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Stage 3 Research Program Summary Report

for Australia's Global Power System Transformation Research Roadmap

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Energy Business Unit

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Acronym glossary

AEMO	Australian Energy Market Operator	**LSTM**	Long-short term memory
AI	Artificial Intelligence	**ML**	Machine Learning
APRC	Adaptive Power Reference Control	**MVA**	Mega Volt-Amp
BESS	Battery Energy Storage System	**NEM**	National Electricity Market
BPNN	Back propagation neural network	**NEMDE**	NEM Dispatch Engine
CRoF	Control room of the future	**NPV**	Net Present Value
CSIRO	Commonwealth Scientific and Industrial Research Organisation	**NQREZ**	North Queensland Renewable Energy Zone
DER	Distributed Energy Resources	**NZE**	Net Zero Emissions
DNSP	Distribution Network Service Provider	**OE**	Operating envelope
DOL	Direct on-line (starting)	**OEM**	Original Equipment Manufacturer
DSM	Demand Side Management	**PoC**	Point of Connection
DSO	Distribution System Operator	**PSA**	Power System Architecture
DPV	Distributed Photovoltaic		
EMS	Energy Manag	**PV**	Photovoltaics
EMT	Electromagnetic Transient	**RES**	Renewable Energy Source
		REZ	Renewable Energy Zone
EPRI	Electrical Power Research Institute	**SCADA**	Supervisory, Control and Data Acquisition
EV	Electric Vehicle	**SEP**	Stable Equilibrium Point
ESS	Energy Storage Systems	**SFR**	System Frequency Response
FCAS	Frequeny Control Ancillary Services	**SOM**	Self-organising map
GFLI	Grid Following Inverter	**SynCon**	Synchronous Condenser
GMFI	Grid Forming Inverter	**TDIM**	Transmission-Distribution Interface Mechanisms
G-PST	Global Power Systems Transformation	**UEP**	Unstable equilibrium point
GW	Gigawatt	**UFLS**	Underfrequency Load Shedding
HESS	Hybrid Energy Storage System	**ULS**	Ultra-large scale
HILP	High Impact Low Probability	**V/Hz**	Volt per Hertz
LWR	Last Worst Regret	**VPP**	Virtual Power Plant
LWWR	Least Worst Weighted Regret	**VSG**	Virtual Synchronous Generator

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Executive summary

Our energy sector is in a once-in-a-lifetime transition. In Australia, our efforts to decarbonise our electricity sector and to electrify other energy sectors, such as transport, have seen a growth in renewable energy sources and the closure (and reduced operation) of coal fired power stations, like many other modern power systems.

As we transform our electricity systems, we must be mindful that the effect of this transition on power system security, reliability, resilience and affordability is generally positive. However, many of the processes, systems, and technologies that we have used in the past to manage the energy trilemma were designed particularly for the energy sources we are replacing. New technologies, such as inverter based resources, employed *en masse* could create challenges for existing processes that must be addressed now to ensure a stable transition that maintains the high level of security, reliability, and affordability that we have always benefited from.

To tackle electricity system transformation challenges, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) published the 2022 *Australian Research Planning for Global Power Systems Transformation*[1] (the Research Roadmap). This roadmap targets areas of research that will enable renewable energy generation to successfully power Australia and, more broadly, the world. While many aspects of our transforming electricity system require attention, the Research Roadmap focuses on four key areas, with two or more specific research priorities in each:

1. **Advanced inverter applications** covers multiple aspects of new power electronic-based energy conversion technology used in utility-scale wind and solar farms. These range from improving the stability of individual devices and assessing the stable interaction between large quantities of such systems to managing large power systems that have very high levels of penetration of inverter based resources (IBR).
2. **Power system planning and design** covers design from the transmission level to the distribution system. High priorities include the effective management of the uncertainty faced by network planners when designing high cost, long asset life, infrastructure in the face of many rapidly changing variables, including climate change, growth of consumer energy resources, and energy sector coupling. At the distribution level in particular, research focuses on defining and designing a suitable architecture that considers the interaction of the many layers that make up power system networks, including physical flows, markets, and data communications.
3. **Power system operation** is already being challenged at these early stages of the electricity network transformation. System strength, low inertia, and minimum system demand are matters that already occupy our system operators, and operating the power system of the future will require an advanced control room that enables them to securely and reliably manage our electricity network in real time. A second aspect investigated is the ability to restore our electricity networks following a region wide blackout, such as occurred in South Australia in 2016. Presently, we use synchronous generators to restart the network, but with many of our synchronous generators already or soon to be retired, new sources will have to be found and methodologies developed to restart our system in case of widespread outages.

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[1] https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap

4. **Distributed Energy Resources integration** investigates techniques to model, in aggregate, the large quantities of solar rooftop inverter, electric vehicles, battery storage systems, and inverter based loads in power system simulations, models that are needed to calculate stability limits and stable operating points. Research also includes other semi-operational considerations such as how to optimally dispatch the growing number of active consumer energy resources in our distribution networks through the use of dynamic operating envelopes, in order to maximise the utilisation of distribution network assets.

The four areas outlined above and the research priorities within them, illustrated diagrammatically in Figure 1, are those that many system operators consider are most critical to resolve right now. Notably, Topic 6, investigating critical essential system services for our future power system, was not pursued this year, with a focus instead placed on progressing the other research areas.

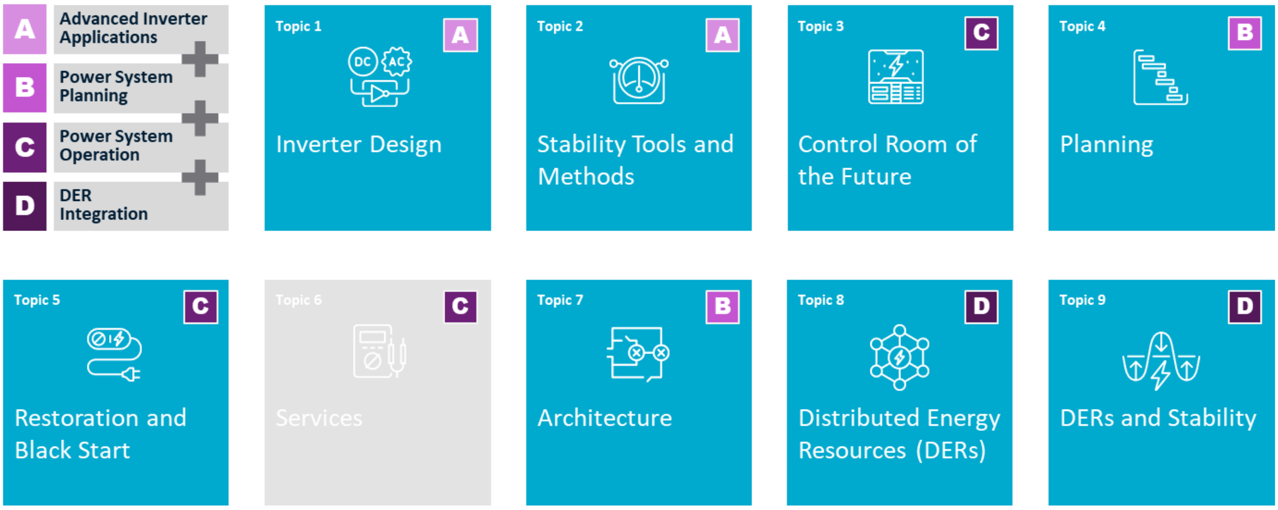

Figure 1: Research areas of the CSIRO Australian G-PST Research Roadmap

During the past twelve months, in this second year of implementation of the CSIRO Research Roadmap, and the third since its inception, a selection of Australia's brightest minds supported by international experts have contributed their expertise to designing power systems for the future as part of this CSIRO funded initiative:

- Topic 1 (Monash University with support from the Electric Power Research Institute (EPRI)) – Inverter Design: Transient Stability enhancement of IBR-dominated grids in the presence of grid forming inverters.
- Topic 2 (Electric Power Research Institute with support of Monash University) – Stability tools: Analytical methods for determination of stable operation of IBRs in a future power system.
- Topic 3 (EPRI) – Control Room of the Future: Machine learning, text, language and network model validation for system operation.
- Topic 4 (University of Melbourne) – Planning and forecasting: Energy infrastructure Planning under deep uncertainty. Assessing impact and benefits of energy system integration on system reliability and resilience.
- Topic 5 (Aurecon) – Restoration and black start: The role of inverter-based resources during system restoration.
- Topic 7 (Energy Catalyst) – Power System Architecture: Application of model based system engineering to the analysis and design of large scale power systems.

- Topic 8 (University of Melbourne) – Distributed Energy Resources (DER): Accelerating the implementation of Operating Envelopes across Australia.
- Topic 9 (University of New South Wales in collaboration with University of Wollongong) – Distributed Energy Resources (DER) and stability: Extending DER, ESS, EV and load testing: Future proofing power system planning, operational and stability analysis.

The topics outlined above represent the highest priority items identified in the Roadmap, and this 2024 report presents the key outcomes and major insights achieved by the research teams. Full detailed reports are available on the CSIRO G-PST website[2]. The website also hosts the roadmap itself and the outcomes of the previous two stages of work.

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[2] https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap

1 Introduction

1.1 Overview

With the world facing a global challenge in climate change, the Paris Agreement requires countries to move to renewable, non-carbon-emitting energy sources to help in the shift towards net zero by 2050. The resulting energy transition within our energy sector is driving rapid change with the uptake of renewable energy technology and the withdrawal of non-renewable energy sources such as coal. Consequently, our energy grids are undergoing major changes, and research in new technologies is necessary to facilitate this transition.

Not only will renewable energy play a significant role in addressing climate concerns but our future energy sources are also expected to resolve security and cost of energy concerns. It is therefore crucial that research is initiated and progressed in the critical areas of the energy sector required to transition to a renewable energy power system that is secure, reliable and affordable.

The energy transition has already seen our electricity system move from primarily linear unidirectional flows, with centralised synchronous generators providing electricity to consumers via our transmission and distribution networks, to a more non-linear, bidirectional and interactive one, with renewable generation, proactive consumers sending energy back into the electricity network, diverse large and small energy storage systems, and more advanced control rooms that are required to manage this more complex system (Figure).

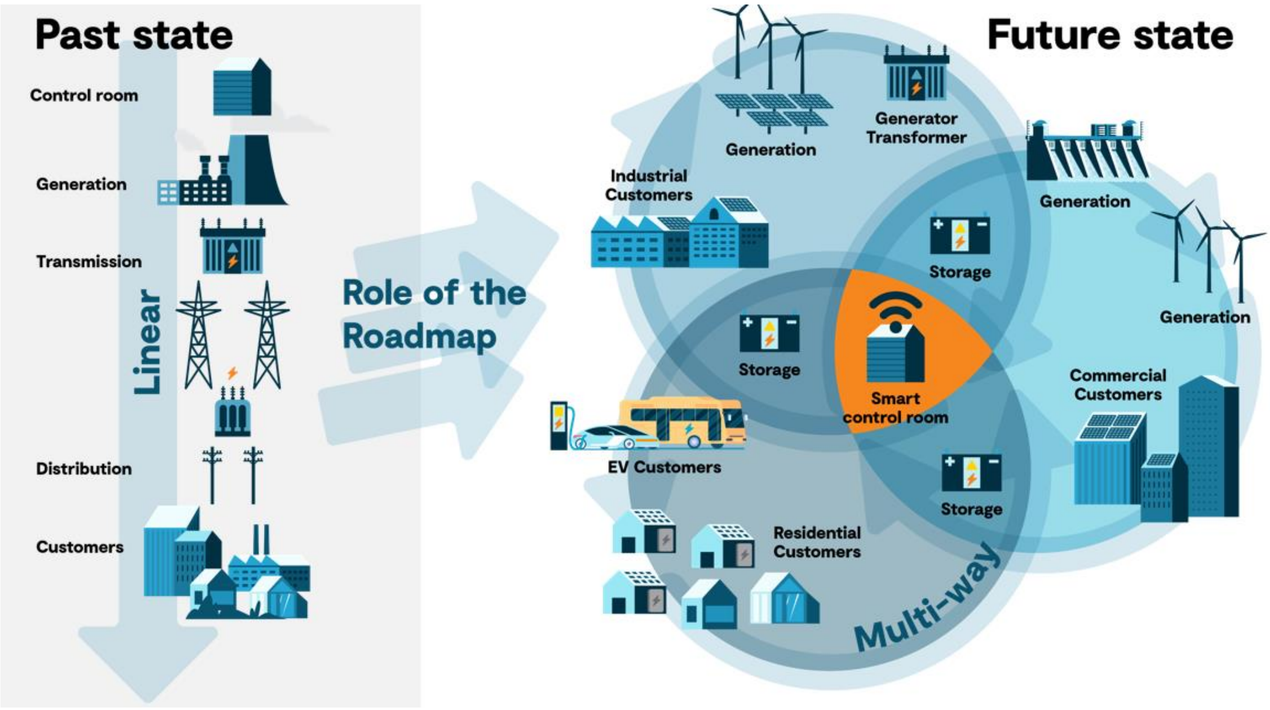

Figure 2: Energy system – past and future state

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) published the *Australian Research Planning for Global Power Systems Transformation* (the Research Roadmap) in 2022. The Research Roadmap outlines a strategy for research in critical areas of our electricity network, with a vision for a bold and accelerated energy transition that will support the Australian power grids to achieve our renewable energy transition[3].

This plan has been put into action with Stage 2 (undertaken in the 2022-23 financial year) producing an initial stage of cutting-edge research in areas such as advanced inverter applications, machine learning and artificial intelligence, and consumer energy resources.

Building on the foundational Stage 2 research, this report outlines the findings of the research undertaken during Stage 3 (2023-24 financial year). The next steps for the CSIRO energy sector research are also outlined. More detail, including full reports produced by the researchers who have contributed to Stage 3, can be found on the CSIRO G-PST website alongside the Research Roadmap[4].

Notably, the research outlined is being undertaken for an Australian context considering specifically Australian challenges, such as world-leading rates of rooftop photovoltaic energy uptake and secure planning and operation of one of the longest transmission systems in the world. However, CSIRO's vision for the application of this research is not confined to Australia. It is intended for collaboration and knowledge sharing with power system experts around the world.

1.2 Global Power System Transformation

The Global Power System Transformation (G-PST) consortium[5] was founded and formed in 2019 by six power system operators with some of the fastest decarbonising energy systems in the world. The G-PST consortium leads cutting-edge research to assist energy systems around the world with the energy transition, to accelerate decarbonisation and to enable a 100% renewable energy grid.

The founding system operators are the National Grid ESO (Great Britain), Ireland's EirGrid, Denmark's Energinet, California's Independent System Operator (CAISO), the Australian Energy Market Operator (AEMO), and the Electric Reliability Council of Texas (ERCOT). The G-PST has core team organisations as outlined in **Error! Reference source not found.**.

Supporting the founding system operators in finding the solutions to the challenges faced by the operators are world renowned research organisations such as CSIRO, Fraunhofer Institute, EPRI, and Imperial College London.

Figure 3: Founding System Operators and Research organisations of the G-PST Consortium [from https://globalpst.org]

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[3] https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap

[4] CSIRO and G-PST Develop Research Roadmap to Support Australia's Energy Transition - Global Power System Transformation Consortium (G-PST) (globalpst.org)

[5] https://globalpst.org

The G-PST works as a group and comprises energy sector experts (system operators, utilities, manufacturers, and researchers) to assist the clean energy transition by providing support and sharing knowledge with other power system operators across the world. There are five Action Pillars that are interconnected, as outlined in Figure 4, which together provide support to the power system operators.

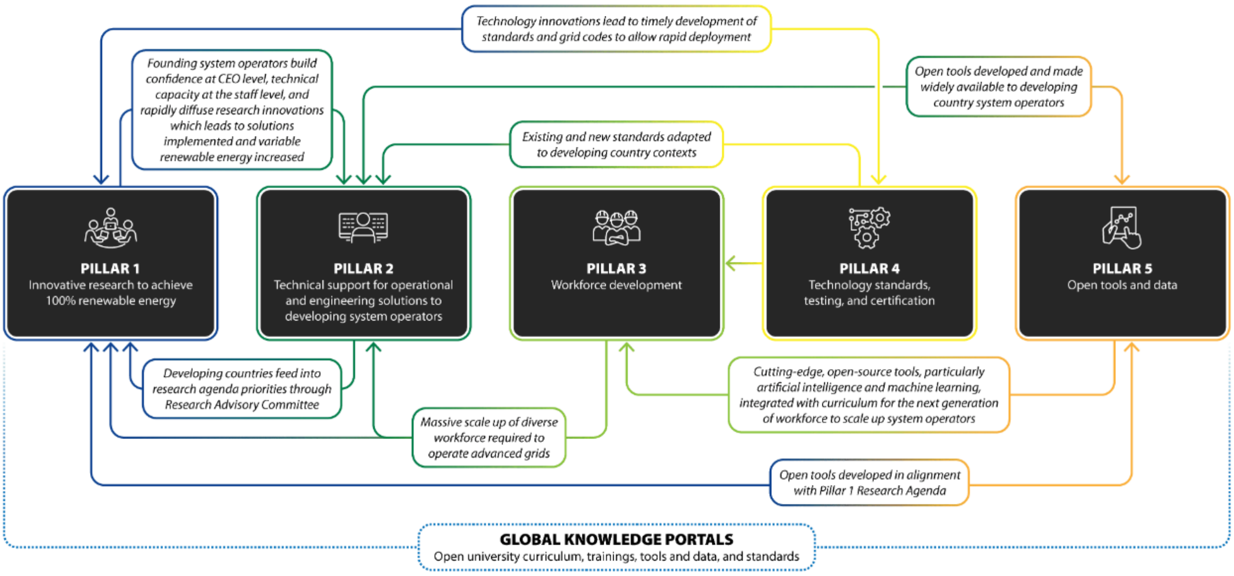

Figure 4: The five G-PST Consortium pillars that inform one another to create an ecosystem of support for power system operators [from https://globalpst.org]

The goals of each pillar are outlined below:

- Pillar 1 – System Operators Research and Peer Learning: Perform and globally disseminate cutting edge applied research to solve pressing challenges for the world's leading system operators.
- Pillar 2 – System Operator Technical Support: Provide implementation support to scale established best practice engineering and operational solutions for system operators in developing countries.
- Pillar 3 – Workforce development: Build the inclusive and diverse workforce of tomorrow through enhanced university curriculum and technical upskilling for utility and system operator staff.
- Pillar 4 – Localised Technology Adoption Support: Adapt modern power system technologies to individual country contexts through technical standards development activities and testing programs.
- Pillar 5 – Open Data & Tools: Support rigorous planning, operational analysis, and enhanced real-time system monitoring through open data and tools.

The research done in this report directly addresses Pillars 1 and 5 and feeds into the other Pillars due to the interconnected nature of the Pillars as outlined in Figure 4.

1.3 CSIRO Power System Research Roadmap

CSIRO, supported by AEMO (a founding system operator of the G-PST), has engaged leading researchers from Australia and across the globe (outlined in Figure 5) to undertake research that is critical to the energy transition in Australia and, more broadly, around the world, allowing Australia to become a leader in the fields of technology and research being studied.

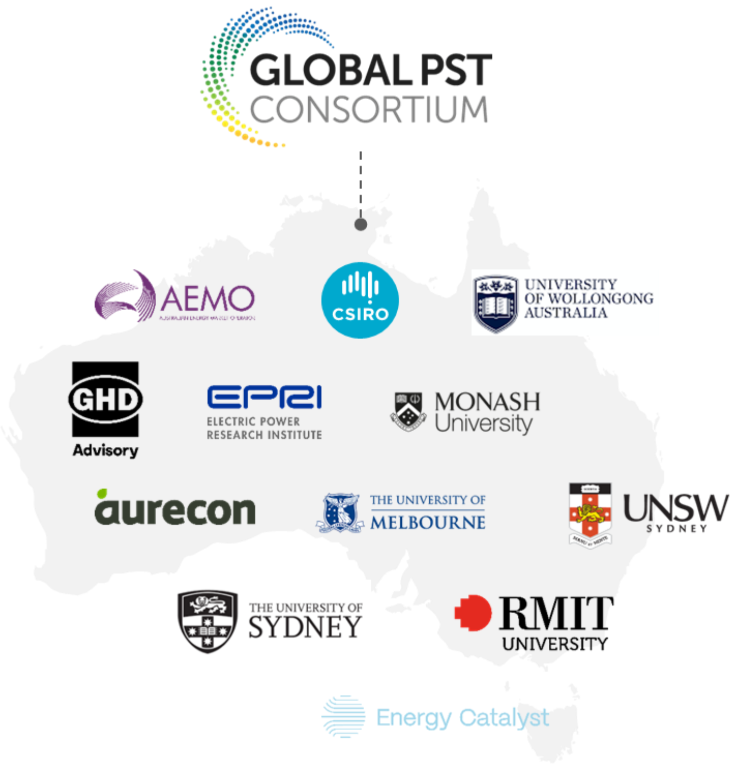

Figure 5: Contributors to the CSIRO Australian G-PST Research Roadmap and Stage 2 implementation.

The work summarised in this report presents Stage 3 of CSIRO's Australian G-PST Research Roadmap; Stage 1 of the research program was the 2022 development of the research roadmap itself, identifying the highest priority tasks in each of the previously described research areas. Stage 2 was the first stage of research and focused on the highest priorities identified in the research roadmap. Stage 3 continues the research undertaken in Stage 2 and considers factors such as new technologies and the changing priorities in the energy sector. Subsequent years of research will be referred to as Stage 4, Stage 5 etc.

Energy sector research is being undertaken in parallel by many other research organisations and system operators outside of the G-PST, and the CSIRO sponsored research seeks to exploit synergies to accelerate the development of solutions to the challenges we face. In particular, the AEMO Engineering Framework[6] and the AEMO Operation Technology Program[7] take into account the Research Roadmap and there is ongoing and continuous engagement between AEMO and CSIRO, and the researchers implementing the Roadmap. Work being undertaken by other research institutes also supports the outcomes of research topics highlighted in the Research Roadmap.

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[6] https://aemo.com.au/en/initiatives/major-programs/engineering-framework

[7] https://aemo.com.au/en/initiatives/major-programs/operations-technology-program

2 Background

2.1 Supporting the Energy Transition

In Australia's National Electricity Market, renewable generation continues to increase rapidly, thereby lifting the amount of energy supplied, particularly from wind and solar. During the first quarter of 2024, renewables supplied 39% of NEM energy, up from 37% the previous year's first quarter. Similarly, the maximum instantaneous penetration of renewable energy sources increased to set a new record of 72.1% during a single 30-minute trading interval i.e., for a half hour period 72.1% of the NEM's energy requirements were supplied from renewable sources, including utility hydro, wind, and solar, as well as rooftop solar installations. Such records are predicted to continue being broken with AEMO's ISP suggesting that by 2025 100% of our demand could be supplied from renewable sources.

While such progress in our energy transition is remarkable, the challenges associated with operating such an electricity grid are also daunting. *En masse* installation of utility scale wind and solar generation, proliferation of rooftop solar installations in our distribution systems and the withdrawal of synchronous generation creates a paradigm shift compared with the way we have operated our electricity networks to date. New technology, new electricity system phenomena, and the challenges associated with both that were becoming all too familiar, led to the establishment of the G-PST by power system operators with the need for new solutions to the reliable, secure, and economic operation and development of our modern electricity grid.

There are many areas of power system design and operation where system operators are now experiencing technical challenges. The G-PST Pillar 1 activities initially included six specific research topics in the Inaugural Research Agenda[8] that the GPST's founding system operators considered most critical to resolve. These six initially identified topics were:

- Topic 1 – Inverter Design: Development of capabilities, services, design methodologies and standards for inverter-based resources (IBR) such as wind and solar generation, and batteries.
- Topic 2 – Stability Tools and Methods: Development of new tools and methods, as well as modifications or supplements to existing tools and methods, required to ensure reliability, security, and stability in power systems.
- Topic 3 – Control Room of the Future: Development of new technologies and approaches for enhanced real-time visibility and analysis in power system operator control rooms.
- Topic 4 – Planning: New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix.
- Topic 5 – Black start and restoration: Creating new procedures for black starting and restoring a power system with high or 100% IBR penetration.
- Topic 6 – Services: developing new techniques and models to manage voltage and frequency control in transitioning power systems.

In Australia, given the rapid and ongoing uptake of rooftop solar photovoltaics and other distributed energy resources, and the need to manage uncertainty in developing our transmission network, as well as ensuring

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[8] https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf

the safe and secure operation of the future electricity system, relevant questions from the research agenda have been grouped into an additional 3 topics. To address these additional challenges a further three topics have been included in the Australian contribution to G-PST research:

- Topic 7 – Power System Architecture: Conceptualisation and development of an overarching power system architecture that brings together critical layers of power system design
- Topic 8 – Distributed Energy Resources (DER) Orchestration: Establishment of tools and methods to better coordinate DER and optimise their integration into, and operation within, the distribution system
- Topic 9 – Distributed Energy Resources (DER) and stability: Development of mathematical models for composite loads, DPV, and DER, based on laboratory testing, suitable for all forms of power system analysis, including dynamic and electromagnetic transient simulations.

These nine topics can be broadly arranged into four areas (Figure 6):

A. Advanced utility scale inverter applications, covering aspects from inverter control system development to creation of operational tools to assist in the continued integration of renewable energy sources.

B. Power system design: Providing solutions and methods for strategic investment and expansion of our power system infrastructure, from the distribution to the transmission system.

C. Power system operation: Delivering practical tools and solutions for system operators and network owners to support the system operators’ real-time management of the future power system.

D. Distributed Energy Resources integration: Providing tools, methods and strategies for the practical integration of DER into power systems design and operation.

Together the nine research topics divided amongst four broad areas are critical to unlocking stable and rapid decarbonisation of our electricity sector while continuing to provide Australian consumers with a secure, reliable, and affordable supply of electric energy.

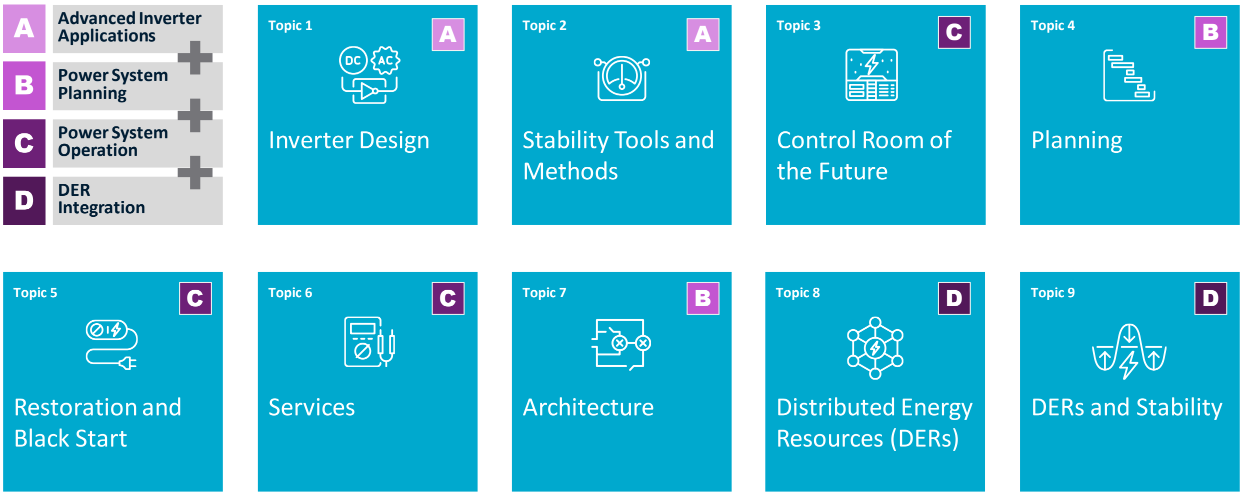

Figure 6: Research areas of the CSIRO Australian G-PST Research Roadmap

2.2 Interconnectivity of the research topics

Our electricity system is an energy ecosystem, where things are connected not only physically, but also overlap operationally and socio-economically, creating dependencies and interdependencies. When we consider the physical extent of our electricity grid that each of the G-PST research topics are focusing on, we observe some that some cover large areas, or even the entire spectrum of our electricity system supply chain, while others are addressing challenges in specific areas only (Figure 7). Similarly, where there is overlap, collaboration between the research teams can accelerate learning and share insights, not only within the CSIRO Roadmap research, but as observed previously, with other research programs outside of this such as AEMO's Operations Technology Program and the Engineering Roadmap. As the completed research builds there are also flow on effects, such as the use of composite load models developed through Topic 9, in the system restart analysis of Topic 5. It is said "If you want to go fast, go alone, but if you need to go far, go together". The CSIRO Research Roadmap realises that solving the challenges to our energy transition will take time and require all of our collective contributions and encourages collaboration among research topics and external research programs. To this end all of the research generated, unless of a confidential nature, is made available publicly; links to the research and data are presented in Section 7.2 of this report. The following sections of this report summarise the research outcomes in each of the four broad areas A, B, C, and D.

Figure 7: Research focus areas of our electricity supply chain investigated by the CSIRO Research Roadmap

3 Integration of Inverter Based Resources

The phasing out of large, centralised fossil fuelled power stations, is seeing a new generation of energy source taking their place; energy sources using water, sun and wind as their fuel. Wind and solar renewable energy sources in particular use power electronics to convert the generated power to a form suitable to inject into 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, the effective coordination and tuning between the many control systems installed in each renewable generation facility, and the secure dispatch and operational oversight of this new generation fleet by the power system operators.

The CSIRO Research Roadmap research on advanced inverter applications and management tools encompasses many aspects of these new inverter based resource technologies, from designing new control systems to developing tools to enable better integration of these technologies. For Stage 3 of the Research Roadmap, CSIRO have funded two research projects in the area of inverter based resource application and integration that will contribute to the electrical industry's body of knowledge and will support Australia's energy transition:

(a) Advanced inverter applications for current-limited grid forming inverters.

(b) Analytical methods for determination of stable operation of IBRs in a future power system.

3.1 Topic 1: Advanced inverter applications for current-limited grid forming inverters

This project presents a study of grid-forming inverters in power systems, focusing on their design, transient stability, and control enhancements. The research aims 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, progressing from assessment of multi-IBR systems, such as those found in Renewable Energy Zones, to the development of a tool for rapid stability assessment of high IBR penetration systems. The research also encompasses an investigation of negative sequence current controls that are used in IBR to assist network operation during unbalanced network faults, as well as a practical investigation of enhancing the transient stability of grid forming current-limited controls for wind turbine generators.

The research continues on from the Stage 2 research completed during 2023 by expanding the concept of a transient stability metric that defines the electrical angular distance between the stable equilibrium (operating) point and the unstable equilibrium point (UEP) for a multi-IBR system (Figure 8), and uses these to determine the stability metric (D_{EP}) as $\mathrm{D}_{\mathrm{EP,h}} = \left|\frac{\delta_{\mathrm{v,h,SEP}} - \delta_{\mathrm{v,h,UEP}}}{\delta_{\mathrm{v,h,SEP}}}\right|$, where the descriptor *h* denotes the bus targeted for stability margin assessment and the magnitude of D_{EP} defines the relative stability of the system.

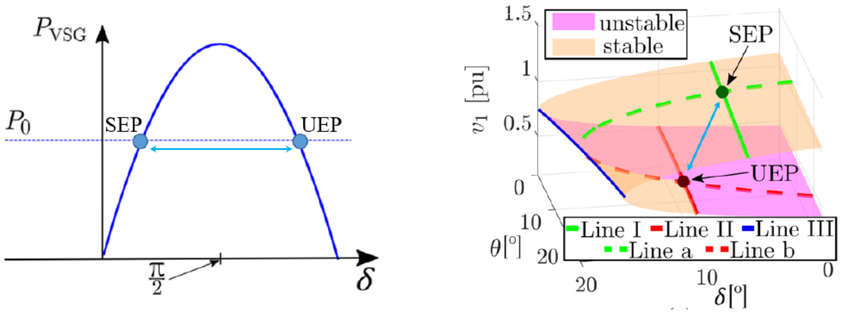

Figure 8: Transient Stability margin definition

In the Stage 3 expansion for an intermeshed network of four separate IBR systems, each consisting of a combination of grid forming and grid following inverters, the concept of stability margin was then used to determine a stability metric for the overall network.

Benefits of this metric based assessment is that it allows for derivation of operating stability boundaries without having to solve differential equations.

The process of calculating D_{EP} for different network configurations, impedances and inverter power outputs is then implemented in an automated tool (Figure 9) that can rapidly calculate system stability for different configurations and operating states. Similarly, the metrics for different operating states can be used to determine the relative stability among them as $\mathrm{D}_{\mathrm{EP,\ relative}} = \frac{\mathrm{D}_{\mathrm{EP,\ case\ x}} - \mathrm{D}_{\mathrm{EP,\ Base\ case}}}{\mathrm{D}_{\mathrm{EP,\ Base\ case}}}$.

The researchers note that conventional means of stability margin calculation using PSCAD requires more computational power and is time-consuming, whereas using the tool allows the stability margin to be calculated not only quickly, but also accurately.

Advantages of the stability assessment process and tool are noted as including:

- The proposed indicator and tool provide a computationally efficient way to determine the Transient stability (TS) margin without solving differential equations.
- The approach enables quick and accurate TS analysis for complex networks, facilitating the integration of renewable energy sources.
- It offers practical insights for optimising network configurations and enhancing stability in renewable energy zones.
- The tool can be refined and expanded to include additional parameters and scenarios for more comprehensive TS analysis.
- Potential applications include grid modernisation efforts and the development of more resilient and sustainable power systems.

One benefit of inverter based systems is their ability to control each phase separately. This permits reduction of voltage unbalance during network faults involving only a single or two phases. Unbalanced faults can give rise to maloperation of protection systems and excessive unfaulted phase voltages (due to over-compensation of positive sequence current injection). Injection of negative sequence current is therefore an opportunity to add additional security and safety to power system operation. This has already been recognised in many jurisdictions, including the Australia' National Electricity Market, where the Australian National Electricity Rules Schedule S5.2.5.5 requires negotiation of the quantity of negative sequence current injection between power electronic based generating facilities and AEMO and the connecting Network Service Provider.

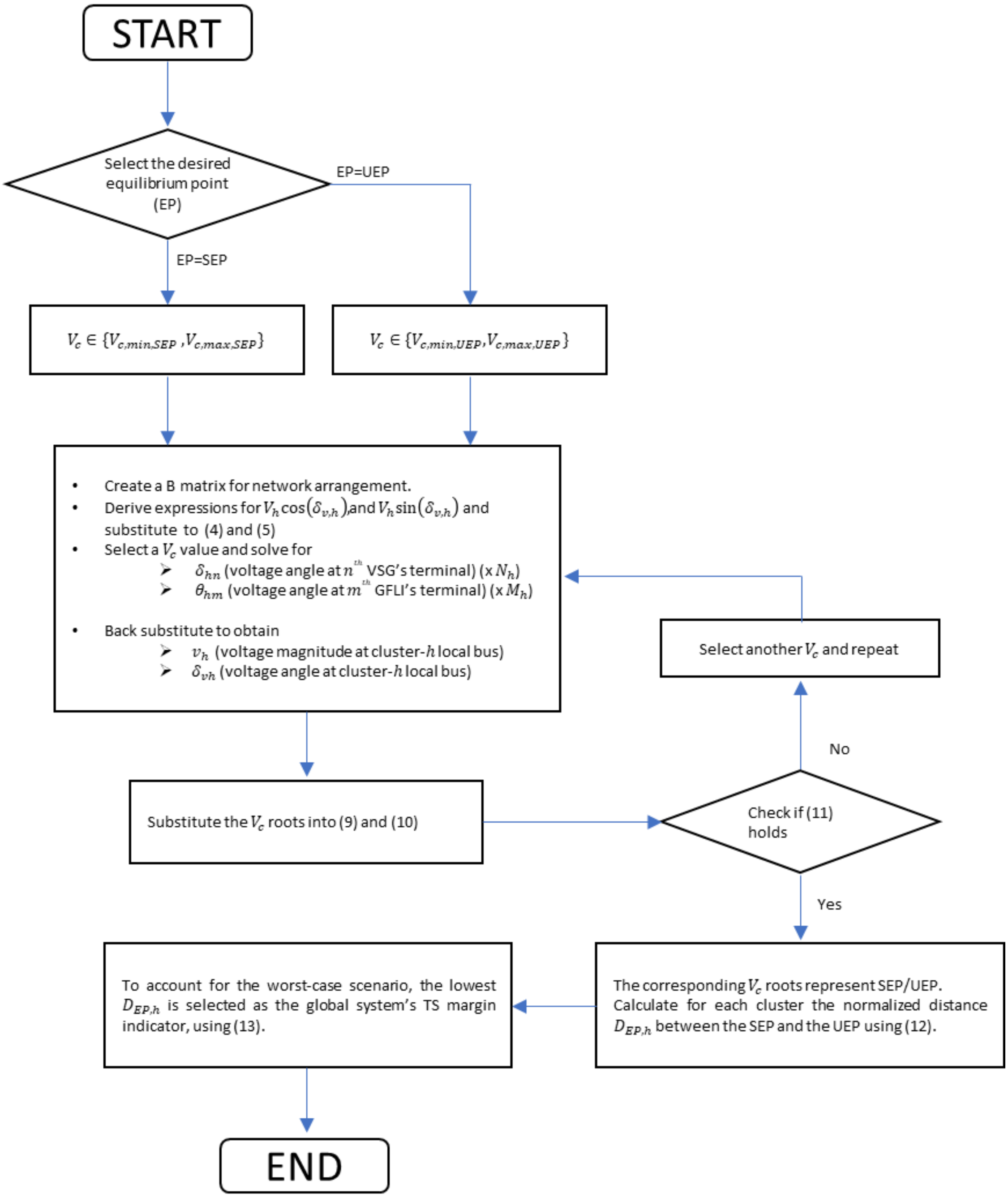

Figure 9: Transient stability analysis process of multi-IBR networks

Increasingly grid codes, including those in the Australian NEM, require the controlled injection of negative sequence current during unbalanced faults. However, while able to provide overall system stability, the injection of negative sequence current by an inverter can also adversely impact the stability of the inverter itself due to the possible maloperation of the phase selection element of inverter protection. The research conducted during Stage 3 investigates in detail the performance of two different current limiting inverter controls, implementing first a PQ priority method and subsequently a virtual impedance one.

The research indicated that the most influential parameters on transient stability when injecting negative sequence current are:

(a) The ratio of positive to negative sequence current, with lower ratios being more prone to inverter instability.

(b) Maximum current due to current limiting, with lower current limits more likely to result in instability.

(c) Network impedance ratio (X/R), with high values more likely to result in adverse impacts.

Knowing the limitations of inverter stability in terms of the above three parameters, an optimised inverter output setting and optimised control method can be selected to ensure inverter stability, while contributing to voltage balancing and overvoltage reduction of a network during unbalanced faults.

The Stage 3 research of Topic 1 concludes with a practical assessment of implementing current limiting grid forming inverter controls, developed in Stage 2 and expanded on in Stage 3, in Type 3 (doubly fed induction generator – with mechanical gearbox to connect the prime mover to an induction generator and a power converter in parallel to the generator) and Type 4 (full power AC converter in series with a variable speed induction or synchronous generator) wind turbines. To date grid- forming controls have only been used in battery energy storage projects and the research investigates a novel way to consider grid strengthening services from future generating sources.

VSG-based GFM-WTG-3 using Q-priority Current Limiting (CL) results in a degraded recovery following a deep fault at rated output. The underlying reason can be attributed to the VSG dynamics, which also contribute to the coupling between the DFIG rotor speed and GFM phasor angle. This dynamic coupling impacts the restoration of an equilibrium point on the rotor speed-active power plane after the fault clearance. The proposed solution determined that inverter active power controller (APC) dynamics can be modified such that the post-fault deceleration of the GFM phasor angle is faster. Implementing such controls result in smaller angle deviations and hence improved stability (Figure 10).

VSG-based APC: $C(s) = \dfrac{1}{2Hs + K_D}$

Lead-Lag based APC: $C(s) = \dfrac{s + K_T}{K_J s + K_D}$

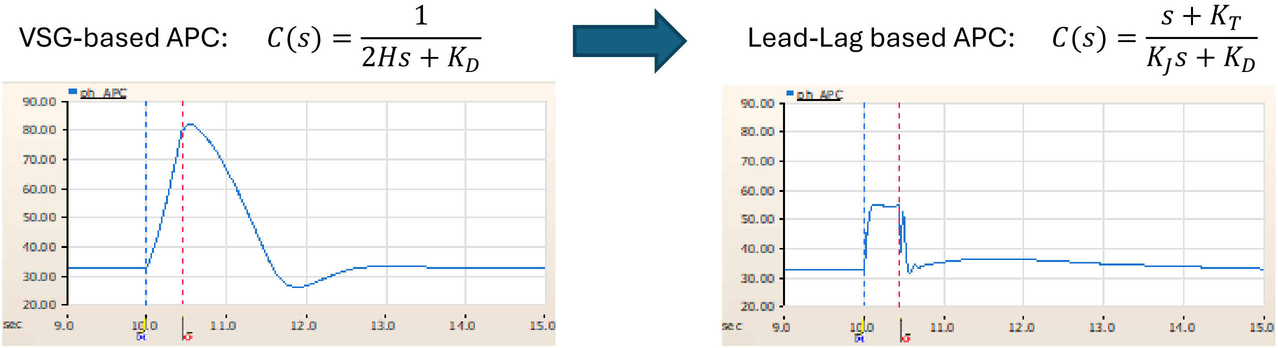

Figure 10: Inverter stability improvements using lead-lag power controller algorithms

Overall, this research contributes valuable knowledge and practical tools for designing, operating, and controlling grid-forming inverters for modern power systems. The results improve the transient stability of these systems and hence helps to ensure secure grid integration of IBR as renewable energy resources continue to expand.

The research tasks that were completed in the 2022/23 Stage 2 work included:

- Advancement of IBR reliability assessment and enhancement.
- Performance assessment of wind turbines with grid forming inverter controls.

Overall progress achieved during the Stage 3 research is summarised in

Table 1.

Table 1: Progress against Topic 1 Research Roadmap

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress[1]
4. Protection and Reliability	4.3: Assessment and enhancement of IBRs reliability	- Task-1: Transient stability analysis of multi-IBR systems considering a wide-area network - Task-2: Development of an analysis tool to conduct transient stability studies for multi-IBR systems	50%
	4.2: Enhancing IBR response during and subsequent to faults	- Task-3: Investigation into the impact of various controls (e.g., GFM controls, current limiting, frequency freezing and K2-factor) of GFMIs on the TS of inverters conforming to IEEE P2800 NS current requirement. - Task-3: Study of the impact of NS current allocation on the protection system, conducted either through a literature review, or, if relay models are available, one or two case studies. - Task-4: Enhancing transient stability of current-limited grid-forming control by implementation in non-BESS IBRs	70%
5. Trending Topics	5.2: Grid-forming capability for HVDC stations and wind and solar farms	- Task-4: Enhancing transient stability of current-limited grid-forming control by implementation in non-BESS IBRs[2]	20%

[1] Progress to date against roadmap tasks.

[2] Stage-3 Task-4 contributes to both Roadmap tasks 4.2 and 5.2 as it addresses IBRs' stability-enhancing response as well as grid-forming capability for wind turbines.

3.2 Topic 2: Analytical methods for determining stable operating points of IBR

Changes to our generation technology, from synchronous generation to inverter based resources, are having far reaching impact on the operation of our electrical networks. As noted by AEMO: "[small signal] Oscillatory modes in the Australian National Electricity Market (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 the oscillations." [9] Power system oscillations, if not adequately damped, 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 inverter-based-resources (IBRs), development of methods for determining oscillatory stability, and stability margins, around different system operating conditions is important. This topic was identified as a critical task in the CSIRO GPST Research Roadmap in Topic 2: Stability Tools and Methods.

Key to such stability margin assessment is the ability to rapidly assess the impedance characteristics of IBR when installed *en masse* in a power system, then to conduct a wide area study on the power system with to identify potential instability, and finding means to address this. Complicating the process is the often hidden electrical and control system structure of IBR, in so called 'black box' representations that are intended to protect the developers' intellectual property. Identifying the characteristics of blackboxed IBR therefore requires new tools and processes.

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[9] https://cse.cigre.org/cse-n028/oscillatory-interaction-between-large-scale-ibr-and-synchronous-generators-in-the-nem.html

In the previous stage of Topic 2 research, two prediction algorithms were developed that can quickly estimate the impedance characteristics of IBRs across a wide range of operating points. One method was a data driven prediction algorithm, the other an analytical prediction one.

The recent Stage 3 research compared the performance of the two algorithms in assessing IBR models with different control architectures, and different operating points and control parameters. The accuracy of estimated impedance was then compared, and it was found that the analytical prediction algorithm results in a better accuracy for all models tested. Further, a 'black box' IBR model was created and utilised to test the performance of the analytical prediction method when the exact IBR control structure is not known.

A second broad objective of EPRI's Stage 3 work was to perform a 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. The aim of the wide area study is to:

- Verify a procedure to utilise the frequency domain impedance characteristics of IBR to form a state space model that can be incorporated into a wide area small signal model.
- Establish a small signal analysis framework to identify any small signal unstable conditions and the devices/states that participate in oscillation modes that are either unstable or poorly damped.
- Use the developed framework and processes to derive a means of optimising network stability through targeted placement of stabilising devices and controls.

To this end, the impact of the approximation of using a positive sequence network admittance model was then tested for a small network. In particular, a small signal stability analysis was performed on a synthetic network model representing the area served by the National Electricity Market (NEM) with more than 2, 000 buses. The analysis framework, consisting of various network modelling assumptions and load representations, was validated using standard small network models and scaled for the larger network model including IBRs. It is expected that this approach will permit stability analysis with blackbox dynamic models.

Finally, the researchers considered the impact of current limits on the stability of IBR, including impedance representation and stability performance. This is important because when electrical current limits are binding, the dynamics and model characteristics can significantly change, potentially invalidating the assumed impedance representation.

The project therefore has multiple tasks and activities, interlinked and interdependent. The overall project method is represented by the process structure of Figure 11.

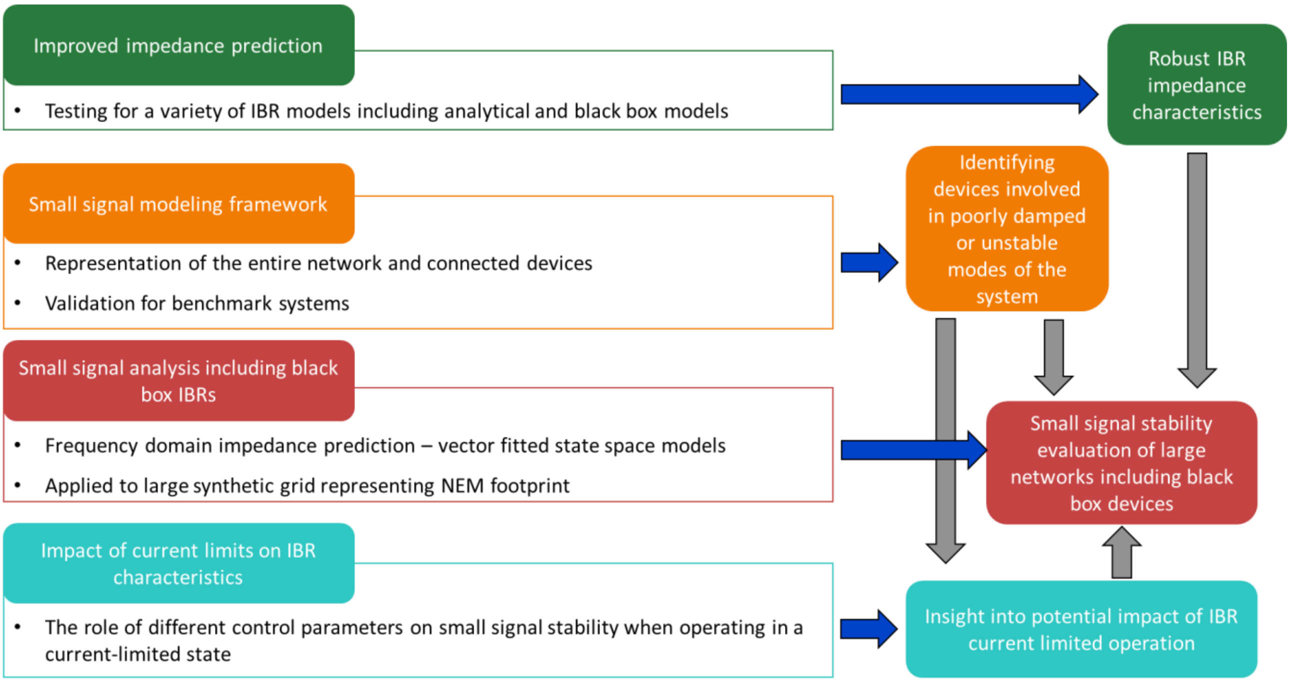
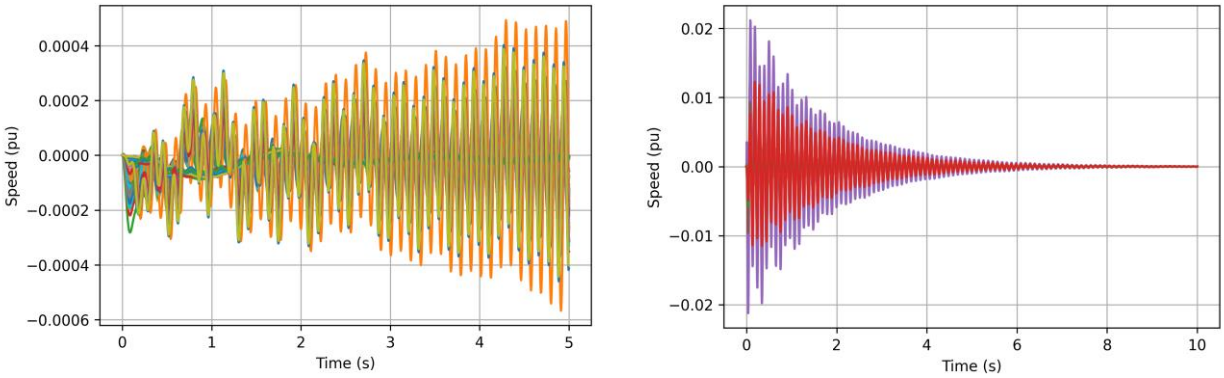


Figure 11: The methodology followed in Stage 3 of Topic 2

Having established their method of developing blackbox IBR impedance representations and validated their small signal assessment framework to utilise positive sequence modelling data, the researchers move on to perform a small signal stability assessment of a large, IBR dominated network, as well as a time domain assessment to verify the small signal results. Using a reduced scale model of the NEM at a time of peak demand, and with 2,000 buses and 200 grid following IBR (as well as some synchronous generators), small signal analysis identified several poorly damped, and fast moving, inter-area modes of oscillation involving several synchronous generators and many IBR from across the NEM. As a countermeasure to these high frequency instabilities, and to the weak state of the grid, droop-based GFM IBRs were installed (in simulation) on the buses with low fault levels.

Whereas previously, a voltage step response at one of the grid following IBR resulted in a poorly damped oscillation at around 9 Hz, the addition of the GFMI systems results in the same mode becoming well damped when the system is subject to the same step response (Figure 12), verifying the improvement in stability introduced by the additional inverters.



(a) Linearised System SG-GFL IBR Speeds Impulse Response

(b) Linearised System SG-IBR Speeds Impulse Response with GFMI installations

Figure 12: **Linearised system generator speeds impulse response (for IBRs Speed is the PLL integrator state)**

When the same studies are repeated with more complex load models, the higher frequency modes are no longer unstable in systems dominated by GFL IBR. Instead, instabilities are observed at much lower frequencies, within the ranges normally associated with electromechanical modes. These are not able to be stabilised through addition of GFMI devices and limits to operation would instead need to be applied.

Wide area studies on the synthetic NEM were conducted using a range of IBR models, both with known impedance characteristics and with blackbox models whose characteristics were estimated using the analytical prediction algorithm. The researchers concluded that if the models' dynamics are adequately captured by the impedance scans and then fitted to a state-space representations, the dynamic behaviour of the closed-loop system can be correctly recovered. Thus they suggest that although one particular hurdle to exploiting state-space methods from the linear analysis of power systems is not having models with access to their internal control structure but only to terminal measurements, this hurdle can be overcome via a combination of system identification and an appropriate interface to the rest of the network.

As a final step in their assessment, and recognising that the IBR tested are current limited devices in practice, the researchers briefly assessed the possible impact, when these limits are binding and IBR controls may be saturated, on the accuracy of the impedance characteristic prediction. Eigenvalue analysis, including sensitivity assessment of control system and network parameters, showed that when IBR are current limited, the roots of the transfer function are often much closer to the imaginary axis, and hence present a greater likelihood system instability.

Stage 3 of the Topic 2 Research Roadmap progressed two of the critical tasks identified (Table 2).

Table 2: Topic 2 progress against the critical tasks identified in the Research Roadmap

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress[1]
1. Stability margin evaluation	Develop tools to evaluate non-linear stability margins using black-box models at multiple operating points	• Comparing two admittance prediction algorithms of IBR impedance characteristics for accuracy and application of most accurate prediction algorithm for verification of different and black box IBR model. • Prediction algorithm optimisation through Identification of minimum operating points to generate training data for prediction of frequency domain characteristics over any operating point on the capability curve. • Identify the impact of current limiting operation on the impedance characteristics of blackbox IBR.	60%
2. Small signal stability screening methods	Development of procedures to use impedance-based methods for network stability screening when using black box IBR models.	• Characterisation of the stability behaviour of a large network such as the Synthetic NEM with high percentage of IBRs. • Use the predicted impedance characteristics of select IBR devices along with positive sequence impedance characteristics of the network to help identify critical nodes of the network wherein various stabilising services from the IBRs may be required.	60%

While this second year of research implementation has made significant inroads to the development of tools and methods to enhance the planner's and operator's ability to manage a power system with increasing IBR, more work remains. In their conclusion, the researchers recommend that subsequent stages of the research should:

- further enhance the admittance estimation algorithm to include additional IBR control system configurations;
- retest the small signal stability framework against an actual utility network;
- investigate the use of positive sequence models to obtain stability relevant frequency characteristics that are currently obtained using computationally burdensome frequency scans;
- expand the response assessment of current limiting GFL and GFM IBR, considering alternative operating modes;
- conduct a comparison between using a multiple-frequency network equivalent, to fundamental frequency network equivalent (used in Stage 3), of a large network such as the synthetic NEM network; and
- expand the assessment of the impact of load on small signal stability, by including composite load models; and
- involve inverter manufacturers and commercial software vendors to assist in streamlining the process of industry adoption of small signal stability assessment.

4 Power System Design

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 their construction.

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 carriers, ageing infrastructure, and increasingly 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, and providing new tools and methods for the way we plan our power system, and consider these new influences as we look to develop the power system of the future:

(a) Energy infrastructure planning under deep uncertainty: Assessing impacts and benefits of energy system integration

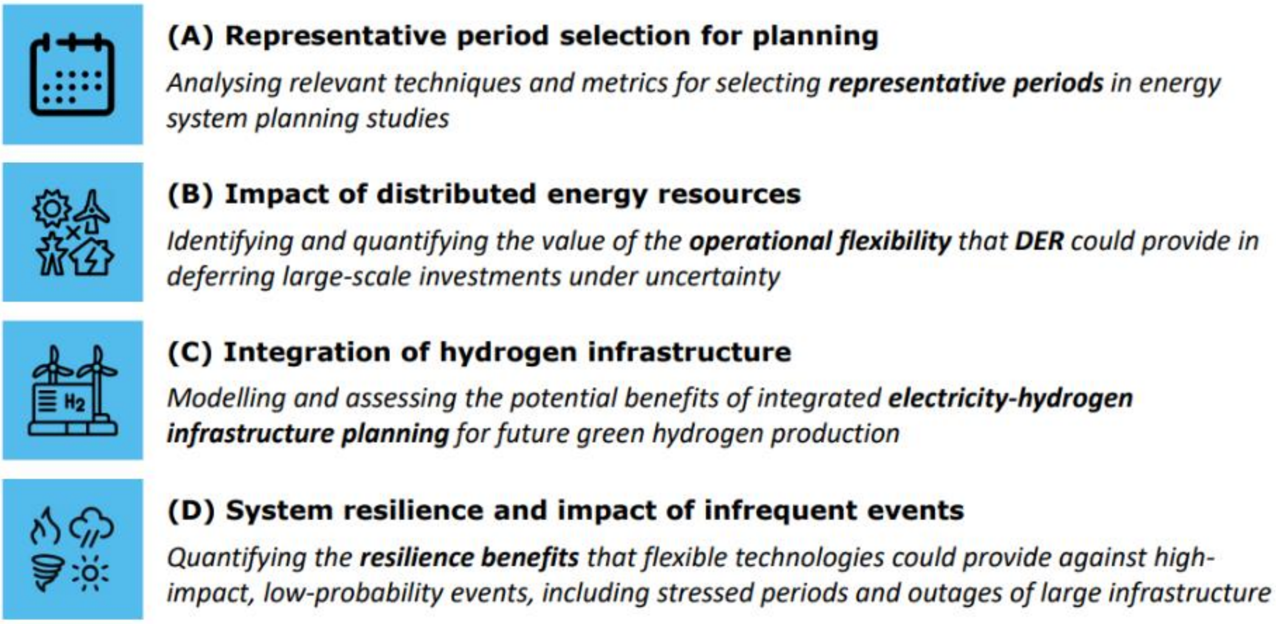
(b) Power System Architecture: Application of model based system engineering to the analysis and design of large scale power systems

4.1 Topic 4: (Power System) Planning

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. However, the development of the REZs, demand growth, the fast uptake of various distributed energy resources, advancements in storage technologies, the retirement of synchronous generation units, and the potential to produce alternative energy carriers such as hydrogen, among many other elements, are subject to deep uncertainties that make the decision to build new large-scale assets both strategic and challenging. Making the right decisions regarding new network investments can yield value for the system through lower costs, enhanced reliability, increased resilience, and reduced renewable energy curtailment, which will largely offset the investment costs. On the other hand, incorrect or untimely decisions could lead to stranded or underutilised assets and potentially higher costs.

Within this context, this stage of Topic 4, "Planning" of the CSIRO – GPST research roadmap, explores the benefits for energy systems of adaptive planning methodologies. The research assesses the impacts of integrating flexible technologies within the transmission planning problem, including distributed energy resources (DER) and hydrogen-related infrastructure. The primary focus of this project lies in identifying methods and technologies to address long-term uncertainties, mitigate risks, promote robust investment decisions, and enhance system resilience against infrastructure outages and extreme events. The core objectives that have been addressed during Stage 3 of the power system planning project and the key relevant activities and outcomes are shown in Figure 13.

The impact of the research subjects that represent the power system objectives are assessed by the researchers using the stochastic decision tree process developed in Stage 2 of the research, using the NEM and most recent AEMO Integrated System Plan[10] as the test platform.



(A) Representative period selection for planning

*Analysing relevant techniques and metrics for selecting **representative periods** in energy system planning studies*

(B) Impact of distributed energy resources

*Identifying and quantifying the value of the **operational flexibility** that **DER** could provide in deferring large-scale investments under uncertainty*

(C) Integration of hydrogen infrastructure

*Modelling and assessing the potential benefits of integrated **electricity-hydrogen infrastructure planning** for future green hydrogen production*

(D) System resilience and impact of infrequent events

*Quantifying the **resilience benefits** that flexible technologies could provide against high-impact, low-probability events, including stressed periods and outages of large infrastructure*

Figure 13: Stage 3 research objectives and key tasks of Topic 4

A. Selection of representative periods

Power system planners employ capacity expansion models to determine optimal investment portfolios for large-scale infrastructure. In this context, it is important to accurately represent the operation of power systems to avoid distorting the potential benefits and requirements of integrating high levels of variable renewable energy (VRE) and flexible technologies such as energy storage, distributed energy resources (DER), and hydrogen infrastructure in long-term decision-making.

Surveys of the methods and practices of power system planners when developing long term investment strategies, and a literature review on the same topic, identified that clustering-based classification algorithms and optimisation problems to approximate representative periods by load duration curves were commonly used. In addition, a growing trend was identified to employ new methods based on machine learning, such as autoencoders.

In summarising their findings, the researchers noted that a thorough selection of representative periods is crucial for accurate power system planning results. This selection should ensure that models can adequately assess the value of flexibility as energy systems integrate numerous alternative technologies. The survey emphasised the need for models with high temporal resolution to support more accurate investment decisions, particularly when assessing the value of infrastructure during extreme and stressed time periods.

Concurrently, as uncertainty in energy systems is increasing, planning problems are becoming even more complex (e.g., stochastic optimisation). In this context, decision-makers such as the Australian Energy Market Operator (AEMO) need to consider the selection of a subset of periods that allows for an adequate representation of energy system operation to reduce computational burden.

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[10] https://aemo.com.au/-/media/files/major-publications/isp/2023/isp-newsletter---december-2023.pdf

B. Impact of distributed energy sources

The continued growth of DER is undisputed. In Australia, rooftop solar already represents over 20 GW of total installed generation capacity, a number set to grow further and to be complemented through consumer technologies such as domestic batteries and electric vehicles (stationary and mobile electric storage).

Presently much installed DER is non-controllable. However, using stochastic decision tree assessment, the researchers found that when DER are controllable and their operational flexibility can be exploited through orchestration, the benefits that can result from delayed or deferred transmission investments can be substantial. Shown in Figure 14 is one set of results obtained by independently running a set of stochastic scenarios derived for different ISP pathways, with each marker representing the outcome of a single scenario. Expected costs can be derived from the relationship between cost and cumulative probability.

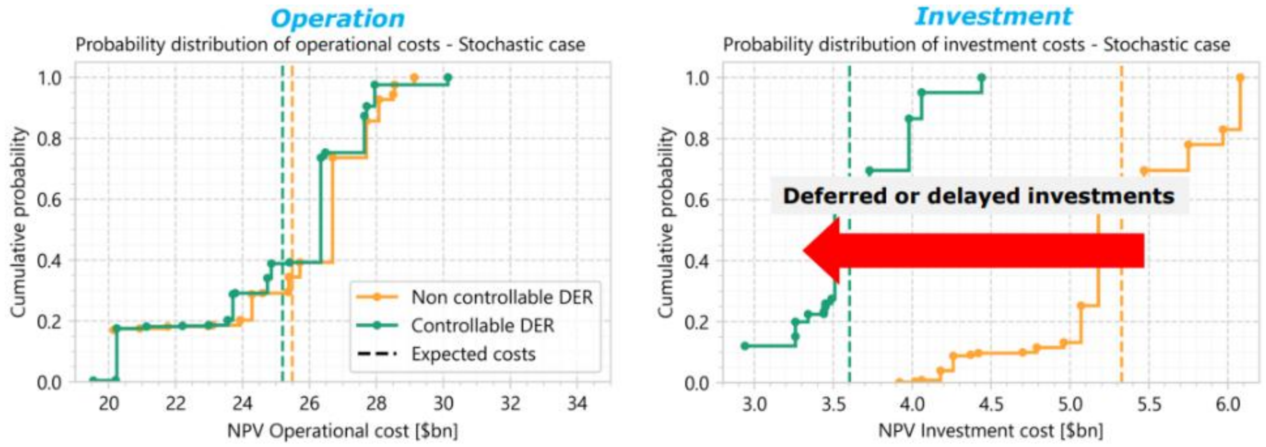


Figure 14: Operational and investment costs of controllable and non-controllable DER

While operational costs do not differ much between controllable and non-controllable cases, the greatest benefit of the operational flexibility of DER is reflected in infrastructure total investment cost, highlighting the opportunity that DER orchestration presents to:

- Allow for anticipatory decision making.
- Reduce investment risk.
- Reduce investment uncertainty.
- Allow a clearer and more robust pathway to be developed.

C. Integration of hydrogen infrastructure

Energy system planners in countries with abundant renewable energy resources, including AEMO in Australia, are actively exploring - in their planning scenarios - the potential deployment of large-scale green hydrogen production (through electrolysis) to decarbonise heavy industries and to serve new export markets. This could lead to a massive increase in the electrical demand associated with such developments, creating significant interactions between electricity and future hydrogen systems. At some point the question will be asked whether we should move, and store, electrons or molecules.

The researchers build two case studies for coupled (electricity and hydrogen) planning using the regional Queensland network, as well as the whole NEM, to address questions such as: (i) whether to transport energy as molecules in hydrogen pipelines or via electrons in electricity transmission lines, (ii) whether renewable energy sources and electrolysers should be co-located, (iii) what are the implications of hydrogen transport infrastructure on the decisions for new electricity transmission lines, (iv) how uncertainties can be managed and modelled to ensure an adequate investment path for an integrated electricity-hydrogen system.

A flexible multi-stage, stochastic, integrated electricity-hydrogen planning framework was employed by the researchers to address the above questions and to identify the impacts and potential techno-economic benefits of integrating electricity and hydrogen infrastructure planning. The basis of the modelling exercise is the AEMO 2022 ISP Hydrogen Super Power scenario.

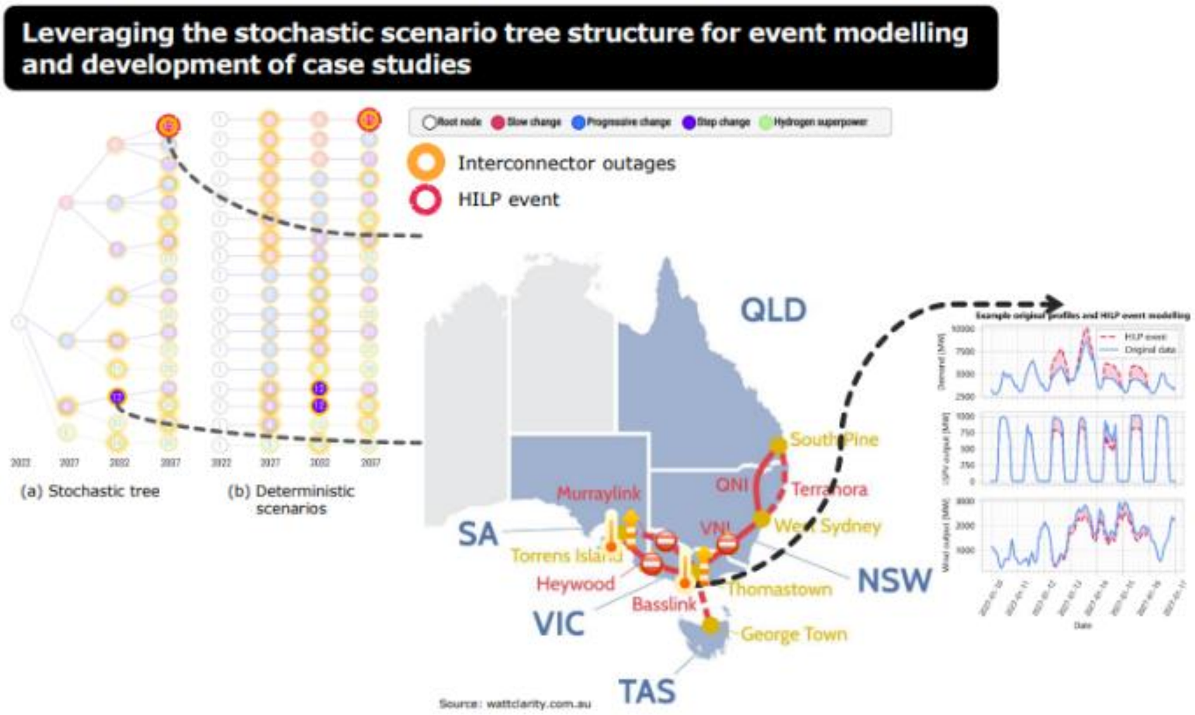
The decision tree based modelling ensures that several constraints on the planned energy system are met. These constraints are associated with infrastructure investments, a detailed understanding of the operation of the electricity system (considering constraints for both unit commitment and distributed energy resources), and of the operation of the hydrogen infrastructure for production and transport.

The researchers found that the greater the flexibility of hydrogen production using electrolysers, the lower the cost of required transmission investments, quantifying benefits of operational flexibility in long-term planning. Even if the flexibility of hydrogen production is reduced due to increased hydrogen demand, flexibility will still reduce and defer capital investment costs.

D. Resilience assessment and network outages in long term planning

The main objective of the final task of the planning research is to study, model, and represent different events that a power system could face, by taking advantage of the capabilities of the developed stochastic planning framework (decision tree) to model uncertainties. Particular focus has been placed on considering events such as planned transmission line outages, generator capacity deratings, and extreme (high-impact, low-probability, HILP) events. Events with these characteristics have the potential to significantly disrupt the normal operation of power systems, and even to determine a need for new, timely infrastructure reinforcements.

Case studies used by the researchers demonstrate the impact of including disruptive events on planning decisions, illustrating potential changes in the timing and scale of required infrastructure investments. The studies primarily utilise the same system model (full NEM) employed in the previous sections of this report to facilitate a direct comparison.



Source: wattclarity.com.au

Figure 15: Resilience assessment and network outages in long term planning

With the completion of Stage 3 of the Topic 4 investigation, the researchers report on progress tracked against the objectives of the CSIRO Research Roadmap as illustrated in Table 3.

Table 3: Progress of the Research Roadmap for Topic 4 after the completion of Stage 3

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress

Task A	Power System operation: Steady state modelling (R2S1P1)	Modelling the steady state operation of the system considering the trade-off between computational efficiency and model precision.	20%
Task B	Decision making: methodologies for decision-making under uncertainty (R4S2P3)	Methodologies and tools to incorporate the assessment of non-network solutions value streams in the network expansion problem.	20%
	Distributed energy Systems: Distributed energy markets and DSF (R5S2P1)	Identifying the sources and availability of demand side flexibility , quantifying its aggregated profile and determining its representation in power system planning.	25%
	Distributed energy Systems: Distributed energy markets and DSF (R5S2P2)	Modelling distributed energy systems (e.g., DER, VPP) operation and determining data requirement to represent their operation for planning studies.	25%
	Distributed Energy Systems: DER impact (R5S3P2)	Modelling and analysing the contribution of DER to system reliability (security and adequacy) and resilience.	20%
Task C	Distributed Energy Systems: Multi-energy systems (R5S1P1)	Modelling the impact and flexibility embedded in the interactions between power systems and other energy systems for planning studies.	20%
Task D	Reliability and resilience: Credible and non-credible contingencies (R3S3P3)	Modelling the impacts and benefits of other infrastructure and sector coupling (e.g., gas, hydrogen) on power system and reliability	50%

4.2 Topic 7: System Architecture

Global progress with the deep decarbonisation of legacy electricity grids presents significant challenges and many grids are now undergoing a pace and scale of change never before experienced in their more than 100 years of history. As a result, many government, research, community and corporate entities are recognising the current decade as decisive to global decarbonisation efforts. Provisioning GW-scale power systems such as the NEM for deep decarbonisation requires the holistic integration of a diverse range of energy technologies, market, regulatory, cyber-physical and other innovations that deliver consumer, societal and system benefits.

Operationally, our power system is a complex interaction of many functionally interdependent structures that make up the power system architecture, including:

- Electricity Infrastructure (Power Flows);
- Digital Infrastructure (Information/Data Exchange, Storage and Processing);
- Operational Coordination Structure; and,
- Transactional Structure.

In this transformational context, the formal Systems Engineering-based tools and methodologies employed by many other advanced and complex sectors become critical to:

- Provide formal tools that enable the decomposition and ‘taming’ of the massive complexity inherent to transforming legacy GW-scale power systems;

- Empower more informed, multi-stakeholder participation by making critical content explicit and tractable which would otherwise remain opaque and intractable; and,
- Increase decision quality, timeliness and traceability to increase the potential for benefits-realisation and avoid the propagation of undesirable unintended consequences.

The Power Systems Architecture (PSA) toolkit advanced through G-PST Stages 1 – 3 of Topic 7 is purpose-built to support holistic grid transformation. The first stage focused on identifying the systems-based tools and methodologies that reflect global best practice. The second stage employed these capabilities to develop a first ever detailed Reference Architecture of Australia's National Electricity Market (NEM). Consistent with Systems Architecture practice illustrated in Figure 16, the most recent third stage has continued to lay the foundation for the Detailed Architecture phase.

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 including AEMO has been a key priority. Consequently, G-PST Stage 3 has actively focused on transitioning from research to an expanding range of applications to demonstrate the practical value of these tools for navigating complex power systems transformation.

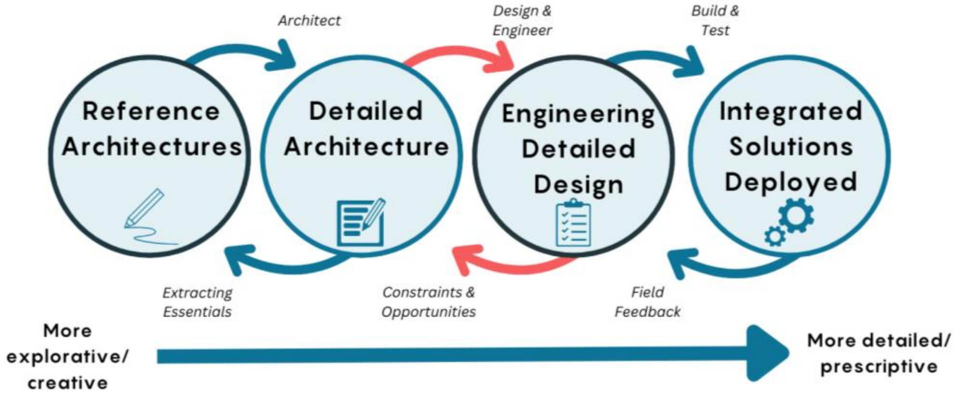


Figure 16: Development process of the power system architecture of Topic 7

Stage 2 focused on developing a detailed set of Reference Architectures of the NEM. Stage 3 has taken these Reference Architectures and instantiated these in a model to enhance the ability to interrogate and collaborate broadly in preparation for a subsequent 'Detailed Architectures' phase. The focus of this year's research has been on the transition of NEM reference architectures and demonstration project architectures into a digital Model Based Systems Engineering (MBSE) environment. It also focuses on stakeholder alignment and process design for the development of a detailed architecture. The workplan progressed to date in key phases of the research is shown in Figure 17.

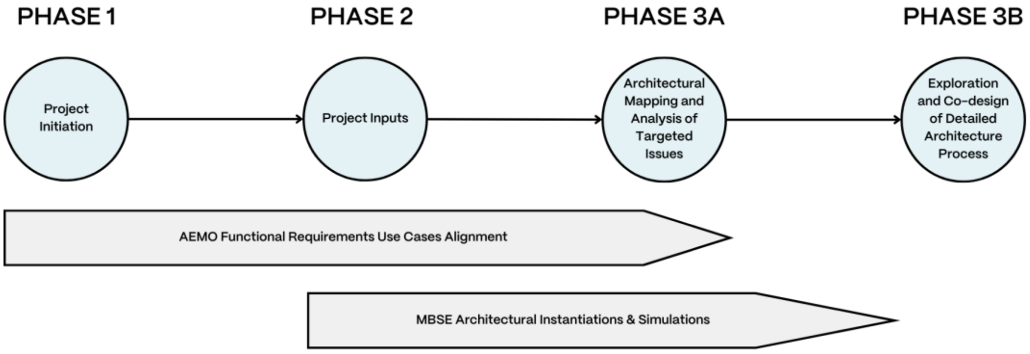


Figure 17: High-level view of Stage 3 workplan

MBSE is an approach to Systems Engineering that employs an integrated digital model to represent the structural and behavioural characteristics of a complex system. It exploits formalised graphical and textual representations from the Systems Modelling Language (SysML) standard. In contrast to traditional paper document-based forms of representation, MBSE empowers diverse stakeholders with powerful visualisations of both current and proposed system structures. Further, it can ultimately provide dynamic visualisations of the operational outcomes arising from the implementation of various change proposals, all derived from a common underlying system model.

Advantages of MBSE are documentation agility, reasoning about structural choices, specificity for interfaces, high-level validation, stakeholder collaboration and alignment, and extensibility. Challenges include a limited existing global 'community of practice', the unique characteristics of power systems, limited precedence for modelling methodology, tool complexity, and sluggish stakeholder acceptance.

EnergyCatalyst applied MBSE to translate the comprehensive set of architectural mappings of the NEM developed in Stage 2 into an advanced digital environment. These have included:

- NEM 'As-built' Reference Architecture; and,
- NEM 'Step Change' Reference Architecture.

Further, the work also completed the first common-format structural mapping of three major recent DER coordination demonstration projects, namely:

- Project EDGE Architecture;
- Project Symphony Architecture; and,
- Project Edith Architecture.

For these demonstration projects EnergyCatalyst used the MBSE tool to create digitally mapped representations of the four interactive structures referred to earlier, namely Electricity Infrastructure (Power Flows), Digital Infrastructure, Operational Coordination Structure, and Transactional Structure. Full graphically formed layers of interactive structure, built by EnergyCatalyst using the Dassault Systems software *CATIA Magic* Product-line for all of the demonstration projects are detailed in the complete research report found on the CSIRO GPST website alongside this summary report. The linked and interdependent blocks of the MBSE model represent actors and processes, and the connections between functional layers succinctly shows the complexity of the interactions that must be understood and mapped to appreciate the behaviour of the system as a whole. Such understanding can allow optimisation, improvements, risk and issues management, and streamlining of complex CER/DER orchestration projects .

In addition to mapping the above three DER coordination demonstration projects, the advanced MBSE tools were also employed to develop common-format structural mappings of the SA Power Networks Emergency DPV curtailment to manage DER during minimum operational demand scenarios to demonstrate significant practical value of the tools for taming complexity and enhancing multi-stakeholder collaboration. The developed MBSE model represents the behavioural characteristics of the EDPVC use case and the associated interactions between system actors, including AEMO, ElectraNet, and SAPN. In the model these are mapped onto a structural diagram to bring to the surface the underpinning architecture. The interactions are also categorised into structure classes across relevant functionally interdependent structures of the NEM Reference Architecture (as per above). Once integrated in this way, a simulation that overlays behaviour on structure can be executed to show the complex interaction of actors and processes.

The researchers reported that through collaborative interactions with various stakeholders, there have been numerous insights gained as existing structural arrangements are made visible and explicit and related architectural trade-offs laid bare. Several key insights are outlined below:

- **Documentation agility:** A key tenet of MBSE is that it provides a holistic ‘single source of truth’ about a given system, and can do so in near real-time.
- **Reasoning about structural choices:** The fidelity of structural analysis of power systems can benefit from a model-based approach as it allows alternate structural configurations to be more efficiently represented using component classes and then simulated in executable models and simulation.
- **Specificity for interfaces:** MBSE can support, and in some cases, automate the documentation of interfaces, demarcations and hand-offs among various system actors across different configurations, and timelines.
- **High-level validation:** An executable model allows for simulation of data flows and exchanges through the end-to-end power system.
- **Stakeholder collaboration and alignment:** Allows to abstract a model commensurate with the level of detail required for a particular cohort of stakeholders.
- **Scalability and extensibility of solutions:** More sophisticated implementations of MBSE could introduce more complex and accurate mathematical proxies for the performance of optimisation algorithms, and centralised and CER/DER fleet dispatch engines.

Stage 3 transitioned the NEM Reference Architectures developed in Stage 2 and developed common-format architectural mappings of Australia’s three large demonstration projects in the digital MBSE environment. Complemented by the end-to-end simulation of the EDPVC Functional Requirement use case, it became clear that the MBSE-based approach can have significant value for promoting a shared understanding of system configuration and credible transformation options.

Stage 3 of the research further developed Phases 2, 4, and 5 of the Topic 7 Research Roadmap developed during Stage 1. The current state of completion of the research following completion of Stage 3 is shown in Table 4.

Table 4: Topic 7 Progress against the Research Roadmap on completion of Stage 3

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress
Phase 1	Explore future system objectives. Identify emerging trends and systemic issues.	• Identify the technical/economic/societal objectives that may plausibly play a key role in shaping power system priorities to 2035 and beyond. • Establish the least regret objectives which would provide optionality for different policy settings. • Examine a diverse range of credible Australian and international studies and scenario planning focused on the 2030-2050 electricity systems futures.	100%

		• Establish the emerging systemic issues that Australia’s GW-scale system must be resilient to, and what the range of impacts arising from these are.	
Phase 2	Document existing architecture and constraints	• Map out the entity relationships across the NEM and WEM that manage control and dispatch of generation and load, system services, regulatory functions, markets, transactions and retail. • Establish the structure of the four foundational architecture layers (out of seven) across the NEM and WEM: Operational control; Market transaction, Information/Data exchange, and power flow. • Identity structural constraints that exist when these layers are overlaid with the entity-relationship map. • Identify which architectural models may have advantages for the Australian context, including transmission-distribution interface design, and DER.	100%
Phase 3	Explore future system qualities, properties and functions	Confirm the key system qualities desired by policymakers and end-users, then establish the system properties and hence system functionalities required to deliver these.	100%
Phase 4	Develop future architectural options	From the outcomes of the previous phases, establish plausible alternatives to the existing entity relationships and interfaces and the functional layers, alternatives that would more effectively support the key desired future system qualities.	50%
Phase 5	Future options and transitions pathways report	Evaluate the combined outcomes of the preceding phases and establish the issues and risks associated with each option, then consider additional issues that must be considered (e.g., resilience, cyber-security).	50%

5 Power System Operation

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.

In Stage 3 of the GPST, research focus has been on the first two topics. The following subsections elaborate the research that has been carried out in each of these two areas, present high level results and the insights drawn from them, as well as recommending future research to continue to develop each of these important fields of power system operation.

5.1 Topic 3: Control room of the future

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. Electricity network operators, in Australia and globally all have common features:

1. The need for operators to process and act on a large quantity of data in real time.
2. The growth of this operational data due to new generation, network technology, markets and interactions with neighbouring or interconnected network operators.
3. The rapidly changing nature of the system that operators are monitoring and controlling due to decarbonisation and electrification.
4. The turnover in knowledgeable, experienced operational staff and difficulties replacing, retaining and training new operators.

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, and potentially increase with increasing complexity and the need to manage a more diverse range of threat vectors. 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 Topic 3 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[11], which recognises the need for continuous development of AI and ML applications for the electricity system control room.

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
    - (b) Task 2: Exploration of Large Language Models (LLM) in the operational context
2. Operational data:
    - (a) Dynamic model validation methodology

Task 1 is characterised through three principal modes of control room operator cognition when trying to solve a problem: Sense Making, Decision Making, and Action Making. The work in Task 1 involves continuation of the Stage 2 research completed in 2023 – but with algorithms directly trained on and applied to real AEMO operational data from a diverse range of operational datasets (Stage 2 was primarily focussed on a synthetic dataset of operational data). 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. Notably, the ability to deploy the prototype is dependent on the maturity and security of the prototype and AEMO IT/OT policies.

Task 2 explores the application of LLM, which can potentially be used to help operators make sense of large quantities of text-based data. This is driven by the fact that the primary feature of operational data in operational technology applications is that they are mostly text based and semi structured. Operator alarm data are classified as semi-structured, as they generally have time stamps and the fields are consistently parameterised but, in some cases, the longer text description is unstructured, truncated and not of a consistent format., in particular the ability to search archive material using prompts could improve operator accuracy and efficiency when diagnosing issues. Hence, the three modes of operator cognition recognised in Task 1 can potentially be augmented and enhance by LLMs. Some other potential use cases for LLM in the CRoF include:

a) Finding patterns in operational and alarm text data.
b) Using filters and query creation using information in voice and text.
c) Search, summarisation, and citation for operational data points from different datasets.

LLMs could be potentially useful and powerful in operations but to date, applications of LLM in operations control rooms are rare and these explorations are very novel. Given this is emerging technology - it was unclear at the outset what could be possible for training and deployment within the stringently secure operational technology environments.

Task 3 explores the achievement of more accurate modelling of our power system. Such models are used to predict system behaviour and limits of operational stability. In the Australian context, for 25 years one of the obligations for connecting to the NEM has required the provision of time domain power system models of the generating systems. These models were then also used by the developers to prove compliance with National Electricity Rules (NER) requirements. A process for validation of the dynamic models was introduced more than 20 years ago. Practically however, the process of validation was difficult to implement and not systematically automated. Due to a lack of relevant large actual disturbances, validation is difficult and was

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[11] AEMO, CSIRO – Operational Technology Roadmap Report 2022 https://aemo.com.au/-/media/files/initiatives/operations-technology-roadmap/executive-summary-report-for-the-otr.pdf

traditionally based on normal operating points, whereas post large disturbances, validation is laborious and reliant on high-speed recording which is not always available in sufficient detail.

As operators push their networks to the boundaries of their stable regions, to accommodate more, smaller, variable, decentralised renewable generation resources, the assumptions for dynamic stability simulations used to define stable operating limits are being challenged in fundamental ways in recent years. Dynamic model inaccuracy puts networks at risk as dynamic security assessments may not detect security issues that require mitigation controls in real time. It also has knock on economic impacts, as dynamic security assessments simulation results may trigger constraints in the market – so if the simulation is not accurate, even including the safety margins - the market may be unnecessarily constrained.

Task 3 involves engaging with modelling subject matter experts in AEMO to assess current model validation processes and activities and to define a methodology for automatically validating dynamic models for use in dynamic simulations using high-speed data recorders.

For Task 1 a ML application with a graphical user interface was developed that includes offline and online processes for evaluation of alarms coming from multiple AEMO data bases, including EMS/SCADA data, EMS state estimator, Operator recorded Electric Power System Operator Control (EPSOC) log, System Market Incident Reporting Kiosk, and the Network Outage System. Input from these multiple sources was combined to create a sandbox environment with 8.8 million alarm records collected during a two-month period.

Once combined and time synchronised, additional context was combined with the datasets. The most efficient and accurate way to achieve this is to work with domain experts (in this case AEMO network operators) to eyeball the data and to explain as clearly as possible what is happening when these data points and correlations emerge. The class of machine learning known as supervised machine learning relies on datasets being pre-labelled with an explanation of what the data represents. This allows a model to be trained on this data where it knows inputs and what the output is. Having a dataset that is labelled allows for comparison of ML models when they are tested. The process of combining on- and off-line data can be pictured as shown in Figure .

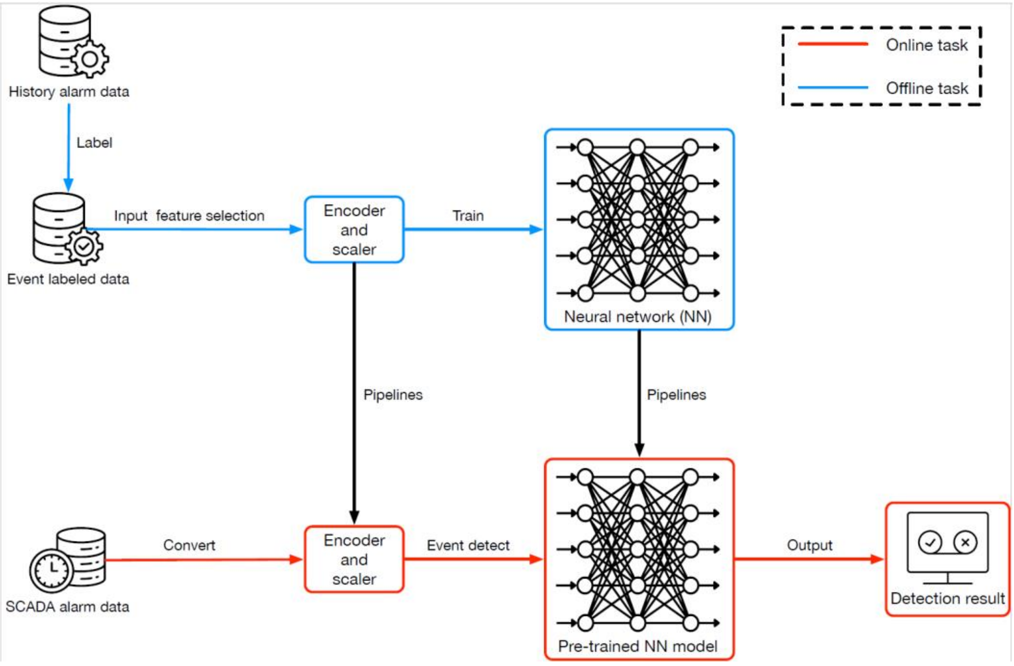


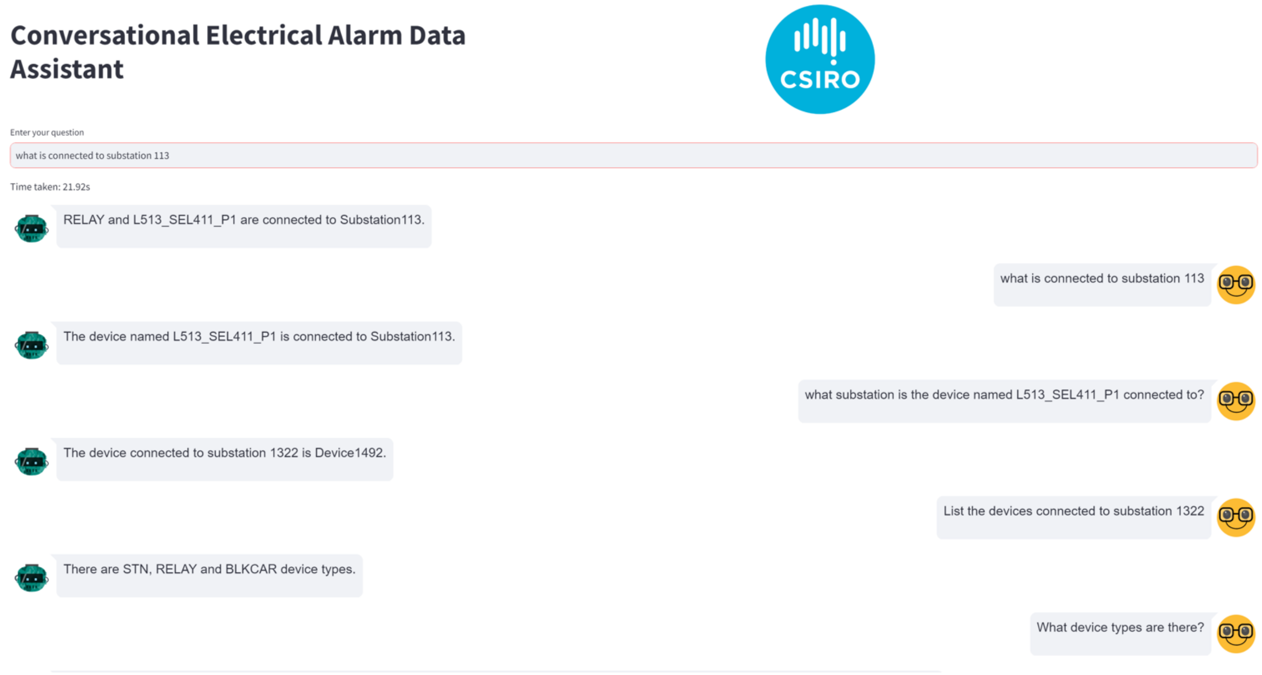
Figure 18: High Level Schematic for the developed ML application showing offline and online processes.

Using the combined and labelled data sets, the offline ML model was able to achieve training accuracy of 93% for the two-month synthetic data sets, identifying events and correlation in alarm data sets. The process was not tested on additional (actual, non-synthetic) operational data (either online or offline) for security reasons.

For the second task the researchers created a working prototype of an application to interact with a synthetic control room alarm dataset via text-based user prompts. The prototype works like commercial LLMs such as *ChatGPT* or *CoPilot* with accurate results from the prompt. This the LLM builds a knowledge graph.

To construct the database, a prompt is engineered that informs the LLM which entities to extract from the data given, and which relationships need to be constructed among these entities. This prompt is run multiple times, once per alarm in the synthetic dataset, and returns the extracted information, which is then parsed into *Cypher* (a database query language) commands.

To allow a user to query this structure - another language prompt is engineered to take the user's plain language query and direct the LLM to reinterpret what the user has asked as a knowledge graph query. In-context learning is used to do this, it works by providing examples of what the desired output might look like as well as context about the database schema (naming schemes used etc). Once a knowledge graph query has been generated by the LLM (from the user's input) it is sent to the knowledge graph. Subsequently, the relevant information contained in the knowledge graph is returned to the LLM which reinterprets it in the context of the user's original question. and provides a plain language answer. An example of the query and responses of the LLM GUI is shown in Figure .



Conversational Electrical Alarm Data Assistant

what is connected to substation 113

Time taken: 21.92s

RELAY and L513_SEL411_P1 are connected to Substation113.

what is connected to substation 113

The device named L513_SEL411_P1 is connected to Substation113.

what substation is the device named L513_SEL411_P1 connected to?

The device connected to substation 1322 is Device1492.

List the devices connected to substation 1322

There are STN, RELAY and BLKCAR device types.

What device types are there?

Figure 19: Multiple prompts and answers to the Alarm Data Assistant developed by the researchers

For the third task the researchers proposed a methodology for automated model validation using operational data. Their proposed framework would use network disturbance data collected using high speed monitoring devices and compare the modelled response against actual network and individual plant performance. Future stages of Topic 3 research aim to explore the testing of the methodology and look for enhancement that may be achievable.

Having completed the described three tasks, the researchers report progress as shown in Table 5.

Table 5: Topic 3 research progress against the Roadmap

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress

CRoF Data models and streaming	Standard approaches to alarm management, asset health monitoring, generation and market participant monitoring.	Task 1: Operational data machine learning use cases	50%
	Control room tools use AI/ML techniques as standard with full archive of operations data for training	Task 2: Exploration of Large Language Models (LLM) in the operational context	25%
	Alignment on operations model standards & requirements, with IEC CIM as cornerstone, especially DER requirements. Widespread use of PMU.	Task 3: Dynamic model validation methodology	15%

For future research areas in Topic 3 CRoF, the researchers believe it may be appropriate to initiate the human factors research actions, which are focussed on decision making, training standardisation, visualisation and developing the capabilities of the future operator. Additional potential research areas to be explored beyond this project are on the ‘facilities and equipment’ research area of the CRoF which focusses on the value of ergonomics and building design to the control room experience and the need for operational readiness centers.

5.2 Topic 5: The role of inverter-based resources during system restoration

For modern power systems, blackouts are thankfully a rare event; the last time a large scale blackout occurred in Australia was in South Australia in 2016 during a once in 50 year weather event, which resulted in electricity network disruptions and power lost to 850, 000 customers, some for up to a week. When such events do occur, the traditional way to reenergise the system and restore electricity supply is to use large synchronous generators to sequentially reenergise the transmission system, while holding system voltages and electrical frequency stable. In the NEM, AEMO contracts restart services in every state (region) from such synchronous generators, to ensure that the electrical network can be restored quickly and efficiently.

As penetration of inverter-based resources (IBRs) increases throughout the NEM, and as existing synchronous coal and gas generators retire, providers of black start and system restart are diminishing. This project investigates the role that IBRs can play in system restart, especially under high or 100% IBR penetration conditions. The Topic 5 research for Stage 3 extends the previous year’s research. Building on the electromagnetic transient models developed and the insights gathered during Stage 2, this year’s research focused on the following matters:

- Investigating the stability boundary conditions of restarted islands that are inclusive of multiple non-black start IBR support devices.
- Analysis of the impact of, and- where possible- reasonable range for, control system parameters of IBR during system restoration.
- Assessment of the impact of the location of black start devices, considering proximity to load centres, synchronous generators, and non-black start IBR.
- Evaluation of the challenges and opportunities with synchronisation of two or more restarted islands, considering both synchronous - and IBR-only - islands during system restoration.

- Observe the impact of distributed energy resources (DER) on the system restart process, with key focus on attempting to determine thresholds for levels of DER for which it is possible to maintain stability during system restart.
- Recommendations on any technical requirements or regulation changes, or otherwise, that should be considered for system restoration under high - or 100% penetration of - IBRs.

To investigate the six aspects of system restoration outlined above, the researcher used the EMT software PSCAD power system model developed in the previous Stage, representing the North Queensland network (**Error! Reference source not found.**). The model includes detailed transmission network elements, vendor specific IBR, and composite load models for the sections of the network involved in a blackstart event.

Figure 20: North Queensland network considered for system restart studies (Source: 2023-27 Powerlink Queensland Revenue Proposal – Map of Powerlink's Transmission Network)

The restart services are provided exclusively by grid forming batteries, while other IBR such as grid following batteries and wind farm were enabled to provide supporting services to represent an IBR dominated system.

Using a North Queensland representative model, the researchers conducted numerous restoration simulation studies, including:

- System restart of islanded networks involving multiple IBR, including transformer energisation and network faults during restarting.
- Blackstart IBR locational sensitivity studies.
- IBR dominated electrical island synchronisation.
- IBR control system parameter sensitivity studies during restart.
- Composite load modelling, including DER.

Key findings across the hundreds of simulations and sensitivities performed were:

- Grid forming (GFM) black start IBR to grid following (GFL) IBR support device ratio of at least 1:10 is recommended as the (GFL) upper limit for system restoration. Increasing the relative proportion of GFL support devices beyond 10 times the GFM capacity is not yet recommended in the absence of case specific studies. The 1:10 ratio was demonstrated as stable for both system restoration and application of a network fault during the restoration process among the scenarios investigated. The 1:10 ratio emphasises that GFM black start IBR can be extremely valuable for supporting system restoration, although energy availability (duration of support) needs to be considered for battery energy storage systems (BESS).
- Voltage and frequency control and protection settings of IBRs are suitable for system restoration without alteration from system normal settings, although adjustment of frequency protection and frequency droop can provide additional benefit to stable restoration. Changes to these settings can be used to optimise the contribution of different devices to frequency management, which is recommended to alleviate GFM black start BESS usage in order to maintain sufficient energy reserves for transient response.

- Inertia and damping characteristics of GFM IBRs should be optimised for system restart conditions. However, typical settings observed under system normal conditions do not present any immediate instability or other concern under system restart conditions.
- Locating GFM black start devices near a synchronous generator facilitates the option for soft energisation of the synchronous generator, provided the GFM device has sufficient headroom, and – for batteries – remaining charge, to supply the required power. This may enable viable system restart scenarios even in cases where the synchronous generator grid-tie transformer is too large for a GFM black start device to energise.
- Synchronisation of two separate restarted islands is viable between both synchronous only and IBR-only islands, with significant but manageable transients observed on synchronisation, but no sustained oscillations or instability present following synchronisation.
- Under- and over-voltages that are observed when energising simulated aggregated DER and load models are driven by the instantaneous connection of the aggregate models. Reconnection 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.
- No control system interactions or network instabilities were observed when connecting DER, although 20% or greater of the aggregated DER was observed to disconnect following a fault. The BESS plants within the system compensated for this behaviour, but BESS energy management will need to be a key focus when managing DER during system restart in future.

Stage 3 of Topic 5 provided solid advancements to the understanding of system restoration using IBR technologies, including opportunities, limitations, and sensitivities. 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. With progress during Stage 3 shown in Table 6, the researchers recommend that future work should focus on modelling of protection relays, network protection schemes, and different control structures and operating modes for IBRs such as static compensator (STATCOM) mode for solar farms and alternative grid-following control implementations.

Table 6: Topic 5 research progress against the Roadmap

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress
Task 1.2	Large scale IBR	Conduct assessment to identify: - What are the boundary conditions for stability of a grid-forming inverter when operating as a black start device and restarting a system? - How do the control system parameters of a grid-forming inverter influence the resilience and stability of a restarted island? - How do grid-forming inverters operating as a black start device interact with other black start devices when synchronising an island to another, already energised, power system?	60%
Task 5.1	Bottom-up restoration	Assess: - Optimal placement of GFMI IBR for system restoration. - The use of various storage technologies as stabilising loads. - Determining whether a re-sequencing or complete avoidance of some restart pathways might be required under high DER conditions. - The coordination of responses of grid-forming black-start IBRs and synchronous generators and condensers during system build up.	60%

		- Complementary use of synchronous condensers and grid-following inverters as black start providers. - Synchronising two or more IBR only power islands.	
Task 4	Technical and regulatory requirements	Investigate the need for new: - Future generator requirements during black starting - Transmission and distribution technical requirements - Power system technical requirements	50%
Task 1.3	Impact of DER	Investigate: - DER stability, in particular with respect to fault ride-through capability during system restoration. This includes investigating the adequacy of system strength in the distribution network during restoration. - Calculating the minimum stabilising load requirements for a region during system restoration as function of time and season, and determining whether any mitigation measures are required. - Mitigation measures to address a reduction in the available load for pick up during early stages of system restoration.	35%

6 Distributed Energy Resources

6.1 Integrating Distributed Energy Resources

As reported by the Clean Energy Council, 2023 saw photovoltaic (PV) installations surpass a total of 20 GW installed capacity in Australia, and is now generating over ten percent of our energy needs[12]. Similarly, it was reported that 57,000 behind the meter batteries were installed in 2023 alone. With AEMO's 2024 ISP stating that the installed capacity of rooftop solar and other behind the meter energy sources is already capable of meeting 48% of underlying energy demand across the NEM in the middle of a sunny day, and a seven-fold projected growth by 2050, there is still much we have to learn to effectively integrate this source of our future energy into our grids.

Despite the large quantity of distributed energy resources (DER) installations, there are still many unknowns about them, including their dynamic behaviour and how they can best be monitored, coordinated, and aggregated. In the past years there have been significant advances through Australian Renewable Energy Agency sponsored projects such as Project Edge[13] and Project Symphony[14], to aid and increase our understanding, modelling and integration of these sources of energy. Yet more work will be required to ensure that the challenges by continued uptake of DER can be met.

The research area of DER Integration includes two projects focusing on research in:

1. Accelerating the implementation of dynamic operating envelopes across Australia
2. DER and Stability, with a focus on analysing and modelling the disturbance responses of DER, Energy Storage systems (ESS), and modern loads.

The following subsections elaborate the research that has been carried out in each of these areas, present results and the insights drawn from them, and recommend future research to continue to develop each of these important fields of power system operation.

6.2 Topic 8: Accelerating the implementation of dynamic operating envelopes across Australia

Australia is leading the world in the adoption of rooftop solar PV with more than one in three houses having PV systems. This and other DERs such as batteries and electric vehicles are creating opportunities to homes and businesses to save or even earn extra money. Savings are achieved by reducing energy bills while extra money can be earned via aggregators, who bundle DERs to participate in the wholesale electricity market run by the Australian Energy Market Operator (AEMO). A challenge, however, is to enable homes and businesses to make the most of their DERs while ensuring the operational integrity of the existing electricity distribution infrastructure (the 'poles and wires').

To tackle this challenge, distribution companies (known as Distribution Network Service Providers [DNSPs]) across Australia are gearing up to offer their customers flexible connection agreements known as operating

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[12] Rooftop solar generates over 10 per cent of Australia's electricity | Clean Energy Council

[13] https://arena.gov.au/projects/project-edge-energy-demand-and-generation-exchange/

[14] https://arena.gov.au/projects/western-australia-distributed-energy-resources-orchestration-pilot/

envelopes (or dynamic operating envelopes); the alternative is constant customer export limits, which are decreasing as more DER is being installed (Figure 21). 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, given that they have different monitoring infrastructures in the distribution network, particularly smart meters and availability of accurate network models. 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.

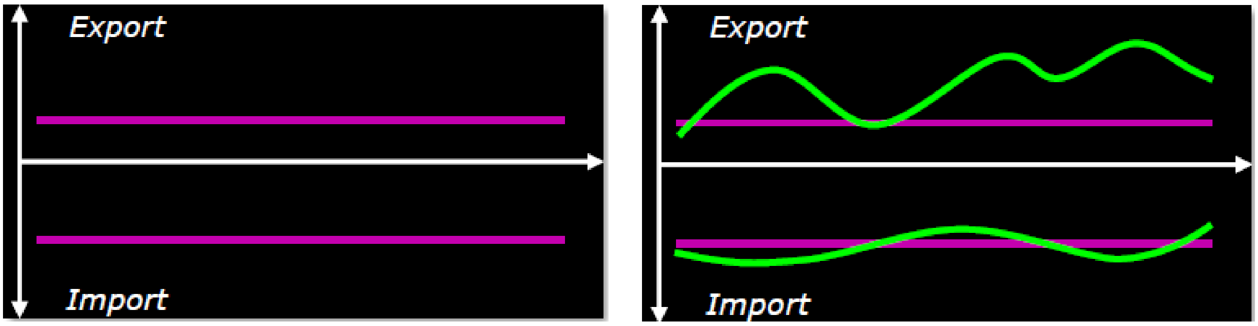

Figure 21: Fixed and flexible operating limits for future DER (operating envelopes) showing DER output limits over time

In this context, the previous Stage 2 Topic 8 project "Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia" carried out by the University of Melbourne, demonstrated that full electrical network models and full monitoring of customers (i.e., 100% smart meter penetration) are not necessarily needed to calculate adequate OEs. Simpler OE implementations that require very limited knowledge of the low voltage (LV) electrical network (to which residential customers are connected to, i.e., 230V line-to-neutral) and very limited monitoring have great potential to be sufficient to solve excessive voltage rise/drop and asset congestion within the LV network, especially at lower quantities of DER capacity.

The Stage 3 research continued the investigations using the four OE implementations – which are the Ideal OE, Asset Capacity OE, Asset Capacity & Critical Voltage OE, and Asset Capacity & Delta Voltage OE – developed in the Stage 2 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.

However, where previously these OEs were applied to individual neighbourhoods, Stage 3 investigated multiple neighbourhoods connected to the same HV feeders (Figure 22). This must take into account the interaction between neighbourhoods that occur in the physical network, such as compounding voltage changes at the HV connection point.

On the first research objective, the researchers concluded that:

- **More accurate OE calculations can be achieved considering both HV and LV aspects** given that it caters for the interactions of multiple LV networks connected to the same HV feeder. This is because the isolated neighbourhood approach does not consider impacts of each individual neighbourhoods (individual LV networks) using OEs on the voltage rise/ drop effects on other neighbourhoods (other LV networks). Further, the isolated neighbourhood approach does not consider the utilisation of HV lines and transformers.

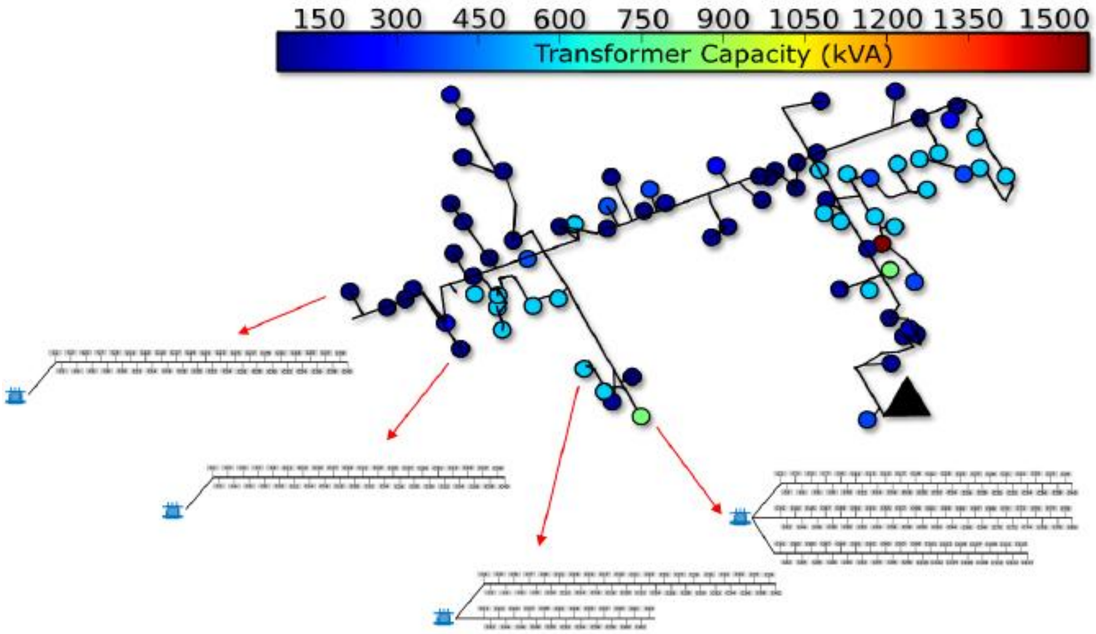

Figure 22: Generic HV-LV network consisting of multiple neighbourhoods

- **The Ideal OE with integrated HV-LV calculation can, as expected, achieve optimal management of technical problems (both voltages and thermal) in integrated HV-LV networks.** In contrast, the Ideal OE with isolated neighbourhood calculation does not avoid voltage problems and it is not capable of avoiding thermal issues on the HV side.
- **The Asset Capacity OE with integrated HV-LV calculation can mitigate thermal problems (lines and transformers) for both HV and LV networks.** In contrast, the Asset Capacity OE with isolated neighbourhood calculation is not capable of avoiding HV thermal issues.
- **The Asset Capacity & Critical Voltage OE with integrated HV-LV calculation can mitigate thermal problems (lines and transformers) for both HV and LV networks and reduce voltage problems.** In contrast, the Asset Capacity & Critical Voltage OE with isolated neighbourhood calculation is not capable of avoiding thermal issues on the HV side. Nevertheless, reduction of voltage problems is the same for both OE calculation approaches.
- **The Asset Capacity & Delta Voltage OE with integrated HV-LV calculation can mitigate thermal problems (lines and transformers) for both HV and LV networks and reduce voltage problems.** In contrast, the Asset Capacity & Delta Voltage OE with isolated neighbourhood calculation is not capable of avoiding thermal issues on the HV side, and it has similar performance on reducing voltage problems.
- **The adoption of any OE implementation** – simplified or advanced – **will allow much more rooftop solar PV generation** if compared to the fixed exports of 1.5kW that DNSPs are likely to offer customers as an alternative to OEs.

On the second objective, the researchers offered some guidance to DNSPs on Data-driven techniques to enhance their electrical modelling processes when determining OEs:

- For the phase grouping of customers, DNSPs can use **clustering techniques such as K-Means or Gaussian Mixture Models** since they do not require prior network information and they are usually faster than other techniques.
- For the topology identification, DNSPs can use **regression-based techniques such as the Multiple Linear Regression as it can handle three-phase unbalanced LV networks.** Such techniques will offer more efficient and accurate models. However, such a technique is likely to require knowledge of phase grouping to improve accuracy.
- For impedance estimation, DNSPs can use **regression techniques such as the Multiple Linear Regression as it can handle three-phase unbalanced LV network**. Such techniques can accurately calculate mutual impedances between conductors while its simplicity and scalability allow for the effective handling of datasets of various sizes and complexities, offering significant advantages. This technique, however, will require knowledge of the phase groups and network topology before estimating impedances to improve accuracy.

Ultimately, DNSPs need to have accurate LV and MV models to make the most efficient use of their network infrastructure. Accurate real-time monitoring of LV networks further requires 100% of smart meter adoption (residential, commercial, and industrial), and, ideally, monitoring at the distribution transformer to capture voltages at the head of the LV feeder. However, if only a fraction of customers has smart meters, DNSPs can still use the simplified OE implementations in parts of the network with low to medium penetration of flexible customers. Meanwhile, DNSPs should prioritise the installation of smart meters in areas with higher penetration of flexible customers (or DER).

Lastly, regarding forecasting techniques the Topic 8 research suggested that:

- For the forecast of LV HoF voltages, DNSPs can use deep learning techniques such as the “Long Short-Term Memory Neural Network Architecture” or the “Encoder Decoder Transformer Architecture”. These are advanced forecast techniques that offer good accuracy, which align well with the requirements for LV HoF voltages due to its large impact on OEs efficacy.
- For the forecast of customers’ active power, DNSPs can use machine learning techniques such as “Random Forest” or “k-Nearest Neighbours” clustering methods. These correspond to simple and effective forecast techniques that offer reasonable accuracy, and which align well with the requirements for customers’ active power due to its reasonable impact on OE efficacy.
- For the forecast of customers’ reactive power, DNSPs can use persistent forecasting techniques. This consists of using the most recent historical data as the forecast, which is sufficient to meet customer requirements due to the limited impact on OE efficacy.

Following the completion of Stage 3, the researchers estimate progress of the Topic 8 Research Roadmap as shown in Table 7. Given the rapid development in the DER space, the researchers further recommend that future focus of Topic 8 be guided towards matters such as:

- Assessing the implications of Australian PV inverter volt-watt and volt-var requirements on the effectiveness of OEs.
- Investigate ways to improve the simplified OE calculations from Stage 3 to avoid voltage violation issues on integrated HV-LV networks.
- Assessment of the performance of OEs considering rural and other urban HV feeders as well as forecast errors.
- How OE can be used to integrate constraints arising from the transmission network.

Table 7: Topic 8 progress during Stage 3

Roadmap Major Tasks	Roadmap Tasks	Stage 3 Tasks	Progress
RQ0.1	What data flows (DER specifications, measurements, forecasts, etc.) are needed to ensure AEMO has enough visibility of DER/net demand to adequately operate a DER-rich system in different time scales (mins to hours)?	Demonstrate that OEs can be quantified across a large area (e.g., a feeder) at the transmission/distribution interface, hence informing AEMO on the extent to which DERs could be utilised by aggregators.	50%
RQ1.3	What is the role of DER standards in concert with the future orchestration of DERs?	Assess the role of inverter standards when used in combination with other DER orchestration techniques. Specifically, the use of volt-watt and volt-var functions with priority to volt-var in order to minimise reactive power flows.	50%
RQ4.1	What are the minimum requirements for a DER-rich distribution network equivalent model to be adequate for its use in system planning studies?	Estimate OEs across a large area (e.g., an HV feeder), to help not only maximise DNSP asset utilisation, but potentially assist AEMO determine the effects of DERs depending on how aggregators use the OEs (fully or partially). This in turn, could help AEMO to develop equivalent models to represent DER-rich distribution networks.	50%
RQ5.1	What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?	Assess the way that OEs calculated by DNSPs will have to consider the limits applied by AEMO at the Transmission-Distribution interface.	50%

6.3 Topic 9: DER and stability

Under Topic 9 - "DER and Stability", the main research focus has been on analysing the reconnection behaviour and analysis of Distributed Energy Resources (DERs), Energy Storage Systems (ESS) and modern loads to ensure system operators can maintain power system security in the current power system operational environment and enhance overall power system security. The work of Stage 3 provides robust, accurate data of the responses of equipment to power system transients based on extensive bench tests using thorough experimental methods. It directly informs the development and use of their composite load model by AEMO and, by extension, other distribution network system providers.

The impetus behind Stage 3 initiatives has been the continuous growth of DER, ESS, and modern loads, along with the need to address untested aspects of the existing DER fleet: specifically, reconnection of systems including point-on-wave (PoW) testing, and the continuation of the tasks from Stage 2. These activities contribute significantly to the enhancement of composite load modelling and the development of more sophisticated load models. These models are designed to accurately represent the responses of DERs, including during grid disturbances, which are crucial for capturing the dynamic behaviour of the modern power system. By improving these models, we can better predict the behaviour of the distribution system as it integrates a growing number of DER and modern electronic loads, supporting more effective planning and operational strategies.

UNSW's and UoW's research during Stage 3 of Topic 9 provide significant insights on DER responses, ESS operation modes, and loads and EVs, predominantly during power system disturbances. The results collected also provide input to the ongoing load modelling activities of AEMO[15]. The ongoing research tasks and activities of Stage 3 (Figure 23) can be summarised as follows:

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[15] https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/operations/der-behaviour-during-disturbances

- **Task 1 – DER and Flexible Load Bench-Testing:** Experimental bench-testing of Distributed Energy Resources (DER) and Energy Storage Systems (ESS) in response to power system transients. It expands previous testing to include Battery ESS (BESS), Hybrid PV and ESS (HESS), Electric Vehicle (EV) charging infrastructure, and various modern inverter-driven loads capable of responding to grid disruptions.
- **Task 2 – Reconnection Testing:** This task entailed the implementation of a test procedure to characterise DER reconnection behaviour, such as reconnection following a system black event or a regional brown out. Additionally, it involved updating the existing models, which previously relied solely on Distributed Energy Resource (DER) disturbance ride-through responses, to incorporate all the new testing outcomes.
- **Task 3 – Point on Wave Testing:** This task involves executing the testing procedure for comprehensive point-on-wave testing, aiming to identify the potential risk of inverter malfunction in response to disturbances occurring at various points along the voltage waveform phase.

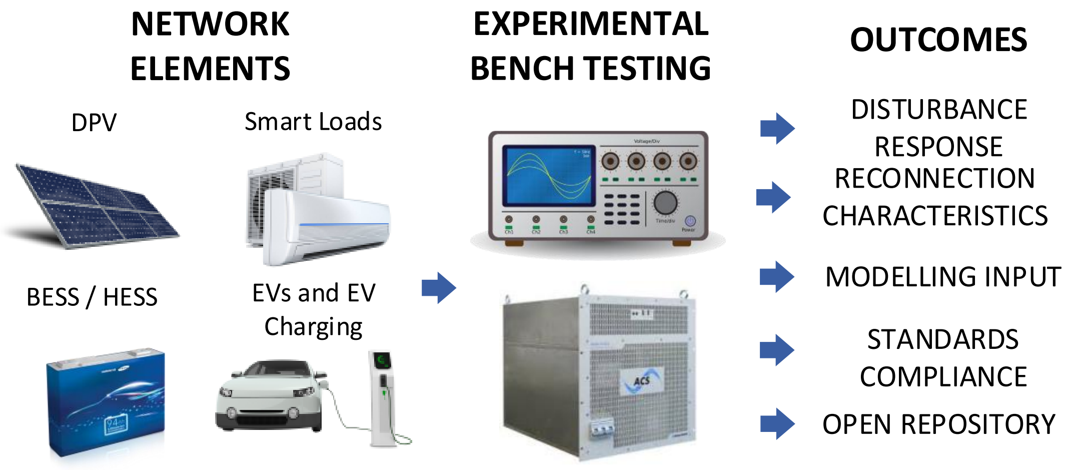

Figure 23: High-level Overview of GPST Stage 3 project for Topic 9

During the Stage 3 research of DER inverter testing, UNSW further streamlined their testing methodologies and investigated the behaviour of one additional solar inverter and seven hybrid systems consisting of solar and storage combined. Based on their tests they concluded that:

- The majority of hybrid inverters tested exhibited ride-through capability during frequency and voltage disturbance tests (including voltage sags, swells, and phase angle jumps) across all operational modes in accordance with AS 4777.2:2020.
- The differences in performance between the BESS and HESS at different power levels indicates a potential need to reassess the AS 4777.2 Standard, particularly the requirement for testing of systems at full power, at which the HESS fared more poorly than the BESS.
- Ongoing collaboration with OEMs has led to firmware and inverter setting improvements. This partnership has also enabled AEMO to request that OEMs implement necessary adjustments to address identified inverter response issues.

An inverter's stability is known to be sensitive to the point on the voltage waveform (PoW) at which a disturbance occurs. The existing inverter standards predominantly focus on evaluating equipment immunity solely during zero-crossing. However, it's crucial to recognise that while the equipment may function appropriately at some specific (phase) points on the wave, it may exhibit different behaviour at others, even when the disturbance magnitudes and durations remain consistent. To investigate this UNSW conducted comprehensive testing on two AS4755:2020 compliant PV inverters to understand the response of inverters to voltage disturbances at different PoWs and verify the impact of PoW on equipment behaviour to an otherwise similar disturbance.

The researchers found that one of the several inverters exhibited three distinct behaviours (ride-through, power curtailment, and disconnection) in response to similar disturbances at different points on the voltage wave. For instance, when subjected to a voltage sag of 0.8 p.u occurring at the zero-crossing, the inverter demonstrated a ride-through response. Conversely, the inverter exhibited power curtailment behaviour when the same disturbance was introduced at PoW 90°. Furthermore, at a phase angle of 120° PoW, the inverter experienced disconnection. Based on this behaviour, the researchers recommended that further testing should be conducted, since by gaining a more complete understanding of these factors, it is possible to develop more effective methods for testing inverter immunity and ensuring that it operates reliably under a wide range of grid conditions.

While the UNSW focus was on DER inverter testing, UoW conducted extensive load modelling, including EVs. Load testing provided some insightful outcomes for the composite load model development by updating the representation of "Motor D" type loads such as found in commercial refrigerator compressors and residential air-conditioning compressors and that are characterised by constant torque load and minimal inertia. Based on the findings, a recommendation has been made to reclassify refrigerators in the "Motor A" category, altering the composition of the "Motor D" loads in AEMO's CMLD. This important update to existing parameters for "Motor D" loads, as determined by testing in Stage 3, is summarised in Table 8.

Table 8: Updates to the parameters of the Motor D following Stage 3 testing

Motor D Parameters	Description	Original	EPRI Latest	AEMO Updated 2024
compPF	Power factor at 1 p.u. voltage	0.71	0.98	1
Vstall	Stall Voltage (p.u.)	0.49	0.45	0.45
Rstall	Stall Resistance (p.u.)	0.143	0.1	0.17
Vrst	Voltage for Restart after stall (p.u.)	0.95	0.95	0.9
Xstall	Stall Reactance (p.u.)	0.143	0.1	0.07
Frst	Fraction Capable of restart (%)	0.1	0.2	0.55
Tth	Heating time constant (s)	15	10	26
Th2t	Temperature where completely tripped (p.u.)	4.59	1.9	1.9

In addition to the review of motor load testing, UoW also tested three EV charging systems. These systems were subjected to preliminary testing during Stage 2, which found that Level 1 (slower GPO connected) and Level 2 (faster, dedicated to EV charging and hardwired) EV chargers[16] exhibit a response to sag disturbances that depends on the specific EV model connected to the charger, as the AC/DC conversion process occurs within the onboard charger of the EV. Extension of testing during this Stage, using the same methodology applied to DER inverters, found that:

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[16] EV charging can be done with AC (alternating current) or DC (direct current) power. Level 1 and Level 2 EV chargers use AC power, while Level 3 EV charging exclusively uses DC power at high, which is why it is also known as DC Fast Charging (DCFC)

- One EV exhibited a varying disconnection time depending on the sag depth.
- One EV exhibited a reconnection pattern with power ramping to half its nominal power, which was not observed for the other EVs.
- One EV demonstrated unpredictable disconnection times for different sag depths, with no correlation with the extremity of the sag.
- One EV occasionally did not fully stop charging following a sag disturbance, but the power dropped to very low levels, prompting questions about categorising these responses into models for a generic EV load.

Given the projected growth of EVs in the future and based on the varied results obtained from testing, UoW highlighted the need for further investigation into the potential network security issues that widespread electrification of such transportation could create.

A key part of Topic 9 and the testing of DER, ESS, loads and EVs is the open and public sharing of the testing results. To reflect these new tests, the project website, which serves as the main repository of our research data, has been updated with new sections available for accessing and downloading test data[17].

The advances achieved by the Topic 9 researchers has progressed the original Research Roadmap for this topic as shown in Table 9.

Table 9: Topic 9 research progress

Roadmap Major Tasks	Stage 3 Tasks	Progress
Load-DER composite load model development	Task 1: DER and Flexible Load Bench-Testing; Motor-D load testing, EV testing. Note that the Motor-D tests were successfully completed during Stage 3.	30%
Inverter responses and sensitivities	Task 2: Reconnection Testing	100%
Inverter benchmarks	Task 3: Point on Wave Testing	20%
Extend AEMO's tool set	Task 1: DER and Flexible Load Bench-Testing; HESS testing Completion is based on the existing systems. Future development will see this area needing to be expanded.	100%
Dynamics of power quality models	Task 1: DER and Flexible Load Bench-Testing; Updated D-Motor load model	25%
Stakeholder engagement	Public data base of inverter test results	80%

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[17] http://pvinverters.ee.unsw.edu.au/

Three years on from the original Topic 9 Roadmap development, some new research paths and potential projects can be also identified as future research directions within or outside of Topic 9:

- Virtual Power Plants (VPPs): Exploration of the potential of VPPs to aggregate and manage the capacities of distributed resources across various locations and the impact of large-scale disturbances to the operational goals of VPPs.
- Resilience and Microgrid Solutions: Deployment of microgrids as a resilient infrastructure solution, focusing on their ability to operate independently of the main grid during outages and integrate various types of renewable energy sources.
- Artificial Intelligence and Grid Management: Development of AI-driven tools to assist to the management of grid operations using data-driven models derived from the extensive tests completed under Stages 2 and 3 of the GPST program.

7 Accelerating the decarbonisation of our electricity system

CSIRO's initiation of the Australian G-PST Research Roadmap began in 2021 with a vision to accelerate the decarbonisation of Australia's energy sector. In collaboration with AEMO and with the support of some of Australia's most capable scientific and engineering institutions, CSIRO published the Roadmap in 2022 as Stage 1 of a long term investment in our energy future. The Roadmap outlines a research pathway that will contribute to power system security during the energy transition while creating jobs, investment opportunities and earning global recognition.

Implementation of the Roadmap during Stage 2 commenced in May 2022, realising many of the highest research priorities identified in the critical areas of power system planning and operation, the integration of DER, and new energy technologies. This Stage 3 report describes the key outcomes and the great progress made over past twelve months in the next phase of research. However, Stage 3, while having yielded many high quality outcomes and generating many invaluable insights, represents only the second step of implementation, and further research will continue to deliver the insights and tools that are necessary to build and operate the power system of the future.

> *"The energy sector is a central contributor to our net-zero future…*
>
> *It accounts for 54 per cent of Australia's emissions and has the most mature range of low emission technology options for immediate and long-term opportunities… The cost of renewable energy is no longer our major challenge – integrating this energy efficiently into our electricity systems is what we need to solve."*
>
> Dr John K Ward, *Research Director, Energy Systems Program, CSIRO*

7.1 Progress to date

Looking back over the past twelve months there has been significant progress in the research that some of Australia's most capable scientific and engineering institutions were invited by CSIRO to deliver. Some of the highlights in the applied research reported by the researchers are presented here to showcase the importance of the investments made and the leadership shown by CSIRO and AEMO in meeting the challenges of our energy transition (Figure 24).

Topic 1

Research has developed and validated a generalised transient stability assessment tool for multi-cluster, multi-inverter-based resource (IBR) networks. This tool demonstrates how accurate stability margin estimates, which are critical for ensuring the resilience of power systems with high penetrations of renewable energy sources, can be calculated efficiently. 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.

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 export limits are key to significantly increase residential solar PV generation when compared to fixed values

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.

Figure 24: Success of the CSIRO G-PST Roadmap in delivering high priority research in critical areas of electricity system planning and operation

Topic 2

To date, research has improved the state of the art in identifying the devices involved in oscillatory modes, using small signal analysis in a large synthetic network based on the NEM footprint. This has been achieved by developing a procedure/framework to estimate the frequency characteristics at any operating point for an IBR, and including the IBR based on these characteristics in small signal analysis. Further, usage of metrics - such as remaining available MVA - have also been established to quickly identify locations with potential stability issues for a range of operating points.

Topic 3

Working closely with AEMO Operations, the Topic 3 researchers have developed a novel prototype application, using machine learning for operational datasets that demonstrates the potential to quickly identify incidents from alarms based on a trained dataset of actual incidents. The prototype application works on real system operator alarm and reporting databases, and the framework can be applied to any electricity operational context with time series alarm data.

Further, the research has led to the development of novel prototype development of a Large Language Model (LLM) application, for querying text-based alarm and operational datasets with prompts. This has been demonstrated as accurate on synthetic operational data and networks. It is not yet operational on real datasets due to data security challenges with LLM, but could be easily applied to real data once security challenges are addressed.

Topic 4

Considering the fast-paced energy transition Australia is experiencing, the two-year research of Topic 4, "Planning", has focused on developing methods, tools and case studies to address long-term uncertainty and the integration of large-scale infrastructure in energy systems, which translates to enhanced decision making in planning. Key outcomes from the research include:

- New flexible planning methods, based on multi-stage stochastic optimisation, to identify the backbone of future network reinforcements, while hedging against risks due to long-term uncertainty and addressing system resilience in transmission expansion.

- Assessment of the impact of flexible technologies in the planning problem, such as distributed energy resources (DER) and hydrogen-related infrastructure under multiple uncertainties, quantifying the potential benefits of a whole-system integration for Australia.
- Various alternative use cases in Australia's east-coast (NEM) power system demonstrate the techno-economic benefits of uncertainty-aware planning compared to deterministic approaches, and illustrate in particular the benefits of flexible technologies in improving decision-making for transmission expansion, aiming for a reliable and affordable low-carbon system.

Topic 5

Investigating system restoration under high or 100% penetration of inverter based resources has concluded that grid-forming battery energy storage systems (BESS) are potentially viable as system restart providers, and could support 100% IBR restart of IBRs that are not inherently black start capable, up to 10 times the MVA rating of the grid-forming black start device. Permitting grid-following BESS black start devices to contribute to system restart ancillary support services (SRAS) in the NEM could greatly expand the potential number of black start providers and potentially offer a range of much cheaper SRAS options.

Topic 7

Through the research completed in the past two years, Power Systems Architecture (PSA) tools have gained industry traction as an enabler of structured grid transformation in Australia. Key examples include:

- The PSA-based tools have been employed to provide key inputs to AEMO's DER/CER Functional Requirements development methodology through 2023/24;
- Similarly, PSA tools were employed by RACE for 2030 to inform the detailed mapping and research gap analysis for almost 200 x DER/CER studies, trials and demonstrations;
- The transition of PSA structural mappings into a digital Model-Based Systems Engineering (MBSE) environment has heightened stakeholder engagement, illustrated the power of process visualisation and enabled multi-stakeholder collaboration on complex system functions; and,
- The PSA tools been applied to provide valued program design inputs to the National CER Roadmap project being led by the Australian Government.

Topic 8

Research has demonstrated that dynamic, flexible export limits are key to significantly increasing residential solar PV generation when compared to static, fixed limits. Furthermore, in the short term, while the adoption of flexible export limits is still modest, can be calculated with limited monitoring and no electrical models without significantly compromising effectiveness. In the meantime, distribution companies must increase monitoring and implement electrical models (or alternatives) to improve such calculations for higher adoption of flexible export limits.

The research has led to broad industry collaboration and engagement on the subject, with UoM working with utilities and other organisations to advance the research.

Topic 9

UNSW and UoW have been working closely with AEMO to undertake inverter and load testing that has been used directly by the system operator to develop advanced load models. This has been achieved through:

- Extensive bench-testing of Distributed Energy Systems, Energy Storage Systems, and loads, resulted in revisions and improvements of load parameters in composite load models, following from previous work which led to revision of the DER model.

- Comprehensive reconnection and point-on-wave tests provided critical insights into inverter behaviours during grid disturbances, and during the recovery process with valuable insights to support system reliability.
- Testing on EVs and EV charging infrastructure highlighted diverse responses to voltage sags, and relations between chargers and EVs connected to chargers, underscoring the need for further tests - especially if EVs play a greater role for ensuring future grid stability.
- Collaboration with OEMs resulted in significant firmware updates following unexpected behaviours and compliance improvements for inverters connected to Australian networks.
- Integration of detailed bench testing results into comprehensive load models improved modelling accuracy, supporting AEMO’s planning and operational activities.
- Insights into load responses to grid disturbances led to the identification of behaviours not currently captured in RMS models, informing the development of more accurate EMT models.
- Our updated project website includes new sections on bench testing, load responses, and reconnection responses, representing the largest open repository of DER and load responses to system disturbances.

The highlights above reflect some of the highest priority research tasks identified in each area of the CSIRO roadmap. While many have scopes of research that extend over three or more years, the fact is that on completion of this Stage 3 many tangible outcomes have been realised already. As outlined in Sections 3 to 6, some research tasks are already complete, with many others close to completion. However, as technology and operational circumstances change, the Roadmap will have to adapt, and a key focus of the next stage of research is to review the Roadmap developed during 2021 and to ensure that it is still addressing the highest priorities.

7.2 Open source information

The full research reports of all of the topics are publicly available on the CSIRO website. Similarly, all of the non-confidential data, tools, and processes used by the researchers are made available on either the CSIRO website or the researchers’ own. This information is shared to allow others to replicate and expand on the research supported by CSIRO and accelerate positive outcomes that will support the energy transition, globally.

CSIRO:

- CSIRO G-PST website, including Stage 1 Roadmap and reports from subsequent stages: https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap

UNSW:

- http://pvinverters.ee.unsw.edu.au/

UoM:

- Ideal OE: https://github.com/Team-Nando/OE1-Ideal_Integrated_MV-LV_Calculation
- Asset Capacity OE: https://github.com/Team-Nando/OE2-Asset_Capacity_Integrated_MV-LV_Calculation
- Asset Capacity & Critical Voltage OE: https://github.com/Team-Nando/OE3-Asset_Capacity_Critical_V_Integrated_MV-LV_Calculation

- Asset Capacity & Delta Voltage OE: https://github.com/Team-Nando/OE4-Asset_Capacity_Delta_V_Integrated_MV-LV_Calculation

In addition to the final Stage 3 reports by each of the research groups, there are several academic and technical papers that were published, or are undergoing review, that describe further detail the theories and outcomes of the research topics. A selection of these are shown below, with further details to be made available on the CSIRO G-PST website:

- Nabil Mohammed, Weihua Zhou, Deepak Ramasubramanian, Behrooz Bahrani, Sudipta Dutta, and Mobolaji Bello, “Data-driven Estimation of Impedance of Inverter-based Resources for Efficient Stability Evaluation, " *[under preparation]*
- Sudipta Dutta, Deepak Ramasubramanian, Mobolaji Bello, Weihua Zhou, Nabil Mohammed, and Behrooz Bahrani, “Analytical Methods for Determination of Stable Operation of IBRs in Future Power System, " 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024, pp. 1-5Jaleel Mesbah, Jingzhe Xu, Weihua Zhou, Behrooz Bahrani, Sushrut Thakar, Stavros Konstantinopoulos, Deepak Ramasubramanian, Mobolaji Bello, “Efficient Prediction of Admittance of Inverter-Based Resources Across Operating Points: A Comprehensive Test, " 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024, pp. 1-5
- Sebastián Püschel-Løvengreen, Sleiman Mhanna, Pierluigi Mancarella, , “Flexible Power System Planning Under Deep Uncertainty” : https://cse.cigre.org/cse-n031/flexible-planning-of-low-carbon-power-systems-under-deep-uncertainty.html
- Pablo Apablaza, Sebastián Püschel-Løvengreen, Rodrigo Moreno, Sleiman Mhanna, Pierluigi Mancarella, “Assessing the impact of DER on the expansion of low-carbon power systems under deep uncertainty”, *Electric Power Systems Research*, Volume 235, 2024, 110824, ISSN 0378-7796, https://doi.org/10.1016/j.epsr.2024.110824

8 Future Research

8.1 Next steps: Priority research tasks

With the completion of the Stage 3 research, Stage 4 is about to commence. Stage 4 will involve continuation of the Research Roadmap and the research undertaken in Stage 3, taking into consideration the evolving technologies and changing priorities in the power sector.

As part of the Stage 3 works, researchers were asked to review the Research Roadmap and consider whether there were any changes necessary to the tasks and goals to keep up to date with contemporary the technology and priorities. This is necessary as the Research Roadmap aims to address the most critical and highest priority research in the Australian power sector.

As the research topics outlined in the Research Roadmap are long term investments, the research being undertaken in Stage 4 will continue to contribute to accelerating the decarbonisation of the energy sector and ensuring reliability, security, and affordability, as we transition to a 100% renewable energy grid.

This report has provided a summary of the second year of research investment, the third stage of the Roadmap. The researchers of the Stage 3 projects submitted an interim report in December 2023, in which they were asked to recommend suitable future research focus areas, based on their progress and insights gained through their research.

Stage 4 continues research in the four identified broad areas and nine research topics, including some of the priority projects outlined in the following sections.

8.1.1 Transient stability enhancements of IBR dominated grids (Topic 1)

Recommendations for future research focus on further enhancing grid-forming inverter technologies and exploring new methods to improve grid stability. Emphasis is placed on real-world implementation and extended field testing to validate theoretical findings and adapt strategies to evolving grid demands.

The following research activities are recommended for the 2024/25 program. The recommendations are made based on CSIRO Australian Research Plan for the G-PST, Task 1 – Inverter Design – Final Report, 2024:

1. Investigation of the transient stability of the GFMIs under various fault profiles and system conditions
2. Expanding transient stability analysis under various fault profiles and system conditions to larger networks and topologies.

8.1.2 Analytical methods for stability assessment of future power systems (Topic 2)

While this first year of research has made significant inroads to the development of tools and methods to enhance the ability of planners and operators to manage a power system with increasing IBR, further work remains. In their conclusion, the researchers recommend that subsequent stages of research should:

1. further enhance the admittance estimation algorithm to include more IBR control system configurations;
2. retest the small signal stability framework against an actual utility network;
3. investigate the use of positive sequence models to obtain frequency scans currently obtained using computationally burdensome time domain simulations;

4. expand the assessment of the current limiting response of GFL and GFM IBR, considering different operating modes;
5. conduct a comparison of using a multiple-frequency network equivalent rather than a fundamental frequency only network equivalent (used in Stage 3), for a large network such as the synthetic NEM network; and
6. expand the assessment of load impacts on small signal stability by including dynamic composite load models; and
7. involve inverter manufacturers and commercial software vendors, to assist in streamlining the process of industry adoption of small signal stability assessment.

8.1.3 Control room of the future (Topic 3)

For future research areas in Topic 3 CRoF, the researchers believe it may be appropriate to initiate the human factors research actions, which are focussed on decision making, training standardisation, visualisation and developing the capabilities of the future operator. Additional potential research areas to be explored beyond this project are on the ‘facilities and equipment’ research area which focusses on the value of ergonomics and building design to the control room experience and the need for operational readiness centres. Additionally, opportunities to apply AI/ML techniques for intelligent alarm management will continue to be explored.

8.1.4 Power system planning and development (Topic 4)

Based on the analysis to date and the interim results obtained in the current project, the researchers recommend focusing on the following activities from the original research plan:

1. Deep dive into the modelling and assessment of integrating distribution and transmission network planning within the expansion planning process (R4S2P3, R4S3P1, R5S2P1, R5S3P1).
2. Analyse the potential economic and operational benefits of better integrating gas and electricity infrastructure planning through hybrid electricity-hydrogen energy hubs (R3S3P3, R5S1P1).
3. Leverage advanced mathematical algorithms to optimise computational efficiency and enhance the performance of long-term planning frameworks (R2S1P1).

8.1.5 Power system restoration (Topic 5)

Stage 3 of Topic 5 provided solid advancements to understanding system restoration using IBR technologies, including opportunities, limitations, and sensitivities. 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. With the completion of Stage 3, the researchers recommend that future work should focus on modelling of protection relays, network protection schemes, and various control structures and operating modes for IBRs - such as a static compensator (STATCOM) mode for solar farms and various grid-following control implementations. This will allow better understanding of the restoration of the power system using future technologies and allow outcomes to potentially influence the development pathway of critical technology and update of relevant policies and procedures.

8.1.6 Power System Architecture (Topic 7)

Following completion of the architectural structure design and evaluation of implementing MBSE for the complex interactions among layers within the power system architecture, the researchers recommend that the next stage of Topic 7 should focus on

- Project governance & stakeholder engagement.
- Socialising the PSA concepts through the development of detailed Stakeholder briefing materials and stakeholder alignment workshops.
- More detailed mapping of the PSA structures and interactions through workshopping of functions, relationships & interfaces.

8.1.7 Dynamic Operating Envelopes (Topic 8)

Based on the work done so far (Stages 2 and 3) and the revised roadmap, below are listed research areas that should be addressed in the near future, which were not included in the original Australian Research Plan for Topic 8 "Distributed Energy Resources".

1. With the increasing adoption of OEs across Australia, assessing the implications of Australian PV inverter volt-watt and volt-var requirements on the effectiveness of OEs is becoming very important to DNSPs. This task falls under RQ1.3, which regards how DER standards work with DER orchestration.
2. With the increasing adoption of OEs across Australia while network models and monitoring are still limited, simplified OE calculations (such as the ones developed for Stage 3) are of great interest to DNSPs. So, it is important to investigate ways to improve the simplified OE calculations from Stage 3 to avoid voltage violation on integrated HV-LV networks. This research task falls under RQ1.2, which regards the most adequate decision-making algorithms to control DER.
3. With the increasing adoption of OEs across Australia, it is becoming very important to DNSPs to properly assess the performance of OEs while comparing rural and other urban HV feeders, as well as considering the impact of forecast errors. This This research task falls under RQ1.2, which regards the most adequate decision-making algorithms to control DER.
4. With the various ways to calculate OEs, aspects of fairness should be explored. This research task falls under RQ1.2, which regards the most adequate decision-making algorithms to control DER.
5. The import component of OEs is becoming increasingly relevant. In practice, imposing a limit on imports is less easy since it is not always possible to reduce demand. Therefore, more studies are required. This task falls under RQ1.2, which considers the most adequate decision-making algorithms to control DER.
6. Another topic that could be explored is how OE can be incorporate constraints from the transmission network (as identified by AEMO). This task again falls under RQ1.2:the most adequate decision-making algorithms to control DER.

8.1.8 DER and stability (Topic 9)

Three years on from the original Topic 9 Roadmap development, some new research paths and potential projects can be also identified as future directions within or outside of Topic 9:

1. Virtual Power Plants (VPPs): Exploration of the potential of VPPs to aggregate and manage the capacities of distributed resources across various locations and the impact of large-scale disturbances to the operational goals of VPPs.

2. Resilience and Microgrid Solutions: Deployment of microgrids as a resilient infrastructure solution, focusing on their ability to operate independently of the main grid during outages and to integrate various types of renewable energy sources.
3. Artificial Intelligence and Grid Management: Development of AI-driven tools to assist to the management of grid operations, using data-driven models derived from the extensive tests completed under Stages 2 and 3 of the GPST program.

8.2 Getting involved

The CSIRO Australian G-PST Research Roadmap is a multi-year and multi-disciplinary program. It envisages energy sector research that provides an opportunity to engineering organisations, research institutes, universities, and others, to be involved and to contribute, or to learn from the research conducted and insights provided.

The first three stages of the Roadmap have now been successfully completed and have:

- Established a research pathway to help Australia's energy transition for the benefit of all consumers.
- Initiated high priority research tasks critical to the success of our energy security.
- Completed critical tasks of research to support he system operator and industry in negotiating the energy transition

There is a substantial body of work still ahead, and although expressions of interest for Stage 4 closed in May 2024, the program is expected to continue to provide critical energy research to assist the Australian (and global) energy transition and to provide tangible benefits to electricity consumers in the years to come.

To ensure the ongoing success of the CSIRO G-PST Research Roadmap, CSIRO welcomes feedback from research organisations, equipment manufacturers, policy makers, system operators, and other stakeholders on the program and its insights, as well as engaging with interested parties to explore future research opportunities and pilot projects of completed research. To get in contact, visit the CSIRO G-PST website: https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap.

9 The power system research ecosystem

The work completed under the CSIRO funded G-PST Research Roadmap does not exist in isolation. There are several other key research programs underway that add to the knowledge base of assisting our energy transition. Three such Australian programs, also closely linked to the CSIRO Research Roadmap, are:

- the AEMO Engineering Roadmap to 100% Renewables[18] and
- the AEMO Operations Technology Program (OTP).
- The National Consumer Energy Resource (CER) Roadmap – Powering Decarbonised Homes and Communities[19].

The first two initiatives were pioneered by AEMO, and with contribution from CSIRO, share much in their research focus areas.

AEMO's Engineering Roadmap to 100% Renewables is a holistic structure of operational, technical, and engineering, requirements that will be needed to prepare the NEM power system for the many changes that the energy transition brings, including operation at 100% penetration of renewable energy. The program was originally launched in 2019 with the publication of the Renewable Integration Study[20] and was later broadened into the Engineering Framework, and in December 2022 to the Engineering Roadmap to 100% Renewables. It is an ongoing and collaborative undertaking that connects particularly to Topic 7 of the CSIRO Research Roadmap, but also many of the other initiatives.

As explained on AEMO's webpage for the OTR:

"In late 2021, AEMO and Commonwealth Scientific and Industrial Research Organisation (CSIRO) engaged EPRI (Electric Power Research Institute) and a team of consultants from Strategen, GridOptimize and Hoffman Power Consulting to work with a dedicated AEMO National Electricity Market (NEM) and Wholesale Electricity Market (WEM) project team to develop an Operations Technology Roadmap (OTR) for AEMO.

…The Operations Technology Roadmap identifies the system operations capability needs to enable this transformative change while maintaining electricity system reliability, security and resilience."

The OTR and the G-PST Research Roadmap are therefore also closely linked through their focus on operations technology, which is reflected in Topic 3 of CSIRO's research – Control Room of the Future. The OTR builds on the work prepared in the creation of the CSIRO Research Roadmap and is tied to ongoing AEMO initiatives, including the Engineering Framework.

When the research areas of each are juxtaposed, apparent links are easily observed (Figure 25). CSIRO and AEMO having a common focus is the driver for continued and close cooperation on these important topics, a collaboration envisaged to endure over the lifetime of these projects.

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[18] https://aemo.com.au/en/initiatives/major-programs/engineering-framework

[19] https://www.energy.gov.au/sites/default/files/2024-03/ECMC%20Communique%201%20March%202024.docx

[20] https://aemo.com.au/energy-systems/major-publications/renewable-integration-study-ris

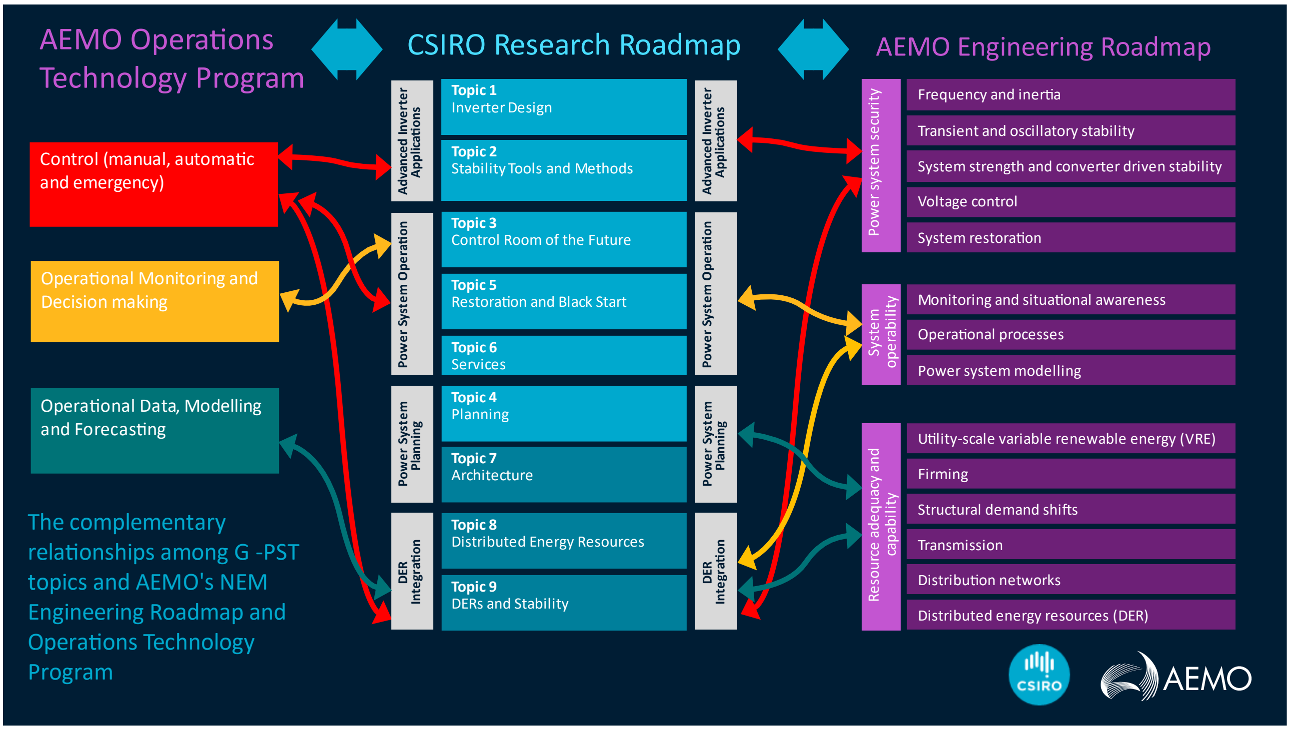

Figure 25: Alignment of the CSIRO Research Roadmap and AEMO's Operations Technology Roadmap and the Engineering Framework

The National CER Roadmap announced by the Energy and Climate Change Ministerial Council will become a blueprint for unlocking consumer benefits of locally created and stored power, and for driving positive outcomes for all consumers. Research such as that underway through Topic 7 will provide invaluable input for this important initiative.

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

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