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

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

June 2023

Australia's National Science Agency

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

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

Administrative & leadership structures

Accelerating local technology adoption

Solving technology challenges with best practice engineering

Standards development

Need for open data and tools

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

Australian scientists and researchers have an opportunity to lead 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 significant technical challenges 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.

engaging-data.com

More information: https://globalpst.org/

“The irreversible energy transition is a challenge and an opportunity...The National Electricity Market (NEM) is supporting a once-in-a-century transformation in the way electricity is generated and consumed in eastern and south-eastern Australia.”

ISP 2022, 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 research institutions, and international research institutes to solve the most pressing challenges in order 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 2 years, CSIRO has:

- Commenced implementation of the CSIRO G-PST Research Roadmap.
- Initiated research in nine critical research topics that will drive accelerated decarbonisation in Australia and beyond.
- Selected 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.
- Delivered the first year of energy sector research projects
- Initiated the next year of research implementation.

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

Our roles

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.

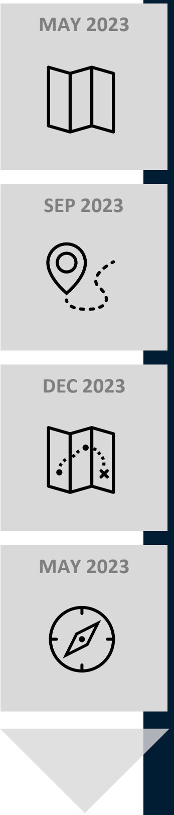
In addition to numerous other functions and responsibilities, AEMO was a Founding System Operator of the G-PST.

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 2022-23, this plan was put into action with seven research and engineering organisations delivering the first year of research implementation.

We're listening to industry needs and reprioritising accordingly



The steps taken so far

Implementing the Roadmap: Stage 2 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 3

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 2

Publication of all results and materials for Stage 2

Next steps

Commence Stage 3 research

The need for further investment

Due to decentralisation, increasing variability, and step changes in energy sector technology we are fast approaching an inflection point in the Australian energy transition.

A huge body of work is underway and must continue to deliver the end-state that is needed during this decade.

This work will be essential for solving Australia's major energy transition challenges. Australian findings will also apply to energy sectors across the world.

"The power system will require additional engineering solutions to provide essential system services...Proven technologies such as synchronous condensers will play a role, alongside newer technologies such as grid-forming inverters."

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

Innovation
Drive technology and innovation leadership

Investment
Create more stability and opportunity for investors

Export
Build an Australian powerhouse of exportable energy solutions

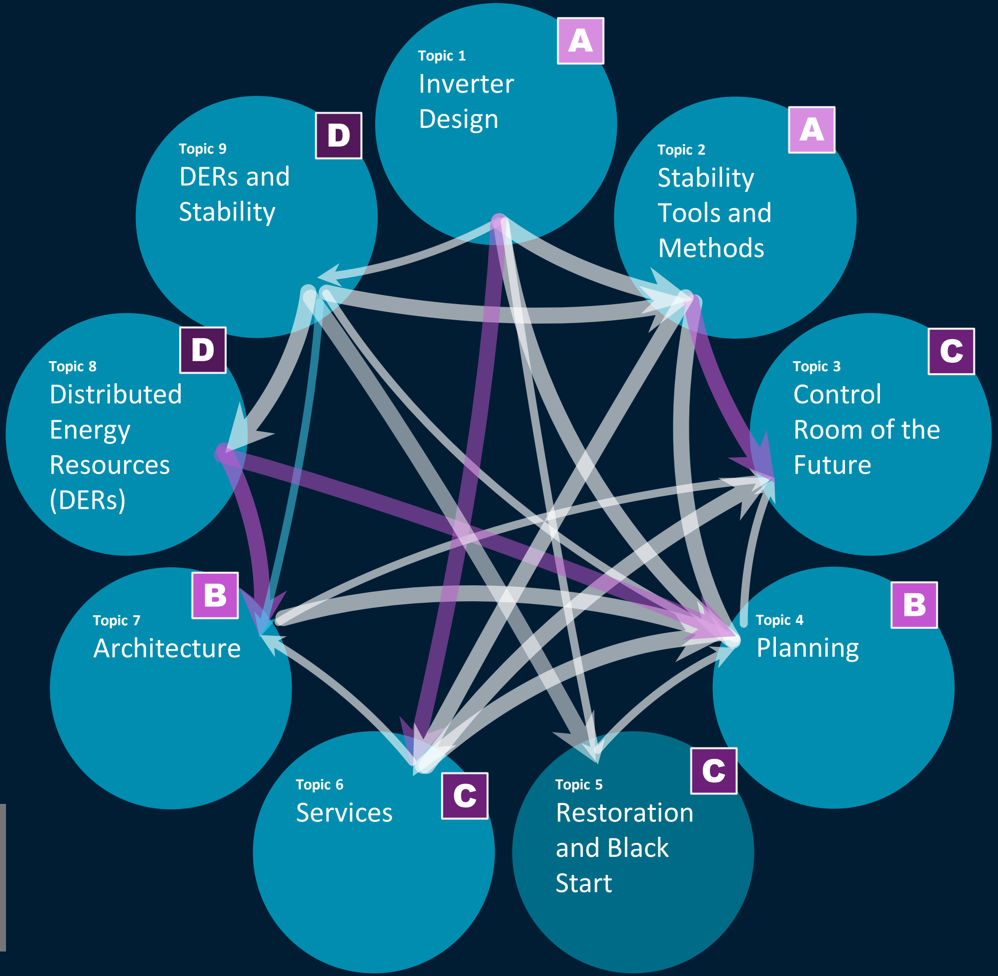
Environment
Support achievement of Australian net-zero emission goals

Research focus areas

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

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

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



Key

- Potential for collaboration
- Engaged in communication
- Interaction encouraged

G-PST purpose:
To accelerate the decarbonisation of electricity grids, in Australia and globally.

Working together to achieve the stable, secure, and affordable operation of the Australian power system

Topic 1
Inverter Design

Topic 2
Stability Tools and Methods

Topic 3
Control Room of the Future

Topic 4
Planning

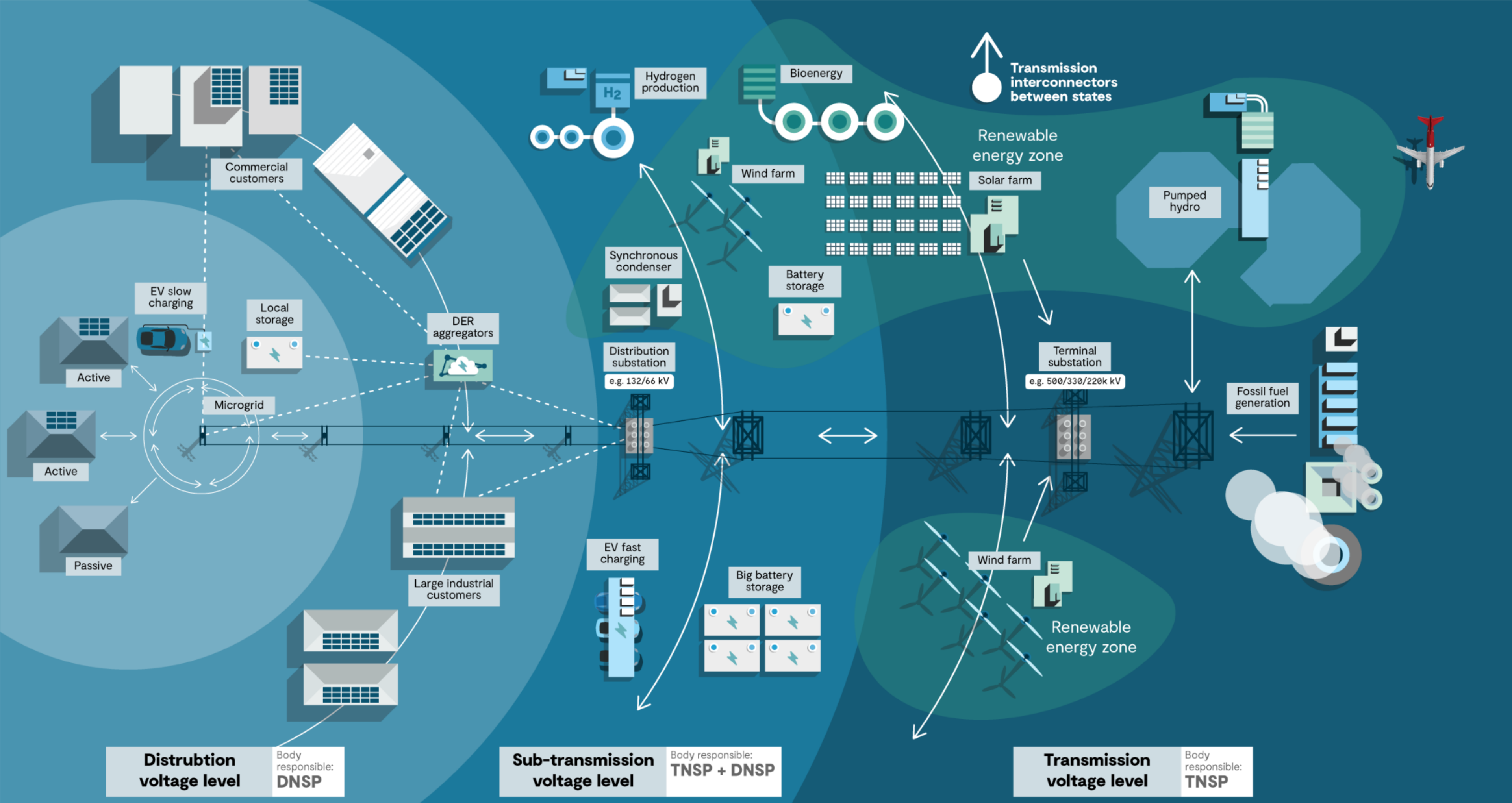
Topic 5
Restoration and Black Start

Topic 6
Services

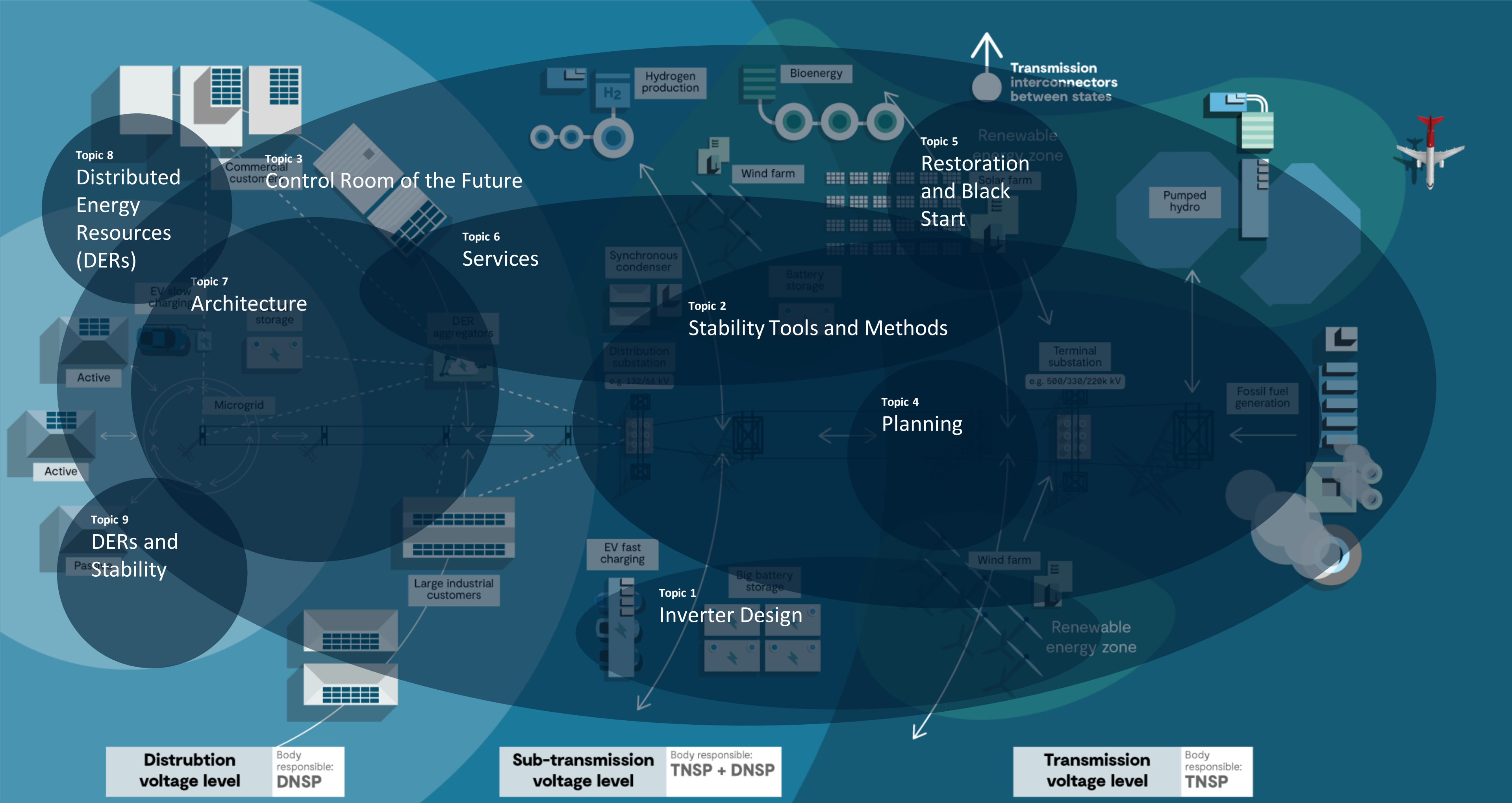
Topic 7
Architecture

Topic 8
Distributed Energy Resource (DER) Orchestration

Topic 9
DERs and Stability



Hydrogen production
H_2
Bioenergy
Transmission interconnectors between states
Renewable energy zone
Commercial customers
Wind farm
Solar farm
Pumped hydro
Synchronous condenser
Battery storage
EV slow charging
Local storage
DER aggregators
Distribution substation
e.g. 132/66 kV
Terminal substation
e.g. 500/330/220k kV
Fossil fuel generation
Active
Microgrid
Active
Passive
EV fast charging
Big battery storage
Large industrial customers
Wind farm
Renewable energy zone
Distrubtion voltage level
Body responsible: DNSP
Sub-transmission voltage level
Body responsible: TNSP + DNSP
Transmission voltage level
Body responsible: TNSP



Topic 8
Distributed Energy Resources (DERs)
Topic 3
Control Room of the Future
Topic 6
Services
Topic 7
Architecture
Topic 5
Restoration and Black Start
Topic 2
Stability Tools and Methods
Topic 4
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Topic 9
DERs and Stability
Topic 1
Inverter Design
Hydrogen production
Bioenergy
Transmission interconnectors between states
Wind farm
Pumped hydro
Synchronous condenser
Commercial customers
Active
Active
Microgrid
Terminal substation
e.g. 500/330/220k kV
Fossil fuel generation
EV fast charging
Large industrial customers
Wind farm
Renewable energy zone
Distrubtion voltage level
Body responsible:
DNSP
Sub-transmission voltage level
Body responsible:
TNSP + DNSP
Transmission voltage level
Body responsible:
TNSP

Advanced inverter applications

Rise of inverter-based energy generation

As in many jurisdictions worldwide, the growth of renewable energy in the Australian National Electricity Market (NEM) has been phenomenal. In 2010 there was 480 MW of utility scale renewable generation, predominantly wind turbines, installed in the NEM. As of May 2023, there is 19.5 GW of transmission connected capacity, comprising wind turbines, battery energy storage systems, and solar photovoltaic (PV) generation of many hundreds of MW for a single installation.

Concurrently, there are renewable energy zones planned to provide thousands of MW in small areas. Furthermore, due to growth of solar rooftop PV installations in the distribution system over the past decade, there is now approximately 19 GW of distributed PV across the NEM.

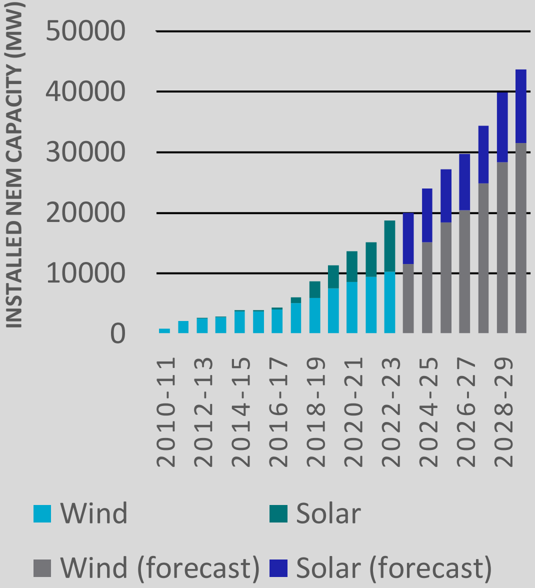
All of these renewable energy sources are power electronically interfaced, or inverter based resources (IBR). IBR have different operating and performance characteristics from our conventional synchronous generators. As they displace our coal and gas fired generators in daily dispatch, we must take action to understand, integrate, and then optimise, the operation of these renewable sources that will drive the energy system transition.

The CSIRO Research Roadmap investigation of advanced inverter applications encompasses many aspects of these new technologies, including designing control systems, to developing tools to enable better integration of these technologies.

Topic 1
Inverted Design

Topic 2
Stability Tools and Methods

NEM UTILITY-SCALED IBR UPTAKE (2010-2030)



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Distributed Energy Resources

Inverter Design

Organisation

MONASH University

Priorities

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

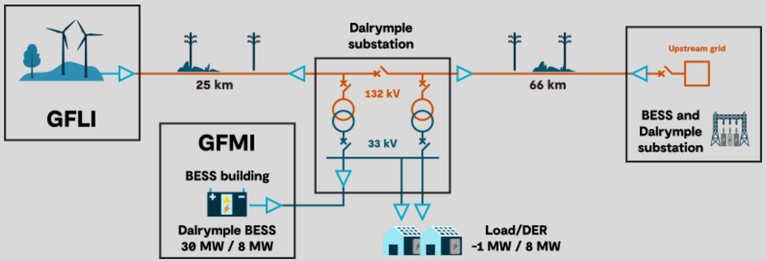
Key Focus

IBR uptake continues to increase rapidly, with the common technology applied still being grid-following inverter systems.

Common locations for renewable generation using IBR are still remote and often in weak grid areas, which could risk system security or lead to unnecessary curtailment of renewable generation.

The project is improving understanding of:

1. the stability limits of grid-forming inverters (GFMIs) and their impact on network stability during faults.
2. the ability of GFMI to support GFLI technology in multi-IBR systems, and what control system changes may be possible to enhance IBR stability.



What has stage 2 delivered?

The achievements of the CSIRO G-PST research plan completed in the 2022/23 Stage 2 include:

1. A technical white paper describing the functional requirements for GFMI.
2. Development of Adaptive Power Reference Control (APRC) to improve the transient stability of parallel GFMI-GFLI systems.
3. Development of a modified q-prioritised current limiter for IBR that will enhance stability by reducing adverse interaction between internal IBR control loops.
4. Development of an inverter active power freezing function that enhances transient stability by avoiding power angle growth that could otherwise lead to IBR instability.

Furthermore, the Stage 2 research has completed foundational work for several other IBR control functions to enhance transient stability:

1. Management of negative sequence current reserves of GFMI.
2. Control system improvements for Multi-IBR system interaction.

Inverter Design

Organisation

MONASH University

Priorities

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

Significance and contribution to Australia

Australia's energy transition and grid decarbonisation continues to accelerate, with the mainstay of our renewable generation, wind and solar, using power electronic inverters to deliver power.

While inverter technology continues to develop, there are challenges still to be resolved so that many of the services provided by the conventional generators that will retire over the coming decades can be replaced.

Not only is the generation technology changing, but sources are fast becoming more decentralised, and being exposed to new and emerging security risks. Thus, stability enhancement and improved interoperability of our future energy sources is more important than ever.

Gigawatt scale renewable energy zones proposed for Australia's NEM will be located more remotely than existing generation, needing new and advanced inverter controls. Topic 1 initiated research has presented new control system functionalities and laid a foundation for future research that will contribute to Australia's energy security in years ahead.

Progress on the Roadmap

Task	Priority	Progress
Frequency Stability	High to critical	Stage 3+
Voltage Stability	Critical	Stage 3+
Interaction Mitigation and Oscillation Damping	Critical	Stage 3+
Protection and Reliability	High to critical	20%
Trending Topics	High	10%

Organisation

Priorities

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

Stability Tools and Methods

Key Focus

Growing penetration of power electronic interfaced renewable generation may adversely affect grid stability. Modelling these new technologies is often difficult due to their black box representation in power system analysis.

To enable safe and reliable power delivery in future power systems with significant contribution from inverter-based-resources (IBRs), methods for determining stability and stability margins at different system operating conditions are needed.

To this end, Topic 2 progressed two critical areas of the CSIRO G-PST research roadmap for Advanced Inverter Design:

1. Development of a process framework to identify the various operating points over which IBR can be expected to operate.
2. Development of an algorithm to assess the control stability of IBRs over the identified range of operating points using black box models.

What has stage 2 delivered?

EPRI's completed Stage 2 research has provided:

1. Two impedance-based frequency scan methods to identify the impedances of IBR black box models and interconnected power systems.
2. The means to rapidly determine power system operating points.
3. A sequenced process to assess the stability of large interconnected power systems containing a high penetration of IBR.

Best Case Preparation 1
Hypersim -> PowerFactory -> IBR mix modified to represent future high penetration

24 Power Flow Case Creation 2
Variation of hourly demand over a day used as input to scale generation and load for different hours

Optimisation of Voltage Profile 3
Adjustment of shunts and generator voltage setpoints

Short-Circuit Assessment 4
Determination of SCR at gen buses and finding gens with possible negative MVA available from 24 power flow cases

Device level impedance characterisation and estimation
Use the prediction methods to evaluate the characteristics at any operating point

System scale analytical evaluation of stability
Use the estimated impedance characteristics along with system information to evaluate network stability

Dynamic Simulation (dyr file + runs) 5
Dynamic behaviour modelled using:
- OEM black box models
- Generic models for IBRs
- GFMs or IBRs which have negative MVA available

Dynamic simulation run with disturbance e.g load trip for each 24-hourly cases

Stability Tools and Methods

Organisation

Priorities

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

Significance and contribution to Australia

The large number of inverter-based resources that are interconnecting to Australia's National Electricity Market continues to increase. The NEM has several network areas with weak points. Hence, the integration of renewables can be limited due to stability concerns of the grid-connected inverters.

The use of black box models with the small signal stability analysis packages that are used presently in the NEM will continue to present a challenge.

It is expected that the project results will be used by system planners and operators in Australia at the forefront of integrating these large number of inverter resources to help plan the evolution of stability in the NEM.

The stability of inverters is relevant to the immediate Australian need for safe and reliable integration of renewables into the NEM paving the way towards the ambitious energy transition goal of 100% renewable energy.

Progress on the Roadmap

Task	Priority	Progress
Stability margin evaluation	Critical	30%
Small signal screening	Critical	30%
Voltage stability Boundary	Critical	Stage 3+
Voltage control & recovery	Critical	Stage 3+
System strength assessment	Critical	Stage 3+
Inertia monitoring	High	Stage 3+
Modelling & model validation	High	Stage 3+
Voltage & Q management	High	25%
Real-time simulators	High	Stage 3+
Critical contingency identification	High	Stage 3+
Real-time Contingency analysis	High	Stage 3+
Protection system coordination	High	Stage 3+

Power System Design

Topic 7
Architecture

Topic 4
Planning

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Planning our energy system

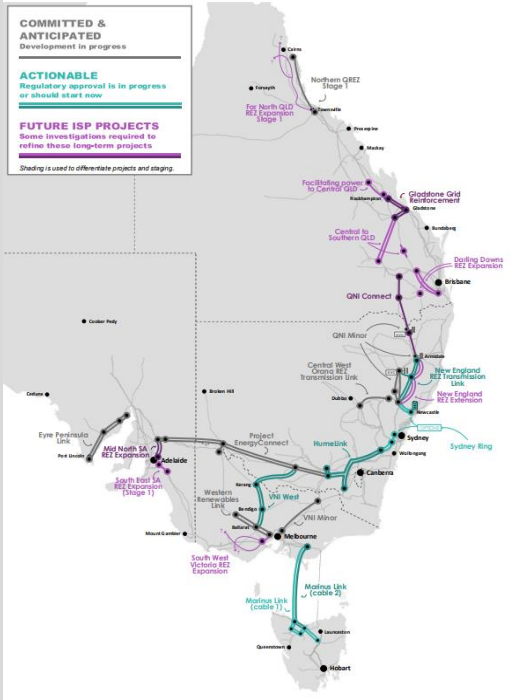
Our interconnected power systems are some of the most complex machines ever built. Often spanning thousands of kilometers and interconnecting millions of customers they have developed and expanded over many decades, enabling secure and economic supply of energy to generations of consumers who have funded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

However, over the past decade many changes have disrupted the way that we plan and fund our power grid infrastructure: increased decentralisation of our energy sources, changes to our generating technologies, ageing infrastructure, and increasingly active consumer participation, all drive the energy transition and the associated decarbonisation of our power system.

Consequently, regulatory and planning processes that have served us well in the past are becoming obsolete, and must adapt to deal with the many changes underway.

CSIRO's Australian G-PST research roadmap has funded two important projects to provide greater understanding of changing needs, and new tools and methods, to consider these new influences when planning and developing our power system of the future:

1. Power system planning with long-term uncertainty
2. Power system architecture



Planning

Organisation

THE UNIVERSITY OF MELBOURNE

Priorities

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

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. Five core activities for this project are:

1. Identifying optimal infrastructure investment solutions and optionality value with multi-stage stochastic planning.
2. Assessing the robustness of transmission plans based on deterministic approaches compared to flexible planning.
3. Quantifying and controlling investment risk associated with deterministic and stochastic planning methodologies.
4. Proposing methodologies to assess and quantify the value of alternative infrastructure investment options in providing resilience to High Impact Low Probability (HILP) events.
5. Assessing and comparing the value of alternative technologies, such as integrated electricity and hydrogen networks, in long-term energy infrastructure planning.

What has stage 2 delivered?

The focus of the Topic 4 Stage 2 research was new planning methods and methodologies to address risks due to long term uncertainty in transmission planning. The twelve month investigation developed new methods and metrics for transmission planning, summarised in a report that details:

- Stochastic planning analysis, using a scenario tree based approach on the 2022 ISP data set, to illustrate features and benefits of alternate planning approaches.
- Quantitative comparison between Least Worst Regret (LWR) and Least Worst Weighted Regret (LWWR), using AEMO ISP investments that show the effectiveness of each approach.
- A risk-aware stochastic planning model so that decision-makers can consider risk appetite when balancing investment costs.
- The impact of HILP events on power system investment decisions compared across alternative methodologies for modelling power system resilience in stochastic planning.
- Case studies investigating the benefits of balanced development of hydrogen pipeline and electricity transmission, for progressing a green hydrogen industry.

Planning

Significance and contribution to Australia

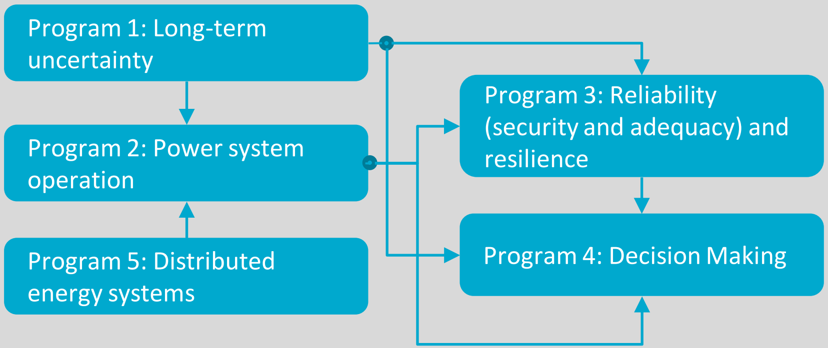
Long-term uncertainty issues in modern power systems internationally include: climate change, antiquated electricity sector regulation & energy policy, unstable electricity markets, rising investment costs, rising fossil fuel prices and decreasing availability, new technologies, increasing renewable generation, and stagnating growth in net load.

Australia's electricity sector is no exception, and navigating these issues is critical to the security and affordability of electricity for all Australians.

Whereas previously, prudent investment favoured a least-cost approach, Australia is one of the few countries leading in developing, and taking a practical approach to implementing, new planning methodologies such as least-worst regret. This is a direct influence of this research and is demonstrating potential for decreased investment costs and risks.

The research also recognises the broader energy ecosystem, in that energy sector coupling should be part of our forward thinking. Topic 4 research considers Australia's Hydrogen superpower ambitions through several case studies that already indicate tangible benefits in balancing electricity transmission and hydrogen piping.

Progress on the Roadmap



Task	Subtask	Progress
Long-term uncertainty	Uncertainty modelling (R1S1P3)	15%
Decision making	Risk modelling (R4S1P1)	25%
	Investment flexibility in planning (R4S2P2)	50%
Distributed Energy Systems	Sector coupling (R5S1P1)	10%

Topic 7

Power System Architecture

Organisation

STRATEGEN

Priorities

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

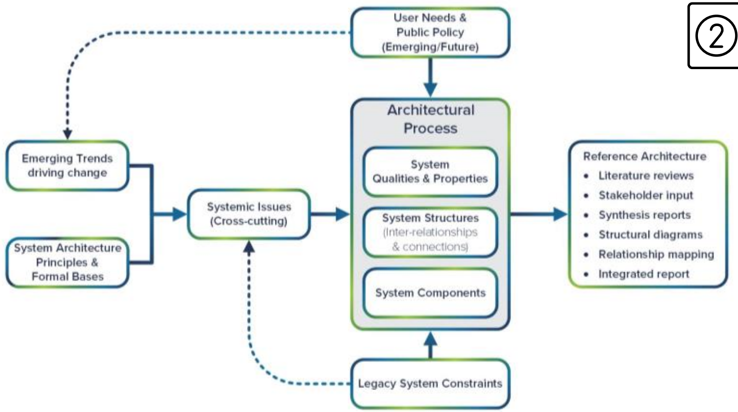
Key Focus

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.

By applying Power System Architecture (PSA) methodologies, Topic 7 Stage 2 research progresses development of a seminal Reference Architecture of the National Electricity Market (NEM) as it experiences profound transformation.

The research addresses many PSA drivers and inputs to the architecture, including not only the NEM's legacy structures and plausible future states, but also intermediate transition requirements.



What has Stage 2 delivered?

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

- Societal and customer objectives that define the requirements of the changing power system,
- Emerging trends that will drive the evolution of the NEM's Gigawatt scale power system over the coming decade and beyond,
- Systemic issues that impede progress and require architectural intervention,
- Emerging system structural methods that map the 'as-built' architecture of the NEM and the plausible architecture required

Power System Architecture

Organisation

STRATEGEN

Priorities

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

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Significance and contribution to Australia

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

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.

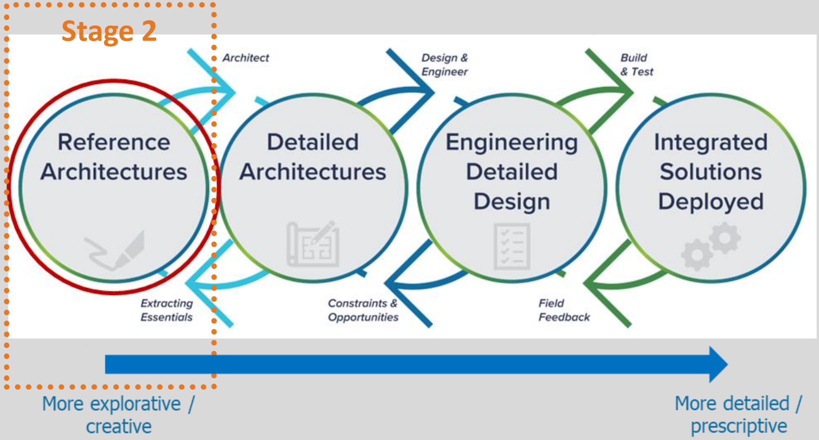
As Australia's power systems transition from hundreds, to tens of millions, of participating energy resources, **the bulk energy, transmission and distribution systems – together with deep demand-side flexibility – must function holistically to enable reliable and efficient operation.**

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 2 of the PSA research has completed the 'Reference Architecture', which presents an initial, prototypical model of an ultra-complex system and its evolving context.

This work sets the path for the detailed architecture to be developed in subsequent sages of this research.



Power System Operation

Keeping the lights on

The Australian power system continues to undergo significant transitions that will only accelerate over the coming years.

Increasing shares of inverter-based & distributed energy resources, and decreasing synchronous generation capacity will challenge system operators in maintaining system security.

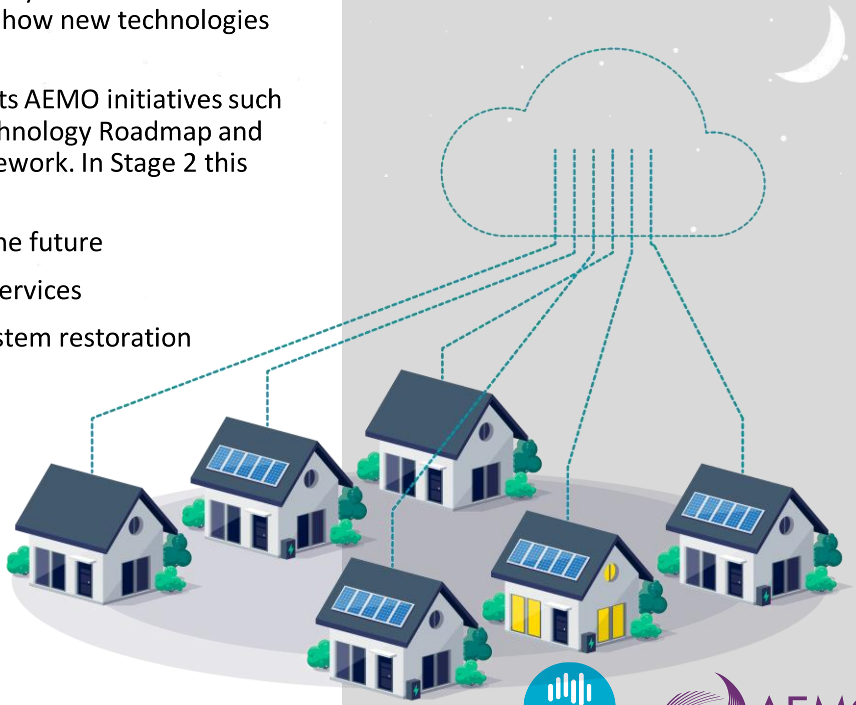
We must rethink the operation of our transforming electricity network.

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

The Power System Operation research combines new control room techniques and tools including machine learning and artificial intelligence in power system operation. It identifies the essential system services of the future, and moreover how new technologies can provide them.

The work complements AEMO initiatives such as the Operations Technology Roadmap and the Engineering Framework. In Stage 2 this includes research in:

1. Control room of the future
2. Essential system services
3. Black start and system restoration



Control Room of the Future

Organisation

EPRI

Priorities

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

Key Focus

System operator and electricity network owner control rooms are critical for system management. Without them it would be impossible to operate large modern power systems.

With the power system rapidly decarbonising, decentralising, and digitising, the challenges for the control room and the operators are becoming more complex. It is critical that we transition from the control room systems of today to those that will be required tomorrow.

The project completed by EPRI during 2022/23 has investigated and developed capability in the artificial intelligence (AI) and machine learning (ML) fields for real time power system applications, with a particular focus on developing use cases for AI/ML in the operational context.

Working with AEMO, the researchers have developed a list of high priority ML applications for the control room i.e., use cases. The different ML methods developed during the project, based on various alternative neural network types, have been applied to multiple data sets to test the performance of methods.

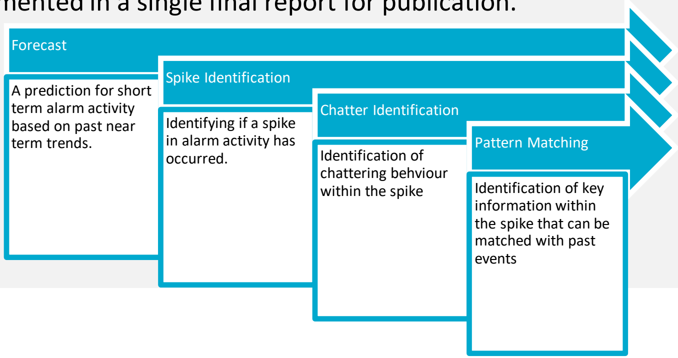
The key use case was the application of ML to the interrogation of control room EMS alarms and assisting rapid operator decision making in an increasingly complex environment.

What has stage 2 delivered?

The Topic 3 research of 2022/23 has:

1. Provided a use case methodology development.
2. Defined a process for use case selection and training data set auditing.
3. Prepared neural network ML methods that have been applied to an “Alarm Management and event analysis” use case, applying:
   a) Alarm forecasting
   b) Alarm spike detection
   c) Alarm chattering
   d) Pattern matching

The results of the methodology development and auditing process, as well as the proof of concept through use case assessment have been documented in a single final report for publication.



Control Room of the Future

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.

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

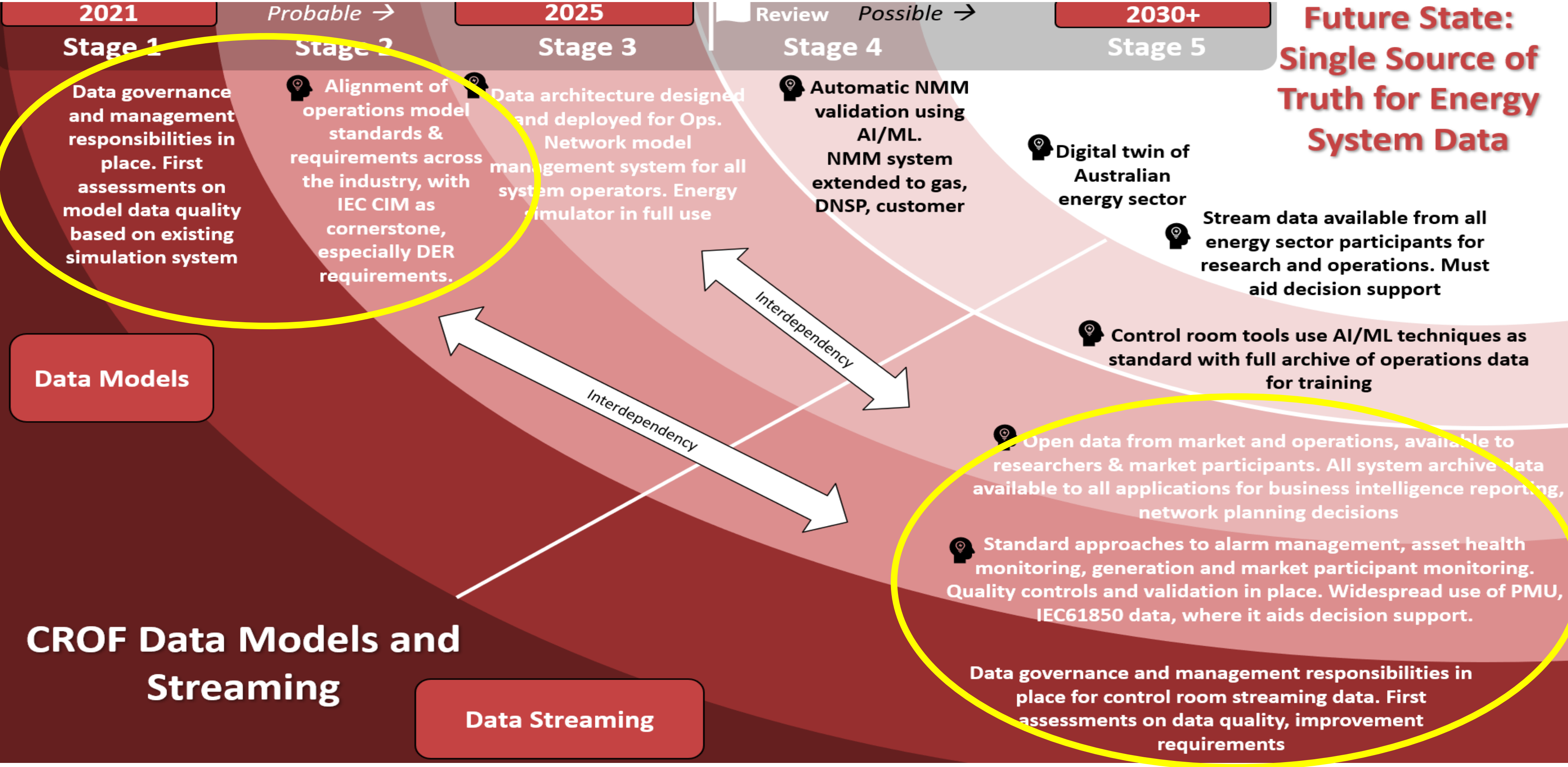
This project aims to add structure to the development of machine learning applications so that they are baselined and benchmarked and can be applied by AEMO and other network operators.

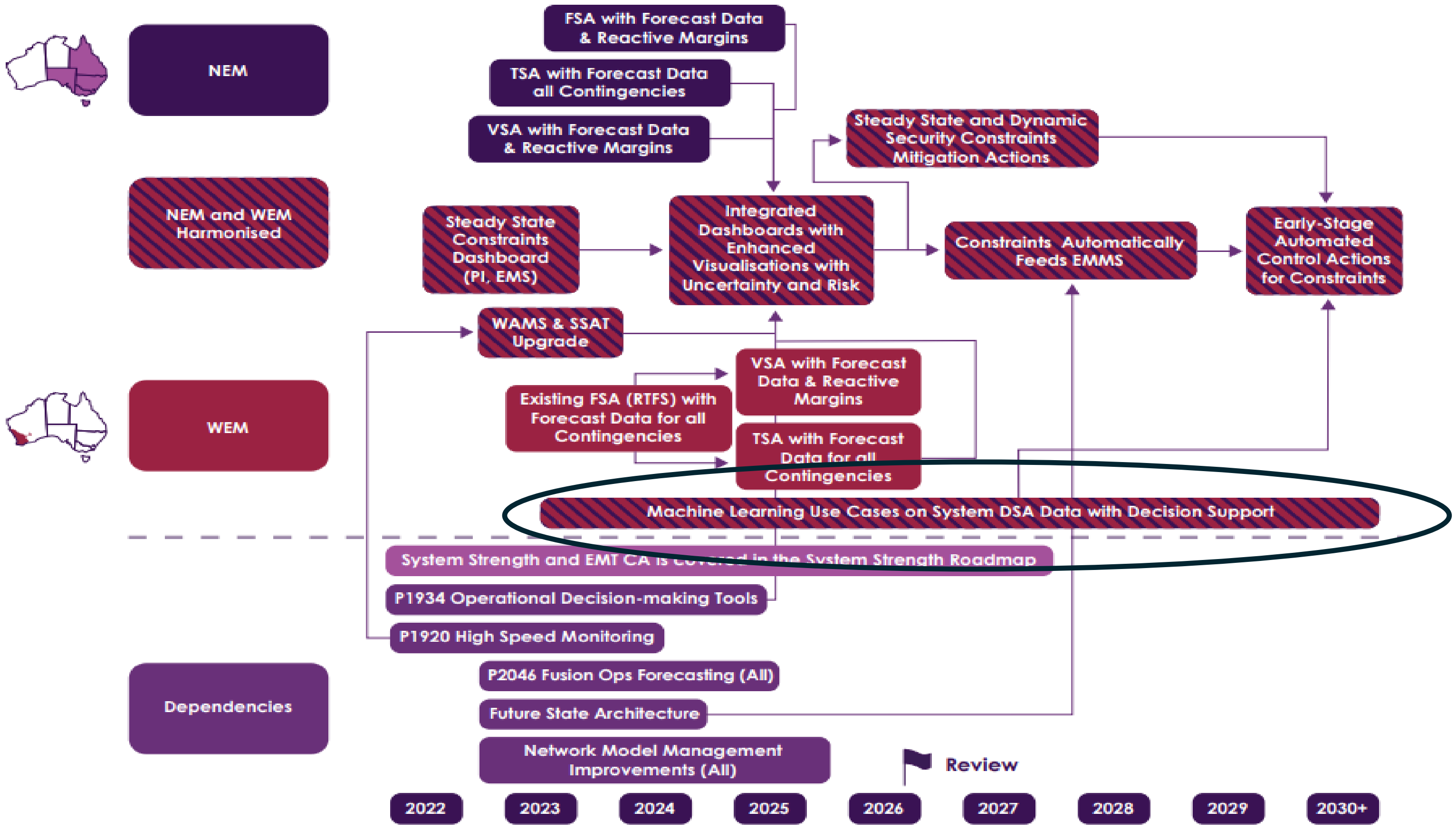
The development of the methodology and use cases in this project can be used by researchers and practitioners in Australia. However, a secondary aim is to also to generalise and extend the methodology and framework, to be applicable to the industry beyond Australia.

Progress on the Roadmap

Task	Priority	Progress
CROF Data Models and Streaming	High to critical	15%
EMS/SCADA and MMS/NEMDE	Critical	Stage 3+and/or OTR
Alarm Management and System Monitoring	Critical	Stage 3+ and/or OTR
Control Room and Operations Engineering	High	Stage 3+ and/or OTR
Operator and Human Factors	High to critical	Stage 3+ and/or OTR
Buildings, Facilities, and Hardware	High	Stage 3+ and/or OTR

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

Priorities

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

Key Focus

System restoration processes to recover from major blackouts are well planned in advance. They rely on conventional generators to restart and resynchronise parts of the network to restore the whole.

With most of the NEM's conventional generation fleet scheduled to retire in the coming decades and no replacements announced, it is critical to commence research into restoring the NEM following a blackout using future generation technology.

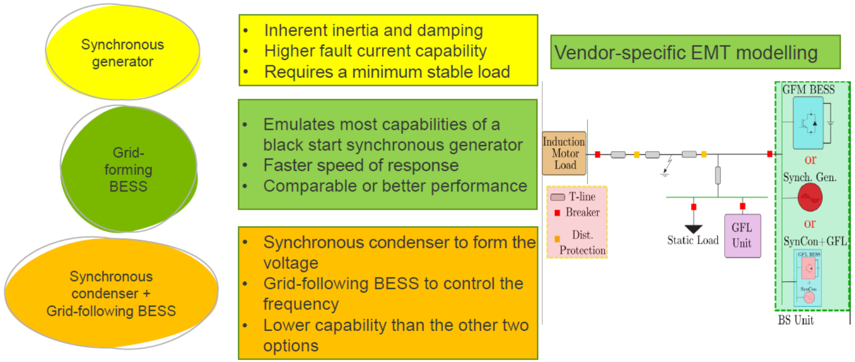
Research by Aurecon, as part of Topic 5 of Australia's G-PST Research Roadmap, supports understanding and expanding the NEM's system restoration capabilities. This focused on:

1. investigating the black start performance, capabilities, and limitations, of alternative GFMI and grid-following inverters (GFLI);
2. restoration support without online synchronous generators in power systems with a high share of IBR.
3. the role of synchronous condensers combined with GFLI in supporting system restoration.

What has stage 2 delivered?

Aurecon's two-phase approach to their research has provided:

1. Capability and limitation analysis of alternative IBR-based restart options, using both simplified realistic, and vendor-specific, EMT models, and subsequently technical specifications for IBR capabilities for black start.
2. Case studies of restoration of the Northern Queensland Renewable Energy Zone using non-conventional methods.



Restoration and Black Start

Organisation

aurecon

Priorities

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

Significance and contribution to Australia

AEMO's ISP step-change scenario projections to 2040 show NEM coal-fired generation retiring, and reduced gas fired generation. These generators are currently contracted to restart the power system in case of a partial or full blackout. Concurrently, climate change continues to increase the frequency and severity of severe weather events.

Restarting a blacked out system is the backstop remnant of power system resilience, and inability to promptly restore a power system is an unacceptable risk to energy security.

Research into restarting our power network with the technology we will have of the future, such as battery storage systems comprising GFMI, is critical to system security and reliability.

The research in Topic 5 during Stage 2 of the CSIRO Roadmap has shown, in simulation, the restart of a blacked out system incorporating IBR, providing valuable insights into future research, testing, and demonstration, required to support the ongoing Australian energy transition.

Progress on the Roadmap

Task	Priority	Progress
Inverter based resources in restart	Critical	50%
Network impact	Critical	Stage 3+
Tools and techniques	Critical	10%
Technical and regulatory requirements	Critical	15%
End-to-end restoration	High	20%

Essential System Services

Organisation

MONASH University

Priorities

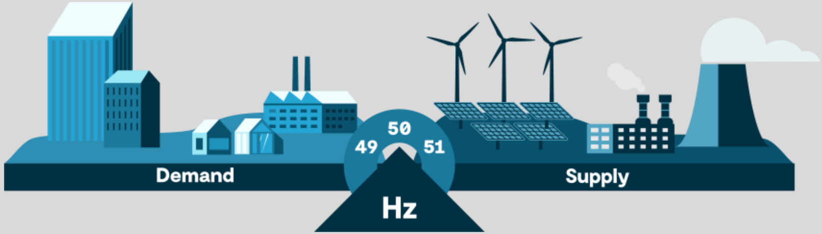
1-2 Years
<5 Years
<10 Years

Key Focus

The NEM, just like other modern power systems, features a range of essential system services to manage the power system frequency and voltages, supported by critical properties such as inertia and system strength.

Stage 2 research of Topic 6 has focused on power system frequency, progressing key technical matters:

1. Developing new metrics to assess frequency performance.
2. Providing frequency control services with DER.
3. Developing a low-order system frequency (SFR) model for the Australian grid.
4. Virtual decoupling of different power regions through the development of input observation (UIO).



What has stage 2 delivered?

The research has provided insights and outcomes that can assist TSOs to manage power system frequency:

1. Developed a holistic frequency response model to analyse wide area interconnected power systems.
2. Proposed new dynamic and static metrics to measure frequency performance, and assessed NEM frequency performance under various ISP scenarios using the frequency model.
3. Prepared a tool to investigate the provision of grid services from emerging and future technology, such as electric vehicles and thermostatically controlled loads.
4. Proposed a tuning method for AEMO AGC, and frequency service provider, control system parameters to improve frequency performance in a network with a high share of IBR.
5. Evaluated the minimum levels of inertia required across the NEM to maintain system stability.

Services

Organisation

MONASH University

Priorities

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

Significance and contribution to Australia

Australia's unique network topology and geographically dispersed nature poses many power systems challenges, including frequency and stability maintenance. Increasing quantities of DPV and renewable energy sources connected to the Australian grid have added to these challenges, particularly power systems frequency.

Phase I of the research work focuses on creating a low-order system frequency response (SFR) model, to help validate and develop Australia's frequency support services. The proposed model is tailored to the Australian grid: including Australia's decarbonisation goals and the ISP scenarios, as well as services from Energy Storage Systems (ESS), Renewable Energy Systems (RES) and IBR as well as conventional generation sources. Stakeholders such as AEMO can adapt the model as relevant.

Progress on the Roadmap

Task	Priority	Progress
Coordination of services (1.1)	Critical	Stage 4+
Influence of energy tariffs (1.2)	Critical	Stage 4+
Fast Frequency Response services (2.1)	Critical	60%
Virtual inertia (2.2)	Critical	60%
Services from distribution system (3.1)	High	15%
Flexible load & VPPs (3.2)	High	15%
Flexibility and ESS (3.3)	High	Stage 4+
Sources of voltage support (4.1, 4.2)	High	Stage 4+
Frequency performance metrics (5.1)	High	25%
New frequency metrics (5.2)	High	25%
Grid flexibility measures (5.3)	High	Stage 4+
Inertia markets (5.4)	High	25%

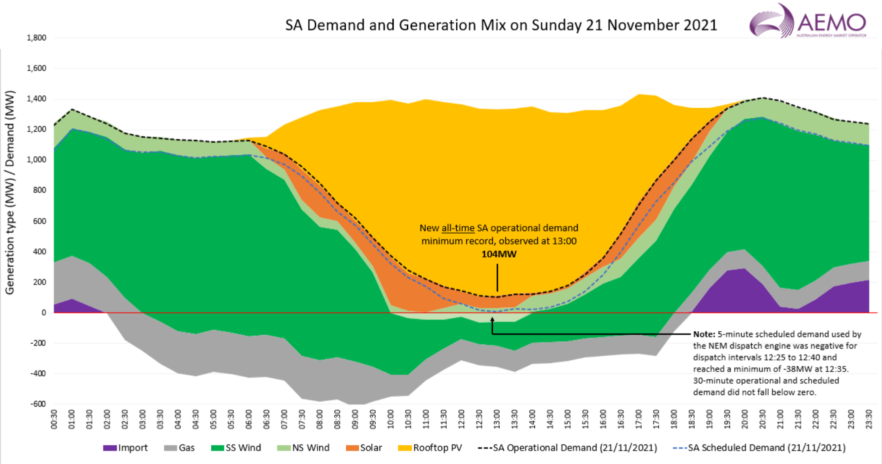
Distributed Energy Resources

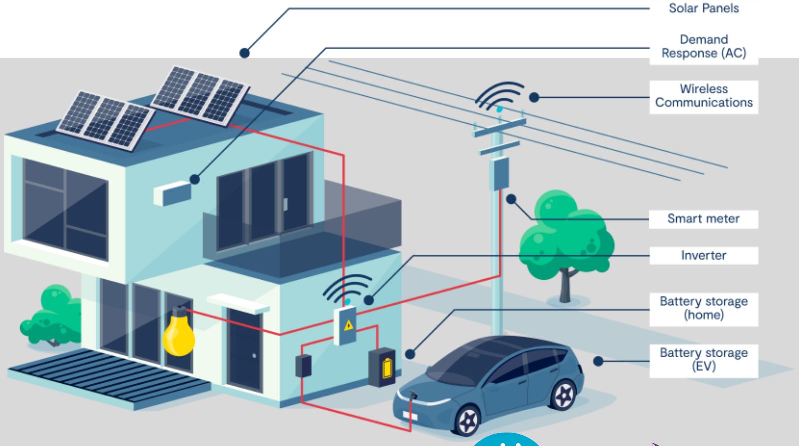
Integrating Distributed Energy Resources

DER, specifically distributed (rooftop solar) photovoltaic (DPV), is now the single largest generator technology category in the NEM. Over 19,000 MW of capacity is installed across the NEM, and AEMO's 2022 ISP estimates as much as 35,000 MW will be by 2030.

Already some network regions, most notably South Australia, report days when distributed generation can meet all regional energy demand; this is expected to become increasingly common so the distribution system could export power to the transmission grid. These scenarios create a challenge for the NEM system operator, AEMO, and the transmission and distribution system network owners.

Despite the high installed capacity of DER, there are still many unknowns, including their dynamic behaviour and appropriate monitoring, coordination, and aggregation. In the past years, Australian Renewable Energy Agency sponsored projects - such as Project Edge and Project Symphony - have made significant advances to our understanding, modelling and integration of these sources of energy. Yet more work is required to meet the challenges of continued uptake of DER.





1
2
Advanced Inverter Applications
4
7
Power System Design
3
5
6
Power System Operation
8
9
Distributed Energy Resources

Topic 8

Distributed Energy Resources (DERs)

Organisation

THE UNIVERSITY OF MELBOURNE

Priorities

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

Key Focus

To assess operating envelopes (OEs) in orchestrate DER across Australia, Topic 8 research focuses on:

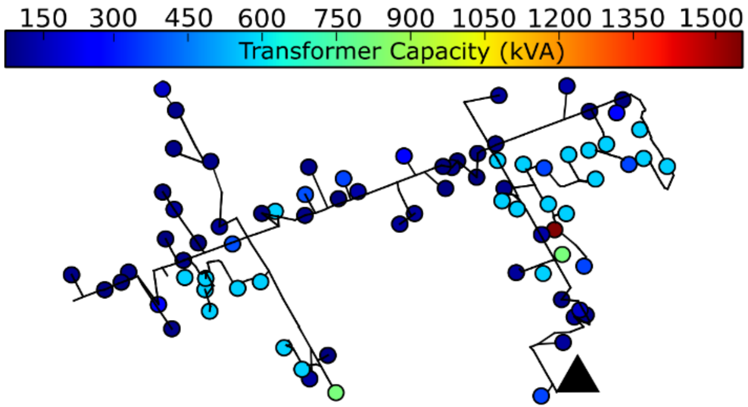
1. Characterising the spectrum of available infrastructure/data across Australian Distribution Network Service Providers (DNSPs).
2. Defining alternative OE implementations (including calculation and allocation) consistent with the spectrum identified.
3. Defining key metrics that capture the interests and concerns of key stakeholders (i.e., customers, DNSPs, AEMO).
4. Simulating power flow in detail, using realistic unbalanced three-phase HV-LV distribution network models, considering alternative OE implementations and various DER mixes and uptake.
5. Assessing the performance of each alternative OE implementation using simulation results, to provide stakeholder recommendations.

What has Stage 2 delivered?

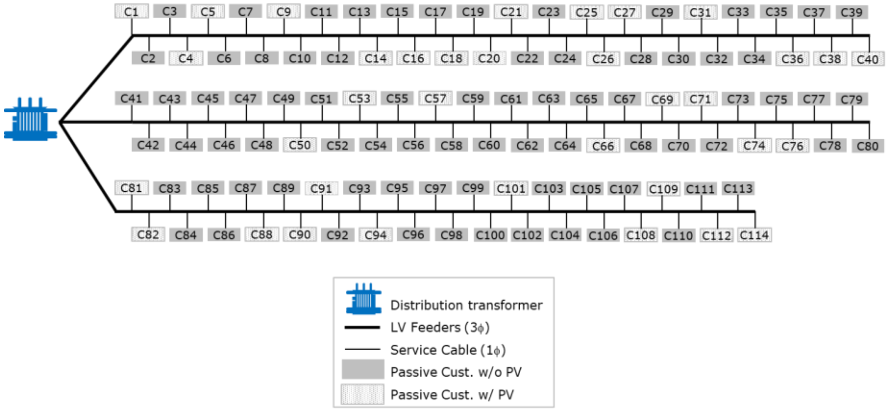
Over the past twelve months the researchers have:

- **Surveyed all Australian DNSPs** on their OE strategies and current state of implementation.
- **Defined four alternative approaches to calculate OEs** using the available infrastructure and DER data identified by the survey including: ideal OE, Asset Capacity OE, Asset Capacity & Critical Voltage OE, Asset Capacity & Delta Voltage OE.
- **Specified nine specific performance metrics** for assessing the performance of various OE strategies including: OE accuracy, voltage compliance, maximum voltage, minimum voltage, asset utilisation, total OE gain, aggregated exports/imports, equity/fairness, and implementation complexity/cost. The four OE methods were compared across performance, customer impact, service provision and feasibility.
- **Compared the performance of the four OE methods** using the specified metrics with a model of an actual distribution network, identifying strengths of each OE methods in real world environments.
- **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)



Real Australian MV feeder (22kV)



Representation of the LV network selected for testing OE implementations

Distributed Energy Resources (DERs)

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.
- The CSIRO G-PST research investigated alternative DOE methods, implementable by Australian distribution businesses, providing analysis and metrics so they can optimise their DOE strategy.

Progress on the Roadmap

Task	Priority	Progress
Define data flows to operate DER	Critical	22%
DER standards for orchestration	Critical	25%
Minimum DER modelling reqs.	Critical	Stage 3+
Organisational and regulatory reqs.	Critical	25%
Distribution level markets	Critical	20%
Cost effective DER control	High	40%
DER decision-making algorithms	High	50%
Cost effective DER ancillary services	High	Stage 3+
DER ancillary services availability	High	30%
DER communications and control	Medium	40%

DERs and Stability

Organisation

Priorities

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

Key Focus

Topic 9 research recognises that accurate models of DER and loads are critical for power system planning and operation. With over 19 GW of NEM DER currently installed, these devices now represent the single largest generation technology category.

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

1. Providing robust and accurate data for measured responses by bench-testing numerous devices via thorough experimental methods, directly informing the load model development activities of AEMO.
2. Modelling and analysis of distributed energy resources (DER): 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.
3. Ensuring that ISOs and TSOs can maintain power system security under very high penetrations of distribution scale IBR such as distributed PV, energy storage, and other resources including inverter-based demand.

What has Stage 2 delivered?

The main conclusions from Stage 2 work are:

- The behaviour of PV inverters when updated to the most recent AS4777.2:2020 standard is generally compliant and aligned with requirements. However, this observation is not true of BESS and HESS systems where diverse responses to grid disturbances were observed during testing.
- Existing RMS load models do not capture the diversity of load responses to grid disturbances. Distinct behaviours are observed among devices within the same load category. The range of options further complicates testing for load modelling.
- EV charging infrastructure should be tested and modelled differently depending on whether the EV chargers include active power electronics . For chargers without active power electronics, the response depends on the connected EV.
- The PV inverter testing experience emphasises the importance of evaluating multiple devices, leading to load models with greater confidence. Preliminary tests on BESS, HESS, EVs, and others loads, provided valuable insights into testing and general behaviour; however, validating initial observations requires additional tests.

DERs and Stability

Organisation

UNSW SYDNEY

Priorities

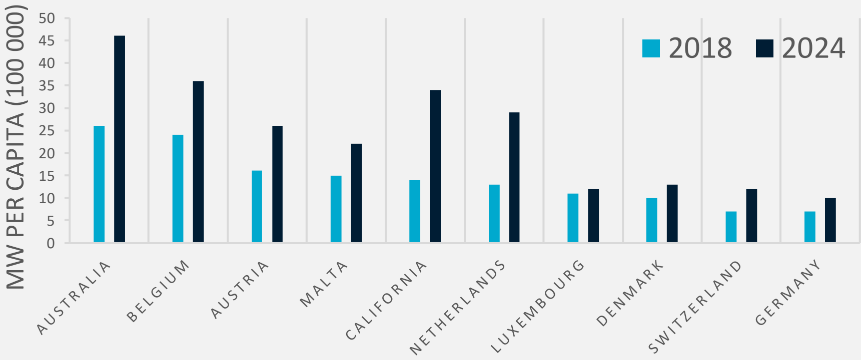
1-2 Years | <5 Years | <10 Years

Significance and contribution to Australia

In the 2022 ISP step-change scenario, 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. Given the ongoing global energy crisis, these projections may be conservative.

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

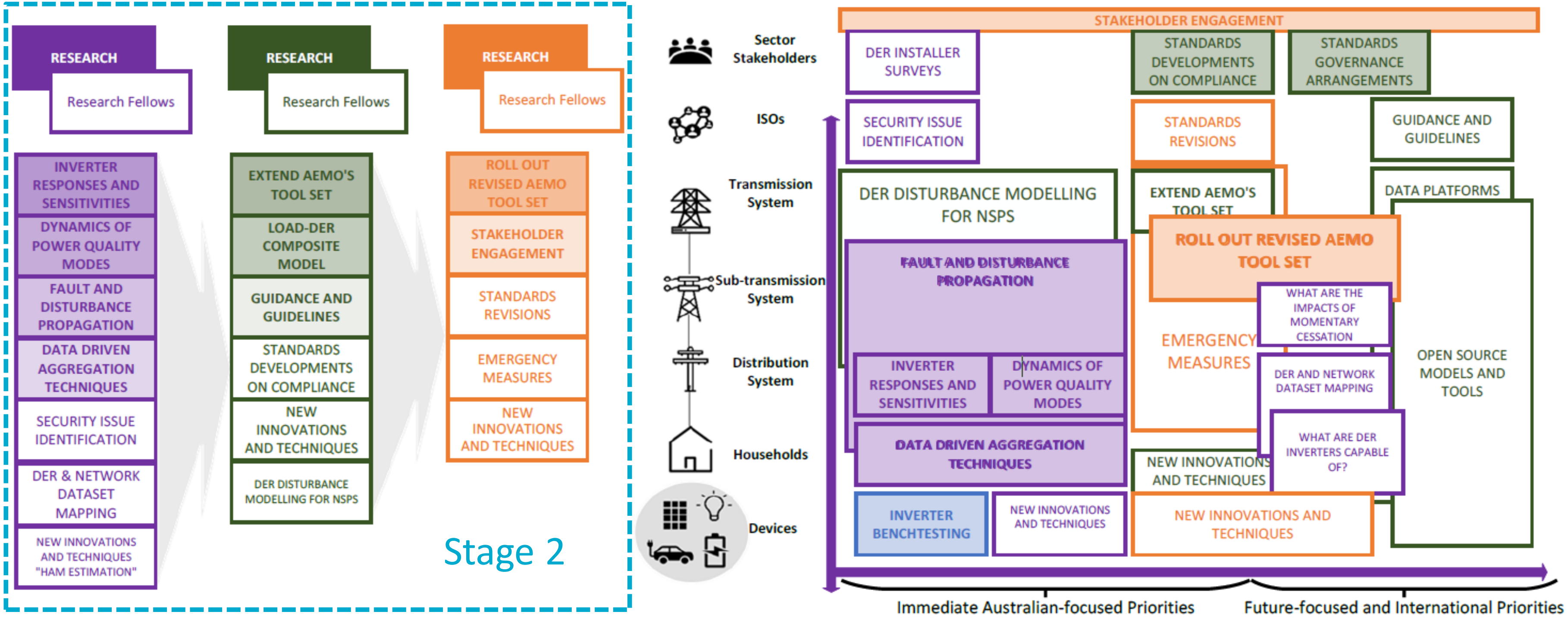
The research will provide the tools and other means for our TSO and NSPs to successfully integrate these valuable resources.



Progress on the Roadmap

Task	Priority	Progress
Continuous testing of inverters	Critical	100%
Testing of BESS and HESS	Critical	50%
Testing of EVs	Critical	10%
Testing of household loads	Critical	40%
Validation against network events	High	20%

Topic 9 Research Roadmap Stage 2

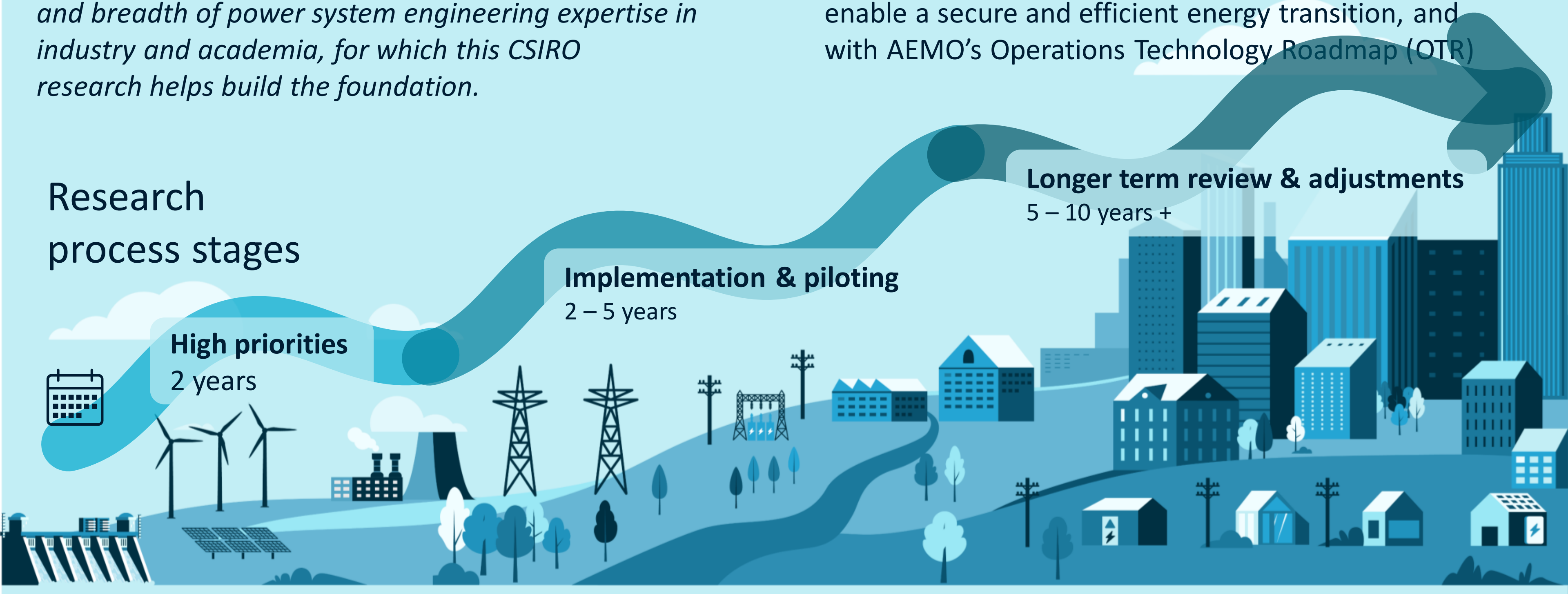


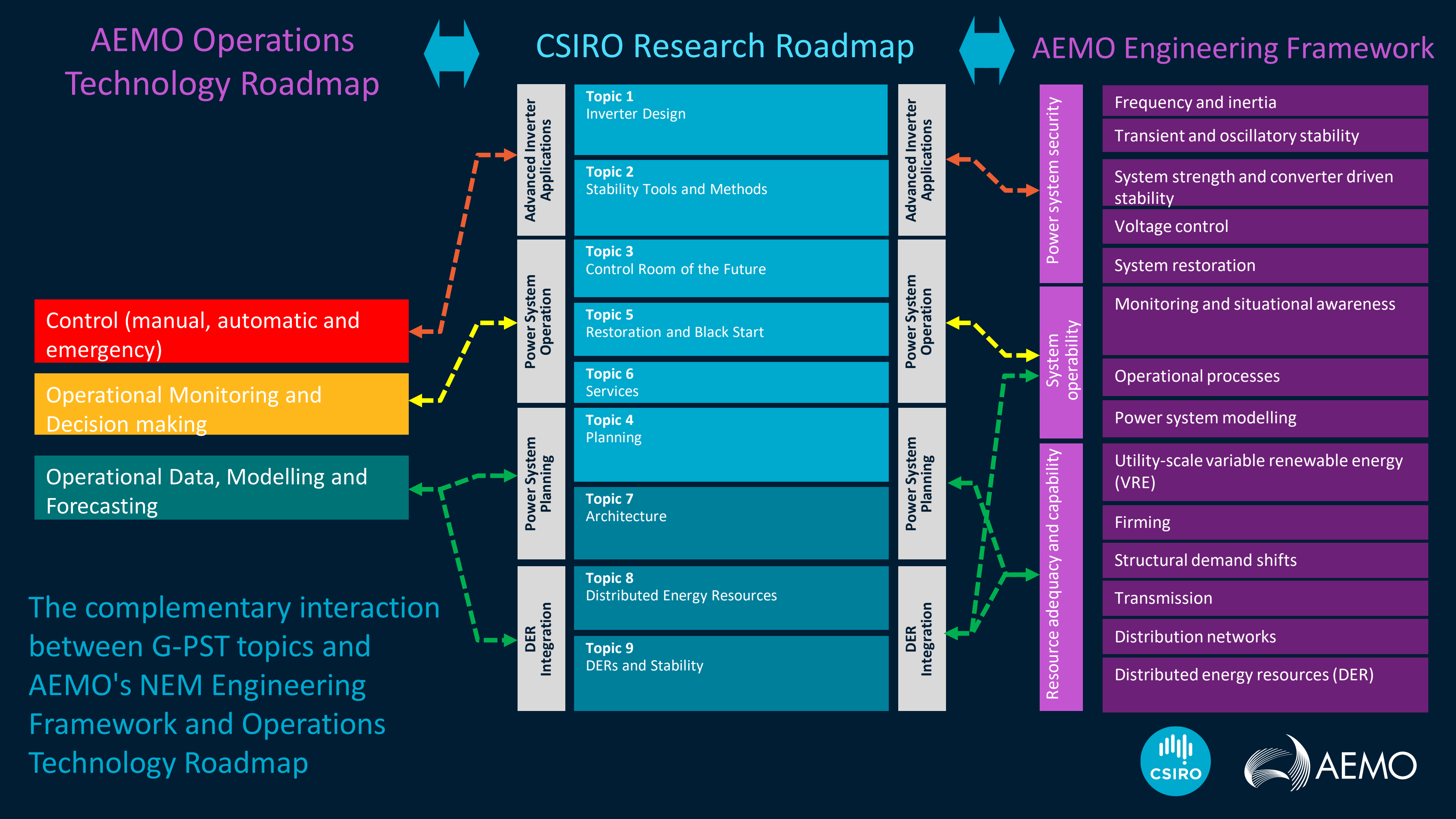
Where to next?

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)

Research process stages




AEMO Operations Technology Roadmap
CSIRO Research Roadmap
AEMO Engineering Framework
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
System operability
Resource adequacy and capability
Frequency and inertia
Transient and oscillatory stability
System strength and converter driven stability
Voltage control
System restoration
Monitoring and situational awareness
Operational processes
Power system modelling
Utility-scale variable renewable energy (VRE)
Firming
Structural demand shifts
Transmission
Distribution networks
Distributed energy resources (DER)
The complementary interaction between G-PST topics and AEMO's NEM Engineering Framework and Operations Technology Roadmap
CSIRO
AEMO

Proudly supported by
GHD Advisory

Thank you

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Australia's National Science Agency