Australian research leadership in the Global Power System Transformation – Stage three

Australian research opportunities to rapidly accelerate the transition to advanced low-emission power systems

July 2024

Australia's National Science Agency

Content

Research Topics

Advanced Inverter Applications
- Inverter Design
- Stability Tools and Methods

Power System Design
- Planning
- Power System Architecture

Power System Operation
- Control Room of the Future
- Restoration and Black Start

Distributed Energy Resources
- Distributed Energy Resources (DERs)
- DERs and Stability

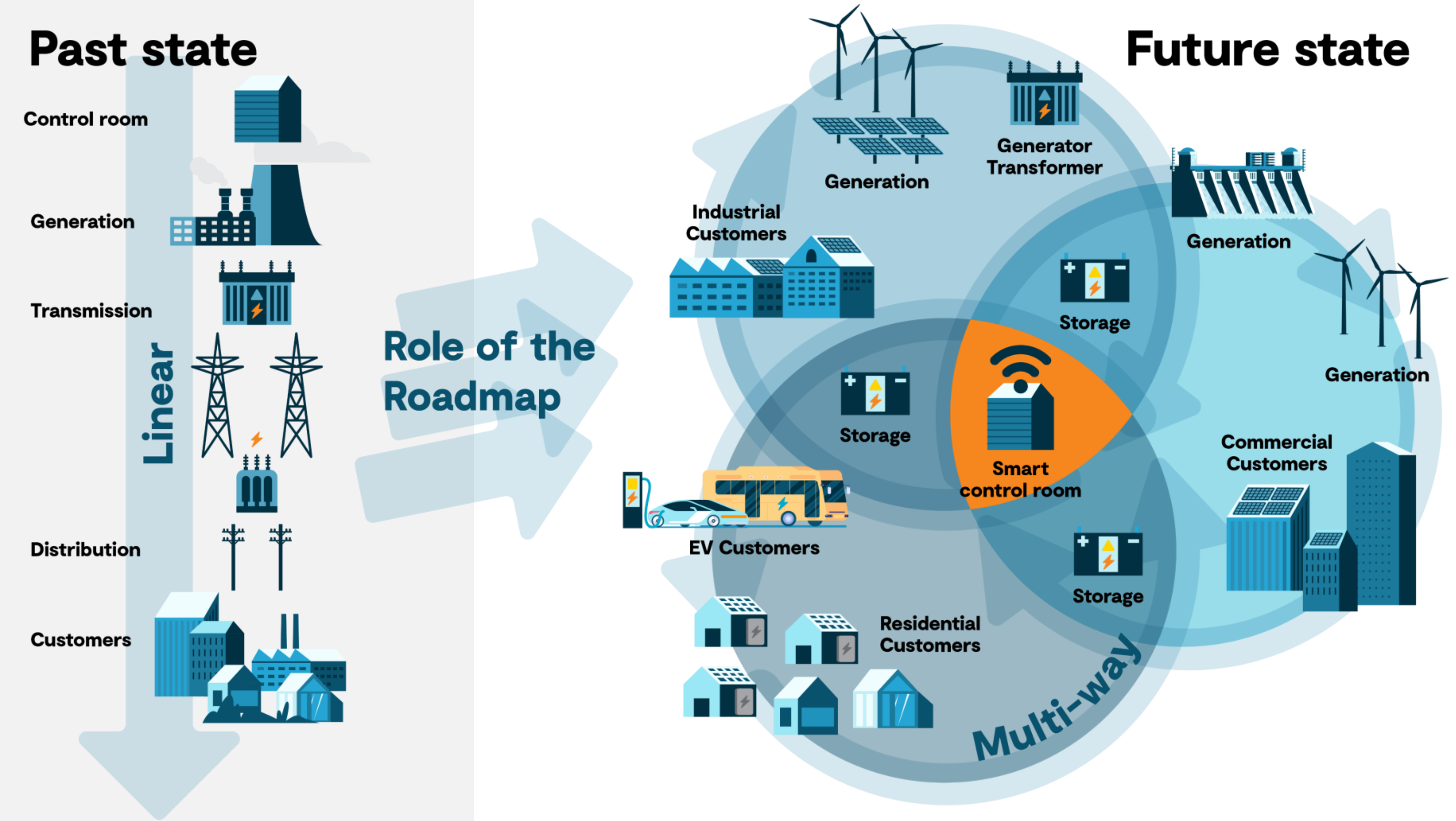
Understanding the Transition

The world is undergoing a clean energy transition at unprecedented speed, scope and scale.

Research is necessary to increase reliability and security and reduce emissions and the price of electricity. Making the transition requires collective problem solving across the value chain – from global system operators, to industry experts, to academia. Overcoming the challenges involved is urgent and vitally important for Australia, and the world.

Countries around the world face similar energy-related challenges.

- Workforce capability & development
- Rise of consumer activism
- Accelerating local technology adoption
- Enabling consumer participation
- Standards development
- Need for open data and tools


Past state
Control room
Generation
Transmission
Linear
Distribution
Customers
Role of the Roadmap
Future state
Generation
Generator Transformer
Industrial Customers
Generation
Storage
Generation
Storage
Smart control room
Commercial Customers
EV Customers
Storage
Residential Customers
Multi-way

Illuminating the Challenge

Solving these challenges is urgent for Australia, and the world.

Australian scientists and researchers are leading the way, ensuring security during the energy transition, while creating jobs, investment, export opportunities and earning global recognition.

Why Australia?

1. Australia's rapid shift away from fossil fuels is creating challenging but manageable technical hurdles for power system operators that must be resolved locally to maintain our energy security.
2. Our energy transition to a sustainable energy future with renewables can create employment and investment to drive economic growth by being a global leader in new technologies.
3. Global decarbonisation is critical to limit the devastating effect of unchecked climate change – Australia has a global responsibility.

We have the opportunity, right now, to collaboratively solve these complex issues, and co-design the best way forward to navigate this energy transition.

More information: https://globalpst.org/

“The energy transition, well underway, is by far the biggest transformation of the National Electricity Market (NEM) since it was formed 25 years ago. As well as the shift from coal to firmed renewables, it will treble capacity to meet future demand, and enable a two-way flow of electricity across the grid.”

Integrated System Plan 2024, AEMO

Global Power System Transformation (G-PST)

CSIRO and the Australian Energy Market Operator (AEMO) are Australian representatives in the Consortium. Working together, we have invited and been driving Australian universities and engineering organisations, and international research institutes to solve the most pressing challenges to accelerate the decarbonisation of our electricity system.

The G-PST Consortium aims to **dramatically accelerate the transition to low-emission and low-cost, secure and reliable power systems.**

G-PST Consortium connects leading organisations across the world to identify common research questions aimed to inform large-scale national research and development investments.

More information: https://globalpst.org/

CSIRO is driving the growth of Australian knowledge to create solutions for the G-PST established research agenda that can be applied right here.

Over the past 3 years, CSIRO:

- Continued implementation of the CSIRO G-PST Research Roadmap.
- Progressed research in nine critical research topics that will drive accelerated decarbonisation in Australia and beyond.
- Engaged leading Australian engineering, academic and research partners to deliver those research topics.
- Formed the separate research topic plans into a cohesive program that aligns with other Australian initiatives such as AEMO's National Electricity Market (NEM) Engineering Framework and the CER National Roadmap Plan.
- Delivered the first two years of energy sector research projects.
- Created a public knowledge base that shares delivered research.
- Initiated the next year of research implementation.

The Research Roadmap is now well underway and has provided solid results and insights to the Australian and global energy industry, with opportunities for more Australian engineering, academic and research organisations to be involved.

Leading the Charge

CSIRO Energy

"As Australia's premier scientific energy research organisation CSIRO Energy delivers the science and technology that will enable Australia's transition to a net-zero emissions energy future."

CSIRO Energy Mission:

- Resolve the national challenges of electricity generation, transmission, distribution, and consumption using simulation & analysis tools, and facilities & know-how, to inform investments in stable electricity grid systems.
- Create value chains across sectors and develop sustainable solutions for domestic and export industries through demonstrating viable technologies for creation, storage, transport and uses of hydrogen as well as for other low-carbon industry processes.
- Understand the social and environmental impacts of the key energy technologies, offer solutions for emission reduction and thereby enable generators and industry to shift from high emission fossil energy towards reduced emissions and sustainable solutions.
- CSIRO Energy is part of the G-PST core team and Research Agenda Group (RAG).

AEMO

"AEMO manages electricity and gas systems and markets across Australia, helping to ensure Australians have access to affordable, secure and reliable energy."

AEMO's primary role is to promote the efficient investment in, and efficient operation and use of, gas and electricity for the long-term interests of Australian consumers in relation to price, quality, safety, reliability and security.

With Australia's energy landscape experiencing significant disruptive, transformational changes, designing an energy system that addresses and harnesses these changes in the long-term interest of energy consumers has become a key focus.

AEMO provides the detailed, independent planning, forecasting and modelling information and advice that drives effective and strategic decision-making, regulatory changes and investment.

In addition to numerous other functions and responsibilities, AEMO was a Founding System Operator of the G-PST.

Charting Our Course

A rapid pathway from research to impact.

The Research Roadmap prepared an action plan to implement the critical research required from the Australian research community.

During FY2024, this second year of implementation of the Research Roadmap, a selection of Australia's brightest minds supported by international experts have contributed their expertise to designing power systems for the future.

We're listening to industry needs and reprioritising accordingly

MAY 2023

SEP 2023

DEC 2023

MAY 2024

The steps taken so far

Implementing the Roadmap: Stage 3 Research

Engage scientific and engineering organisations to implement the Roadmap research

Progress review and scope realignment

Review progress of the research

Share progress with Australian and international research partners

Forward planning for Stage 4

Consider whether energy system developments have reprioritised existing tasks and/or created new urgent research

Determine what critical tasks must be addressed in the next stage of research

Completion of Stage 3

Publication of all results and materials for Stage 3

Next steps

Commence Stage 4 research

Sparking Investment

Power systems are becoming less centralised and facing new challenges due to a decrease in synchronous generation and an increase in inverter based resources (IBRs) with the uptake of renewable energy generation.

As such, the energy grid is undergoing major changes and research into new technologies is is essential to facilitate the energy transition in Australia and the world more broadly.

"As coal-fired power stations retire, renewables – connected with transition and distribution, supported by hydro, batteries and gas-fired power generation – is the lowest cost way to supply electricity to homes and businesses."

Daniel Westerman, Australian Energy Market Operator

Why continue to invest in this research?

Security
Facilitate a safe, cost-effective energy transition for consumers

Research
Advance critically needed Australian research

Reliability
Controlling the chaos of weather dependent energy systems

Affordability
Create more stability and financial security for consumers

Knowledge sharing
Share knowledge and export solutions to support a global transition

Environment
Support achievement of Australian net-zero emission goals

CSIRO AEMO

Research focus areas

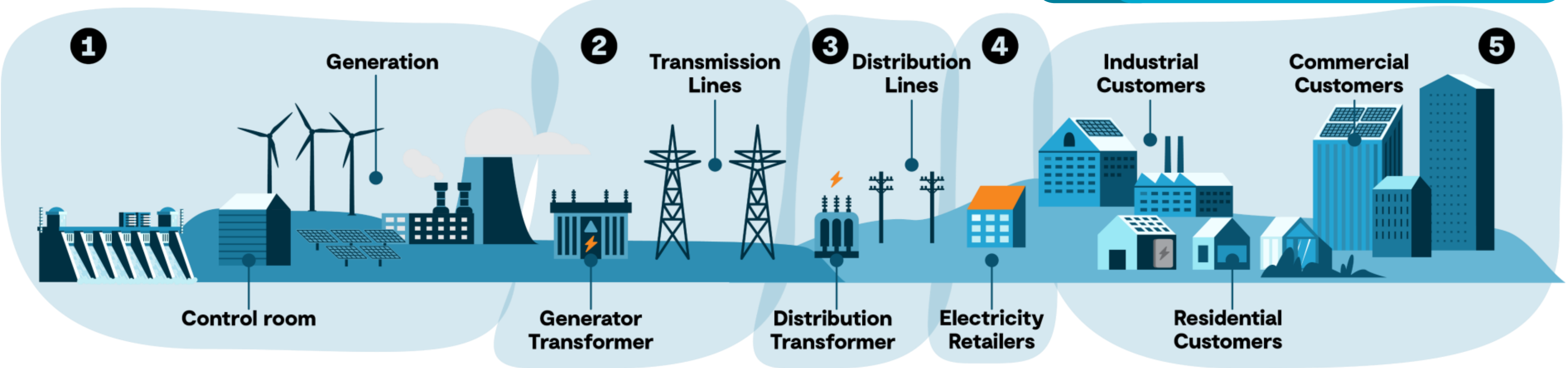
A	Advanced Inverter Applications
B	Power System Planning
C	Power System Operation
D	DER Integration

Topic	Area	Title
Topic 1	A	Inverter Design
Topic 2	A	Stability Tools and Methods
Topic 3	C	Control Room of the Future
Topic 4	B	System Planning
Topic 5	C	Restoration and Black Start
Topic 6	C	Essential System Services
Topic 7	B	Power Systems Architecture
Topic 8	D	Distributed Energy Resources (DERs)
Topic 9	D	DERs and Stability

CSIRO AEMO

Research focus areas across the supply chain

- Topic 6 Essential System Services
- Topic 1 Inverter Design
- Topic 7 Power Systems Architecture
- Topic 2 Stability Tools and Methods
- Topic 3 Control Room of the Future
- Topic 4 System Planning
- Topic 8 Distributed Energy Resources (DERs)
- Topic 5 Restoration and Black Start
- Topic 9 DERs and Stability



Roadmap at a glance

$11.5M Total Investment to date

3 Years

9 Topics

2024 We are here

KEY BREAK THROUGHS TOPIC 1:
Transient stability assessment tool for multi-IBR networks

KEY BREAK THROUGHS TOPIC 2:
Framework to estimate the frequency characteristics at any operating point for an IBR

KEY BREAK THROUGHS TOPIC 3:
Prototype that uses machine learning to identify incidents from alarms in operational data sets.

KEY BREAK THROUGHS TOPIC 4:
New multi-stage stochastic planning methods that can hedge against long-term uncertainty

KEY BREAK THROUGHS TOPIC 5:
Ability to support 100% IBR restart of black start incapable IBRs up to 10 times the MVA rating of the black start device

KEY BREAK THROUGHS TOPIC 7:
Gaining industry traction for Power Systems Architecture as an enabler of structured grid transformation in Australia.

KEY BREAK THROUGHS TOPIC 8:
Demonstrate flexible dynamic export limits are key to significantly increase residential solar PV generation rather than fixed limits.

KEY BREAK THROUGHS TOPIC 9:
Extensive testing of DER, ESS, loads has led to AEMO producing more accurate composite load models for system security assessment

Future focus

FUTURE FOCUS TOPIC 1:
Focus on refining grid-forming inverter technologies and conducting extended field testing to enhance grid stability under various fault profiles and system conditions.

FUTURE FOCUS TOPIC 2:
Enhance admittance estimation algorithms, retest stability frameworks against real networks, and expand the assessment of current limiting responses and composite load impacts.

FUTURE FOCUS TOPIC 3:
Initiate human factors research focusing on decision-making, training standardisation, visualisation, and developing operator capabilities, as well as exploring ergonomics and building design in control rooms.

FUTURE FOCUS TOPIC 4:
Integrate distribution and transmission network planning, analyse economic and operational benefits of hybrid energy hubs, and optimise planning frameworks using advanced mathematical algorithms.

FUTURE FOCUS TOPIC 5:
Model protection relays, network protection schemes, and control structures for IBRs to guide system restoration in high penetration and 100% IBR networks.

FUTURE FOCUS TOPIC 6:
Develop EMT models to assess essential service requirements for a 100% IBR system, and the translatability to other modelling domains

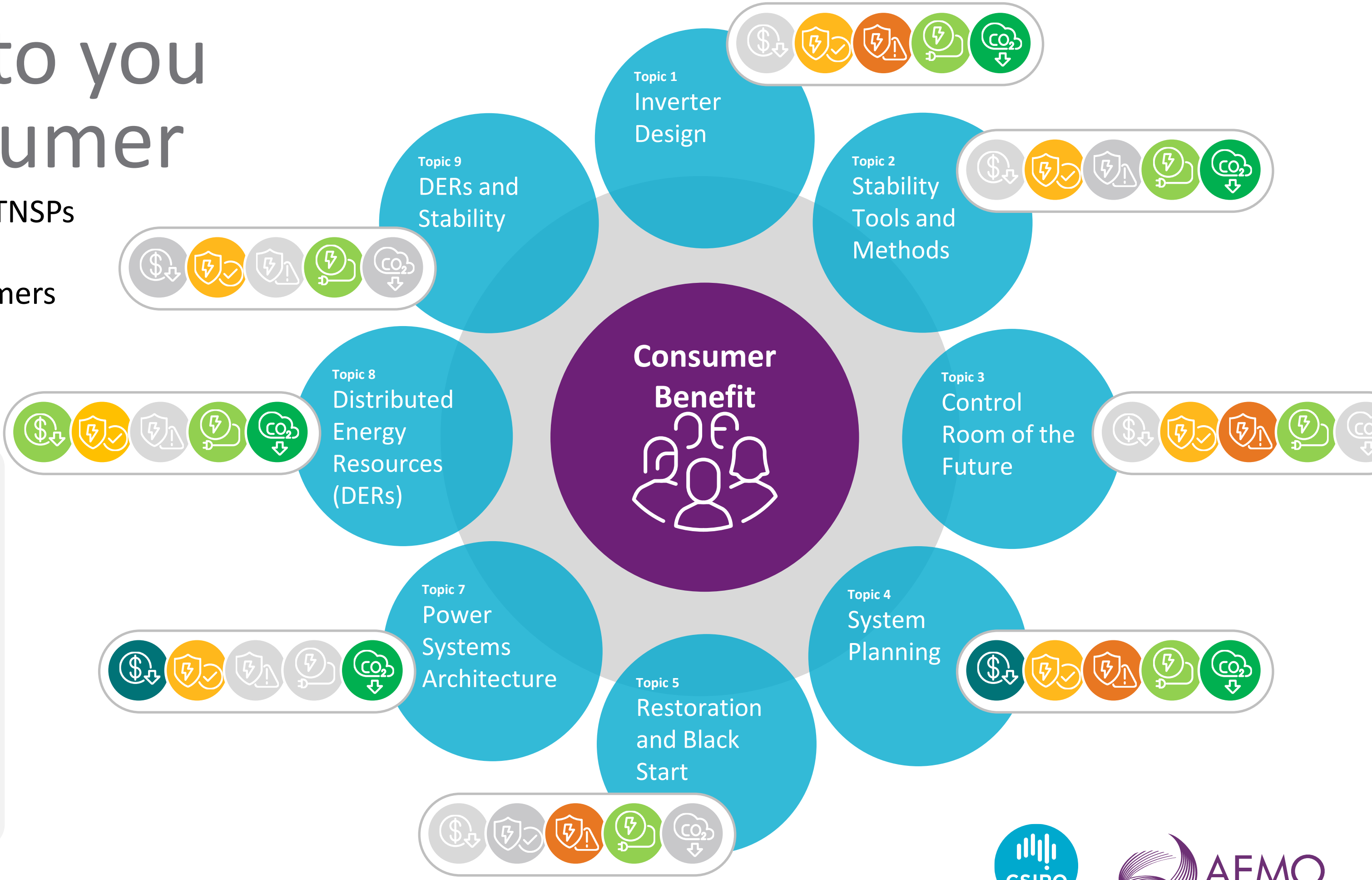
FUTURE FOCUS TOPIC 7:
Focus on project governance, stakeholder engagement, and detailed mapping of power system architecture functions, relationships, and interfaces.

FUTURE FOCUS TOPIC 8:
Assess the impact of PV inverter standards, improve OE calculations, evaluate OE performance, and explore fairness and import limits in dynamic operating envelopes.

FUTURE FOCUS TOPIC 9:
Explore the potential of Virtual Power Plants, microgrid solutions for resilience, and AI-driven tools for grid management.

Benefits to you as a consumer

These not only benefit TNSPs and AEMO but also has many benefits to customers



Key:

- More affordable
- More reliable
- Safer
- System security
- Lower emissions

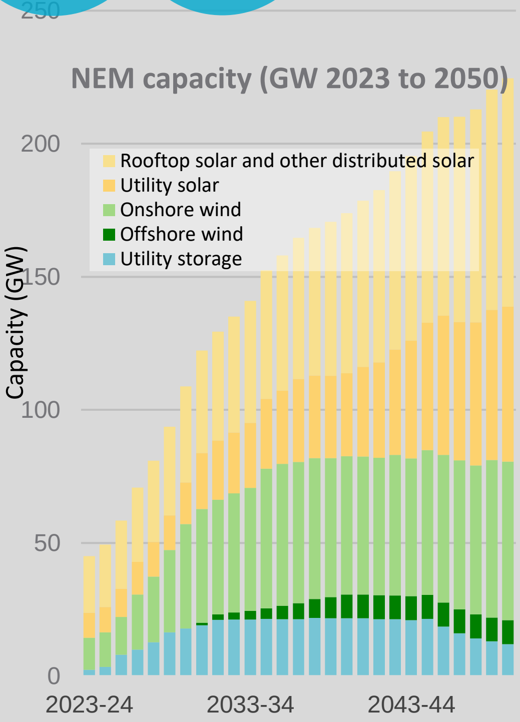
Advanced inverter applications

Integration of inverter-based energy generation

With the energy transition fully underway, Australia is experiencing an unprecedented increase in Inverter Based Resource integration. AEMO's 2024 Draft ISP projects that by 2030 the National Electricity Market will see an increase from the present 19 GW of grid-scale wind and solar generation to potentially 57 GW, and that by 2050 the current amount of installation with increase 7-fold. These increases are driven by the retirement of the NEM's coal-based generation fleet and increased demand due to electrification of other energy carriers such as in transportation, as well as potential large scale green hydrogen production.

It is understood that the energy transition will see a change of the way we manage and operate our electricity networks. The phasing out of large, centralised fossil fuelled power stations, as these reach their end of life, will see a new generation of energy sources take their place; energy sources that will use the sun and wind as their fuel.

These renewable energy sources will use power electronics to convert the generated power to a form suitable to inject into our electricity networks. While the power electronic technology used in these processes is not new, the scale at which it will be adapted is a significant change that will have to be managed, including development of the right control systems to manage the power electronics used, effective coordination between the many control systems installed in each renewable generation facility, and secure dispatch and operational oversight of this new generation fleet by the power system operators.



Inverter Design

Organisation

MONASH University

Priorities

1-2 Years <5 Years <10 Years

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Objective and key focus

This project presents a comprehensive study of grid-forming inverters in power systems, focusing on their design, transient stability, and control enhancements. Aim is to improve the performance and reliability of inverter-based resources (IBRs) as they become increasingly essential in modern power systems.

The research project consists of several interconnected tasks:

1. Assessment of multi-IBR systems, such as found in Renewable Energy Zones.
2. The development of a tool for rapid stability assessment of high IBR penetration systems.
3. Investigation of negative sequence current controls that are used in IBR to assist network operation during unbalanced network faults.
4. Assessment of enhancing the transient stability of grid forming current-limited controls for wind turbine generators.

What has stage 3 delivered?

Topic 1 research has successfully delivered several key outcomes to advance understanding and optimisation of inverter-based generation and their control systems, including:

1. Successful adaptation of stability point analysis for interconnected inverter systems.
2. Development of a software tool that can rapidly assess stability metrics for different network configurations and different operating points.
3. Identified critical sensitivities impacting IBR when providing negative sequence current contributions.
4. Applied GFM technology to type 3 and 4 wind turbines and identified operational benefits over GFL types

“The most significant milestone in the past two years has been the development and validation of a generalised transient stability assessment tool for multi-cluster, multi IBR networks.

This tool enables accurate and efficient stability margin estimations, which are critical for ensuring the resilience of power systems with high penetrations of renewable energy sources. The ability to integrate and stabilise diverse renewable resources across large and complex network configurations represents a major advancement in supporting the sustainable transition of energy systems.”

Inverter Design

Priority Key
- Critical
- High to critical
- High
- Medium

Organisation: MONASH University

Priorities: 1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

Overall, this research contributes valuable knowledge and practical tools for designing, operating, and controlling grid-forming inverters in modern power systems. The results not only improve the transient stability of these systems and but also ensure secure grid integration of IBR as renewable energy resources continue to expand.

This research facilitates renewable energy integration, enhances grid stability, and supports grid modernisation in Australia. It contributes to the development of grid codes and standards, particularly for negative sequence current injection during faults. By extending grid-forming controls to wind turbines, the research drives technological innovation, bolstering the reliability and efficiency of Australia's power systems as they increasingly depend on renewable energy sources.

Progress on the Roadmap

Task	Priority	Progress	Relevance
Assessment and enhancement of IBRs reliability	High to critical	50%	Still relevant
Enhancing IBR response during and subsequent to faults	High	70%	Still relevant
Grid-forming capability for HVDC stations and wind and solar farms	High	20%	Still relevant

Stability Tools and Methods

Organisation

EPRI

Priorities

1-2 Years | <5 Years | <10 Years

Objective and key focus

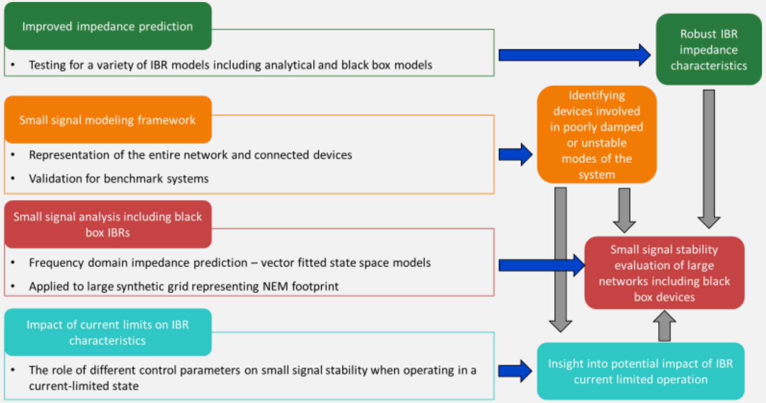
Changes to our generation technology, from synchronous generation to IBR, are impacting the operation of our electrical networks, including the frequency and damping of oscillations. Power system oscillations can result in power system instability, loss of generation, loss of load, or partial blackouts.

To enable safe and reliable power delivery in future power systems with significant contribution from IBR, Topic 2 focused on the several key activities:

1. Compare the performance of the two impedance prediction algorithms for assessing IBR models with different control architectures and different operating points and control parameters.
2. Perform small signal stability analysis of a large network using positive sequence network models and the predicted impedance characteristics of IBRs identified using the analytical prediction algorithm.
3. Establish a small signal analysis framework to identify any small signal unstable conditions and the devices/states that participate in oscillation modes that are unstable or poorly damped.
4. Assess the impact of current limiting on the stability of IBR, including representation and performance.

What has stage 3 delivered?

- Developed an analytical prediction algorithm to identify the impedance characteristics of black box IBR, using only small number of operating points.
- Verified the small signal analysis framework effectiveness in identifying unstable conditions in a reduced scale model of the NEM and optimise countermeasures to dampen the unstable OPs.
- Established the wide area stability and security risks resulting from current limited IBR.



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Stability Tools and Methods

Priority Key
- Critical
- High to critical
- High
- Medium

Organisation

EPRI

Priorities

1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

"Modes in the Australian NEM are changing due to network topology changes, the addition of new generations, and the retirement of synchronous generators from the market. These factors influence the frequency and damping of oscillations." AEMO

- Power system oscillations if not damped, can result in power system instability, loss of generation, loss of load, or partial blackouts.
- With more rapidly changing operating conditions due to our weather dependent energy system, traditional methods of security assessment are becoming less effective.
- Complicating assessment further are the often hidden electrical and control system structures of IBR that make traditional methods also less accurate.

Progress on the Roadmap

Task	Priority	Progress	Relevance
Develop tools to evaluate non-linear stability margins using black-box models at multiple operating points	Critical	60%	Still relevant
Development of procedures to use impedance-based methods for network stability screening when using black box IBR models.	Critical	60%	Still relevant

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Power System Design

Planning our energy system

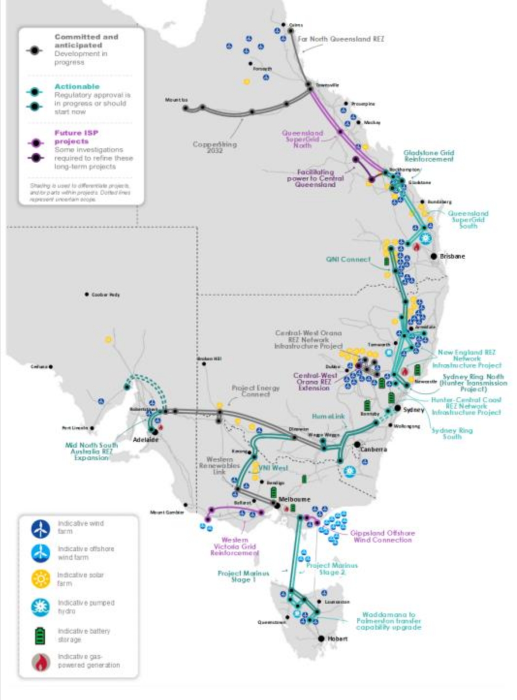
Our interconnected power systems are some of the most complex machines ever built. Commonly spanning thousands of kilometres and interconnecting millions of customers, they have developed and expanded over many decades and have enabled secure and economic supply of energy to generations of consumers who have funded the development of the electrical network.

However, for the past decade there have been many changes that have disrupted the way that we plan and fund our power grid infrastructure. Increased decentralisation of our energy sources, changes to our generating technologies, electrification of other energy vectors, ageing infrastructure, and increasing active consumer participation in the energy system, all drive the decarbonisation of our power system and the associated energy transition we are in.

As a result, the regulatory and planning processes that have served us so well in the past are becoming obsolete, unable to deal with the many changes underway.

CSIRO's Australian G-PST research roadmap has funded two important projects that are providing greater understanding of the changing needs, new tools, and methods to the way we plan our power system, and connect the new influences we must consider as we look to develop the power system of the future:

1. Energy infrastructure planning under deep uncertainty: Assessing impacts and benefits of energy system integration
2. Power System Architecture



Planning

Organisation

THE UNIVERSITY OF MELBOURNE

Priorities

1-2 Years | <5 Years | <10 Years

Objective and key focus

The evolving and complex long-term uncertainties relevant to power systems, and their implications, has made it increasingly important for power system engineers and planners to consider new planning methodologies, to improve infrastructure investment decisions including cost. Four core activities for this project are:

1. Analysing relevant techniques and metrics for selecting representative periods in energy system planning studies
2. Identifying and quantifying the value of the operational flexibility that DER could provide in deferring large-scale investments under uncertainty
3. Modelling and assessing the potential benefits of integrated electricity-hydrogen infrastructure planning for future green hydrogen production
4. Quantifying the resilience benefits that flexible technologies could provide against high-impact, low-probability events, including outages of large infrastructure

What has stage 3 delivered?

The investigation developed new methods and metrics for transmission planning, summarised in a report that details:

- A thorough assessment and literature survey regarding the techniques, metrics, and alternative practices for selecting representative periods in energy system planning studies
- Stochastic planning analysis of the impact of flexible DER on power systems investments utilising the 2022 ISP datasets, highlighting the benefits and features of these technologies in developing more robust decision-making and hedging against risky scenarios
- Quantitative comparison between deterministic and stochastic planning to show the capabilities and limitations of each approach to leverage the flexibility from DER with long-term investment purposes
- Analysis of the benefits and trade-offs of planning an integrated electricity-hydrogen energy system through a set of regional and NEM-wide studies, underscoring the potential role of hydrogen infrastructure in accommodating greater levels of renewable energy while reducing costs.
- Characterisation of different non-average and HILP events that could impact planning tasks and a flexible planning approach considering resilience, tested through illustrative use cases considering different technologies and operational conditions.

Planning

Organisation

THE UNIVERSITY OF MELBOURNE

Priorities

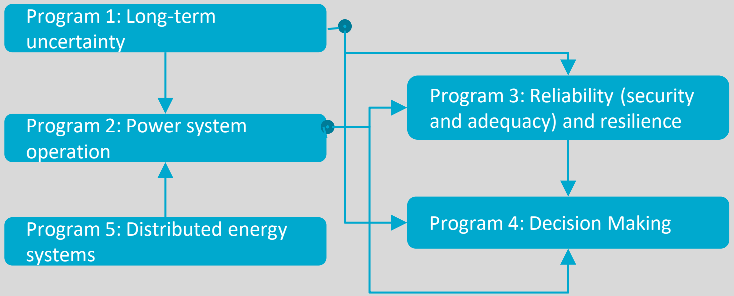
1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

- **Australia's power system is at a crossroads** when making decisions about new infrastructure. Transmission is key to unlocking renewable energy zones (REZs) nationwide and transporting energy to load centres.
- REZ development, demand growth, fast uptake of DER, advancements in storage technologies, the retirement of synchronous units, and alternative energy carriers, are subject to deep uncertainties that make the **decision to build new large-scale assets both strategic and challenging**.
- Making the **right investment decisions can yield value** for the system through lower costs, enhanced reliability, increased resilience, and reduced renewable energy curtailment.
- **Incorrect or untimely decisions could lead to** stranded or underutilised assets and potentially **higher costs to consumers**.

Progress on the Roadmap

Task	Progress	
Power System operation: Steady state modelling (P1)	20%	Still relevant
Decision-making: methodologies for decision-making under uncertainty (P3)	20%	Still relevant
Distributed energy Systems: Distributed energy markets and DSF (P1, P2)	25%	Still relevant
Distributed Energy Systems: DER impact (P2)	20%	Still relevant
Distributed Energy Systems: Multi-energy systems (P1)	20%	Still relevant
Reliability and resilience: Credible and non-credible contingencies (P3)	50%	Still relevant



Power System Architecture

Organisation

Energy Catalyst

Priorities

1-2 Years | <5 Years | <10 Years

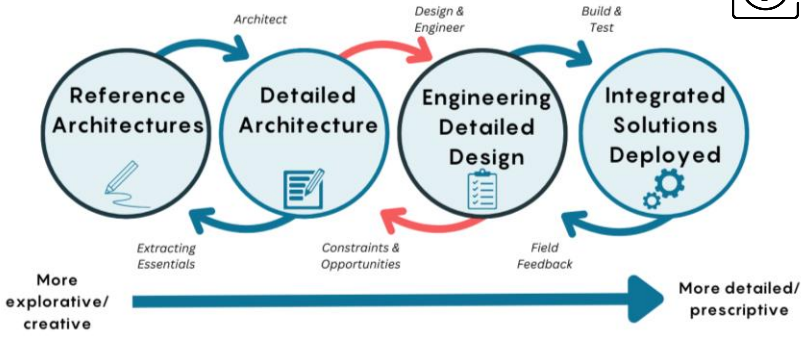
Objective and key focus

PSA is an integrated set of disciplines supporting the structural transformation of legacy power systems to meet future policy and customer expectations, by:

1. Providing formal tools to decompose and 'tame' the massive complexity inherent in transitioning power systems;
2. Empowering more informed, multi-stakeholder participation, by making explicit and tractable key power system features and choices that would otherwise remain opaque and intractable;
3. Improving decision quality, timeliness, and traceability, to proceed towards full benefits-realisation, while avoiding unintended consequences.

To expand industry awareness of the relevance of Systems Engineering disciplines, and to maximise the actionable impact of the PSA toolkit, ongoing collaboration with industry stakeholders and AEMO's Future Energy Systems (FES) team has been a key priority.

To this effect, G-PST Stage 3 has actively focused on transitioning from research completed in the prior stage to an expanding range of applications that demonstrate the practical value of these tools for navigating complex power systems transformation.



What has Stage 3 delivered?

Energy Catalyst's research provides a reference framework for the NEM's architecture, include key aspects of:

- Applied Model Based System Engineering (MBSE) to translate the comprehensive set of architectural mappings of the NEM into a digital environment.
- Completed the first common-format structural mapping of recent DER demonstration projects: Project EDGE, Project Symphony, and Project Edith.
- Employed common-format structural mapping to the SAPN Emergency DPV curtailment to manage DER during minimum demand scenarios.

Power System Architecture

Organisation

Energy Catalyst

Priorities

1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

Australia's power systems are leading the world in navigating a once-in-a-century scale of transformation. However, a system is not the sum of its parts, but the product of the interactions of those parts.

As Australia's power systems transition from hundreds, to tens of millions, of participating energy resources, **the bulk energy, transmission and distribution systems – together with deep demand-side flexibility – must function holistically to enable reliable and efficient operation.**

The PSA work in the G-PST Roadmap considers entirely new approaches to 'Operational Coordination' of the entire power system. This can provide structure to the turbulence of Australia's rapid and fundamental change, taming the complexity of the energy transition to unlock $-billions in system efficiency value for customers and society.

Progress on the Roadmap

Stage 3 has expanded upon the Reference Architectures to include the structural mapping of several demonstration projects to enable stakeholders to compare and contrast the different approaches trialled.

It also transitioned all content into the digital MBSE environment to empower multi-stakeholder collaboration in the subsequent Detailed Architecture phase to interrogate and mature this content. This work sets the path for the detailed architecture to be developed in subsequent sages of this research.

Task	Progress	
Explore future system objectives Identify emerging trends and systemic issues	100%	Still relevant
Document existing architectures and constraints	100%	Still relevant
Explore future system qualities, properties and functions	100%	Still relevant
Develop future architectural options	50%	Still relevant
Future options and transitions pathways report	50%	Still relevant

The underpinning structures of any complex system impact what the system can safely, reliably, and cost-efficiently do far more than any individual technology.

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Power System Operation

Keeping the lights on

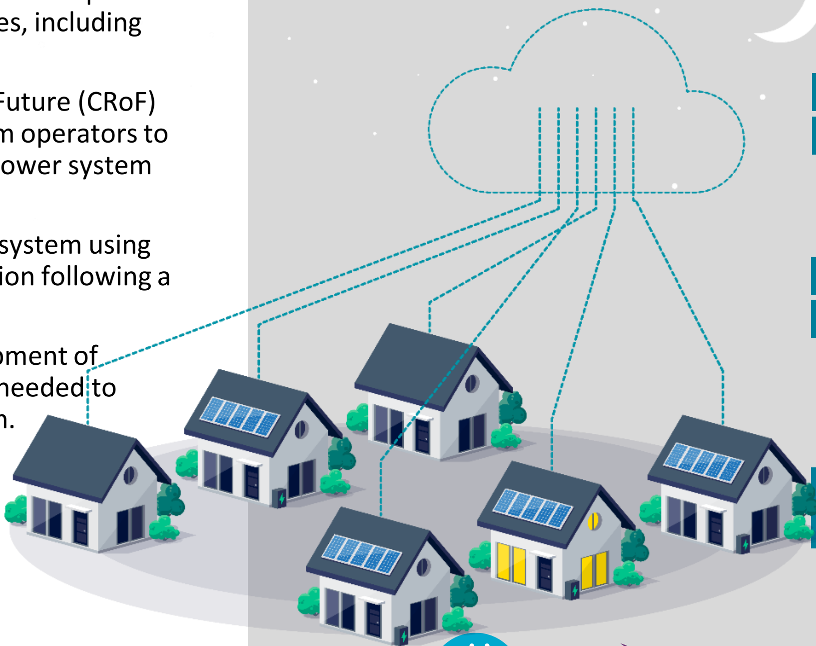
The power system of the past with centralised large thermal generating plant and predictable consumer behaviour is being transformed into a system of intermittent and decentralised utility scale power plant and distributed consumer energy sources.

As the Australian power system continues to transform to a decentralised, decarbonised, and digitised one, we will have to adapt and expand the technology, processes, and controls that we use to operate this complex system of systems.

CSIRO’s Australian G-PST research recognises the need to advance our understanding and implementation of new technologies and techniques that will ensure that the power grid of the future can continue to operate stably, efficiently, and economically.

To support the growth of the body of knowledge and new technology applications, the research area of Power System Operation includes three critical initiatives, including research in:

1. The Control Room of the Future (CRoF) that will enable our system operators to continue to manage our power system securely and reliably.
2. Restoration of the power system using non-synchronous generation following a regional blackout.
3. Identification and development of essential system services needed to operate our power system.



Control Room of the Future

Organisation

EPRI

Priorities

1-2 Years | <5 Years | <10 Years

Objective and key focus

The control rooms operated by system operators and electricity network owners are at the very centre of stable, secure, and reliable electricity supply. From here the power system operators control network voltages and frequency, dispatch generation, monitor the power system for any abnormal behaviour that must be corrected, and much more. Without such control rooms it would not be possible to operate large modern power systems.

While the quantity of data and the risks to networks are growing, the number of operators in control rooms is expected to stay relatively constant, the alarm data handling mechanisms in EMS/SCADA are not expected to evolve significantly in the near term. One way to redress the imbalance of increased data with finite human resources is to develop innovations in how data is processed, filtered and presented to operators in real time.

The research leverages the CSIRO research roadmap but with focus on the pathways for operational applications and technology developments in the coming decade, to meet the monitoring and assessment needs of AEMO in their role as the electricity system and market operator. It is closely linked to the AEMO Operations Technology Roadmap , which recognises the need for continuous development of AI and ML applications for the electricity system control room.

What has stage 3 delivered?

To advance the concepts and methods required of the CRoF EPRI have progressed three topics of the original Topic 3 Roadmap:

1. Software applications:

    a) Task 1: Operational data machine learning use cases

    Used algorithms directly trained and applied on real AEMO operational data from diverse range of operational datasets. Ultimately the aim is for a deployment of an operational data prototype directly on AEMO systems that uses real time AEMO operational data, to augment operator sense making.

    a) Task 2: Exploration of Large Language Models (LLM) in the operational context

    Explored the application of LLM, which can potentially be used to help operators make sense of large quantities of text-based data.

2. Operational data:

    a) Task 3: Dynamic model validation methodology

    Explored the achievement of more accurate modelling of our power system. Such models are used to predict system behaviour and limits of operational stability. Proposed a methodology for automated model validation using operational data.

1 2 Advanced Inverter Applications
4 7 Power System Design
3 5 Power System Operation
8 9 Distributed Energy Resources

Topic 3

Control Room of the Future

Priority Key
- Critical
- High to critical
- High
- Medium

Organisation: EPRI

Priorities: 1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

Currently there is no existing machine learning project methodology for power system use cases, and yet the need for increased automation and rapid decision-making increases with growing renewable generation, decentralisation, and digitisation.

Despite industry adoption of machine learning, there is limited application in power systems and energy sector more broadly, both in Australia and around the world.

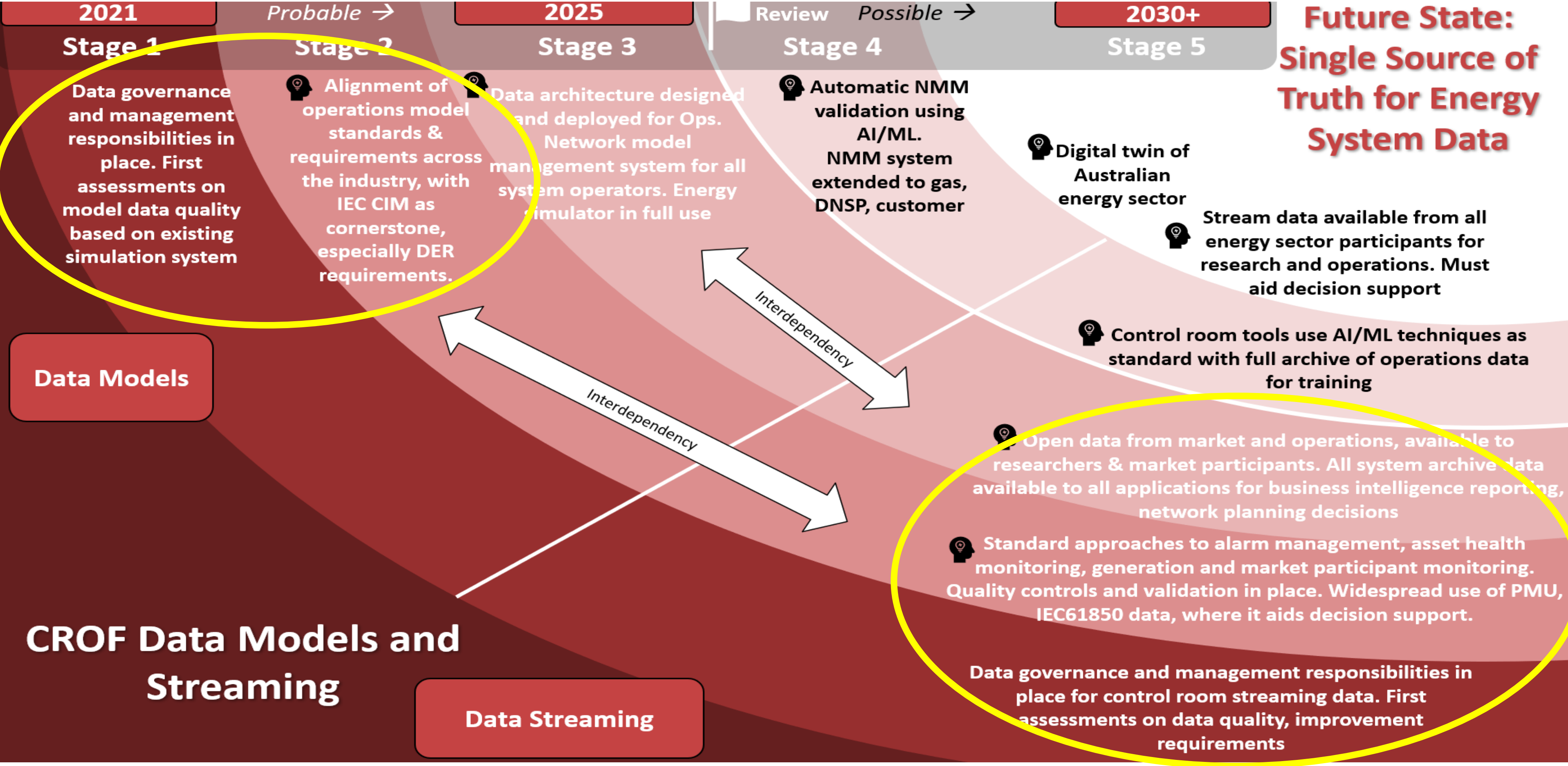
This project aims to add structure to the development of machine learning applications so that they are baselined and benchmarked and can be applied by AEMO and other system operators.

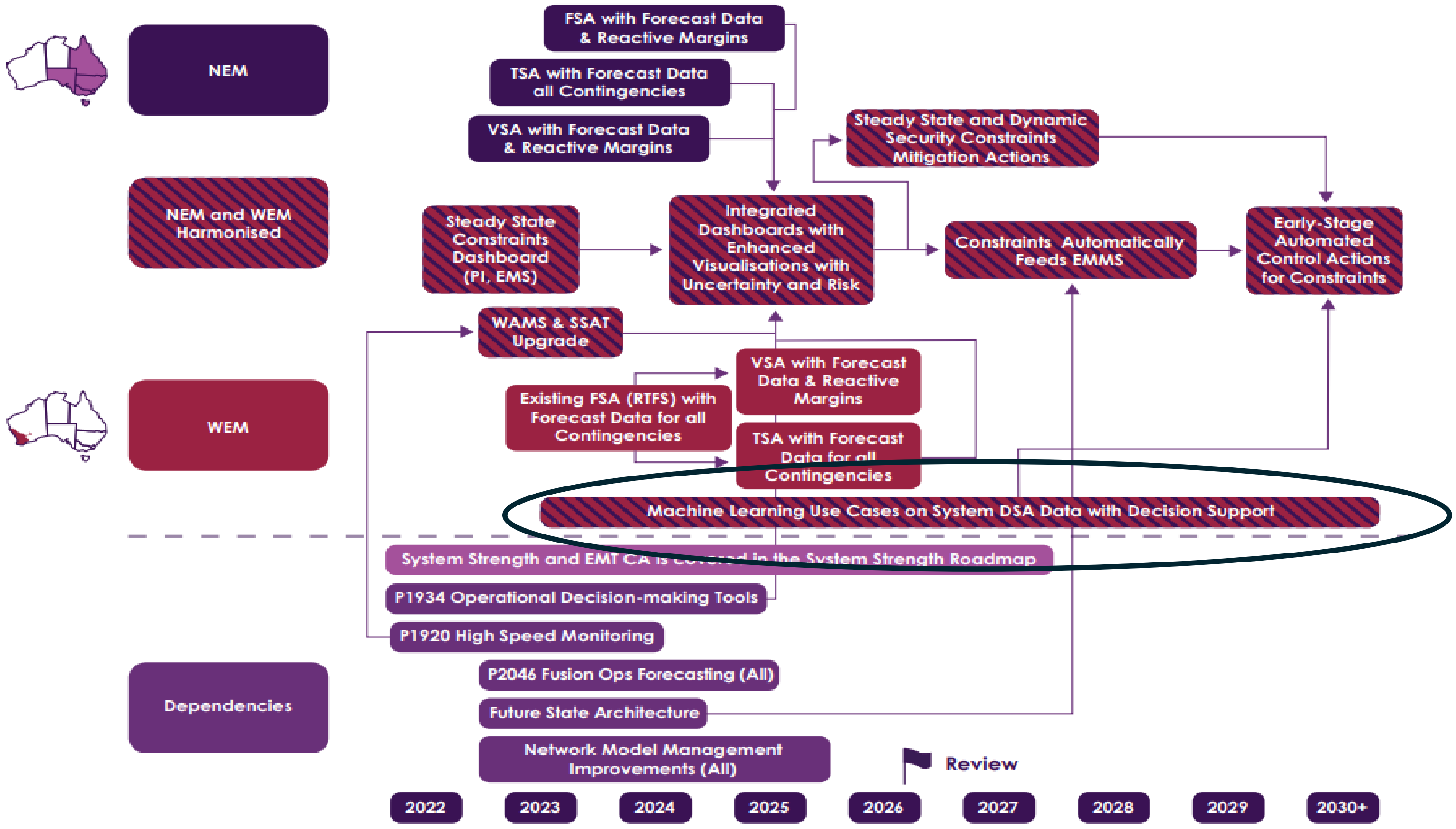
The development of the methodology and use cases in this project can be used by researchers and practitioners in Australia. However, a secondary aim is to also to generalise and extend the methodology and framework, to be applicable to the industry beyond Australia.

Progress on the Roadmap

Task	Priority	Progress	Relevance
Standard approaches to alarm management, asset health monitoring, generation and market participant monitoring.	High to critical	50%	Still relevant
Control room tools use AI/ML techniques as standard with full archive of operations data for training	Critical	25%	Still relevant
Alignment on operations model standards & requirements, with IEC CIM as cornerstone, especially DER requirements. Widespread use of PMU.	Critical	15%	Still relevant

Progress of the CROF Research Agenda




NEM
NEM and WEM Harmonised
WEM
Dependencies
FSA with Forecast Data & Reactive Margins
TSA with Forecast Data all Contingencies
VSA with Forecast Data & Reactive Margins
Steady State and Dynamic Security Constraints Mitigation Actions
Steady State Constraints Dashboard (PI, EMS)
Integrated Dashboards with Enhanced Visualisations with Uncertainty and Risk
Constraints Automatically Feeds EMMS
Early-Stage Automated Control Actions for Constraints
WAMS & SSAT Upgrade
VSA with Forecast Data & Reactive Margins
Existing FSA (RTFS) with Forecast Data for all Contingencies
TSA with Forecast Data for all Contingencies
Machine Learning Use Cases on System DSA Data with Decision Support
System Strength and EMT CA is covered in the System Strength Roadmap
P1934 Operational Decision-making Tools
P1920 High Speed Monitoring
P2046 Fusion Ops Forecasting (All)
Future State Architecture
Network Model Management Improvements (All)
Review
2022
2023
2024
2025
2026
2027
2028
2029
2030+

Restoration and Black Start

Organisation

aurecon

Priorities

1-2 Years | <5 Years | <10 Years

Objective and key focus

The restoration of a blacked-out power system is a process heavily reliant on existing synchronous generation technology. With AEMO predicting the large-scale closure of the generator over the coming decade, finding alternatives to system restoration is critical to our system security.

Building on insights gathered during Stage 2, Stage 3 research focuses on:

1. Investigating the stability boundary conditions of restarted islands which are inclusive of multiple non-black start IBR support devices.
2. Analysis of the impact of and reasonable range for control system parameters of IBR during system restoration.
3. Assessing impact of location of black start devices, considering their proximity to load centres, presence of synchronous generators, and non-black start IBR.
4. Synchronisation of two or more restarted islands, considering both synchronous and IBR-only islands during system restoration.
5. Impact of DER on the system restart process to determine thresholds for levels of DER to maintain stability during system restart.
6. Recommendations on any technical requirements or regulation changes, or otherwise, that should be considered for system restoration under high or 100% penetration of IBRs.

What has stage 3 delivered?

Aurecon conducted detailed EMT modelling of a simplified QLD regional network to assesses the viability of alternative system restoration methods.

Research provided solid advancements to the understanding of system restoration using IBR technologies, including opportunities, limitations, and sensitivities. Their findings included several new insights to the potential of GFM inverters as black start providers:

- Investigating system restoration under high or 100% penetration of IBR has determined that GFM BESS are viable as a system restart provider.
- Analysis showed GFM BESS able to restore systems with a ten times the BESS rating of GFL IBR.
- Synchronisation of two separate restarted islands is viable between both synchronous only and IBR-only islands.
- Reconnect functionality with ramped active and reactive power response of DER and load models over seconds and minutes is required to fully capture the impact to system restart and to capture how voltage management would need to be implemented.

Topic 5

Restoration and Black Start

Priority Key
Critical
High to critical
High
Medium

Organisation: aurecon

Priorities: 1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

In Australia and globally, system restoration following a black-out or brown out is based on the use of conventional synchronous generation.

While not occurring frequently, such events can have devastating economic and social impact, as was experienced in Australia during the black out of South Australia in 2016, or more recently in Victoria during Feb 2024 where 500,000 customers were left without power

As penetration of inverter-based resources (IBRs) increases throughout the NEM and existing synchronous coal- and gas-powered generators retire, providers of black start and system restart are diminishing. The lack of such services could put system security at unacceptable risk

This project investigates the role IBRs can play in system restart, especially under high or 100% IBR penetration conditions.

Progress on the Roadmap

Stage 3 provided solid advancements to the understanding of system restoration using IBR technologies. However, Significant further research is still needed to guide the power industry on future options for system restoration in high penetration and 100% IBR networks.

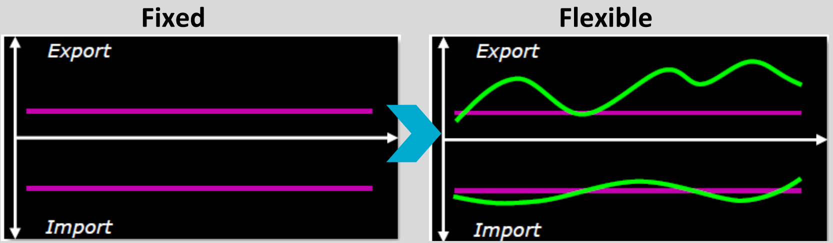
Task	Priority	Progress	Relevance
Large scale IBR	Critical	60%	Still relevant
Bottom-up restoration	Critical	60%	Still relevant
Technical and regulatory requirements	Critical	50%	Still relevant
Impact of DER	Critical	35%	Still relevant

Distributed Energy Resources

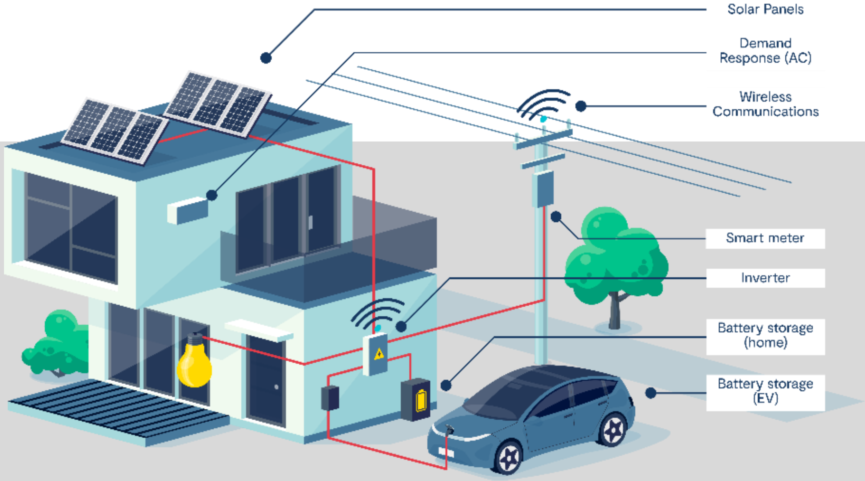
Integrating Distributed Energy Resources

Australia is leading the world in the adoption of rooftop solar PV, with the draft 2024 ISP projecting continued growth in these consumer resources. The challenge is to enable homes and businesses to make the most of their DERs while ensuring the integrity of the existing electricity distribution infrastructure (the 'poles and wires').

To tackle this challenge DNSPs across Australia are gearing up to offer their customers flexible connection agreements known as operating envelopes. These operating envelopes (OEs) can be used to orchestrate the bidirectional flows from DERs whilst ensuring the integrity of the poles and wires.



However, DNSPs in different States and Territories are likely to calculate and allocate OEs differently due to different network monitoring infrastructures. Therefore, it is important for DNSPs and, ultimately, to AEMO, to understand the spectrum of potential benefits and drawbacks of using the different OE implementations



Distributed Energy Resources (DERs)

Organisation

THE UNIVERSITY OF MELBOURNE

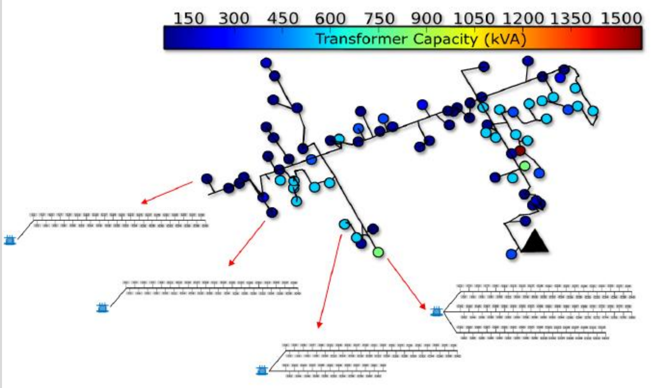
Priorities

1-2 Years | <5 Years | <10 Years

Objective and key focus

To assess operating envelopes (OEs) effectiveness to orchestrate LV network connected DER across Australia, Topic 8 research focuses on expanding Stage 2 research to encompass multiple neighbourhoods (rather than a single distribution feeder) to:

1. Assess the implications of large scale (integrated HV-LV) OE calculations in terms of accuracy, necessary algorithmic adaptations, and computational requirements.
2. Provide guidance on data driven techniques that can enhance DNSPs electrical modelling processes.
3. Provide guidance on forecasting techniques for OEs.



What has Stage 2 delivered?

Over the past twelve months the researchers have:

- **Improved on the accuracy of the per neighbourhood OE calculations** by considering both HV and LV networks.
- **Applied the improved OE methods to multiple neighbourhood networks** by considering the HV and LV impacts, particularly interdependent feeder voltages and head of feeder transformer thermal capacity.
- **Compared the performance of the four established OE methods** using the specified metrics with a model of an actual multiple feeder distribution network, identifying strengths of each OE methods in real world environments.
- **Considered the benefits of regression techniques** in estimating the impedances of three phase unbalanced networks.
- **Projected the improvement in DER hosting capacity** achieved by simple or advanced OE methods.
- **Shared results and insights with the DNSPs** to raise industry awareness and knowledge.
- **Established a database of models and input data** that is shared with the scientific community as open source .

Distributed Energy Resources (DERs)

Priority Key
- Critical
- High to critical
- High
- Medium

Organisation: THE UNIVERSITY OF MELBOURNE

Priorities: 1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

- Australia leads the world in rooftop solar photovoltaic installations with more than one in three houses participating.
- AEMO's ISP and ESOO project continuing uptake of DPV, home batteries and electric vehicles over the coming decades.
- Australia's Distributed Energy Resources (DER) are creating opportunities for homes and businesses to reduce energy bills, and participate in the electricity market managed by AEMO.
- Orchestrating DERs through Dynamic Operating Envelopes (DOE), that is, by dynamically recalculating export and/or import limits, either for the DER technology itself or at the customer connection point, can unlock network hosting capacity, enabling DER utilisation and essential system services for the broader network.

Progress on the Roadmap

Task	Priority	Progress	Relevance
What data flows (DER specs, measurements, forecasts, etc.) are needed to ensure AEMO has enough DER/net demand visibility to adequately operate a DER-rich system in different time scales (mins to hours)?	Critical	50%	Still relevant
What is the role of DER standards in concert with the future orchestration of DERs?	Critical	50%	Still relevant
What are the minimum requirements for a DER-rich distribution network equivalent model to be adequate for its use in system planning studies?	Critical	50%	Still relevant
What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?	Critical	50%	Still relevant

DERs and Stability

Organisation

UNSW SYDNEY

Priorities

1-2 Years | <5 Years | <10 Years

Objective and key focus

Topic 9 research recognises that accurate models of DER and loads are critical for power system planning and operation. With over 20 GW of NEM DER currently installed, these devices now represent the single largest generation technology category present in the NEM.

Under Topic 9 - DER and Stability, UNSW and their partner, University of Wollongong, have focused on:

1. Assessing behaviours of a broad range of consumer energy resources (CER): energy storage systems (ESS) both as standalone battery energy storage systems (BESS), and those integrated with PV systems (hybrid energy storage systems - HESS), Electric Vehicles (EVs) and a broad variety of modern loads.
2. Providing robust and accurate data for measured responses to power system transient disturbances by bench-testing numerous devices via thorough experimental methods, directly informing the load model development activities of AEMO.
3. Testing the reconnection characteristics of DER following a system black or regional brown out event to provide further input to AEMO's composite load model.
4. Implementing procedures for point-on-wave testing of inverters to investigate the potential risk of inverter malfunction that could occur on different points of the voltage waveform.

What has Stage 2 delivered?

The main outcomes from Stage 3 work include:

- The behaviour of battery- and hybrid energy storage systems (BESS and HESS) was assessed against AS4777.2:2020. Identification of non-compliance and collaboration with OEMs has led to firmware and settings improvements.
- Extensive experimental testing of devices typically represented by Motor D elements of CMLD was able to generate data that AEMO was able to update their CMLD model with for planning and operational use.
- Expansion of EV charging infrastructure for several Level 1 and Level 2 chargers revealed concerns around voltage sag ride through, including unpredictable disconnection times. Based on predicted growth rates of EVs in Australia, this identifies and urgent need for further testing and standardisation of performance of these devices.
- Black start and enhanced voltage management testing of 45 previously assessed inverter provided important insights to their behaviour following disconnection and responses following reconnection. Particularly the observed active power recovery and voltage management of many devices could lead to substantial voltage fluctuations following a wide area black out.

Topic 9

DERs and Stability

Priority Key
- Critical
- High to critical
- High
- Medium

Organisation: UNSW Sydney

Priorities: 1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

AEMO projects the detached home DPV installation rate of 30% today will rise to 50% by 2032, and to 65% by 2050, with most complemented by BESS.

Currently installed 21 GW will quadruple by 2050 under AEMO's 2024 ISP Step Change scenario.

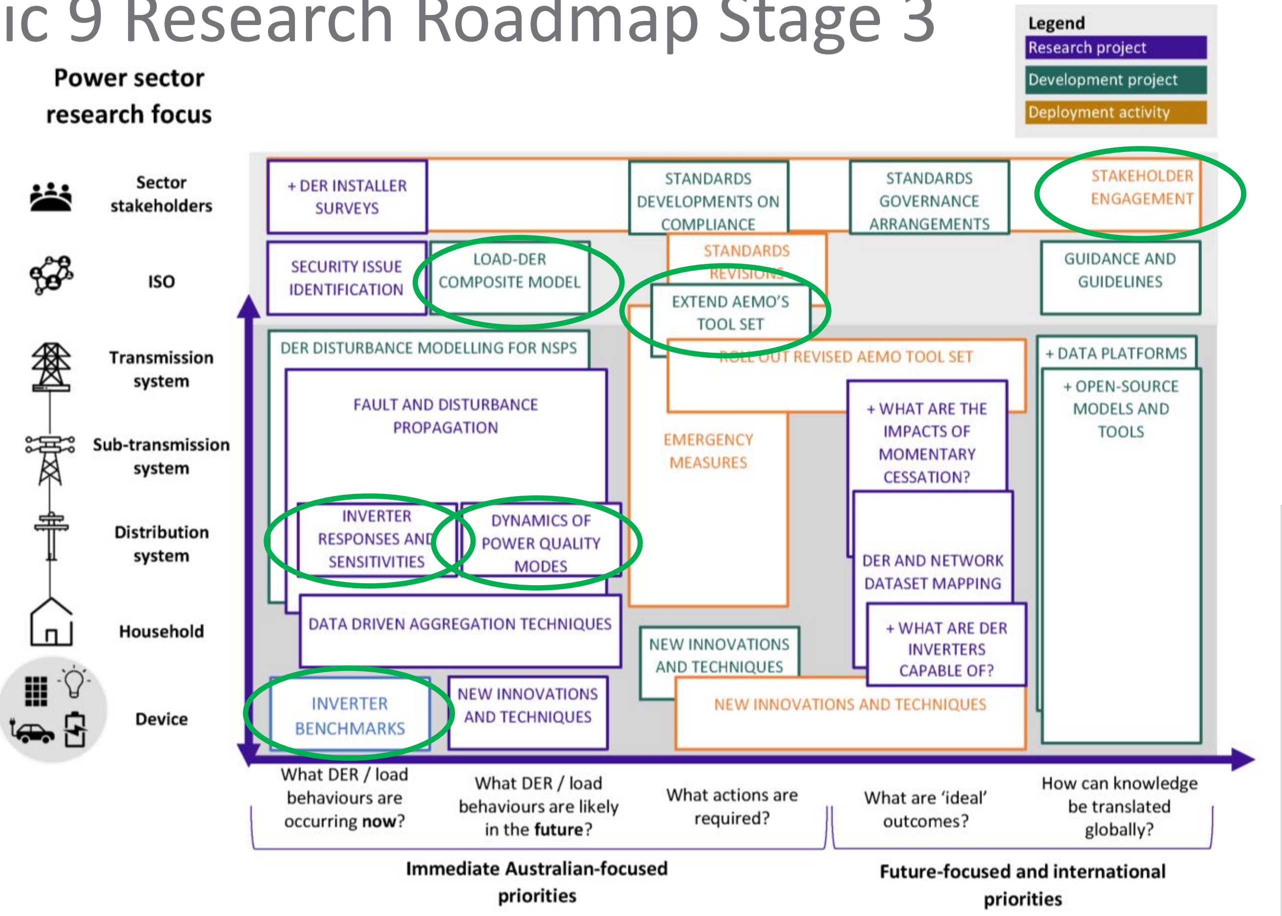
The impact DER and load behaviour and response will have on NEM security and stability is significant; it must be predictable and controllable to ensure our energy security.

The research creates the data and ultimately the models and other means for our TSO and NSPs to successfully integrate consumer energy resources resources.

Progress on the Roadmap

Task	Priority	Progress	Relevance
Load-DER composite load model development	Critical	30%	Still relevant
Inverter responses and sensitivities	Critical	100%	Still relevant
Inverter benchmarks	Critical	20%	Still relevant
Extend AEMO's tool set	Critical	100%	Still relevant
Dynamics of power quality models	Critical	25%	Still relevant
Stakeholder engagement	Critical	50%	Still relevant

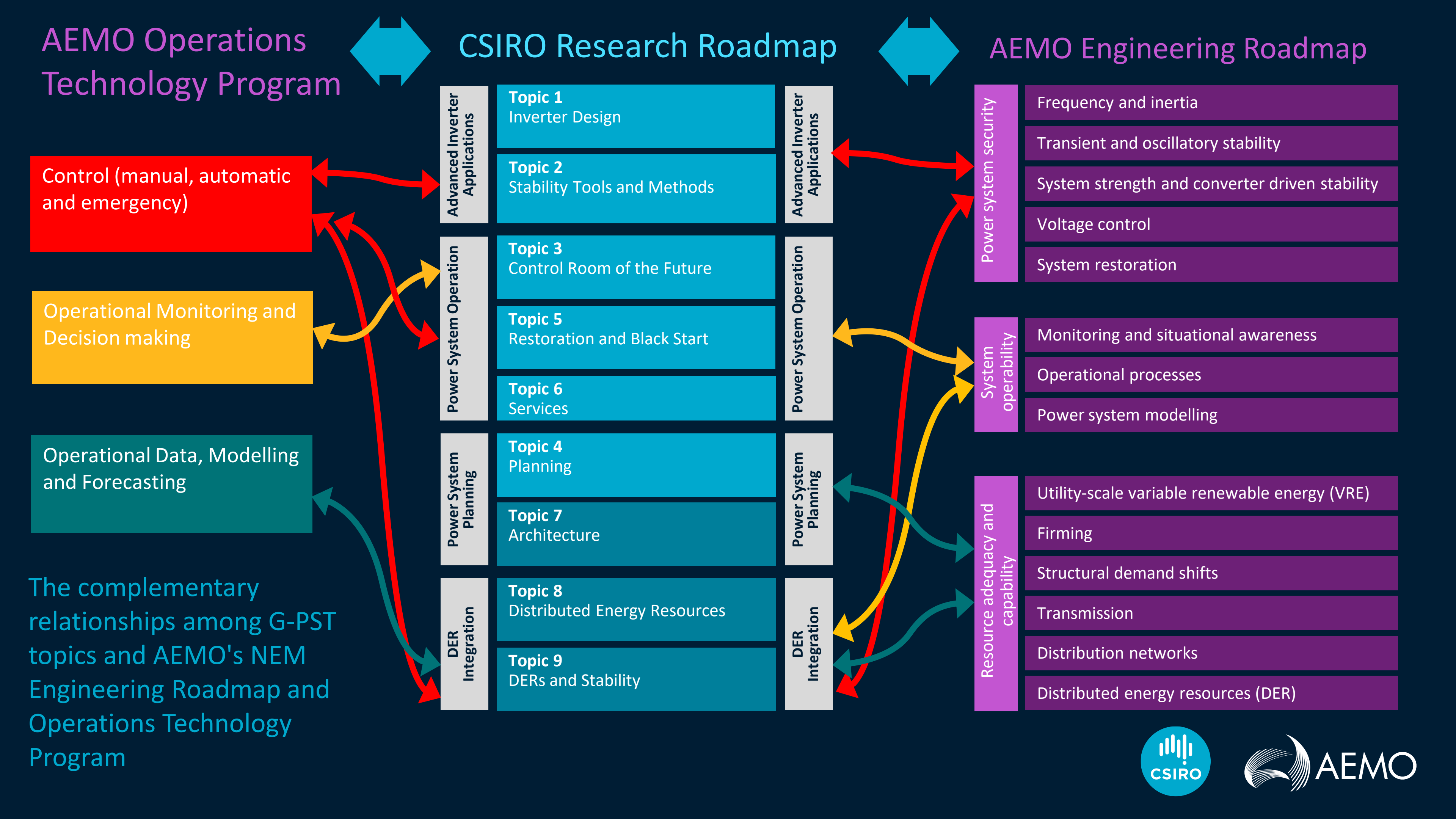
Topic 9 Research Roadmap Stage 3



Where to next?

A huge body of work is needed across industry over the next 10 years, necessitating a material uplift in the depth and breadth of power system engineering expertise in industry and academia, for which this CSIRO research helps build the foundation.

This research aligns with the **AEMO's National Electricity Market (NEM) Engineering Framework,** a roadmap to enable a secure and efficient energy transition, and with AEMO's Operations Technology Roadmap (OTR)



AEMO Operations Technology Program
CSIRO Research Roadmap
AEMO Engineering Roadmap
Control (manual, automatic and emergency)
Operational Monitoring and Decision making
Operational Data, Modelling and Forecasting
Advanced Inverter Applications
Power System Operation
Power System Planning
DER Integration
Topic 1
Inverter Design
Topic 2
Stability Tools and Methods
Topic 3
Control Room of the Future
Topic 5
Restoration and Black Start
Topic 6
Services
Topic 4
Planning
Topic 7
Architecture
Topic 8
Distributed Energy Resources
Topic 9
DERs and Stability
Advanced Inverter Applications
Power System Operation
Power System Planning
DER Integration
Power system security
Frequency and inertia
Transient and oscillatory stability
System strength and converter driven stability
Voltage control
System restoration
System operability
Monitoring and situational awareness
Operational processes
Power system modelling
Resource adequacy and capability
Utility-scale variable renewable energy (VRE)
Firming
Structural demand shifts
Transmission
Distribution networks
Distributed energy resources (DER)
The complementary relationships among G-PST topics and AEMO's NEM Engineering Roadmap and Operations Technology Program
CSIRO
AEMO

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Thank you

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