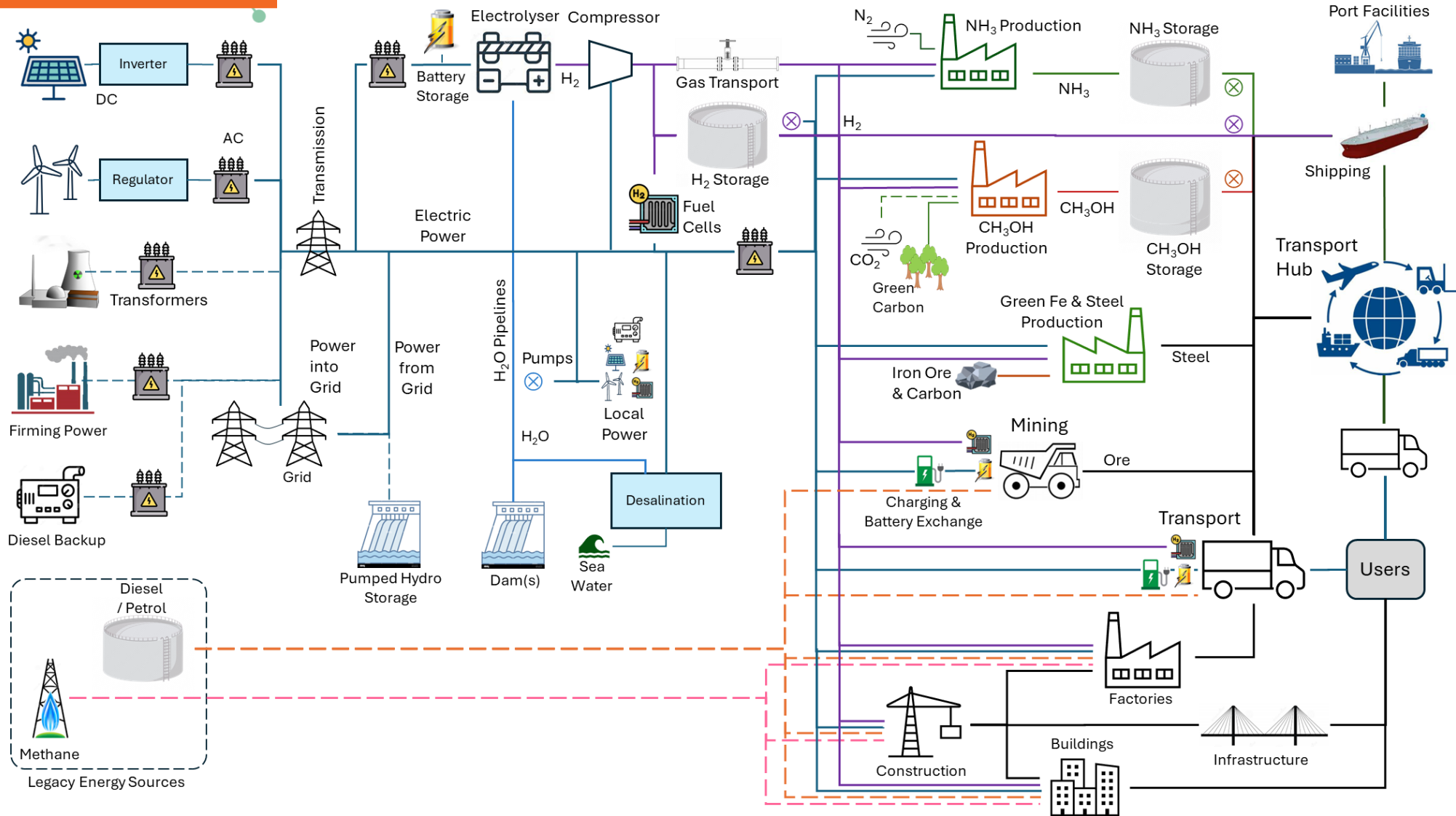
- CED systems and projects need SE & SoSE for:
 - Advice to government departments
 - Advice to investors
 - Through-life support
- Government agencies and large corporation undertake internal modelling and analysis
- SE support by SMEs is currently emergent
- **Creates a business opportunity for SMEs**
 - Supporting the large number of CED projects
 - Harnessing and realising opportunities
 - Identifying and reducing risks and wasted resources





Complex Energy Decarbonisation Systems

Scope of CED Systems

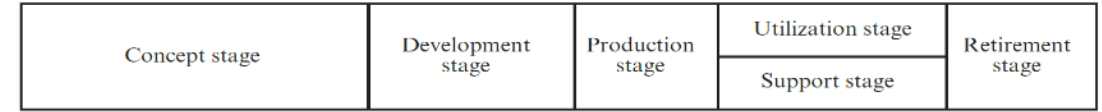


CED Project Stages

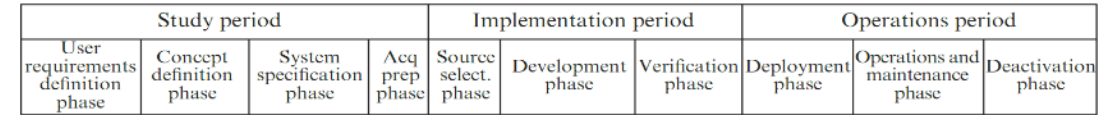
Key stages in CED Project

1. Feasibility Studies
 2. Conceptual Design
 3. Pre-FEED
 4. FEED
- Front End Engineering Design
5. Detailed Design
 6. Procurement and Fabrication
 7. Construction and Installation
 8. Pre-Comm
 9. Handover
- Mapped on standard lifecycle models
 - Focus of work is up to FEED stage

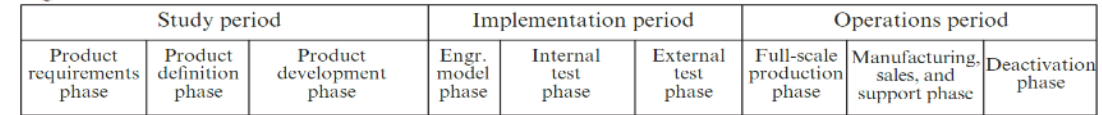
Generic life cycle (ISO/IEC/IEEE 15288:2023)



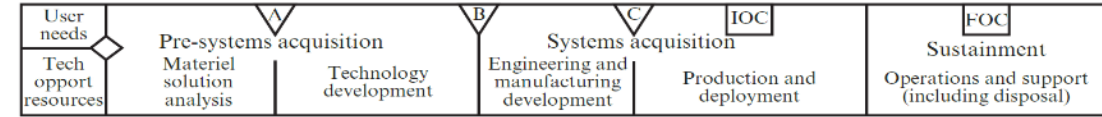
Typical high-tech commercial systems integrator



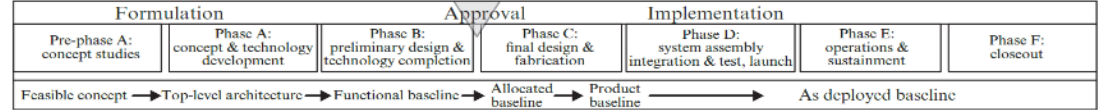
Typical high-tech commercial manufacturer



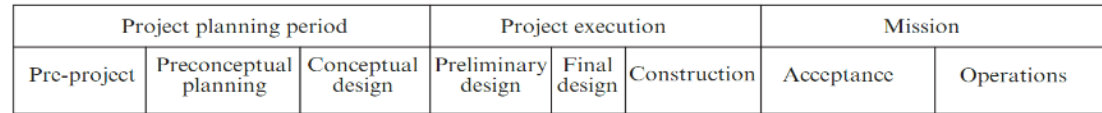
US Department of Defense (DoD)



National Aeronautics and Space Administration (NASA)



US Department of Energy (DoE)



Typical decision gates

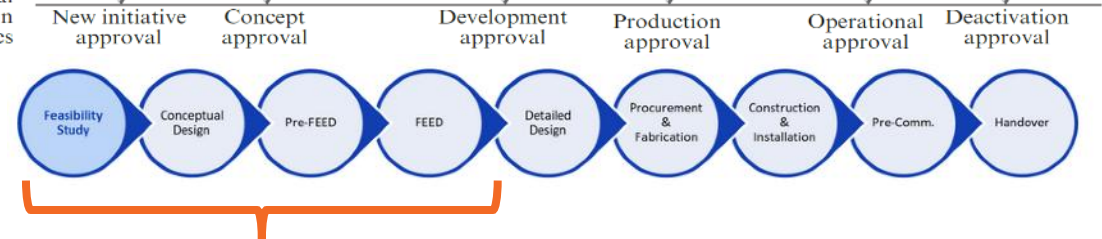
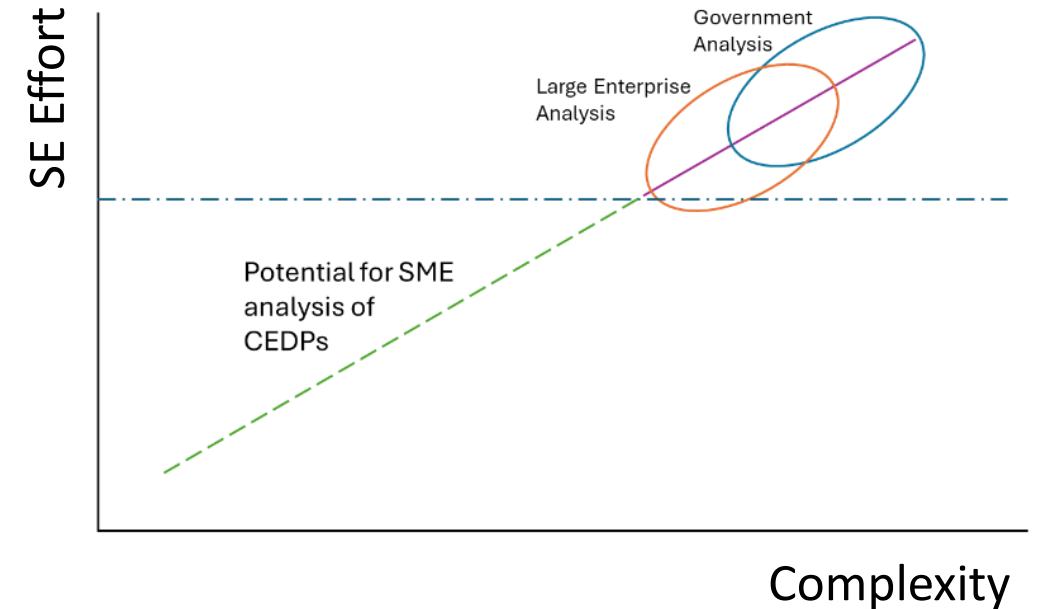


Image source: INCOSE SE Handbook 5th Edition

Opportunity for SE SMEs

- SE-based analysis increases with complexity
- Very complex systems (e.g. warfighting) undertaken by governments & large corporations
- There are a range of moderately complex CED systems that will need support
- **Creates an opportunity for SMEs**
 - For CED projects
 - For complex CED SoSs



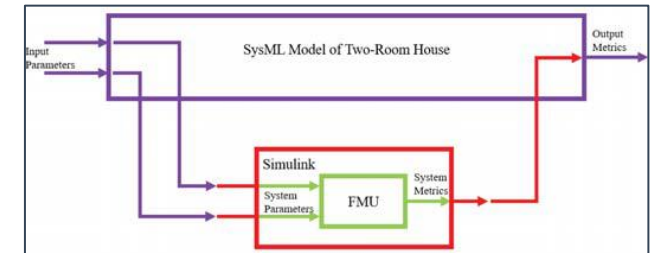
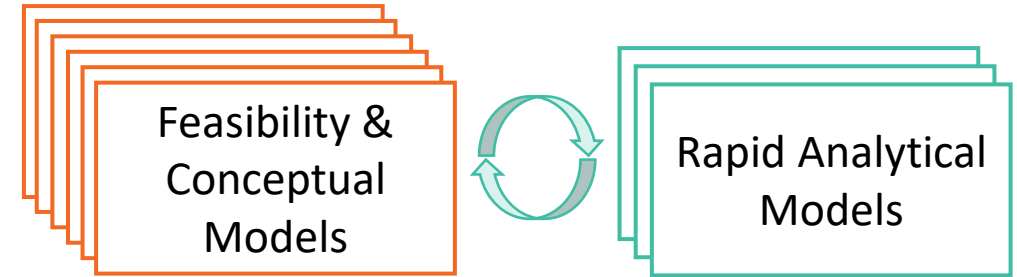


CED Project System Modelling & Analysis

Approach
Skilled personnel
Development Environment

Approach – Modular DE

- Leverage similarities between many CED systems
- Build tailorable modelling and analysis modules
 - Conceptual models
 - MBSE modules (SysML / UAF)
 - Analytical models
- **Match SE modelling & analysis to the project stage**
 - SE to address many early-stage conceptual options
- **Keep the analytical models as simple as possible**
- Experimented with loose and tight MBSE to analysis coupling
 - Loose MBSE – analytical coupling in early stages
 - Rapid turnaround for early stages
 - Tighter MBSE – analytical coupling in later stages
 - Higher overheads, more suitable for Pre-FEED and later



Cawasji and Baras (2018)



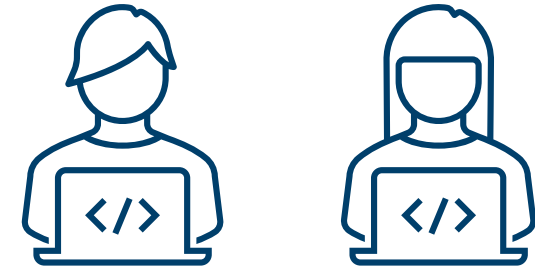
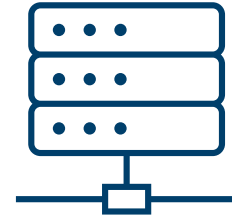
Skilled Personnel


- The effort of skilled personnel is the dominant cost
- Build on existing skills of personnel
- Choose tools that suit the personnel
- Align with skills of university graduates
- Shoal's skills build on:
 - MBSE – SysML / UAF
 - Modelling and simulation using a range of tools
 - OR experience
- Extensive experience across:
 - Defence, Space, Transport, Infrastructure



Development Environment

- An effective development environment is essential to deliver cost effective analysis of CED systems
- Information management
 - Models
 - Underpinning data
 - Analysis results
- Knowledge management
 - Processes and lessons
 - Rapid integration of new team members
- Appropriate tools
 - Spreadsheets for initial modelling
 - MBSE
 - Modelling and simulation
 - Operations Research
 - Visualisation





Modular DE Modelling & Analysis Examples for Projects



Decarbonised Haulage Operations

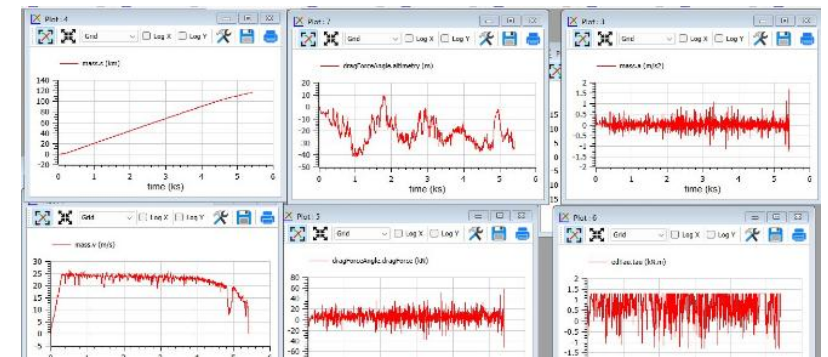
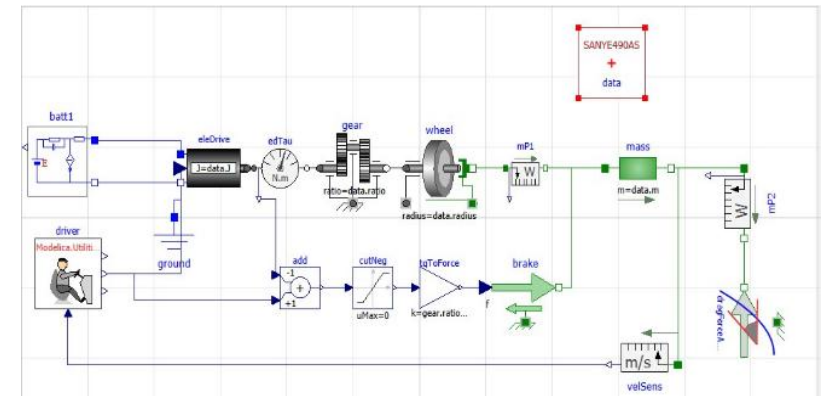
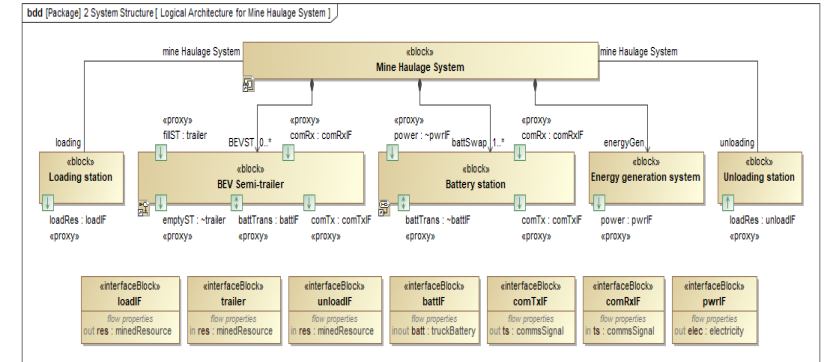
- Diesel → Green haulage operations
 - Efficient green (e.g. electric) transport of bulk materials
 - Trucks to use, Operations,
 - Throughput, energy usage ...
- Support to Solarh2e transport decarbonisation
 - Inter-city haulage (Melbourne to Sydney)
 - Regional to city haulage
 - Intra-city haulage
 - Mining haulage to processing centre or port
- Systemic SE support – Owner’s Systems Engineer



Sourced from SANY

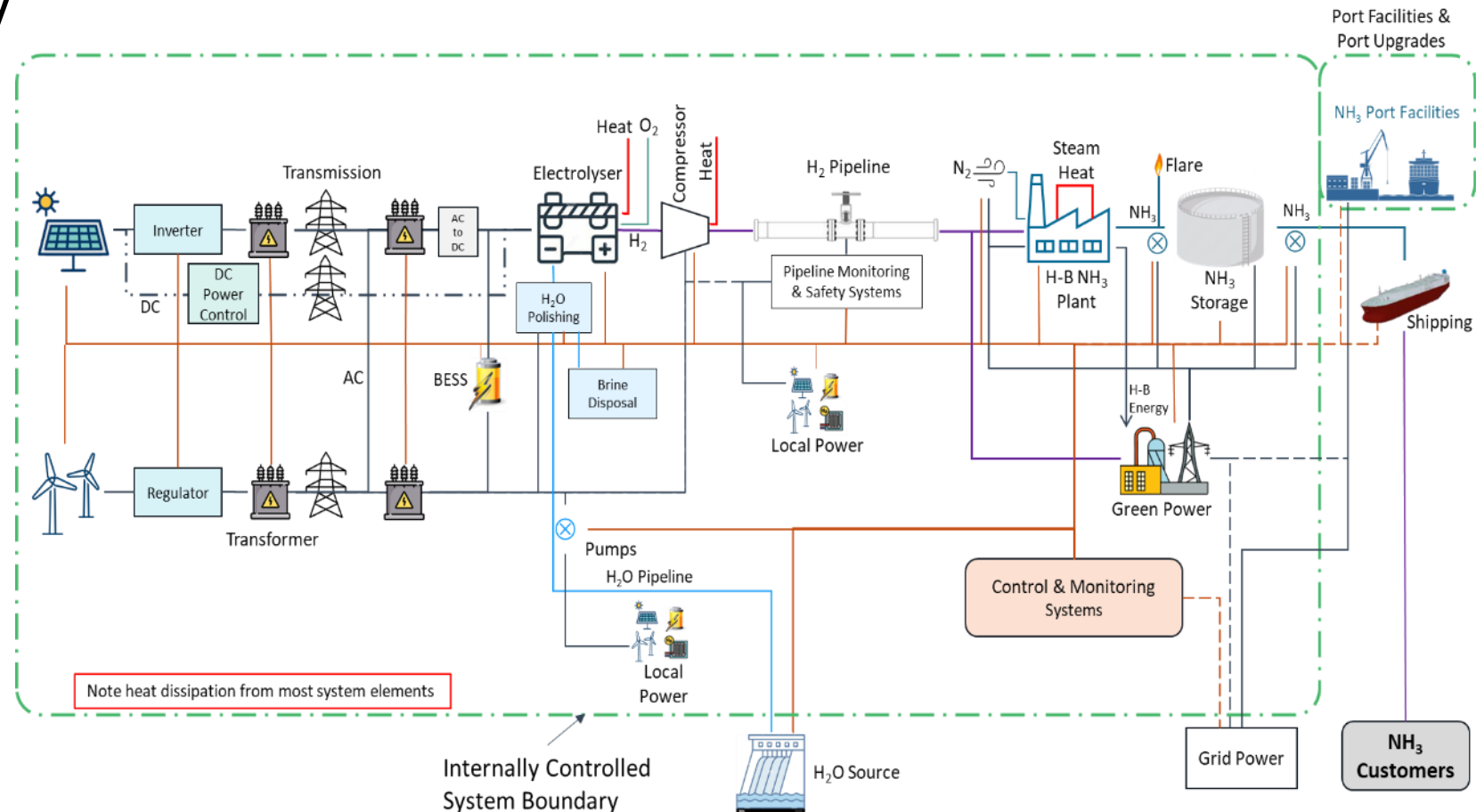
Modelling & Simulation

- Systems Engineering
 - Enables the whole capability to be considered and understood
 - Identifies and manages the risks and opportunities
- Digital Engineering based Modelling & Simulation
 - Use simplest viable level of analysis and modelling
 - Combines functional and physical modelling
 - Provides flexible modular modelling
 - Models the behaviour of the whole capability
 - Captures the design, interfaces, gaps and risks
 - Enables understanding, optimisation, and impacts of changes
- Analyse many ideas at low cost
 - Project feasibility
 - Energy requirements
 - Project risks and opportunities



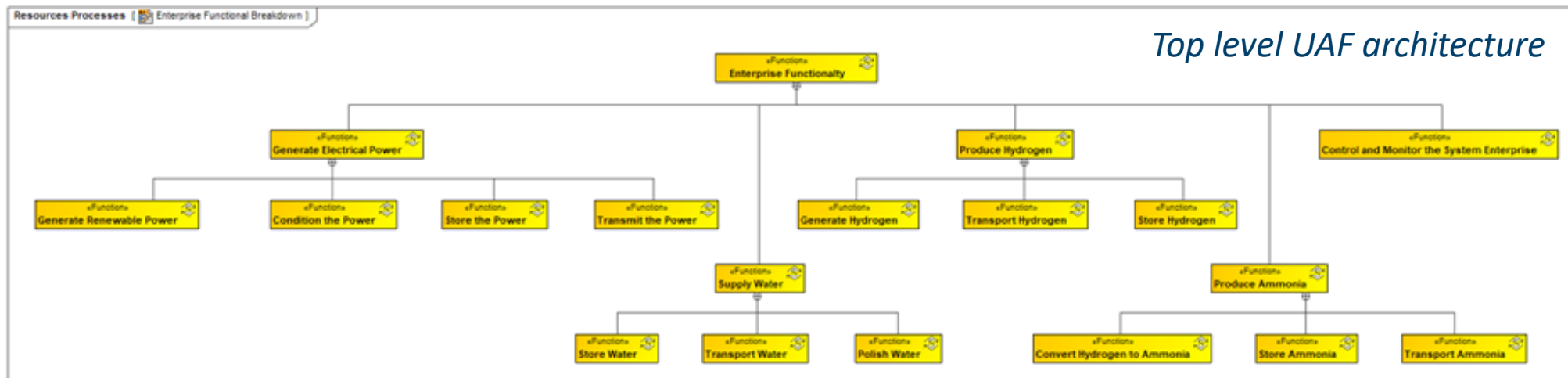
Analysis of Large-Scale Hydrogen & Ammonia

- Large scale green energy project
 - ~ US\$20 B
 - Pre-FEED stage
- Solar and Wind energy
 - ➔ Hydrogen
 - ➔ Ammonia
- Ammonia for export
- NH₃ Applications:
 - Powering Shipping
 - Green Energy generation



Analysis of Large-Scale Hydrogen & Ammonia

- High-level Excel-based modelling
- Provided key insights, including:
 - Whole-of-system energy requirements
 - Hydrogen production and transport issues
 - Heat dissipation
 - System and SoS risks
- ‘Owner’s SE’ role – quality assurance
- Underpinned by DE-based analysis
- Risk and opportunity analysis
- Sensitivity and trade-off analysis





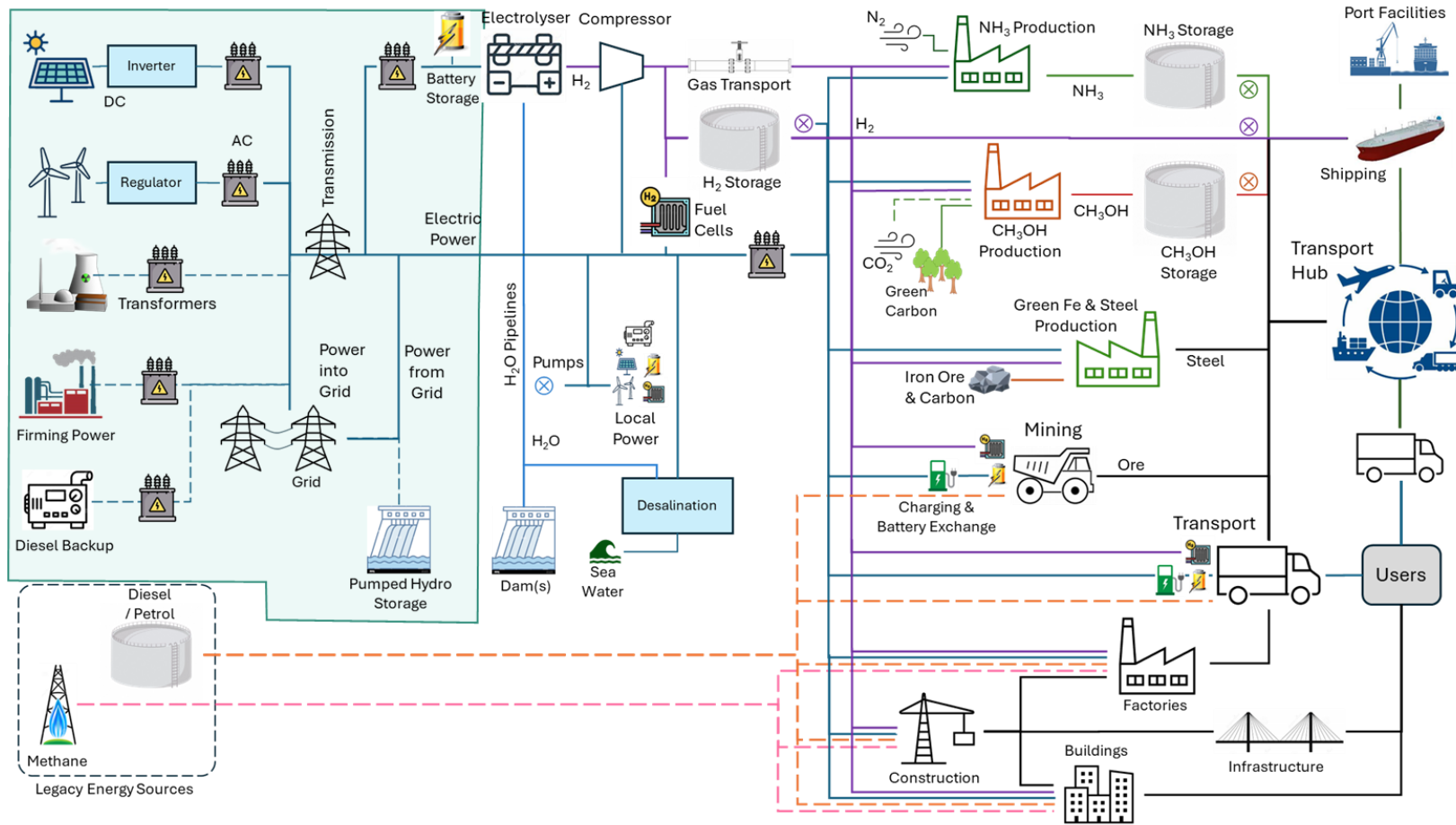
Electricity Grids in the Energy Transition



SHOAL™

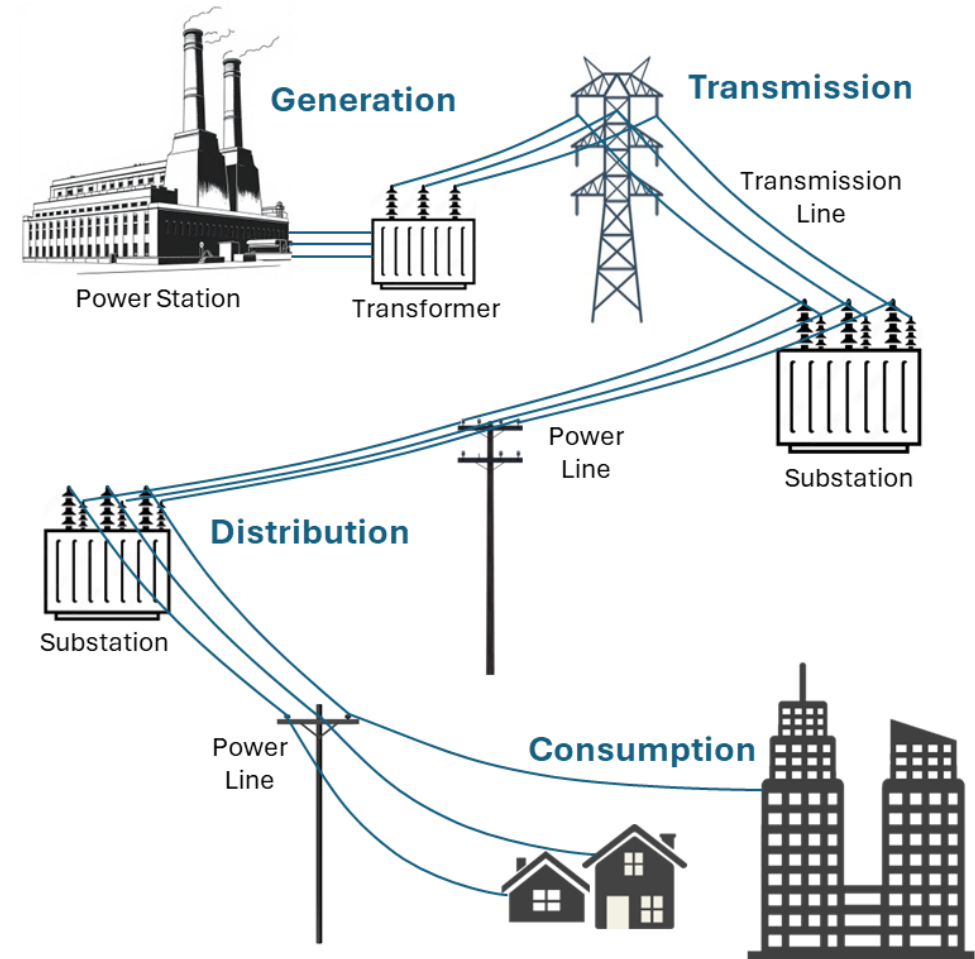


Scope of Electricity Grid Within Energy Transition



Initial Local Electricity Networks

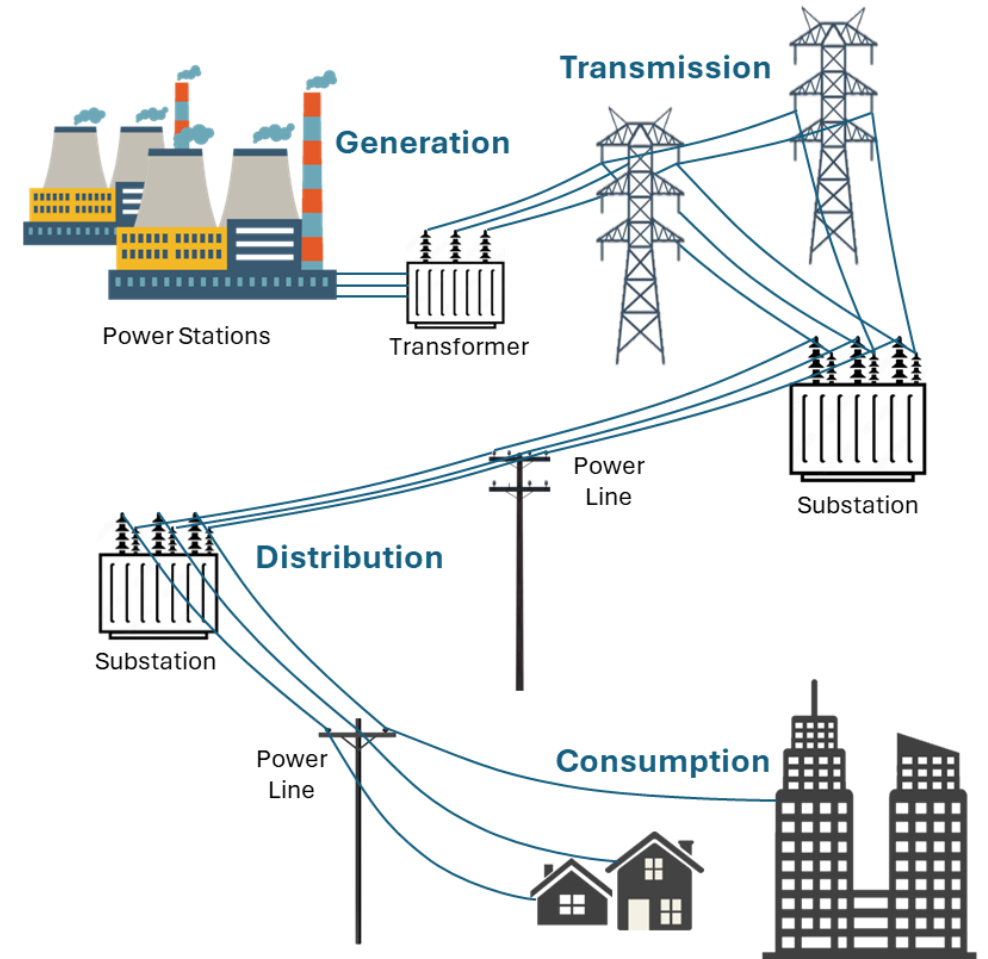
- Electricity networks commenced with a single power station serving a group of consumers.
 - Simple and easy to control
 - But no redundancy



An electricity grid with a single generator

Evolution to State Owned Island Networks

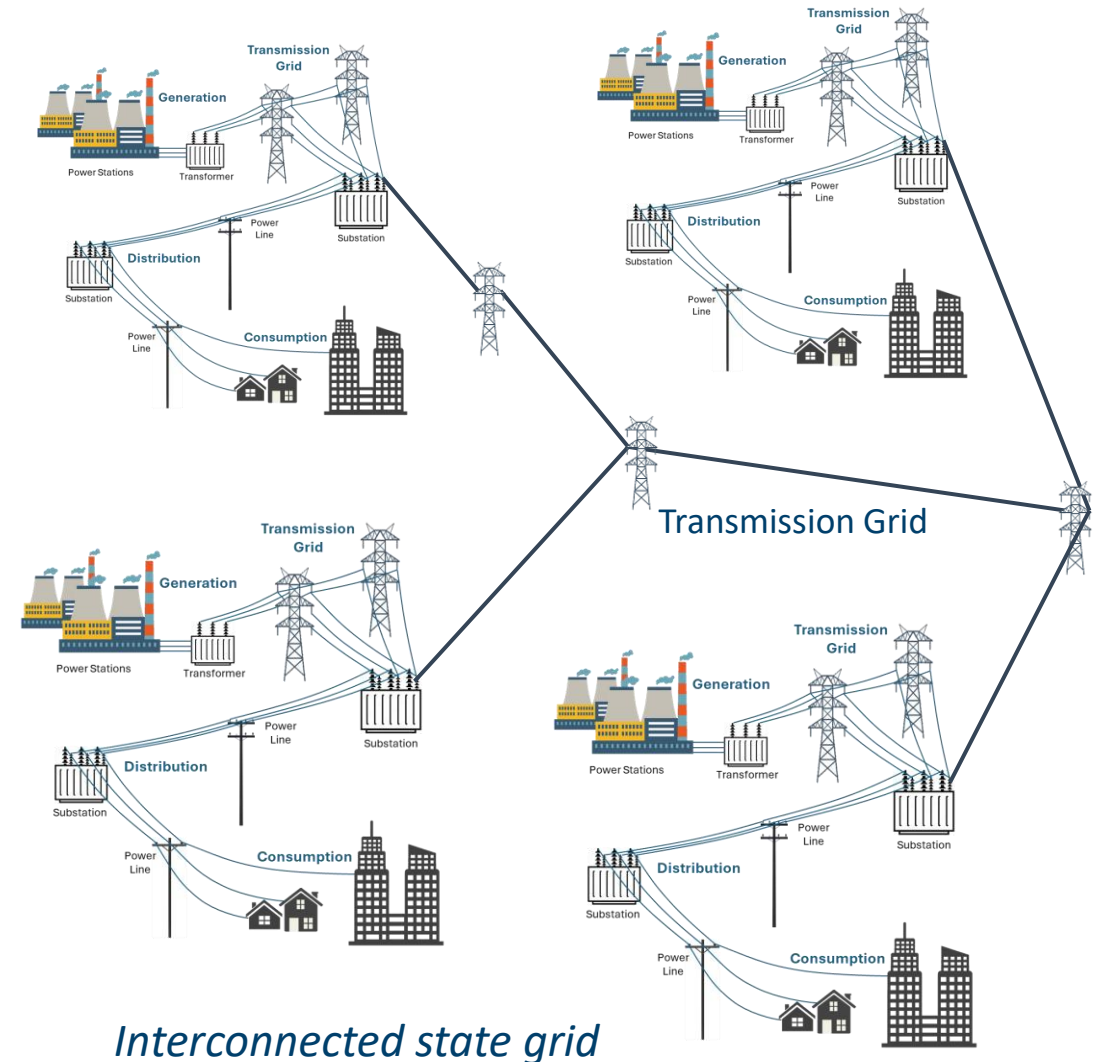
- Evolved into State owned or controlled networks
 - Multiple generators and redundant transmission infrastructure
 - Central planning and operations management
 - Designed to meet network quality needs: resilience, system strength
 - Low technical and commercial risk



A state grid with multiple generators and redundant distribution

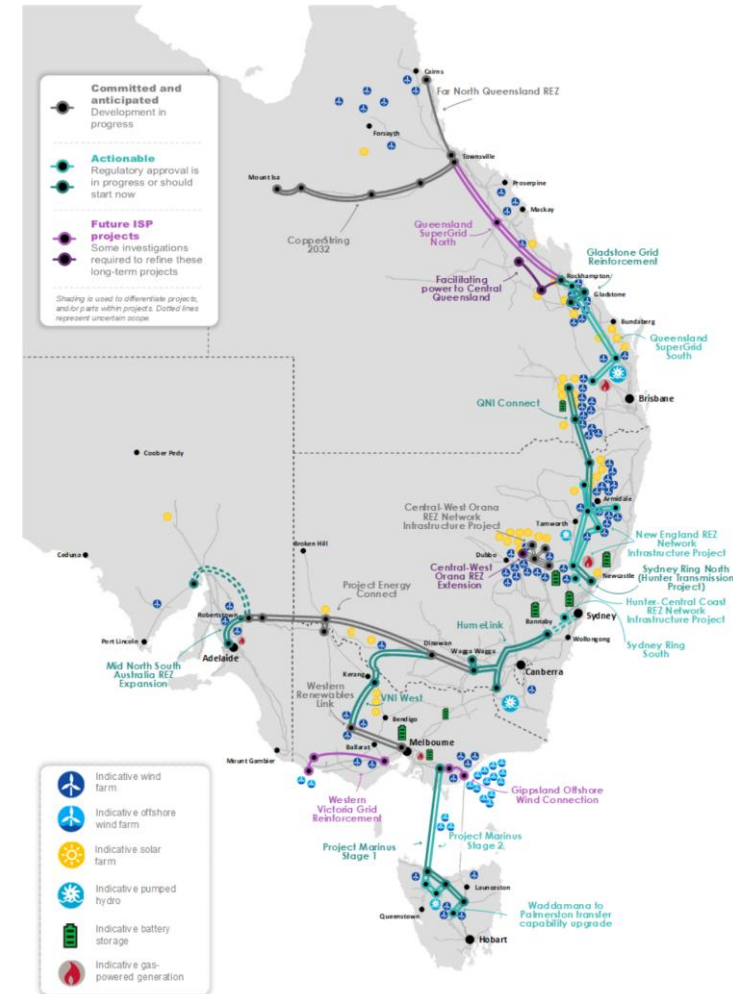
Interconnection of State Island Grids

- 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



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

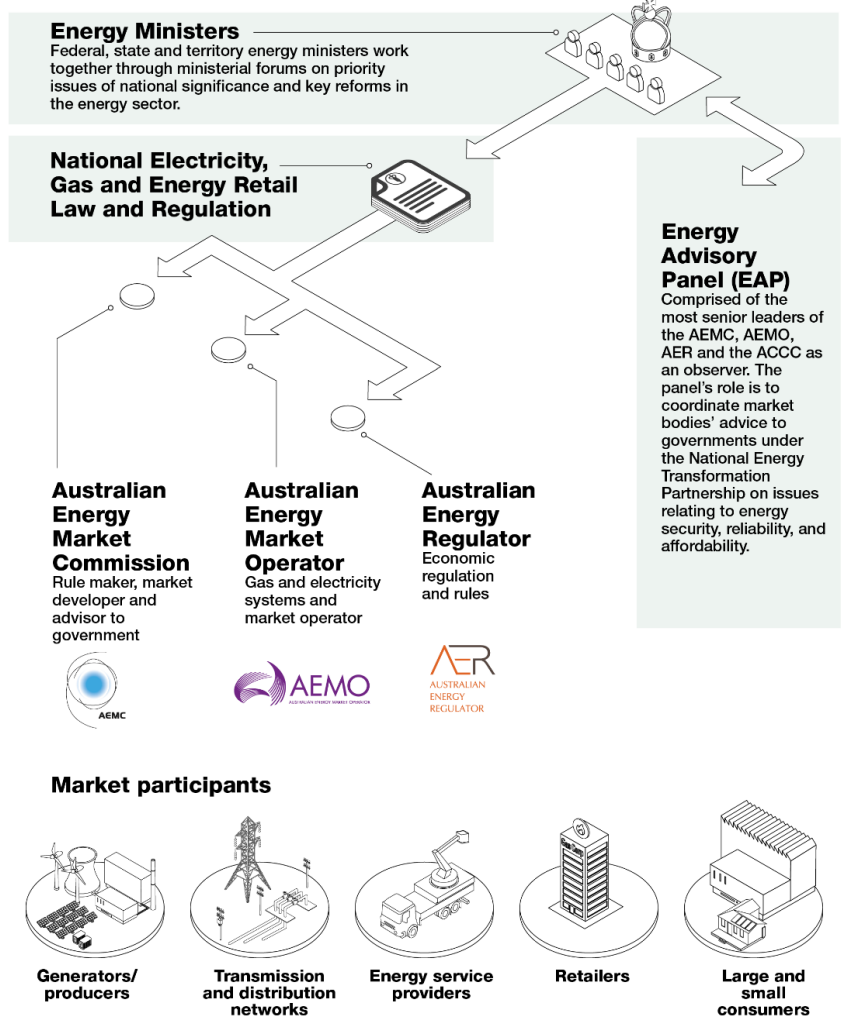


NEM grid (AEMO Integrated System Plan 2025)

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.

National energy market governance



Sourced from AER

Challenges and Risks of Interconnected Grids¹

- The efficiency gains from better utilisation 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



A Systems / SoS Engineering View of Grid Resilience

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. These constituent systems are:
 - Operationally independent
 - Managerially independent
 - Geographically distributed
 - Often pre-existing and they evolve over time
- “**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

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 Resilience¹ (1)

- Design and planning means

¹Cook S.C., Unewisse M.H. & Wylie M. 2025. Towards a Resilient Net-Zero National Electricity Grid: A Systems-of-Systems Engineering Perspective, *Climate Smart Engineering Conference*, Engineers Australia.

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.

NEM Grid – Multiple SoS Types¹

- 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)

¹ ISO/IEC/IEEE 21841 *Systems and software engineering — Taxonomy of systems of systems.*

SoSE to Manage Socio-Technical Grid Transition Risks

- Robustness and resilience evaluation and improvement
- Whole-of-systems analysis
- Design across multiple, disaggregated systems and timeframes
- Enhanced systems intelligence
- Decision-making optimisation
- Improved coordination between disparate subsystems
- Address social impact of transition
- Enhanced risk and safety management
- Efficiency and performance enhancement
- System complexity reduction
- Consideration of environmental impact and sustainability
- Application of automation and AI integration and optimisation
- Improved real-time operational optimisation strategies



Conclusions

Conclusion – DE Analysis of CED Projects

- Multitude of CED systems and projects
 - ~ \$100s billions over next 25 years
 - High risks without whole-of-system consideration
- Enable early identification of the risks and opportunities
 - Supporting entrepreneurs, investors, and engineers
 - Avoid wasting limited national resources
- SMEs have an opportunity to support and derisk these projects
- Shoal has developed an austere DE approach for CED systems
- Critical to underpin investor confidence
- Early-stage DE support to CED projects at SME scale

Conclusion – Grid Resilience

- Australian 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
 - SoSE is critical to derisking the grid transition

Questions



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