Australia's National
Science Agency

Stage 2 Research Program Summary Report

for Australia's Global Power System Transformation Research Roadmap

July 2023

Energy Business Unit

Citation

CSIRO (2023) Stage 2 Research Program Summary Report for Australia's Global Power System Transformation (G-PST) Research Roadmap. CSIRO, Australia.

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Acronym glossary

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

Acknowledgments

The work summarised in this report would not have been possible without the funding and technical guidance and oversight of the Commonwealth Scientific and Industrial Research Organisation. Similarly, the contributions and guidance of the Australian Energy Market Operator have been invaluable. We would especially like to thank GHD Pty Ltd, especially Christian Schaefer and Berk Bakici, for their support in project coordination and preparing this summary report.

Acknowledgement of project partners

This report summarises and provides insights into Australia's G-PST research roadmap. We would like to thank all the partners for their efforts in implementing the nine research plans:

- Monash University (with EPRI and the University of Sydney) for Topic 1 - *Inverter Design* (Si Phu Me, Mohammad Hasan Ravanji, Bruno Leonardi, Nazila Rajaei, Deepak Ramasubramanian, Jin Ma, Behrooz Bahrani), and
  - Topic 6 – *Services* (Hassan Haes Alhelou, Behrooz Bahrani, Jin Ma, David J. Hill),
- EPRI (with Monash University) for Topic 2 - *Stability Tools and Methods* (Sudipta Dutta, Weihua Zhou, Nabil Mohammed, Behrooz Bahrani, Mobolaji Bello, Deepak Ramasubramanian), and
  - (with the Royal Melbourne Institute of Technology and AEMO) Topic 3 - *Control Room of Future* (Adrian Kelly, Mobolaji Bello, Xinghuo Yu, Chen Liu, Geordie Dalzell, Elena Kranz),
- The University of Melbourne (with EPRI) for Topic 4 - *Planning* (Sebastian Püschel-Løvengreen, Sleiman Mhanna, Pablo Apablaza, Pierluigi Mancarella, Jesse Bukenberger, Miguel Ortega-Vazquez), and
  - Topic 8 - *Distributed Energy Resources (DER) Orchestration*, (Luis [Nando] Ochoa, Arthur Gonçalves Givisiez, Michael Z. Liu, Vincenzo Bassi),
- Aurecon for Topic 5 - *Restoration and Black Start* (Nathan Crooks, Babak Badrzadeh),
- Strategen for Topic 7 – *Architecture* (Mark Paterson, Jeffrey Taft, Matthew Bird, Thomas Prisk, Gabriel Bohnen, Archie Chapman, Stephen Wilson), and
- The University of NSW (with the University of Wollongong and AEMO) for Topic 9 - *DERs and Stability* (Georgios Konstantinou, Awais Ahmad, Obaidur Rahman, Sean Elphick, Duane Robinson, John Fletcher, Jenny Riesz, Pat Graham).

We would also like to thank AEMO for their partnership and support under the G-PST consortium, especially Luke Robinson for his efforts in the project coordination, and acknowledge John Ward, Brian Liu, Chris Knight, and Thomas Brinsmead from CSIRO for project coordination efforts.

Thanks also to AEMO and CSIRO topic and report reviewers: Emad Areed, Saliw Cleto, Chris Davies, Ehsan Farahani, Rama Ganguli, Natalia Kostecki, Shihanur Rahman, Jay Ramamurthy, Jenny Riesz, Karin Rodrigues, Tjaart van der Walt, Jose Viada Galvez, and Jane Yu (AEMO), Mahathir Almashor, Alireza Barzegar, Julio Braslavsky, Rahmat Heidari, Nariman Mahdavi Mazdeh, and Ghulam Mohy Ud Din (CSIRO).

Executive summary

Many of the world's power systems are rapidly becoming more decentralised, digitised, and renewable. The rapid uptake of wind, solar, and other renewable energy sources, coupled with the retirement and withdrawal of conventional carbon intense forms of power generation, as well as the adaption of new technology, sector coupling, and proactive consumerism of are creating challenges in many areas of our energy sector.

To support Australia in meeting these challenges, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) published the 2022 *Australian Research Planning for Global Power Systems Transformation*[1] (the Research Roadmap) – a bold vision to accelerate solutions that will enable our power grid to run on 100% renewable energy. That Research Roadmap has now been put into action.

There are many areas of power system design and operation where system operators are now experiencing challenges. The Research Roadmap activities represent nine specific research topics that many system operators consider are most critical to resolve (Figure 1).

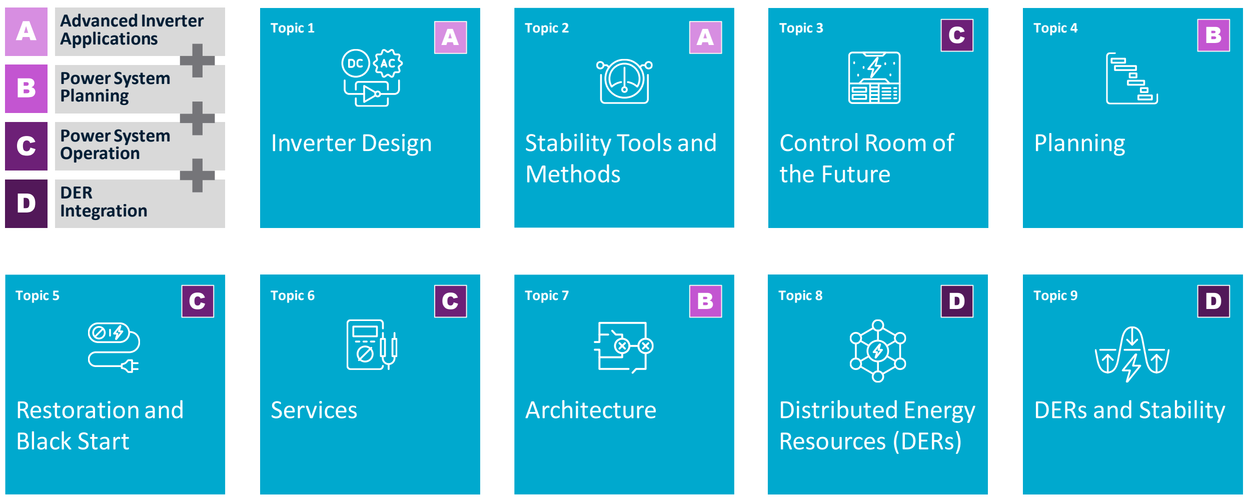

Figure 1: Research areas of the CSIRO Australian G-PST Research Roadmap

During FY2023, this first year of implementation of the Research Roadmap, a selection of Australia's brightest minds have contributed their expertise to designing power systems for the future, as part of this CSIRO funded initiative:

- Topic 1 (Monash University) – Inverter Design: Development of capabilities, services, design methodologies and standards for inverter-based resources (IBRs) such as wind and solar generation, and batteries.
- Topic 2 (Electric Power Research Institute) – 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.

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

- Topic 3 (Electric Power Research Institute) – 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 (University of Melbourne) – Planning: New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix.
- Topic 5 (Aurecon) – Black start and restoration: Creating new procedures for black starting and restoring a power system with high or 100% IBR penetrations.
- Topic 6 (Monash University) – Services: developing new techniques and models to manage frequency control in transitioning power systems.
- Topic 7 (Strategen) – Power System Architecture: Conceptualise and develop an overarching power system architecture that brings together critical layers of power system development
- Topic 8 (University of Melbourne) – 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 (University of New South Wales and University of Wollongong) – Distributed Energy Resources (DER) and stability: Development of mathematical models for composite loads, Distributed Photovoltaic, and DER from laboratory testing suitable for all forms of power system analysis, including dynamic and electromagnetic transient simulations.

This 2023 report presents the outcomes and insights of the first year of implementing the CSIRO Australian G-PST Research Roadmap, summarising the findings from each of the nine topics.

1 Introduction

1.1 Overview

CSIRO's *Australian Research Planning for Global Power Systems Transformation* (i.e. the Research Roadmap) – a bold vision to accelerate solutions that will enable our power grid to run on 100% renewable energy and published in 2022[2] – has been put into action.

A selection of Australia's brightest minds are contributing their expertise to designing power systems for the future around the world, as part of the Global Power System Transformation (G-PST).

This report presents the outcomes and insights of the first year of implementing the Research Roadmap.

Australia has its own unique challenges in managing our energy transition compared to other countries, driven in part by the rapid uptake of rooftop solar panels, the largest uptake of any country in the world. The Australian roadmap ensures these unique challenges will be addressed to remove potential roadblocks from preventing the necessary transformation in the electricity system.

This report presents a summary of both the work carried out over the past 12 months, directed by CSIRO, and the findings. Further details of each of the sponsored projects can be found on the CSIRO G-PST website alongside the Research Roadmap.

The Research Roadmap is a long-term plan for supporting Australia's energy transition and this 2023 summary report includes an agenda for the next steps and the ongoing research needed, as well as how interested organisations can become involved.

1.2 Global Power System Transformation

The Global Power System Transformation initiative and consortium[3] was founded in 2019 by the system operators of six of the fastest decarbonising energy systems in the world, located in Australia, Ireland, Great Britain, the USA (California and Texas) and Denmark. Supported by some of the most innovative and thought leading research organisations, the G-PST's objective is to accelerate solutions to enable grids across the world to run on 100% renewable energy (Figure 2).

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

[3] https://globalpst.org

Figure 2: Founding System Operators and Research organisations of the G-PST Consortium [from https://globalpst.org]

G-PST is not a single organisation, but rather a group that convenes energy sector expertise across a global network of system operators, research institutions, utilities, and manufacturers. The work of the consortium is divided into five pillars with a focus on each of 1) research, 2) knowledge sharing, 3) workforce development, 4) technology standardisation, and 5) open data (Figure 3).

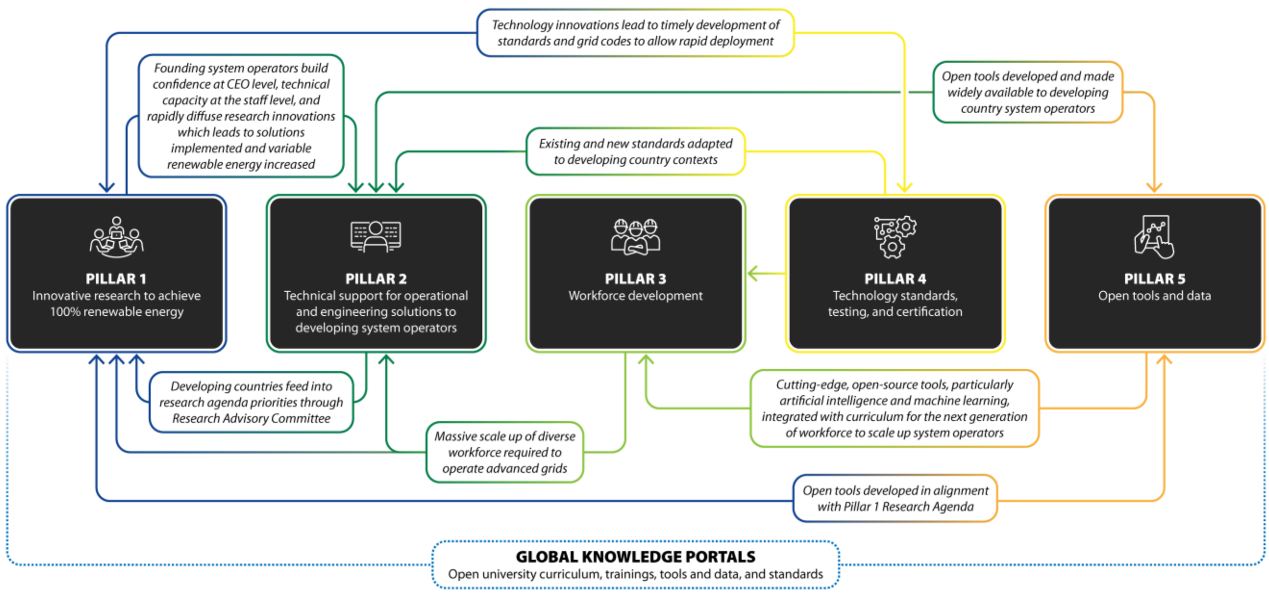

Figure 3: The five G-PST Consortium pillars that inform one another to create an ecosystem of support for power system operators [from https://globalpst.org]

Each of the pillars has a specific goal that is supported by activities in other pillars:

- 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 developing country system operators.
- 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 the standards development activities and testing programs.
- Pillar 5 – Open Data & Tools: Open data and tools to support rigorous planning, operational analysis, and enhanced real-time system monitoring .

1.3 Supporting the Energy Transition

Many of the world's power systems are rapidly becoming more decentralised, digitised, and renewable. The rapid uptake of wind, solar, and other renewable energy sources, coupled with the retirement and withdrawal of conventional carbon intense forms of power generation, as well as the adaption of new technology, sector coupling, and proactive consumerism of are creating challenges in many areas of our energy sector.

The global energy crisis, which began in 2021 during the course of the COVID-19 pandemic, triggered unprecedented momentum behind renewables, with the world set to add as much renewable power in the next 5 years as it has in the past 20[4].

For example, energy security concerns caused by Russia's invasion of Ukraine have motivated countries to increasingly turn to renewables to reduce reliance on imported fossil fuels, showing how quickly government policy can change.

Concurrently, record high prices in the energy spot market caused by global shortages of coal and gas supplies are contributing to increased energy poverty in Australia[5]. Energy poverty occurs when energy bills represent a high percentage of consumers' incomes, or when they must reduce household energy consumption to a degree that negatively impacts their health and well-being.

Hence, changes to global power system designs are urgently required, both to reduce the cost of energy and to keep pace with the rapid increase in renewable energy, which plays a significant part in alleviating these security and fuel cost issues.

There are many areas of power system design and operation where system operators are now experiencing challenges. The G-PST Pillar 1 activities initially included six specific research topics that the founding system operators considered most critical to resolve. These initial six 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.

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4 https://www.iea.org/news/renewable-power-s-growth-is-being-turbocharged-as-countries-seek-to-strengthen-energy-security

5 https://www.abc.net.au/news/2022-12-01/australian-energy-crisis-widens-divide-between-rich-and-poor/101718038

- Topic 6 – Services: developing new techniques and models to manage frequency control in transitioning power systems.

In Australia there are additional challenges that present themselves to the system operator in managing our energy transition. These are driven by the rapid and ongoing uptake of rooftop solar photovoltaics and other distributed energy resources. To address these additional challenges there are a further three topics that have been included in the Australian contributions to the G-PST objective:

- 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 from 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 of power system research (Figure 4):

A. Advanced inverter applications, covering aspects from inverter control system development to development 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.

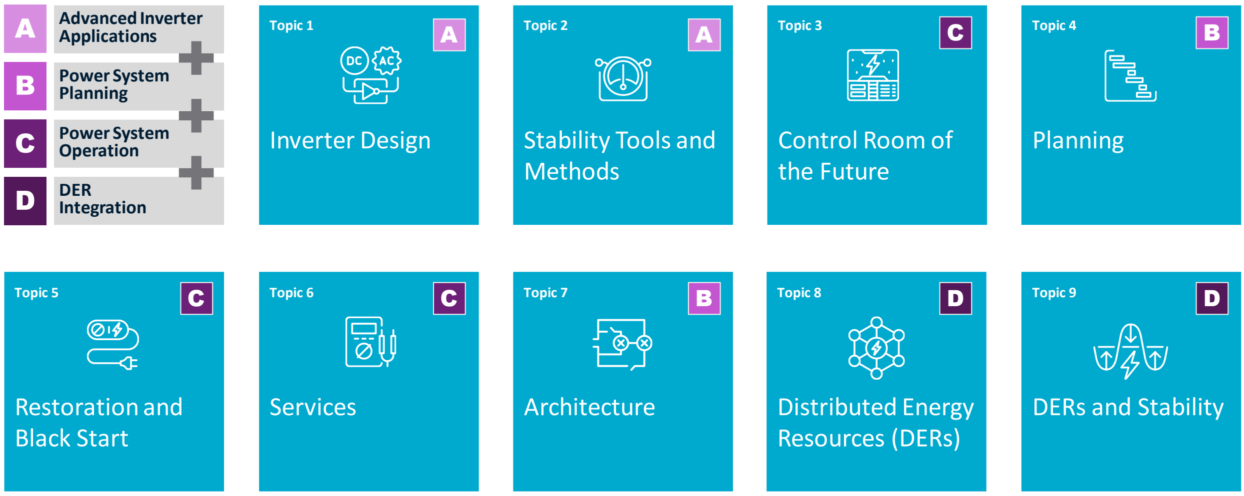

Figure 4: Research areas of the CSIRO Australian G-PST Research Roadmap

1.4 CSIRO Power System Research Roadmap

CSIRO, supported by AEMO (one of the G-PST founding system operators), has engaged some of Australia's and the world's leading researchers and engineering experts (Figure 5) to carry out critical research in the areas of energy technology outlined above.

This will support Australia's energy transition in the long-term interests of consumers, and also will provide opportunities for Australia to become a world leader in these fields of research and technology.

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

The work presented in this summary report presents Stage 2 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 that would have to be carried out in each of the previously described research areas.

Stage 2 has focused on the highest research priorities identified in the Research Roadmap to ensure maximum value and greatest impact.

This research program does not exist in isolation. There are several similar or related activities being advanced by other research institutes in Australia and overseas, as well as by AEMO. Examples include the AEMO Engineering Framework[6] and the AEMO Operation Technology Roadmap[7]. Both of these have been considered and engaged with in this CSIRO research program. Similarly, there are several other industry projects that have been previously carried out that have helped to build some of the research topic outcomes, such as EPRI development of tools and processes that helped to support the outcomes of Topic 2.

CSIRO recognises that there is a huge body of work needed across the energy industry in the coming decade and beyond. This will require a significant increase in the depth and breadth of power system engineering expertise both in academia and industry. CSIRO's Australian G-PST Research Roadmap work is helping build the foundation for this.

With the 2023 completed Stage 2 work, the Research Roadmap has now been put into action, helping to facilitate Australia's transition to a stable, secure and affordable power system.

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

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

2 Advanced inverter applications

2.1 Rise of inverter-based energy generation

Just like in many other jurisdictions worldwide, the growth of renewable energy penetration in the Australian National Electricity Market (NEM) has been phenomenal. In 2010 there were 480 MW of utility scale renewable generation, predominantly wind turbines, installed across the entire NEM. At the time of writing, there is 18 GW of utility scale renewable generation installed, comprising wind turbines, battery energy storage systems, and solar photovoltaic (PV) generation of many hundreds of MW for a single installation. At the same time there are renewable energy zones planned that will aggregate thousands of MW in a very small area. Furthermore, the growth of solar rooftop PV installations in the distribution system over the past decade means that there are now also approximately 19 GW of distributed PV connected in the distribution systems across the NEM.

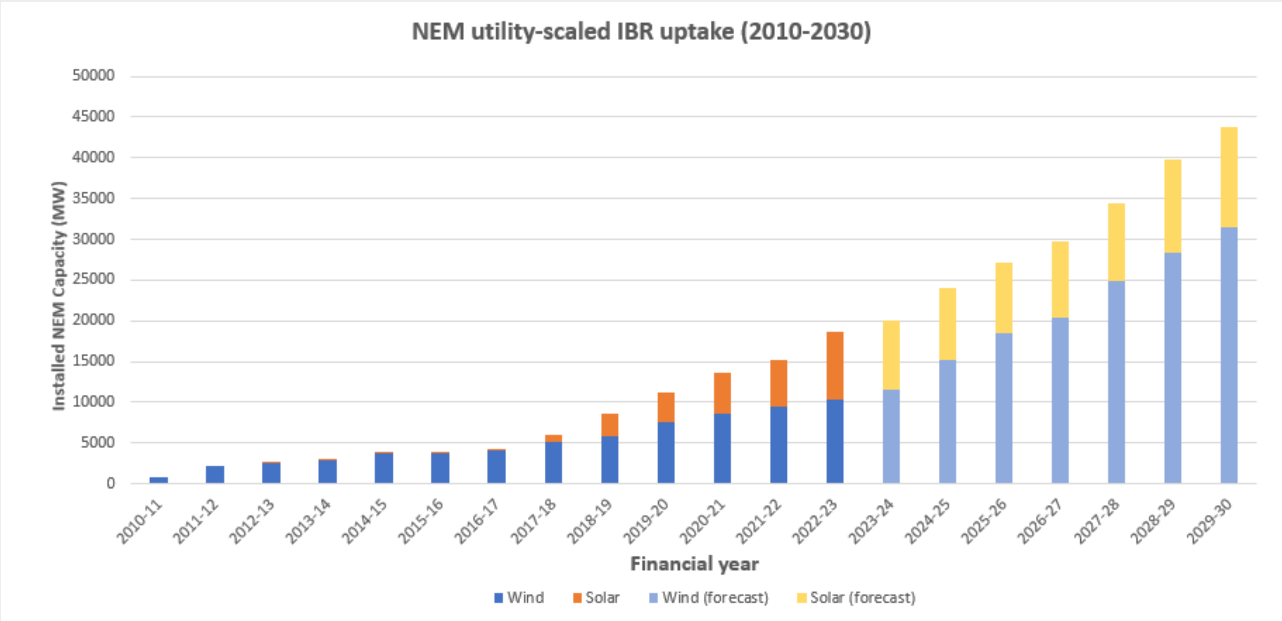

Figure 6: Growth of Inverter Based Resources in the NEM from 2010 to present and ISP projected growth until 2030

All of these renewable energy sources are power electronically interfaced, or inverter based resources (IBR). IBR do not have the same operating and performance characteristics that our conventional synchronous generators have and as these new technologies displace our coal- and gas- fired generators in daily dispatch, we must take action to understand, integrate, and where possible optimise the operation of these renewable sources that will drive the energy system transition.

The CSIRO Research Roadmap investigation of advanced inverter applications encompassing many aspects of these new technologies, from designing control systems, to developing tools to enable better integration of these technologies. During Stage 2 of the Research Roadmap CSIRO have funded two research projects in the area of inverter application and integration:

(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.

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

This project presents a comprehensive 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 inverter design specifications to the analysis of complex multi-IBR systems.

The research begins with a thorough review of global grid codes and existing performance standards to derive inverter design specifications that enhance their ability to remain connected to the grid during large signal events. This foundation enables the investigation of transient stability in grid-forming inverters equipped with current limiters, which protect the inverter from overheating and may be activated during contingencies. The study emphasises the importance of q-prioritised current limiters, which are commonly employed in the industry.

Building on these insights, documented in a technical white paper that is published on the CSIRO G-PST website also for public reference, the research explores the transient stability of paralleled systems, including grid-forming and grid-following inverters. This analysis leads to the development of an adaptive power reference control (APRC), designed to enhance transient stability in various scenarios.

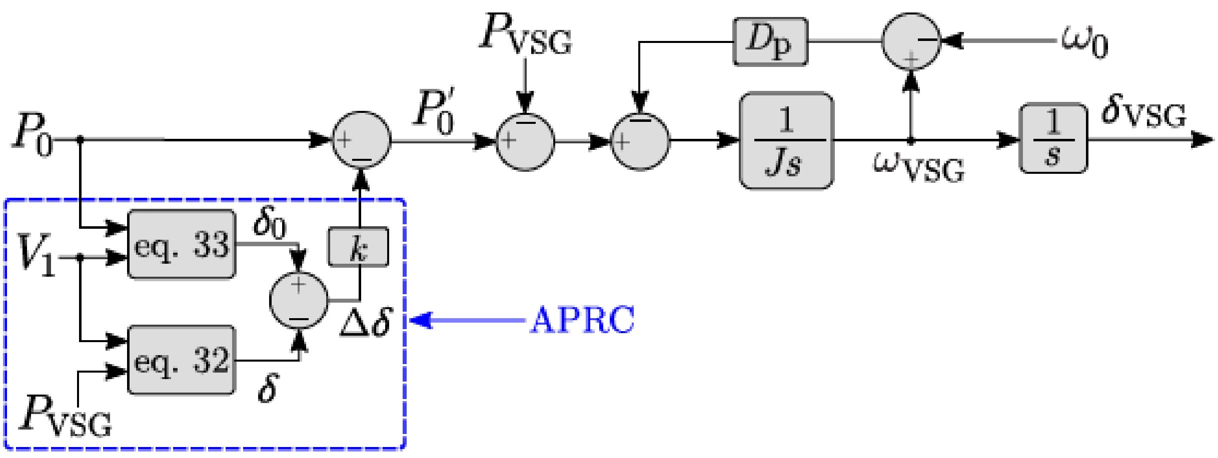

Figure 7: Diagram of the Monash University developed APRC

Experimental benchmarking using laboratory set up at Monash University demonstrate the effectiveness of the APRC in improving the damping and stability of the inverters analysed. Monash University reports several benefits of implementing an APRC for such IBR controls:

- In a VSG the APRC acts as a variable power-frequency droop gain. When the common bus voltage V_1 drops deeply due to a fault in the system, the APRC reduces the overall droop gain of the power-frequency control to help the VSG remain stable. However, this behaviour can affect the power sharing of the VSG in a steady state. Thus, the APRC is only active when the PoC voltage falls below a certain value, e.g., 85% of nominal.
- It is also shown that the APRC improves the damping of Active Power Controller of the VSG.
- Moreover, if the fault is too severe for a stable equilibrium point of a paralleled system to exist, the APRC adjusts the power reference in a way such that a new SEP is created for the OP of the system to converge to.

- Besides, the APRC is designed to maintain the steady-state common bus voltage V_1 above a given threshold value. The threshold value for V_1 can be selected by the operators and by this approach, the stability of a GFLI is also enhanced in a multi-IBR system.

Subsequently to testing individual IBR devices, the research also extends to multi-IBR systems. The goal is to develop indices or indicators that allow for quick measurement of transient stability margins, taking into account the distance between stable and unstable equilibrium points in the system's operating domain. This analysis aims to eventually provide a practical tool for evaluating the performance and stability of complex power systems with multiple IBRs. Detailed results and insights are found in the researcher's main reports, but ultimately, the research reports comparable successes for multi-IBR systems as for individual devices: improved stability of both individual systems and the concerted interaction of all modelled devices. Notably the multi-IBR studies considered a system of two GFMI and two GFLI systems operating in relative electrical proximity.

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

The research plan tasks that have been completed in the 2022/23 Stage 2 work include:

- Enhancing IBR response during and subsequent to faults.
- Developing alternative control methodologies for GFMIs.

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

With growing penetration of renewable energy resources which are power electronics based, there are concerns about their impact on the stability of the grid. To enable safe and reliable power delivery in future power systems with significant contribution from inverter-based-resources (IBRs), development of methods for determining stability and stability margins around different system operating conditions is important. This topic was identified as a critical topic in the Research Roadmap around Stability Tools and Methods.

In a conventional synchronous machine system, since most models are standardised, it is relatively easier for a transmission planner/operator to evaluate the stability of the network, especially from an analytical perspective. However, with IBRs, knowledge of the IBR control details is generally not available to the transmission planner/operator due to intellectual property (IP) management of the original equipment manufacturer (OEM). This can result in an inability to analytically evaluate the stability of the network and rather, the only resort left is to carry out numerous time domain simulations.

These time domain simulations can be computationally demanding and can take many hours to run and thus may not be efficient for near real time evaluation of stability of a network with large percentage of inverter based resources. Further, as IBRs are current limited devices, their operating point has a larger impact on their stability, as compared to the impact of operating point on the stability of traditional synchronous generators.

To help address this dual challenge, this project has two main objectives:

(i) Development of a framework to assess multiple operating points over which the IBR can be expected to operate, and

(ii) Develop an algorithm to assess control stability of IBRs using black box models over the multiple operating points determined in (i) .

To achieve the first objective of assessment of operating points, a framework process has been developed by EPRI that utilises the following approach:

- Determine a baseline power flow case that can represent the evolution of a network over successive periods such as 24 hour period
- Evaluate system strength across the entire region to identify locations that have reduced capability to host IBRs. The characterisation of this system strength will be a combination of small signal steady state metrics such as short circuit ratio and remaining MVA available.
- Identify the voltage control areas of the region to outline need for and magnitude of reactive power reserves. This analysis will allow for rating of reactive resource adequacy in each portion of the system.
- Develop a unit commitment and dispatch profile to help evaluate the active power output of the IBRs in the network over the successive periods
- Evaluate if there would be any prioritisation issues of reactive power versus active power delivery of the IBRs
- Preliminary time domain simulation exercises are to be carried out to identify if any stability issues arise as the operating point changes.

The process established by EPRI is depicted graphically in Figure 8. To implement this process, EPRI has utilised a number of existing EPRI developed software tools, such as the Grid Strength Assessment Tool (GSAT) and Voltage Control Areas (VCA) Studio.

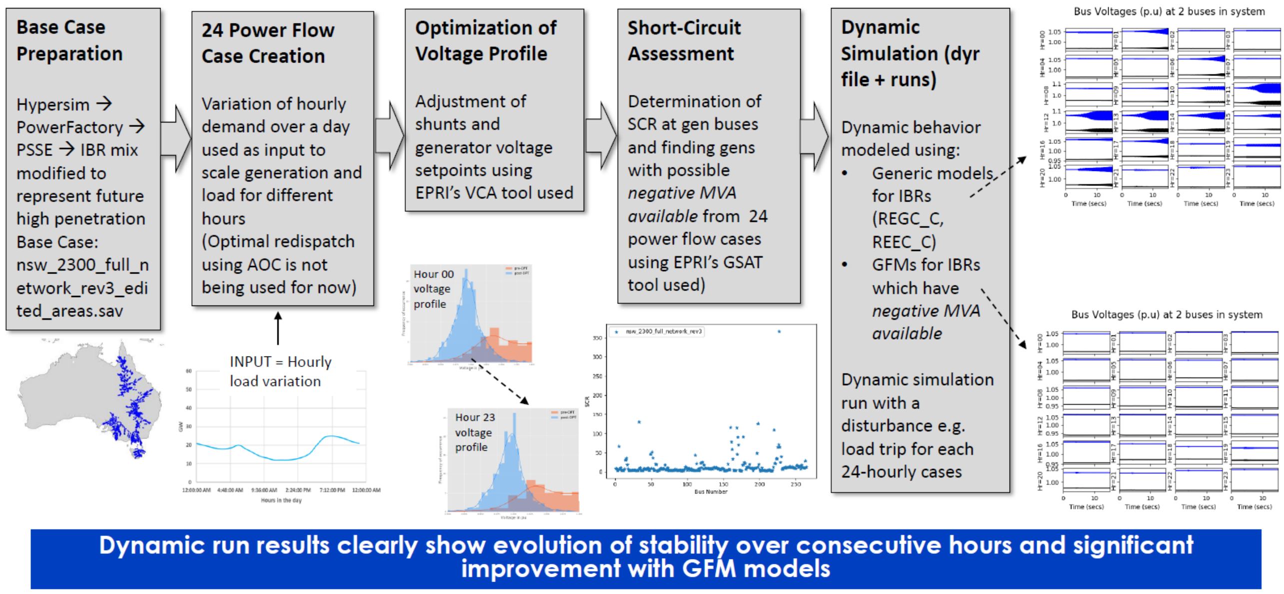

Figure 8: Process flow of stability assessment of system with high IBR [EPRI]

The second objective has been achieved through preliminary work to develop both an analytical and a data driven prediction algorithm that can estimate the impedance characteristics of a device at any arbitrary operating point, by using only few operating points as inputs to develop a set of training data.

The results show the use of metrics such as remaining available MVA to identify locations that can have potential stability issues at different operating points. Further, the application of the training algorithm on different IBR control structures has been showcased. Using the obtained estimated impedance characteristics, a system planner and operator can make a determination whether a particular operating point (after running the described screening analysis) is going to be small signal stable or not. Based on the result, the operating point can be changed to help move the network towards a more stable operating point.

Further, in this project, a proof of concept has been showcased to illustrate the development of prediction based algorithms to evaluate the stability of a network at any arbitrary operating points. This approach can significantly reduce the computation time of stability evaluation and as a result, have potential application to real time operations.

While this first year of research has made significant inroads to the development of tools and methods to enhance the planner and operator’s ability to manage a power system with increasing IBR, more work remains. In relation to the 2021 Topic 2 Research Roadmap, the work done in this project addresses the topics listed below:

- Stability margin evaluation (Critical topic)
- Small signal stability screening methods (Critical topic)
- Voltage and reactive power management (High priority topic)

Subsequent stages of the EPRI proposed research would further optimise the estimation processes, streamline and potentially automate more of the overall process and importantly, extend to a full NEM model assessment rather than a simplified test case.

3 Power System Design

3.1 Planning our energy system

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

However, for the past decade there have been many changes that have disrupted the way that we plan and fund our power grid infrastructure; increased decentralisation of our energy sources, changes to our generating technologies, ageing infrastructure, and increasing active consumer participation in the energy system, all drive the decarbonisation of our power system and the associated energy transition we are in. As a result, the regulatory and planning processes that have served us so well in the past are becoming obsolete, unable to deal with the many changes underway.

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

(a) Assessing flexibility, risk, and resilience in low-carbon power system planning under deep uncertainty

(b) Power System Architecture

3.2 Topic 4: (Power System) Planning

The increasingly complex nature of manifold long-term uncertainties that could impact power system planning calls for considering new methodologies that can propose more cost-effective and potentially less risky infrastructure investment and development paths. In this context, this project explores the value of adaptive, flexible planning methodologies in power system infrastructure investment, focusing on addressing long-term uncertainty, risk, robustness, and resilience. The core objectives that have been addressed during the project, in line with the CSIRO G-PST Roadmap of 2021, are organised into five groups:

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

Each of these works provides tools and methods for power system planners to employ in strategic network expansion.

1. <u>Flexible expansion plan based on multi-stage stochastic optimisation</u>

This stage of the project delves into multi-stage stochastic planning for power system expansion under uncertain conditions, aiming to address the complexities associated with strategically expanding power systems. The stochastic planning model generally uses a scenario tree (see Figure 9) to capture the uncertainty in various parameters, such as load profile and evolution, renewable energy installed capacity, conventional generation unit decommission, technology investment, various operation costs (e.g., associated with fuels), and so forth. Each node in the tree represents operation and investment for a specific year, considering the uncertainty in the aforementioned variables. The expansion planning problem seeks to minimise the total expected costs associated with investment and operation decisions made in each node of the scenario tree. The optimisation problem is subject to various constraints, including investment constraints ("non-anticipativity" and potential rules of investment across options), power system constraints (energy balances, reserve provision, power flow, and transmission limits), and unit-commitment constraints (including technical characteristics of conventional units).

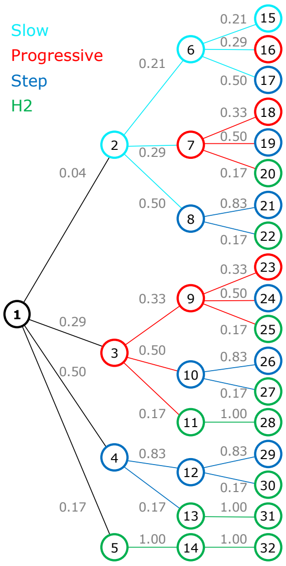

Figure 9: Scenario Tree

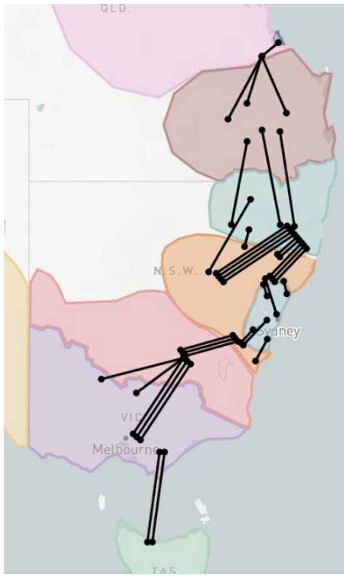

Figure 10: Transmission candidate investment options

The first part of the project focused on using data from the ISP 2022 to inform and validate the stochastic planning model previously developed by the project team at the University of Melbourne. This was then used to determine optimal portfolio of investment options using multi-stage stochastic optimisation for power system expansion under uncertain conditions. The core of the analysis was centred on minimisation of the expected cost considering decisions on new transmission investments, with some extensions to the co-optimisation of transmission and storage assets. The results may be illustrated effectively via the cumulative probabilities of the total (investment and operation) cost across the different scenarios, as for instance shown in Figure 11, which considers the 34 major candidate lines as described in the ISP 2022. In this particular example, the optimal solution for the transmission-only instance resulted in a total expected cost (at 50% cumulative probability) of some $23 billion for 20 years of operation and investment in new transmission lines, as highlighted by the vertical dotted line in the figure.

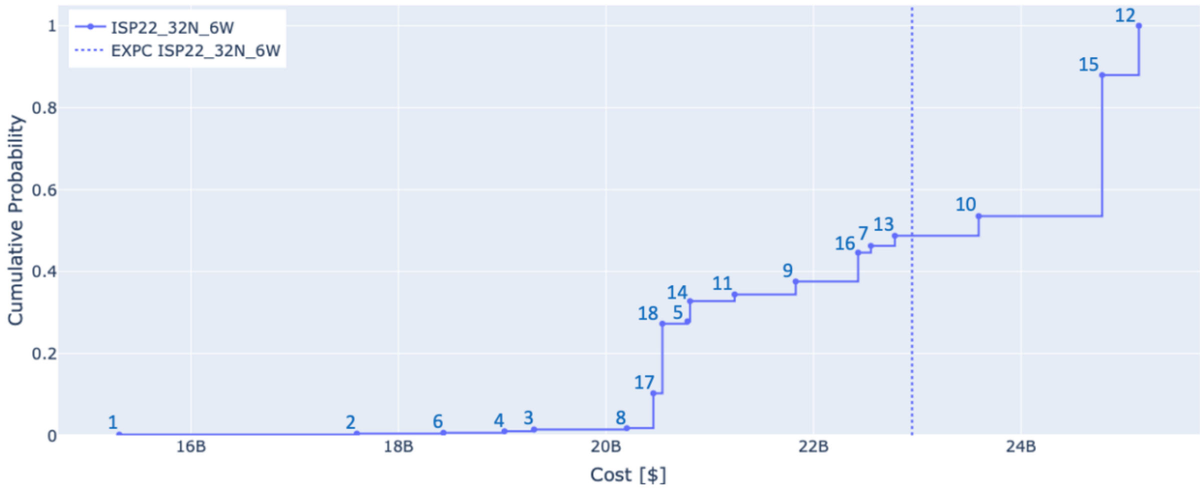

Figure 11: Distribution of total costs of operation and investment for each of the 18 scenarios included in the scenario tree

Key findings of the study include the identification of the reinforcement of the future network based on flexible investment options. In conclusion, the optimal transmission investment decisions are heavily influenced by the representation of operational options, and to a lesser extent by the inclusion of additional storage options.

2. Deterministic planning

Deterministic planning is widely used in transmission expansion methodologies around the world. This analyses various scenarios from a deterministic perspective. Some approaches then use an additional metric to select the optimal plan based on the results. Two deterministic-based metrics used by major system operators in the world, most noticeably AEMO in Australia and National Grid Electricity System Operator (ESO) in Great Britain, are Least-Worst Regret (LWR) and Least-Worst Weighted Regret (LWWR).

Originally adopted by National Grid ESO, LWR decisions use regrets, which indicate the difference between the cost of applying a specific portfolio of investment options and some reference cost, this difference being a measure of proximity to the optimal solution. The methodology involves several steps:

- Selecting scenarios and investment options,
- determining the optimal portfolio for each scenario,
- calculating the investment and operational costs,
- determining the specific development path that produces the lowest cost,
- calculating the regret for each development path,
- finding the worst (maximum) regret, and finally,
- selecting the development path with the least-worst regret.

LWWR is a recently proposed variant of LWR, currently adopted by both AEMO and National Grid ESO, that incorporates scenario probability weights to account for beliefs about different likelihoods of occurrence. This approach aims to include the impact of scenario probabilities in the LWR method, which otherwise assumes equal probability for all scenarios.

A quantitative comparison among LWR, LWWR, and a stochastic planning approach was conducted in the project for the first time. Applying LWR and LWWR metrics identifies the best development path resulting from the deterministic analysis of all scenarios, which (in the case considered) turns out to be the same for both LWR and LWWR. Furthermore, results produced from the comparison among the various planning approaches to ISP base case studies demonstrate that the stochastic planning approach exhibits superior performance in addressing planning uncertainty, relative to the deterministic-based LWR and Least-Worst Weighted Regret (LWWR) methodologies . Minimising the worst regret may lead to riskier portfolios than stochastic plans, suggesting that categorising LWR as a risk-averse metric might be appropriate only under a deterministic metric for assessing plans across a range of uncertainties, while superior risk-hedge strategies could be identified through optimising across stochastically aggregated assessment metric. The different objectives implied by each metric can result in significantly divergent investment strategies under conditions of profound uncertainty, as demonstrated in the case study discussed in this report. Overall, the results illustrate how a stochastic planning approach can provide a much more sensitive perspective across all future scenarios and can identify development paths that are intrinsically both less expensive and less risky relative to an aggregate view across decisions performed over multiple independent deterministic scenarios.

3. Controlling the risk of the portfolio

The next part of the project aimed to highlight the benefits of incorporating risk management principles in the process of defining the optimal portfolio of investments for the system when uncertainty is present. This is particularly important as risk assessment and analysis are not clearly modelled or even captured at all in currently implemented methodologies. One of the ideas was also to study how, even though controlling expected cost and risk are generally competing objectives in portfolio optimisation, introducing new investment alternatives, such as flexible technologies, could eventually reduce both expected and extreme outcome costs simultaneously.

A risk-aware stochastic planning assessment metric was proposed, which includes a risk parameter (β) to represent different risk appetites. This metric allows decision-makers to balance their position on risk, with a more *risk-averse* approach favouring minimisation of extreme risks at the expense of increasing the expected total cost, while a *risk-neutral* approach focuses solely on minimising expected cost. Such a risk parameter permits determination of efficient frontiers where each point represents an optimal balance of expected cost and costs of more extreme risks, in turn enabling the definition of an optimal *risk-aware* portfolio for the system.

Understanding risk metrics is crucial for this process. Several risk metrics were considered during the project, but the final analysis focused on what was deemed to be the most relevant metric in the context of the studies performed here, namely, the Conditional Value-at-Risk (CVaR). More specifically, while the Value-at-Risk (VaR) metric provides information about a predefined likelihood threshold for the "worst-case" cost (e.g., the 95% likelihood threshold across all scenarios), CVaR informs about the expected cost of those worst-case scenarios (e.g., the expected cost of the worst 5% scenarios), thus implicitly also accounting for their distribution. In fact, CVaR was preferred for its ability to identify low-probability but high-cost scenarios, making it an advantageous risk metric for transmission expansion planning problems, especially where resilience (that is, amelioration mechanisms against high-impact, low-probability events) is also important.

A case study was conducted using ISP scenarios and investments, and while the results are purely illustrative, the efficient frontier analysis was shown to be a potentially important tool to explore the benefits of alternative investment options and their cost-risk implication.

4. Methodologies to incorporate resilience analysis in stochastic planning

Extreme (weather) events have caused significant economic damage to power grids both in Australia as well as overseas, calling for a comprehensive understanding of their impact on power system infrastructure[8, 9]. Power system resilience, which refers to a system's ability to withstand high-impact, low-

[8]http://www.climatechangeinaustralia.gov.au/media/ccia/2.2/cms_page_media/734/ESCI Case Study 6_Impact of extreme events 090721.pdf https://www.climatechangeinaustralia.gov.au/en/projects/esci/

[9] https://www.iea.org/commentaries/the-world-s-electricity-systems-must-be-ready-to-counter-the-growing-climate-threat

probability (HILP) events, recover quickly, and adapt for future events, has become a focal point for researchers and policymakers in the past few years.

Various frameworks, methodologies, and measures have been proposed to improve power system resilience, including stochastic optimisation, hardening infrastructure, and risk aversion in network design and operation. In this context, in the project the researchers proposed a set of resilience-oriented planning methodologies that could build on the stochastic planning framework.

Besides introducing alternative approaches to model high-impact low-probability events with different occurrence characteristics within scenario trees; as key part of the project, three methodologies were proposed for studying the effect of extreme events in power system planning:

1. Risk-averse planning for resilience enhancement.
2. Resilience-aware stochastic power system planning.
3. Two-step resilience-aware stochastic power system planning: This methodology (see Figure 12) involves two steps - first, planning the system for reliability using an approach based on adequacy and security standards. Secondly, high-impact, low-probability scenarios are overlaid on the original scenario tree to identify new optimal plans for developing the remaining transmission options, resulting in the resilience-oriented portfolio.

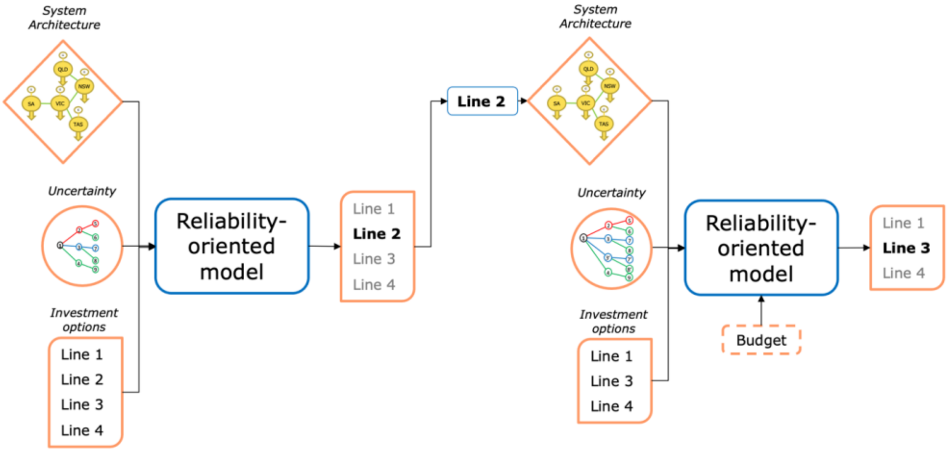

Figure 12: Illustration of the two-step methodology to determine resilience-oriented portfolios (methodology 3)

Various case study applications were considered in order to demonstrate the resilient planning methodologies proposed, including different HILP event occurrences within the scenario tree. The results show how incorporating resilience aspects into the planning approach can change the investment portfolios. Importantly, the stochastic planning approach can reveal the need for anticipative investments such as early system reinforcements in anticipation of extreme events. Comparing stochastic planning to deterministic planning, more variation in investment decisions and greater flexibility can be recognised in the stochastic approach, while maintaining the expected costs relatively stable across different cases. This suggests that, in the context of formally introducing resilience in the planning exercise, the adaptable investments that stochastic planning naturally proposes could subsequently enable further investments that protect the system in the face of extreme events, but without significantly increasing total costs.

5. <u>Role of hydrogen infrastructure</u>

In the final part of the project, an integrated electricity and hydrogen transmission infrastructure planning model developed by the University of Melbourne team within the Future Fuels Cooperative Research Centre was used to quantify the impact of large-scale green hydrogen production on the investment planning. The modelling was assessed, as a proof of concept, on a case study consisting of proposed provisional corridors connecting renewable energy zones (REZ) and large hydrogen export demand in the superpower scenario of AEMO's ISP for the years (epochs) 2027, 2032, and 2037.

Under the cost and technical assumptions of the specific case study, looking into the most cost-effective *greenfield* infrastructure design that could connect REZ to large-scale green hydrogen demands, the results show that hydrogen pipelines may generally be more cost-effective than their electricity counterparts under the specific corridor lengths and energy volumes considered. Specifically, the optimal solution, which consists of hydrogen pipelines exclusively as transport infrastructure, has a net present value (NPV) that is some 40% smaller than HVAC transmission links and some three times smaller than HVDC options. As the longest corridor is this greenfield case study has a length of 480km, these results are congruent with HVAC vs HVDC comparisons in existing literature, which identify a break-even distance of around 600km, beyond which HVDC becomes more cost effective. Overall, the results suggest that for envisaged developments of large-scale green hydrogen demand hubs, hydrogen pipelines should be considered alongside electricity corridors to achieve an overall cost-efficient whole-system planning.

3.3 Topic 7: System Architecture

Australia is experiencing one of the fastest power system transformations on the planet. The nation provides a window on the energy future for many global jurisdictions.

The combined impacts of the '4 x Ds' – decarbonisation, digitisation, democratisation and decentralisation – are driving Australia's unparalleled transformation. These, in turn, are being accelerated by a complex range of societal, technological, economic and commercial shifts, many of which transcend the direct control of traditional power sector regulatory and governance mechanisms.

In this context, Stage 1 of the G-PST Topic 7 project completed in early 2022 reviewed the various approaches employed globally to evaluate the underpinning structures of GW-scale Power Systems and examine how an orderly transition may be supported toward Net Zero Emissions (NZE) future. The Stage 1 report surveyed over twenty global initiatives and approaches to provide an action plan for applying best practices in Australia, and set the path for Stage 2 of Strategen's research which was developed during 2022-2023.

Following on from last year's work, a key aim of this Stage 2 work is to demonstrate how systems-based methodologies such as Power Systems Architecture can help 'tame' the deep complexity inherent in our legacy power systems and enhance the development of more holistic solutions. As such, while focused largely on the NEM, the methodology is universally transferrable to all legacy power systems experiencing deep decarbonisation.

At the highest level, the PSA methodologies applied by Strategen may be summarised as:

> *An integrated set of disciplines that support the structural transformation of legacy Power Systems to meet future policy and customer expectations, by:*
>
> + *Providing formal tools that enable the decomposition and 'taming' of massive complexity that is inherent in transforming Power Systems;*
> + *Empowering more informed, multi-stakeholder participation by making critical content explicit and tractable which would otherwise remain opaque and intractable; and,*
> + *Increasing decision quality, timeliness and traceability to increase the potential for full benefits-realisation and avoiding the propagation of unintended consequences.*

Through the application of these Power System Architecture (PSA) methodologies, Stage 2 of Topic 7 research aims to provide a seminal Reference Architecture of the National Electricity Market (NEM) as it experiences profound transformation. In their work Strategen has taken account of the many drivers and inputs to the architecture (Figure 13), and considers both the NEM's legacy structures and plausible future state and intermediate transition requirements.

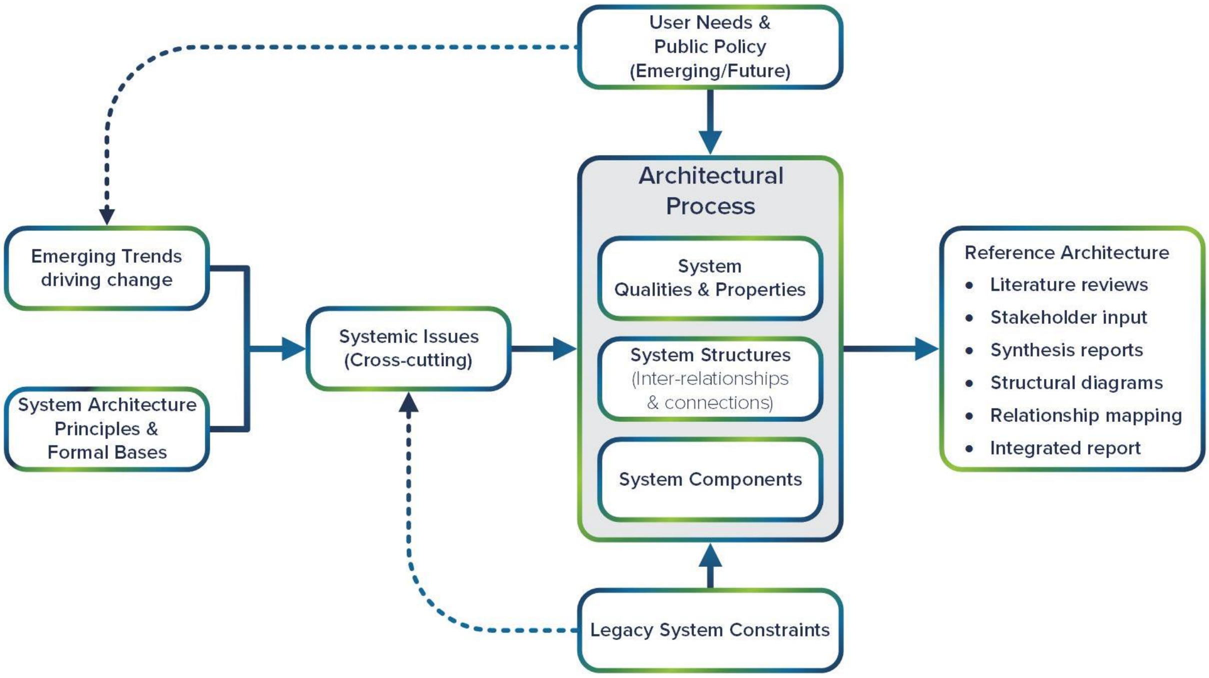

Figure 13: Power Systems Architecture provides a systematic methodology for supporting the structural transformation of legacy Power Systems to meet future policy and customer expectations[10]

However, the development of a reference architecture conducted in Stage 2 is only the first step, leading on to detailed architecture, engineering design, and implementation (Figure 14). Similarly, it is not a linear unidirectional process, but one that will necessitate iteration.

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[10] This model has been adapted from the seminal work undertaken by Pacific Northwest National Laboratory.

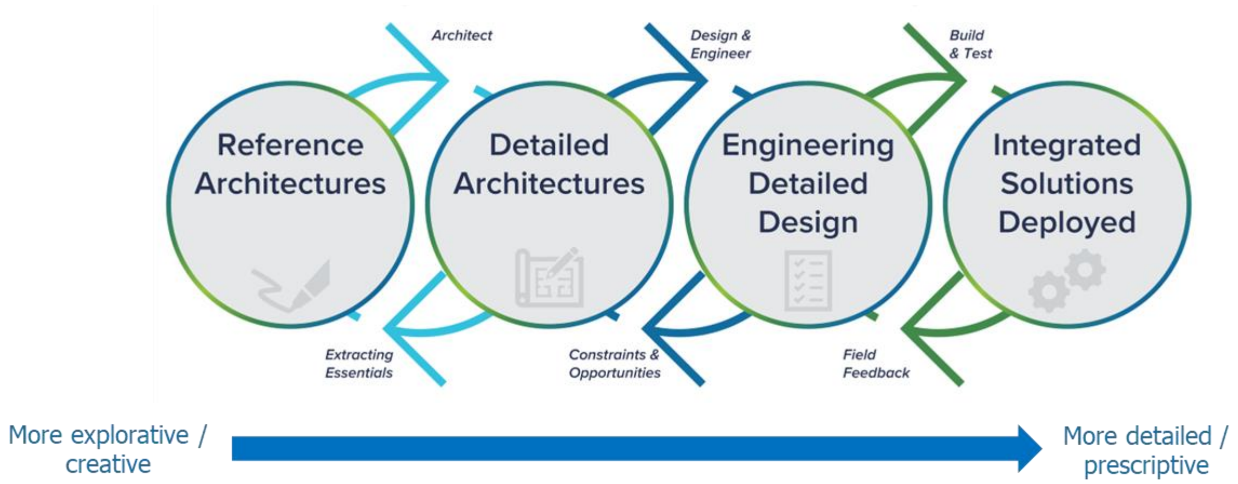
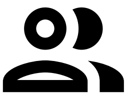


Figure 14: Reference Architecture development is a key first step in the application of Systems Architecture disciplines to an ultra-complex System.

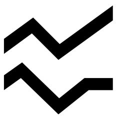
The development of a seminal Reference Architecture of the NEM is – not unexpectedly – an inherently complex undertaking. For this reason, its development has been advanced through the delivery of four major tasks which function as key building blocks. Consistent with the PSA methodology illustrated in Figure 13, the following tasks have been sequentially addressed as part of the Topic 7 research:



Task 1

Customer & Societal Objectives variously state that the future power system must be:

1. **DEPENDABLE**: Safe, secure, adequate, reliable and resilient;
2. **AFFORDABLE**: Efficient and cost-effective;
3. **SUSTAINABLE**: Enables 2030 and 2050 decarbonisation goals;
4. **EQUITABLE**: Broad accessibility of benefits and the fair sharing of costs;
5. **EMPOWERING**: Advances customer and community agency, optionality, and customisation;
6. **EXPANDABLE**: Enables electrification of transport, building services and industrial processes;
7. **ADAPTABLE**: Flexible and adaptive to change, including technological, regulatory and business model innovation; and,
8. **BENEFICIAL**: Socially trusted, public good/benefits, commercially investable and financeable.



Task 2

Emerging Trends that are driving change in GW-scale power systems:

+ *Drivers of change that may significantly influence the evolution of Australia's GW-scale power systems over the next decade and beyond.*
+ *These drivers present challenges and impediments and/or new opportunities and potentialities that are either probable or plausible (not simply possible).*

		+ *While some may be endogenous to the power system, they are typically exogenous and include the impacts of evolving customer & societal expectations of future power systems.*
	Task 3	**Systemic Issues** that impede progress and require architectural interventions: *Systemic Issues are cross-cutting conditions and/or structural settings that:* + *Currently exist in the NEM and/or will arise from the convergence of various emerging trends; and,* + *Will require architectural interventions if the emerging customer & societal expectations of the NEM are to be enabled in a secure, cost-efficient, timely and scalable manner.*
	Task 4	**Emerging System Structures** derived from mapping the 'as built' architecture of the NEM and the plausible architectural settings required to accommodate a 'Step Change' type of future, including: + *The NEM's transition from hundreds of participating energy resources to tens of millions;* + *Increasing volatility throughout and across all tiers/layers of the power system (including bulk power, transmission and distribution systems) with the transition to highly variable generation; and,* + *Power system digitalisation driving the transition from slow data sampling to fast streaming data, vast data volumes and a declining tolerance for latency.*

This development approach enabled progressive review by, workshopping with and feedback from CSIRO and AEMO staff, the International Expert Panel and diverse Australian stakeholders on Tasks 1 – 4 above. Considered together, these four tasks illustrate how the PSA methodology helps systematically decompose some of the otherwise intractable complexity of grid transformation. This enables a quality of analysis, stakeholder engagement and collective decision making that would be otherwise difficult or impossible.

Initially, the preparation of this seminal Reference Architecture provides additional whole-system perspective of the entire NEM in its current, transitional and plausible future operational contexts. Developed through the application of the best practice methodologies identified in Stage 1, the Reference Architecture is somewhat like an initial 'prototype' of a highly complex system. As such, it does not presume to provide '*the* answer'. However, it does provide a powerful mechanism for shared insight and collective reasoning about such a complex system as it experiences unparalleled transformation.

Ultimately, the project highlights how the application of formal Power System Architecture (PSA) methodologies, in combination with conventional tools and techniques, can profoundly enhance the ability to develop holistic and future-ready approaches to power system transformation. This is because PSA:

1. Provides powerful techniques to interrogate and manage the Ultra-Large-Scale (ULS) complexity of transforming power systems, informed by ULS theory, systems architecture, network theory, and other related disciplines.
2. Enhances multi-stakeholder participation and trust by providing formal and transferrable methodologies, templates and frameworks that can be employed by diverse stakeholders to collectively examine and more effectively reason about transformation options and trade-offs.

3. Enables planners, regulators and market/system operators to describe both current and potential future power system structures in a wholistic and uniform manner, which enables more precise interrogation of desired system characteristics before committing large investments to effect change.
4. Provides the means for early detection and avoidance of architectural issues that with otherwise impede the future scalability of investments, risking unintended consequences and unrealised benefits, and without which would not be discovered until long after investments had been made.
5. Simplifies downstream decisions and provides all entities working on individual components or subsystems of the NEM greater latitude to innovate, better understanding how their work interfaces with the rest of the system and assurance that unintended consequences will not emerge to hamper or invalidate their work.
6. Provides empirically based approaches for moderating the complexity of advanced operational coordination, expanding the future readiness of the system as it transforms toward a context involving many millions of participating energy resources located across several tiers/layers of the power system.
7. Enables the robust and timely consideration of alternative Distribution System Operator (DSO) models and Transmission-Distribution Interface Mechanisms (TDIM), together with their respective merits in the context of current and plausible future architectural arrangements.
8. Enhances far more detailed consideration of roles & responsibilities, together with their granular system interfaces and interdependences over several time horizons, through the application of whole-system architectural analyses and supporting formal methodologies.
9. Provides a shared, fit-for-purpose and transparent set of methodologies that one and/or many entities may apply to collectively ensure the future readiness of the end-to-end NEM systems architecture for a future where all segments of the power system must function far more holistically and dynamically together.

For these reasons, it is not just important, but crucial, that the structural issues addressed by PSA be systematically considered as a key element of provisioning the NEM to meet current and future needs.

4 Power System Operation

4.1 Keeping the lights on

As the Australian power system continues to undergo significant transitions that will only accelerate over the coming years – including increasing shares of inverter-based resources and distributed energy resources and decreasing synchronous generation capacity – Australia will have to rethink the way we operate our transforming electricity network. 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.

The research area of *Power System Operation* includes three critical initiatives, including research in:

1. The Control Room of the Future (CRoF) that will allow the system operator to continue to operate.
2. Restoration of the power system following a regional blackout using non-synchronous generation.
3. Provision of system services in the electricity grid of the future.

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.

4.2 Topic 3: Control room of the future

The control rooms operated by system operators and electricity network owners are at the very centre of successful energy system management. From here the 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.

However, just as Australia's energy sources and technology is changing, so too are the challenges in the control room. Transitioning from the systems in the control rooms of today to the systems in the control room of the future requires a rethink of how the elements of the control are configured, based on a redefined purpose and vision for the future.

To advance this critical work, EPRI supported by the Royal Melbourne Institute of Technology (RMIT) have conducted research on the CSIRO GPST Topic 3 Control Room of the Future (CRoF) outlined in the 2022 research plan of the same topic[11]. The work being conducted in this stage of the CSIRO sponsored research aligns with the "Data Models and Streaming" pillar of the CRoF Roadmap, and involves close interaction with AEMO to identify a methodology for developing machine learning projects, data, and use cases that could improve efficiency and effectiveness inside the electricity grid control room of our system and network operators.

More specifically, the project aims to develop the capability in the artificial intelligence (AI) and machine learning (ML) fields for real time power system applications, with particular focus on developing use cases for AI/ML in the operational context.

Little work currently exists on the development of AI/ML algorithms and use cases for application in electricity system management and control. As a foundational concept the researchers implemented the

11 https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-3-Control-Room-of-Future-Final-Report-with-alt-text-2.pdf

EPRI developed *Intelligrid Smart Grid Methodology*[12] process that was prepared specifically for conceptualising energy sector smart grid applications and use cases. This process was chosen as the most appropriate starting point for development but is adapted to address the challenges of developing AI/ML use cases and the ML project life cycle. From this basis, several ML methods were developed.

To test the efficacy of the developed methodology, EPRI working with AEMO developed a list of use cases to test the prepared methodology and to attempt prototype development. However, given the time constraints for the project, the highest priority use case of "alarm management/event identification" was selected for advancement and testing through the developed ML methodology.

The importance of alarm management/event analysis algorithm is due to operators in control rooms being tasked with analysing vast quantities of alarms that appear on their screens via SCADA. The majority of these alarms are basis status or situational information, that do not require intervention. However, a small percentage of alarms will require attention or may be a pre-cursor to an incident occurring. When a major power system disturbance occurs, the alarm "load" will increase dramatically, which can make distinguishing critical ones difficult.

Hence, the objectives of the alarm management/event identification AI/ML are to:

- Reduce alarm noise levels, based on identified operator issues with alarms.
- Develop methods to identify alarm anomalies or system abnormities from alarm spikes and alarm chattering behaviour.
- Intelligent alarming – condensing multiple alarms from an event into one, log data + SCADA data. Utilise time series SCADA/EMS data for training. Potentially synchronise with other data sources. Use as a foundation for incident identification method and constraints automation method.

To develop the ML algorithm two training data sets were used, a synthetic one with around one million alarms and one month's worth of alarms from AEMO's energy management system containing around 3.5 million alarms. The two data sets were analysed using four methods, as shown in Figure 15.

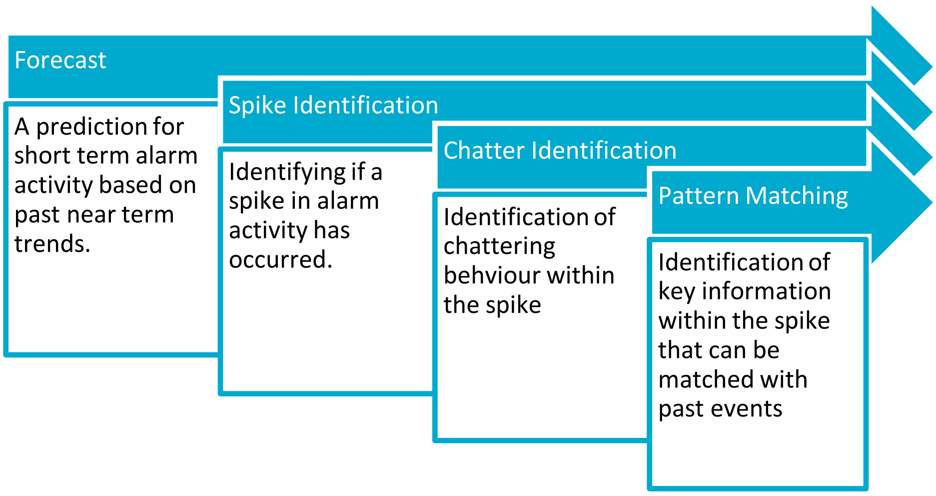
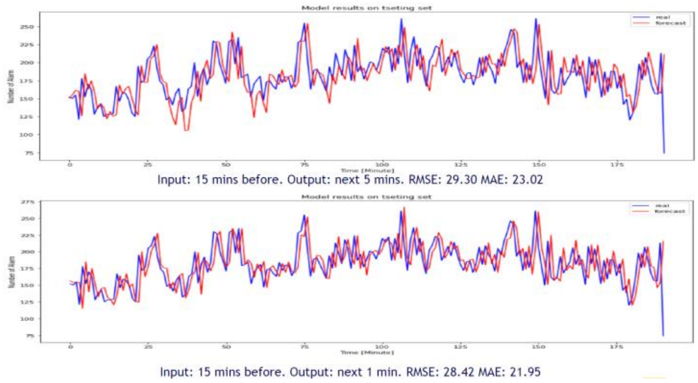


Figure 15: The four aims of the alarm management/event analysis AIML use case prepared in Topic 3

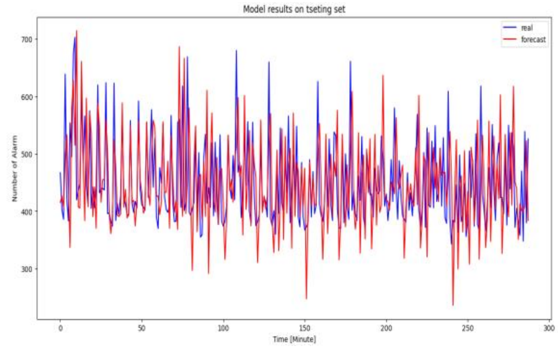
The alarm forecasting method used was long-short term memory or LSTM. LSTM models are advantageous for time series and predictions as they do not rely on single inputs but can take in multiple datapoints or sequences of data as its input to predict the output. The objective was to present an early warning system that would advise the operators of a predicted uplift in alarm

12 https://www.epri.com/#/pages/product/1026747/

activity. Results obtained showed a good estimation for both data sets, with a root-mean square error of 28 and 87 for the synthetic and real data set, and a means absolute error of approximately 22 and 66, respectively.



(a) Synthetic dataset with a 15 minute sliding window (15 minutes before and up to 5 minutes prediction)



(b) Real AEMO dataset for one day with a 20 minute sliding window

Figure 16: Results of the alarm forecast LSTM model on the synthetic and AEMO data sets

The spike identification method looks to identify abnormal activity in alarm loading, where "Alarm spikes" are deviations in alarm activity above the normal background alarm rates. The method used was based on a classical neural network with a weight for the input spike label set at either 1 or 2. The ML algorithm showed a clear ability to pick up alarm spikes, where more than three standard deviations above the baseline alarm quantity indicates an alarm spike. The results show that accuracy in not misidentifying alarm spikes is very high. Accuracy of identifying spikes is also very good, accounting for low number of spikes at higher standard deviations (Table 1).

Table 1: Results of the spike detection baseline model

Spike Standard Deviation	Spike Weight	Number of Actual Spikes in Test Dataset	Correct Negative Prediction	Correct Positive Prediction	Incorrect Negative Prediction	Incorrect Positive Prediction	% Of Correct Spike Predictions	% Of Correct Non Spike Predictions	Time for Test (seconds)
3+	2	285	8505	214	71	1	75%	96.75%	1.3
6+	1	25	8766	23	0	2	92%	99.72%	1.5
11+	1	10	8781	8	2	0	80%	99.89%	1.4
16+	1	2	8789	1	1	0	50%	99.98%	1.5

Next the researchers considered alarm chattering using a back propagation neural network (BPNN). An LSTM model was also tested but proved to be less accurate when compared to the BPNN method "Chattering" is characterised by the same alarm appearing multiple times in rapid succession due to flickering status changes, e.g., ON-OFF-ON-OFF.

The BPNN model was trained and tested on one month of real alarm dataset. The results were very promising. For one month of data the testing accuracy was 89%, meaning in 89% of cases the chattering behaviour was correctly identified by the ML model when compared to the rule-based labelling for chattering, which picked up 77% correctly.

The last ML applied was "pattern matching". When the alarm spikes have been identified and chattering alarms filtered out, it will be necessary to intelligently assess the alarms in the spikes to aid operator decision support and guide them quickly to the source of the system disturbance that generated the spike. The most important step in alarm spike analysis is to automatically identify what is happening within the spike and condense the language in an understandable way.

To match patterns, an unsupervised clustering algorithm is required that could use machine learning. The approach taken was to combine the text in the alarms of each spike separately and to analyse the text in the entire alarm spike to gain insights. The approach used consisted of:

- Combining the text from the spikes into a single "document.
- Using the Doc2Vec python package which uses neural networks to convert the text in the documents in vectors. There should be one vector for each alarm spike.
- Use a "self-organising map" (SOM) which is neural network that clusters the spike vectors visually, which should show patterns of closely aligned words within the spikes.

At this stage of the research, the model was only applied to the synthetic alarm dataset due to the early maturity in the ML development and the need for further exploration and tuning to the synthetic dataset to be appropriate for use on the real alarm dataset. However, the results of the mapping was clearly able to identify clusters of particular alarms that can add further intelligence to the operator decision making, as shown in the example of a SOM shown in Figure 17.

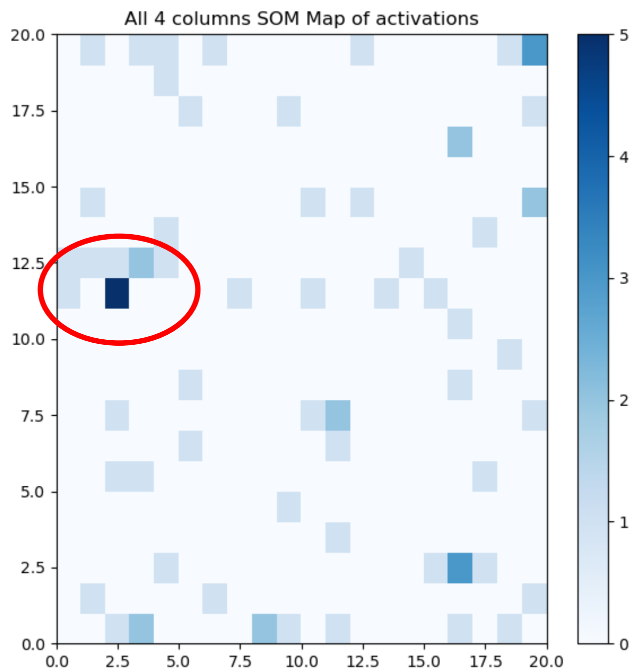


Figure 17: SOM of alarm spikes in the synthetic dataset for the four alarm attributes AOR, Substation, DeviceType and Device. The red circle indicates an intense cluster of activity.

The research presented by EPRI and their partner RMIT, shows promising first steps in the development of ML methods for alarm management. Further work will only enhance and build on the good achievements to date.

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

Thankfully, the complete black out of a power system is a rare occurrence. The last time such an event happened in Australia was the collapse of the South Australia power grid in 2016. Thankfully to the fast and coordinated response of the South Australian transmission and distribution network owners and the system operator, AEMO, power was able to be restored quickly, although it took many more weeks to repair damage caused by the storms that caused the event in the first instance.

The restoration of a blacked-out network is process that is well planned out in advance, and services are procured by AEMO to ensure that this can be managed in an effective and efficient manner. However, with significant changes occurring across Australia's power system, such effective and efficient restoration may not be guaranteed in the future, unless our processes and services can adapt.

The research being conducted by Aurecon as part of Topic 5 of Australia's G-PST Research Roadmap[13], support the understanding and expanding of system restoration capabilities in the NEM. Aurecon's research focused on:

(a) investigating the performance, capabilities, and limitations of different types of GFMI and grid-following inverters (GFLI) with respect to black start capability; and
(b) restoration support in power systems with a high share of inverter-based resources (IBR) and no synchronous generators online during system restoration.
(c) the role of synchronous condensers in supporting system restoration when combined with GFLI.

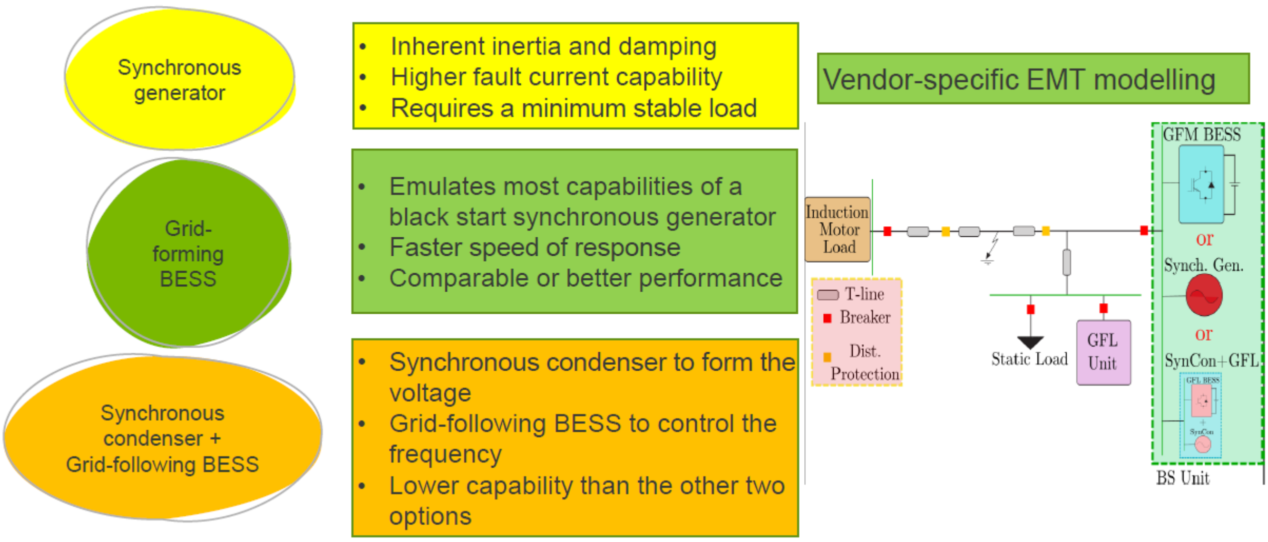


Figure 18: Stage 1 Test set up and options evaluated for black start sources

To test ability of various inverter and synchronous condenser combinations to facilitate system restoration, Aurecon developed three non-traditional black start methods, including (Figure 18):

- single GFMI BESS
- single GFLI BESS and one or more synchronous condensers
- single GFMI BESS and one or more synchronous condensers

The response of each option and factors influencing its performance was assessed with the use of detailed vendor-specific electromagnetic transient (EMT) simulation models. This research is in line with the highest priority task of the Topic 5 research plan.

Aurecon's Stage 2 work was divided into two phases:

1. Development of simplified, but realistic EMT network models and vendor specific IBR, to assess the capabilities and limitations of various black start options and to develop high-level functional

[13] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-5-Blackouts-and-System-Restoration-Final-Report-with-alt-text-2.pdf

specifications for the use of IBR during system restoration based on results obtained from several hundreds of PSCAD™/EMTDC™ simulation studies.

2. Assessment of the restoration of a more extensive part of the actual NEM power system using the Northern Queensland Renewable Energy Zone (NQREZ) and implementing the options assessed in phase 1 of this project (Figure 19).

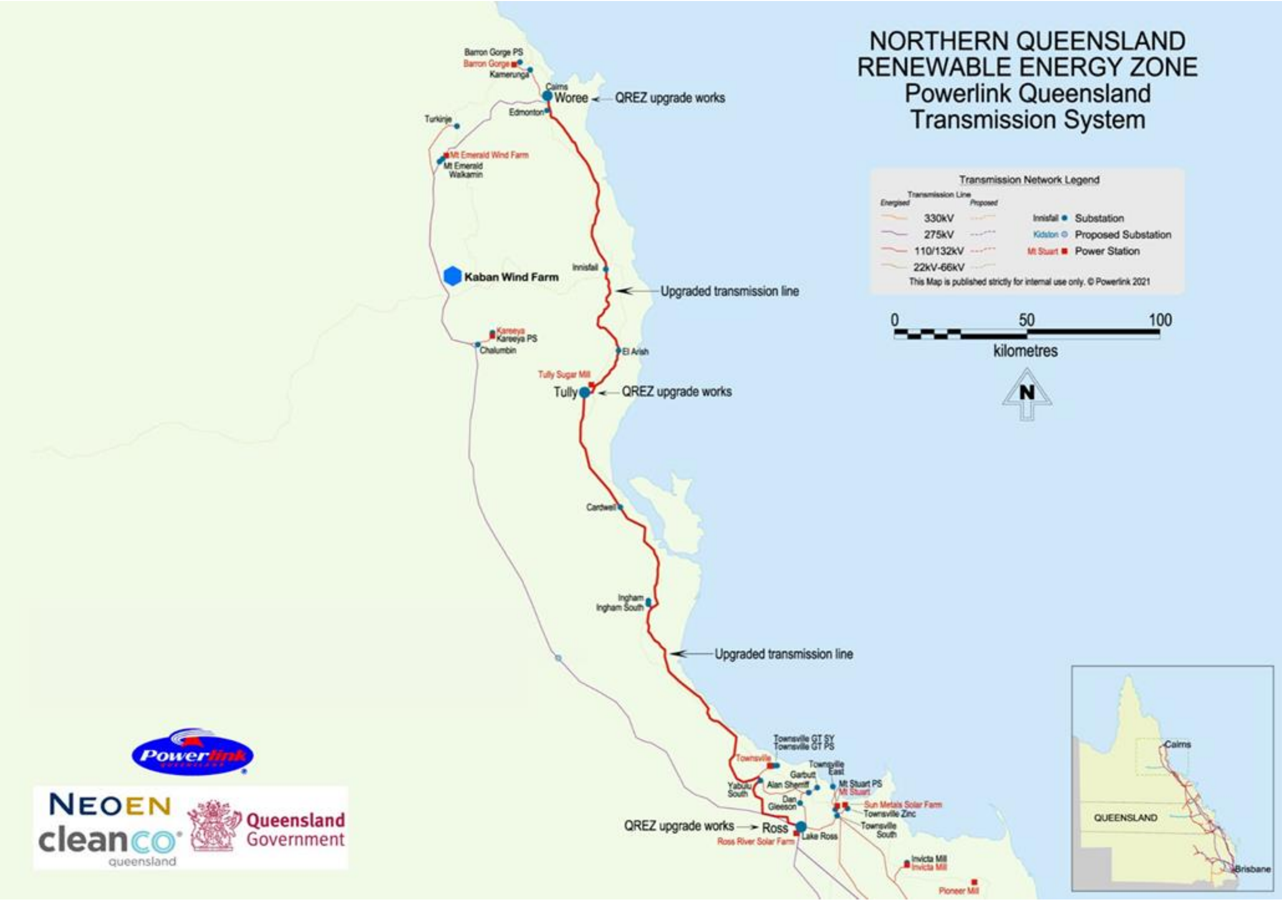


Figure 19: Northern Queensland power system studied for Topic 5 second phase (Powerlink Queensland)

Consistent with the observations in phase 1, the GFM BESS provided superior performance compared to the synchronous generator and combined GFL BESS and SynCon. The combination of GFL BESS and SynCon exhibited the most inferior performance failing in many scenarios. A key contributor for this behaviour was the electrical distance between the GFL BESS and SynCon. Once this distance was reduced and in particular when it was removed, this option provided a better response albeit still the most inferior option. Bespoke tuning of the SynCon excitation system and GFL BESS inverter control can potentially improve the performance.

Regardless of the primary black start technology used, the key limiting factor to a successful energisation path was reactive power capability. Several line and substation reactors were required to minimise reactive power loading on the black start source and ensure dynamic voltage control was available. Where line reactors were not used, and the reactive power capability of the black start provider was exceeded, sustained over-voltages and atypical generator performance were commonly observed. Long transmission lines in the North Queensland REZ investigated contribute significant line charging and more densely configured REZ in other regions may be less prone to this limitation.

The response of the GFM BESS and synchronous generator was also compared when subject to a wide range of network faults. It was observed that the GFM BESS was able to ride-through all faults applied whereas the synchronous generator tripped in one scenario due to the operation of negative-sequence current and V/Hz relays.

Overall the project showed alternatives to system restoration using new and emerging technologies, indicating that the retirement of Australia's coal fired generation may not necessarily create the risk that could have otherwise been expected.

4.4 Topic 6: Services

System services required to operate a power system include those used for frequency control, voltage control, provision of system strength and more, and are provided by generators, as well as in some instances large loads. Without these services or with insufficient services being available, the power system risks instability, both during normal operation and during disturbances.

The CSIRO GPST research plan for Topic 6[14] has advanced a number of critical research tasks to develop a framework for future services in power grids, articulating these in terms of five research questions:

1. What services are needed to achieve the technical requirements of Australia's future power grid to maintain the supply-demand balance while keeping the grid under control at least cost?
2. Are frequency support services suitably configured to achieve the long-term interests of electricity stakeholders including reliability, affordability, flexibility and zero emission?
3. Are voltage support services suitably configured to achieve the long-term interests of electricity stakeholders?
4. What metrics should be used to define services in inverter-based resources (IBR) dominated grids?
5. What system services are needed to maximise the benefits of stakeholders and to achieve an at least cost transition, given the non-steady state nature of investments and emerging technologies in the power grid?

The Stage 2 implementation of the research plan by Monash University focuses on services needed to ensure active power supply-demand balance, and stable and secure operation of the frequency in power systems with high penetration of inverter-based resources (IBR). As such, the research focus has focused predominantly on technical analysis with research include five key tasks:

- In phase I, the project proposes a new system frequency response (SFR) model that considers different potential providers of services to support frequency in power systems during the energy transition and beyond. The proposed SFR model considers the services from energy storage systems (ESSs), renewable energy sources (RESs) and IBRs, and conventional power plants. It is useful for studying the dynamic interaction between different services and hence has some merits for minimising the required services for stabilising the system from frequency stability view of point.
- Phase II of the project develops new dynamic and static metrics for providing better understanding of the active power balance and frequency stability of power systems. The designed metrics provide the required knowledge to the system operators in light of the required services and what actions are required to maintain the power system frequency stability.
- Phase III takes advantage of the previously designed research phases on this project to evaluate and assess the dynamic response from frequency stability view of point. In this regard, different scenarios are considered including future scenarios of power system transformation based on the integrated system plan (ISP), especially scenarios for 2030 and 2050. The outcomes of the assessment give the

[14] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-6-Services-Final-Report-with-alt-text.pdf

power systems operators and planners the required knowledge to consider some risks and to optimally plan for power system transformation.

- Based on the identified risks that verify the need for new and sophisticated sources for providing services to support the frequency in power systems, Phase IV investigates the capability of some future features of the grid for providing affordable services.

  Monash University's work has carefully and in-depth analysed the ability of eMobility, especially electric vehicles (EVs), and thermostatically controlled loads to provide an affordable reserve for controlling the frequency after severe contingencies and credible events. To this end, a new tool has been proposed to estimate the available contingency frequency control ancillary services (FCAS) from EVs and demand-side thermostatically controlled loads. The tool has estimated the EV demand on the system level in Australia for 2030 and 2050 based on the ISP's scenarios.

- In the phase V of Topic 6 project, the research team is looking at optimally setting the frequency controllers' and FCAS providers' parameters in order to achieve the best dynamic performance in power systems with high power share from IBRs, which enable power system transformation and energy transition.

A key outcome of the research is the development of a frequency response model. The system frequency response model prepared by Monash University describes the average network frequency response in one power region after a disturbance and has been applied to a wide variety of dynamic studies. Furthermore, this work also proposes an advanced technique to estimate the parameters' values for SFR model using real-world system measurements and data. In this regard, an advanced subspace system identification technique-N4SD is proposed for estimating the data and identifying the suitable model's dynamic order.

The topology of the developed model is shown in Figure 20, with a more detailed representation of one of the regions shown in Figure 21.

The developed low-order SFR model is applicable for multi-machine multi-area interconnected power systems as well. model has several applications including system frequency control, frequency stability, and dynamic model reduction. useful for identifying challenges and issues related to frequency control and stability and is unique for understanding the requirements of regional inertia and frequency control ancillary services.

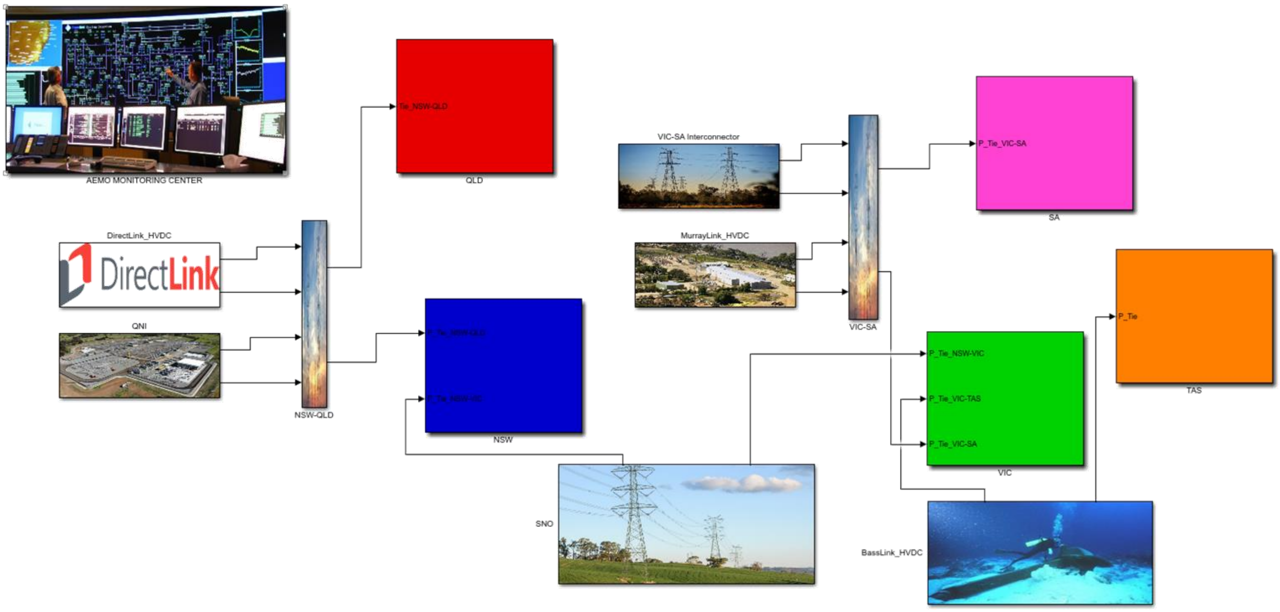


Figure 20: The topology of the main SFR model built for the NEM

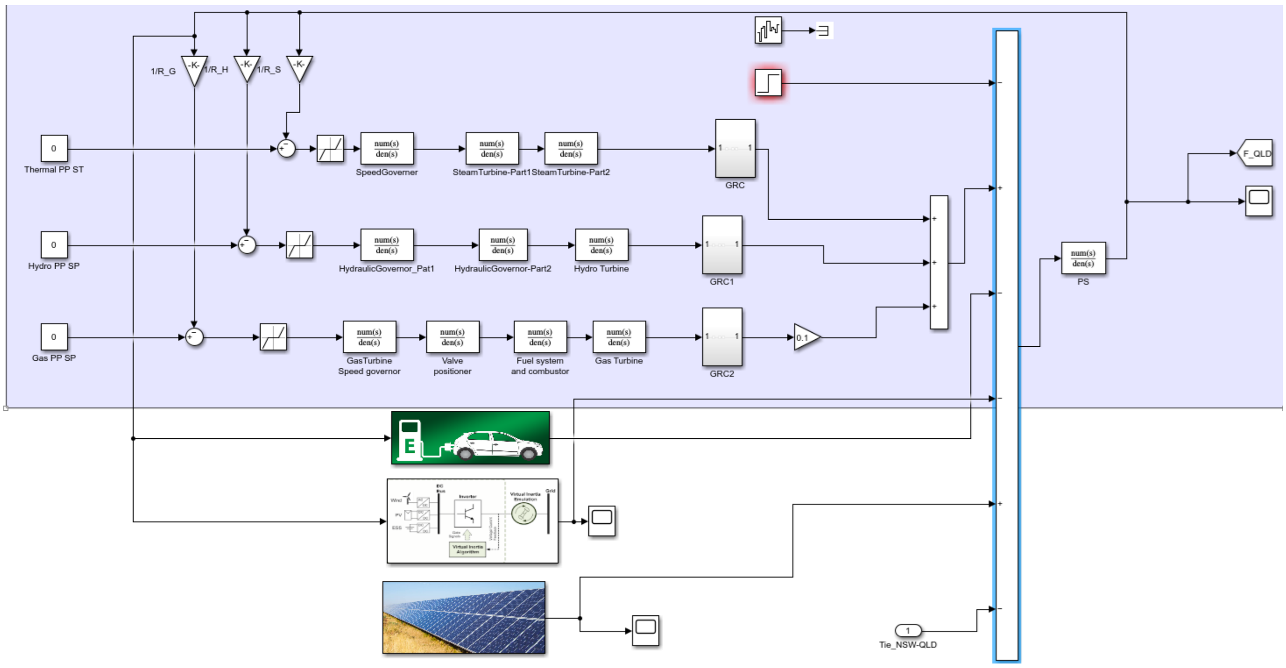


Figure 21: Sample of [QLD] power region model showing the generation mix and the sources of frequency support services and the sources of variations

Monash University describes the insights and outcomes of their model development as:

1. A sophisticated low-order system frequency response model considers RESs, VPPs, DSM, ESSs, and FCAS services providers. The model is, therefore, more efficient from the computing and real-time implementation requirements.
2. Considering the high-level system topology and modelling the different types of interconnectors/tie-lines, providing the capability to understand the limitation and boundaries for transferring FCAS between different power regions. The model is, therefore, useful for understanding the requirements for FCAS regionalisation.

3. The model considers future scenarios of the power systems during the energy transition and transformation. It is, therefore, useful for understanding the requirements from FCAS and frequency control perspectives for enabling the power system transformation and achieving future scenarios, e.g. ISP's scenarios.
4. The developed model is beneficial for identifying the challenges and issues that would encounter energy transition from the frequency control view of point; it is, therefore, useful for power system operators and planners by divining the required insights for enabling energy transition.
5. The model is capable for identifying the research gaps and technical issues related to frequency support in modern and future power systems going through energy transition.
6. The is capable for testing and validating frequency control methods and frequency support services techniques.
7. The model is applicable for understanding, designing, and analysing the UFLS techniques for power systems, therefore, the model is useful for power system frequency protection studies.
8. The model is useful for determining the requirements of services in a specific power region of an interconnected power system. This means the model is useful for understanding the requirements for frequency control ancillary services regionalisation.
9. The model is capable for determining the required minimum rotating synchronous inertia in a specific power region, considering the interconnectors and their capability to transfer the inertial response from one region to others.
10. The model is useful for coordination between different frequency service providers to achieve the optimal frequency response; this means the model can be useful for coordinating between primary frequency control, secondary frequency control, and inertia response in order of obtaining a satisfactory frequency response after a disturbance.
11. The model is unique for determining the optimal setting of frequency controllers and service providers to get a stable and secure frequency response.

In summary, Monash notes that the model can be useful for assessing and evaluating the frequency risk in modern and future power systems under different possible scenarios.

The project further explores other challenges associated with frequency control in wide area interconnected power systems and proposes several additional tools to assist operators:

- Frequency control method for NEM and international power systems based on advanced dynamic state estimation method to improve stability.
- Electric Vehicle (EV) aggregation method scheme for participation of EVs in primary frequency control.
- Method for the aggregation of the estimated demand of thermostatically controlled loads and their impact on rate of change of frequency in interconnected power systems, and their ability to provide frequency response services.
- Investigation into minimum inertia requirements for interconnected systems and the replacement of synchronous inertia with synthetic inertia.

5 Distributed Energy Resources

5.1 Integrating Distributed Energy Resources

DER, specifically rooftop solar photovoltaic (DPV) is now the single largest generator technology in the NEM. With over 18,000 MW of installed capacity installed across the NEM, AEMO's 2022 ISP estimated that by 2030 there could be as much as 35,000 MW. Already some parts of the network, most notably South Australia are reporting days when all energy demand in the state can be met through distributed generation, and these conditions are expected to increase in frequency to the point where the distribution system could be exporting power to the transmission grid. These scenarios create a challenge for the NEM system operator, AEMO, and the transmission and distribution system network owners.

Despite the large quantity of installations, there are still many unknowns about DER, 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[15] and Project Symphony[16], 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, including research in:

1. Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia
2. DER and Stability

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.

5.2 Topic 8: Using operating envelopes to orchestrate DER across Australia

Australia is leading the world on rooftop solar photovoltaic (PV) with more than one in three houses having the technology. This and other Distributed Energy Resources (DER) such as batteries and electric vehicles are creating opportunities to homes and businesses as they can reduce energy bills but also, through aggregators, can participate in the electricity market managed by the Australian Energy Market Operator (AEMO). The challenge, however, is to ensure we make the most of the existing electricity distribution infrastructure (e.g., distribution lines, transformers) connecting homes and businesses whilst ensuring its integrity.

One way for distribution companies – who own and operate the electricity distribution infrastructure and are known in Australia as Distribution Network Service Providers (DNSPs) – to ensure the integrity of the electricity distribution infrastructure is by orchestrating DERs, in other words, by actively defining export and/or import limits at the connection point of customers or for the DER technology itself. This concept is

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

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

known in Australia as *Operating Envelopes* (OEs, aka Dynamic Operating Envelopes) and is being demonstrated by different DNSPs through multi-million trials funded by the Australian Renewable Energy Agency (ARENA). While these trials are extremely valuable in understanding the different aspects associated with the implementation of OEs, in practice, each DNSP is adopting different approaches. This is because different DNSPs, due to regional and/or historical reasons, have different data availability when it comes to residential Low Voltage (LV) electrical network models (topology, impedances, phase grouping) and customer monitoring (smart meters).

This Stage 2 Topic 8 project has carried out an assessment of the benefits and drawbacks of different OE implementations likely to be seen across Australia. It provides metrics and recommendations for DNSPs and AEMO to assist them in their decision-making process by investigating in detail, quantitatively and qualitatively, different potential OE implementations (specifically, different approaches to calculate OEs at the customer connection point). This project draws recommendations by:

(a) Characterising the spectrum of available infrastructure/data across Australian DNSPs.

(b) Defining the potential OE implementations (including calculation and allocation) according to the spectrum identified.

(c) Defining key metrics that capture the interests and concerns of key stakeholders (i.e., customers, DNSPs, AEMO).

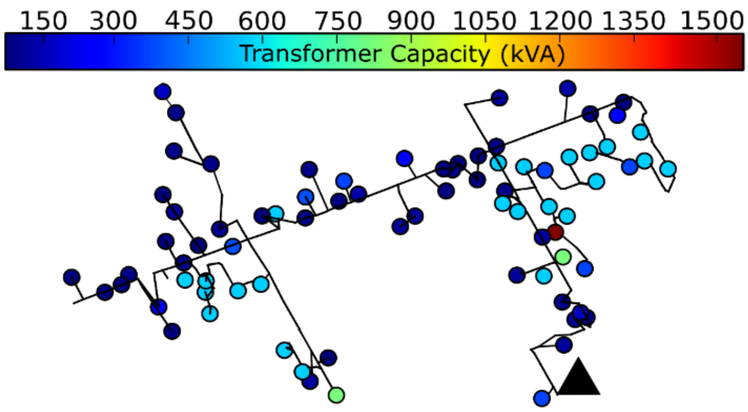
(d) Carrying out detailed power flow simulations using realistic unbalanced three-phase HV-LV distribution network models considering the different OE implementations and different DER mixes and uptake.

(e) Using the results of the simulations to assess the performance of each OE implementation, and to provide recommendations for stakeholders.

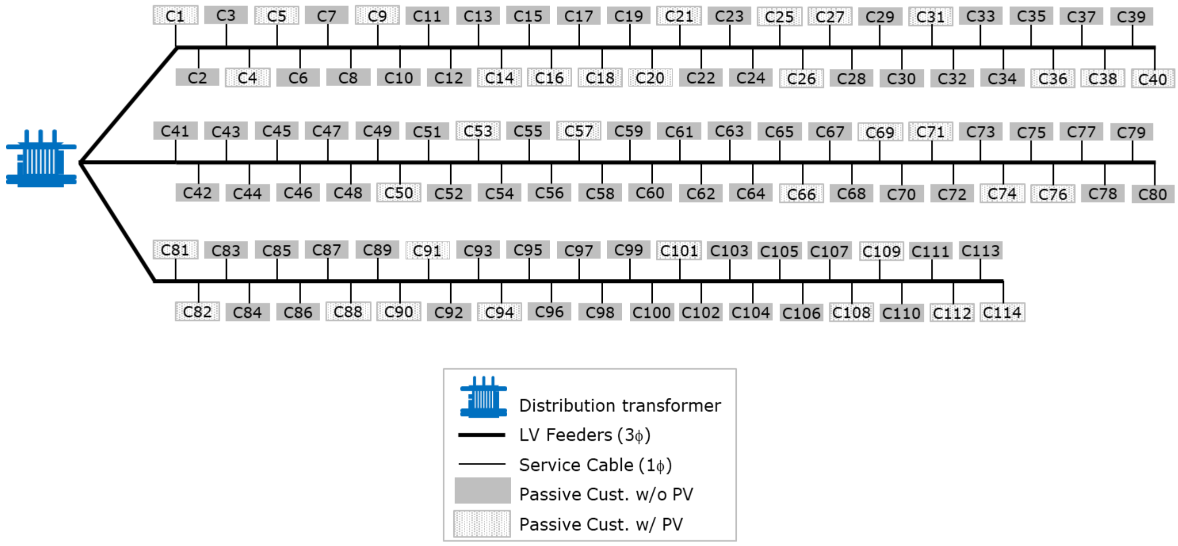
By means of a survey, in which all Australian distribution network owners participated, University of Melbourne collected the currently available infrastructure and data these businesses have available and identified four different approaches to calculate OEs:

1. Ideal OE (used as benchmark) as the most advanced method that requires full electrical network models and full distribution-customer and -transformer monitoring.
2. Asset Capacity OE, which is the least advanced and only considers the thermal capacity of the distribution transformer to determine network capacity to distribute amongst customers.
3. Asset Capacity & Critical Voltage (AC_CrV) OE, as a more advanced for of the Asset Capacity OE, as both voltage and thermal capacity limits are considered. However, voltage is only monitored at the critical customer node.
4. Asset Capacity & Delta Voltage (AC_ΔV) OE, which is a more advanced form of the AC_CrV as it monitors voltage at both the critical customer node and the upstream network connection, as well as the transformer thermal capacity.

Using nine specific performance metrics, including OE accuracy, voltage compliance, maximum voltage, minimum voltage, asset utilisation, total OE gain, aggregated exports/imports, equity/fairness, and complexity and cost of implementation, the four methods were compared in performance, customer impact, service provision and feasibility. The network model used is that of a real Australian medium voltage (22kV) feeder, as shown in Figure 22. In their work the researcher considered sensitivity of performance on levels of active customer participation.



(a) Real Australian MV feeder (22kV)



(b) Representation of the LV network selected for testing OE implementations.

Figure 22: Distribution system model used to evaluate and compare the performance of the four OEs considered

The following recommendations consider the OE implementations investigated in this project, their capacity on keeping the network within the required technical limits (i.e., voltages and thermal) according to the penetration of active customers, and which DNSPs currently have (or a close to have) the capabilities to use each OE implementation.

Asset Capacity OE

1. **Can be used by DNSPs that monitor distribution transformers**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy and South Australia Power Networks), Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy) and Step Transition cluster (Evoenergy), may already have the required capabilities to implement the Asset Capacity OE.
2. **Can be used in the short-term or in areas with low numbers of active customers**. Although the Asset Capacity OE implementation does not cater for voltage aspects, the latest PV inverter standard that combines Volt-Watt and Volt-var functions may help in areas with low numbers of active customers. However, it is not recommended in areas with medium or high numbers of active customers.

3. **Can be used in areas with thermal problems but not voltage problems**. The Asset Capacity OE implementation only consider thermal aspects on its calculation.

Asset Capacity & Critical Voltage OE

1. **Can be used by DNSPs that monitor distribution transformers and have historical non-market data from some LV customers (or critical points of the LV networks)**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy) and Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_CrV OE.
2. **Can be used by DNSPs with full monitoring of LV customers**. The full monitoring of LV customers could be used to estimate the power flow on the distribution transformer. The DNSPs that fall in this category are Ausnet Services, CitiPower, Horizon Power, Jemena, Powercor, and United Energy.
3. **Can be used in the medium-term or in areas with medium numbers of active customers**. The performance of the AC_CrV OE implementation may be enough for areas with a medium number of active customers, but it is not recommended in areas with high numbers.

Asset Capacity & Delta Voltage OE

1. **Can be used by DNSPs that monitor distribution transformers and have historical non-market data from some LV customers (or critical points of the LV networks)**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy) and Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_ΔV OE.
2. **Can be used in the medium-term or in areas with medium numbers of active customers**. The performance of the AC_ΔV OE implementation may be enough for areas with a medium number of active customers, but it is not recommended in areas with high numbers.

Ideal OE

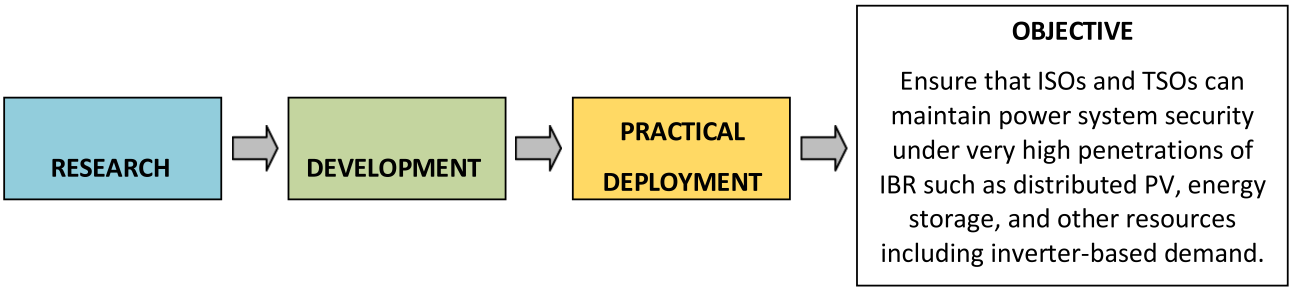
1. **To be used in the long-term or in areas with high numbers of active customers**. The Ideal OE implementation is the most accurate OE approach, however, it is recommended to be used for high numbers of active customers. Since it requires full electrical LV network model and full monitoring of customers plus transformer monitoring, it is likely that DNSPs might require a few years to fully adopt this OE implementation.
2. Although none of the DNSPs have all the required capabilities to implement the Ideal OE today, the DNSPs of the Step Transition cluster (Evoenergy and Horizon Power) and some of the Very Fast Transition (Ausgrid, Citipower, Powercor, and United Energy) cluster are the ones with the highest potential to use it first in the near future in some parts of their network.

University of Melbourne concluded that this project has demonstrated that full electrical LV network models and full monitoring of network/customers are not necessarily needed to calculate adequate OEs for low/medium numbers of active customers. Simpler OE implementations that require very limited knowledge of the electrical network and very limited monitoring may be good enough (not perfect though) to solve excessive voltage rise/drop and asset congestion on areas with low to medium numbers of active customers. This suggests that for the near future, complex OE implementations are not needed in most of the distribution network areas. Nevertheless, for the long-term, more advanced OE implementations will be required.

5.3 Topic 9: DER and stability

UNSW Sydney in collaboration with the University of Wollongong and support from the Common- wealth Scientific and Industrial Research Organisation (CSIRO), the Australian Energy Market Operator (AEMO) and GHD is undertaking Stage 2 of the Australian Research Program for the Global Power System Transformation (G-PST) Consortium.

Under Topic 9 - DER and Stability, UNSW and UoW have focused on modelling and analysis of distributed energy resources (DER), battery energy storage systems (BESS) both as standalone systems, as well as those integrated with PV systems (hybrid energy storage systems - HESS) and a broad variety of modern loads to ensure system operators can maintain power system security in the current challenging power system operation environment. The work that has been undertaken provides robust and accurate data for responses from a large number of devices which have been bench-tested using thorough experimental methods and directly informing the load model development activities of AEMO[17].



IN their Stage 2 work, UNSW's and UoW report on their findings to date on DER responses, BESS and HESS operating modes, testing resources, and load testing during grid disturbances. The results collected also serve as inputs to ongoing load modelling activities. The main conclusions of Stage 2 work for Topic 9 are:

1. The behaviour of PV inverters when updated to the most recent AS4777.2:2020 standard is generally compliant and aligned with requirements. However, this observation does not extend to BESS and HESS systems where diverse responses to grid disturbances were observed in this round of testing.
2. The current RMS load models do not capture the diversity of load responses to grid disturbances. Distinct behaviours have been observed among devices within the same load category and the range of options further complicates testing for load modelling.

[17] https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/operations/power-system-model-development

3. EV charging infrastructure should be tested and modelled depending on whether the EV chargers include active power electronics or not. When chargers do not have active power electronics, the response will depend on the connected EV.
4. The PV inverter testing experience emphasises the importance of evaluating multiple devices, with the results contributing to load models with greater confidence. Preliminary tests on BESS, HESS, EVs and loads have provided valuable insights into testing and general behaviour; however additional tests are required to validate observations.

The research has further produced specific learnings and insights on individual technologies, described by the researchers in the following key points.

Key findings for PV Inverters

- Each tested single-phase grid-connected PV inverter configured to the AS/NZS 4777.2:2020 standard followed the defined fault-ride-through behaviour when subjected to voltage disturbances.
- Each single-phase grid-connected PV inverter presented expected ride-through and power curtailment behaviour when subjected to frequency disturbance.
- All the tested inverters rode through voltage phase-angle jump disturbance without significant output disruption.
- Extensive testing on the single-phase grid-connected PV inverters allowed AEMO to develop and tune the parameters of the composite load model, which further led to the update of AS4777.2:2020, yielding compliance from grid-connected PV inverters.

Key findings for Battery Energy Storage Systems (BESS)

- The single BESS tested could only ride-through the voltage disturbance and provide Volt-Watt and Volt-Var responses. It was unable to meet expectations during the comprehensive voltage sag testing.
- While the performance during voltage swell testing was improved, compared to that observed during voltage sag events, it still did not meet all requirements and expectations.
- During frequency and phase jump disturbances, power oscillations were also observed leading to the eventual disconnection of the BESS inverter from the grid.
- When reconnecting after a disturbance, the BESS resumes operation from the same power level at which it got disconnected, causing high power injection or absorption from the grid.

Key findings for Hybrid Energy Storage Systems (HESS)

- In Stage 2, only a small number of hybrid inverters were tested. While these tests provided useful insights, the limited scope cannot offer a comprehensive understanding of hybrid inverter behaviour under grid disturbances, unlike the more extensive PV inverter testing.
- Drawing from our prior experience with single-phase inverter testing, hybrid inverters underwent extensive voltage sag and swell testing to identify any undesirable behaviour presented by hybrid inverters when subjected to grid disturbances of less than 1s. The results indicated that only one hybrid inverter managed to ride through all the sag disturbances, both at full and half power. Conversely, just two out of the four inverters successfully rode through at full power, while all four managed to ride through at half power.
- Testing at different power levels provides evidence that warrants reconsideration of the AS 4777.2 Standard and whether testing should be conducted at full power. To ensure credibility of the findings, additional hybrid inverters should be tested if a revision of the AS 4777.2:2020 is proposed.

- Only one out of four hybrid inverters that were tested was able to provide ride-through behaviour under frequency disturbance tests under all modes of operation.
- Only one out of four hybrid inverters that were tested was able to ride-through all voltage disturbances. The remaining three inverters presented volt-watt response grid support functionality directed by AS 4777.2:2020
- Three out of the four inverters tested were unable to ride through all voltage phase-angle jump disturbances. This highlights a major issue with voltage phase-angle jump requirements that were introduced recently in AS 4777.2:2020.

Insights into Load responses

- Load responses to grid disturbances verify certain characteristics of loads that are not modelled in the current rms composite load model. These characteristics include capacitor current overshoots and motor inrush currents. As EMT models of the composite load model are developed, results from Stage 2 can be used to incorporate these characteristics into EMT models.
- The current rms model of the composite load model fails to consider phase angle jumps often observed after grid faults. The results of this study provide preliminary results for incorporating phase angle jump behaviour into the EMT models.
- Most of the appliances tested exhibited only temporary power cessation during disturbances before resuming normal operation once the disturbances were cleared. However, inverter-based air conditioners disconnected after voltage sag events.
- Appliances with inverter-based interfaces, such as refrigerators and air conditioners, for disturbances which caused their traditional (DOL) counterparts to stall. This suggests that they should be included in the Electronic Load element of the load model instead of being represented separately.
- Electronic loads remained unaffected by frequency disturbance tests, except for the inverter-based microwave oven. Further tests are needed to determine if some of these loads are influenced by frequency variations.
- The operation of most tested loads remained unaffected by phase angle jump disturbances, except for the DOL motor-based refrigerator and air conditioner.
- Static loads responded as anticipated by the composite load model, behaving like constant load, power, or impedance loads.
- Similar to the DER inverter tests, testing multiple devices of the same type provides additional insights in their operation and modelling requirements. In Stage 3, attention should be given to other motor types (A, B, and C), including water pumps and commercial refrigerator systems.

Insights into EV Charger responses

- The current complex load model lacks a component that represents EVs or EV Chargers.
- Many small residential EV chargers comprise electrical contactors, communication and control elements but lack active power electronics. The response of the EV charger to a grid disturbance will depend on the response of the EV onboard power electronics as well as any additional behaviour (e.g., internal tripping) of the EV charger itself.
- Given that the response depends on the EV fleet, a stochastic model for the behaviour of residential EV chargers could be more suitable.
- Since only one EV was available to the project during Stage 2, additional testing involving various EVs is required.

- Fast chargers (or Level 3 chargers) incorporate power electronics and mitigate the impact of individual EVs to grid disturbances. Stage 2 did not include testing on fast chargers.

Engagement with Stakeholders and OEMs

- BESS and HESS testing results were shared with stakeholders and OEMs to gather feedback on the methods and help us understand the captured behaviours.
- OEMs were provided with detailed results of unexplained or unexpected behaviours identifying recommended or necessary firmware updates.
- All tested systems were connected to OEM cloud services allowing interrogation of responses during faults from locally and remotely captured data.

6 Starting the journey

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.

The second stage of the Roadmap commenced in May 2022, implementing 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 report describes the key outcomes and the great progress made over that past twelve months since initiation. However, Stage 2 represents only the first 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 Ward, *Research Director, Energy Systems Program, CSIRO*

6.1 Progress to date

Commencing in May 2022, nine research projects were instigated by CSIRO to work on (and further develop) the highest research priorities for each of the topics that make up the CSIRO G-PST Research Roadmap.

Since the commencement of Stage 2 over the course of the past year, each research topic has been progressed, initially driving forward the most critical tasks that are urgent and/or foundational to the subsequent research. The following sections indicate the approximate progress made in each area funded by CSIRO.

6.1.1 Topic 1: Advanced inverter design

Topic 1 of the CSIRO G-PST Research Roadmap tackles critical tasks in the development of capabilities and associated services, design methodologies, and standards, for IBR, which are now the most commonly used technology for interfacing renewable energy sources with the power grid. The Roadmap defined five major tasks of this research topic as shown in Figure 23.

Figure 23: **Major tasks defined for the 'Inverter Design' Research Plan.**

The Roadmap for Topic 1 has defined several subtasks within each major task.In addition to these, a further five tasks that are shared across G-PST topics have been defined with the Australian energy sector in mind.

The Stage 2 research of Topic 1 has progressed tasks of the 'Advanced Inverter Design' roadmap as shown in Table 2.

Table 2: **Priority and stage of completion for the research tasks of Topic 1**

Major Task/ Shared Task	Subtask	Priority	Completion
Frequency Stability	Defining the response of GFLIs and GFMIs for a credible contingency	Urgent	*Future Stages*
	Control of ESS based on the capability of the energy source to provide various frequency services	Next 5 years	*Future Stages*
	Coordinated/distributed control of BESSs for frequency control	Next 10 years	*Future Stages*
Voltage Stability	Investigation of IBR reactive power provision capabilities against the backdrop of losing synchronous machines	Next 5 years	*Future Stages*
	Interactions between synchronous machine AVR, GFMI AVR and GFLI in providing reactive power support	Urgent	*Future Stages*
Interaction Mitigation and Oscillation Damping	Identifying the nature of oscillations in IBR-dominated grids	Urgent	*Future Stages*
	Standardising the models of IBRs	Urgent	*Future Stages*
	Modelling, analysis, control and coordination of IBRs for oscillation damping	Urgent	*Future Stages*
Protection and Reliability	IBRs effect on existing protection systems	Next 5 years	*Future Stages*

	Enhancing IBR response during, and subsequent to, faults	Urgent	40%
	Assessment and enhancement of IBRs reliability	Next 10 years	*Future Stages*
	Cyber-secure inverter design for grid-connected applications	Next 5 years	*Future Stages*
Trending Topics	Developing alternative control methodologies for GFMIs	Next 5 years	25%
	Grid-forming capability for HVDC stations and wind and solar farms	Next 5 years	*Future Stages*
	AI in IBRs control	Next 10 years	*Future Stages*
with Topic 2: Stability Tools	Implementation of efficient simulation tools	Next 5 years	*Future Stages*
	Determination of the best level of modelling detail for different phenomena in IBR-dominated grids	Next 5 years	*Future Stages*
with Topic 3: Future Control Rooms	New measuring and monitoring systems for frequency and RoCoF	Urgent	*Future Stages*
with Topic 5: Restoration and Black Start	IBR control for black start and restoration	Next 5 years	*Future Stages*
with Topic 6: Services	Fast response voltage control in IBR-dominated power systems	Urgent	*Future Stages*
with Topic 8+2: DER & Stability Tools	Effects of a high level of DERs on the transmission system	Next 5 years	*Future Stages*

6.1.2 Topic 2: Stability Tools and Methods

Topic 2 of the CSIRO G-PST Research Roadmap has outlined a number of urgent, high-, medium- and low-priority tasks. The urgent and high priority ones and their progression during Stage 2 of the research are shown in Table 3.

Table 3: Summary of high priority topics addressed in Topic 2 along with main research areas

Topic	Expected Research Outcomes	Completion
1. Stability margin evaluation	• Tools to evaluate non-linear stability margins using black-box models. • Evaluation of stability at multiple operating points	30%
2. Small signal stability screening methods	• Development of procedures to use impedance-based methods for stability screening. • Development of linear analysis techniques with black box IBR models.	30%
3. Voltage stability boundary	• Tools to identify new boundaries between source and sink regions • Recognise voltage stability boundary as a new constraint/criterion for system operation	*Future Stages*
4. Voltage control, recovery, collapse	• Improvement in way loads and IBRs are considered in Volt/Var tools • Tools to assist operator with high voltage mitigation due to increase in IBR output	*Future Stages*

Topic	Expected Research Outcomes	Completion
5. Online identification of system strength	• Methods/tools to efficiently identify system strength in real time operations • Analytical evaluation of locations at which system strength is to be determined	*Future Stages*
6. Monitoring inertia in real time	• Tools to identify of levels of demand side inertia contribution • Quantify regional inertia impact on frequency response.	*Future Stages*
7. Modelling and model validation	• Development of generic models for newly emerging IBR control modes. • Validation and maintenance of aggregated representation of load and DERs.	*Future Stages*
8. Voltage and reactive power management	• Tools to be used in operations to coordinate and control deployment of reactive power devices • Determination of area of vulnerability for large loads.	25%
9. Real time simulators	• Development of expertise in utilising HIL setups. • Integrating HIL as part of system planning	*Future Stages*
10. Critical contingency identification	• Tools to consider IBR dynamics while analytically evaluating and ranking criticality of contingencies • Use of machine learning methods to classify and rank evolution of contingencies	*Future Stages*
11. Real time contingency analysis	• Improvements in multi-core computing to extend the applicability of parallel processing • Improved identification of critical contingencies to be evaluated.	*Future Stages*
12. Protection system operation and coordination	• Development of accurate IBR short circuit models for use in simulation tools • Tools to carry out advanced fault studies and configure protection relaying settings with change in IBR output.	*Future Stages*

6.1.3 Topic 3: Control Room of the Future

As part of the Stage 2 effort of Topic 3, EPRI has progressed critical tasks of the research roadmap developed for the control room of the future. Of the five overarching areas, Stage 2 has successfully progressed the CRoF Data Models and Streaming task, as shown in Table 5. Other areas are being explored and advanced as part of the AEMO Operations Technology Roadmap, or are planned for later stages of the G-PST research.

Table 4: Progress of Topic 3 research against the 2022 Research Roadmap tasks

	RESEARCH TASK	Completion progress
	1 CRoF Data Models and Streaming	
1.1	Data governance and management responsibilities. First assessments on model quality based on existing simulation system.	10%
1.2	Alignment of operations model standards& requirements across industry	5%
1.3	Data Governance and management responsibilities for control room streaming data.	10%
1.4	Standard approaches to alarm management, asset health monitoring, generation and market participant monitoring.	30%
1.5	Open data from market and operations, availability.	5%

	2 EMS/SCADA and MMS/NEMDE	Stage 4+ and/or OTR
	3 Control Room and Operations Engineering	Stage 4+ and/or OTR
	4 Operator and Human Factors	Stage 4+ and/or OTR
	5 Buildings, Facilities, and Hardware	Stage 4+ and/or OTR

6.1.4 Topic 4: Power System Planning

Research for Topic 4 has been arranged into five interactive tasks, as shown in Figure 24. University of Melbourne's research for Stage 2 has focused on research tasks within programs 1, 4, and 5, tackling the most critical matters first.

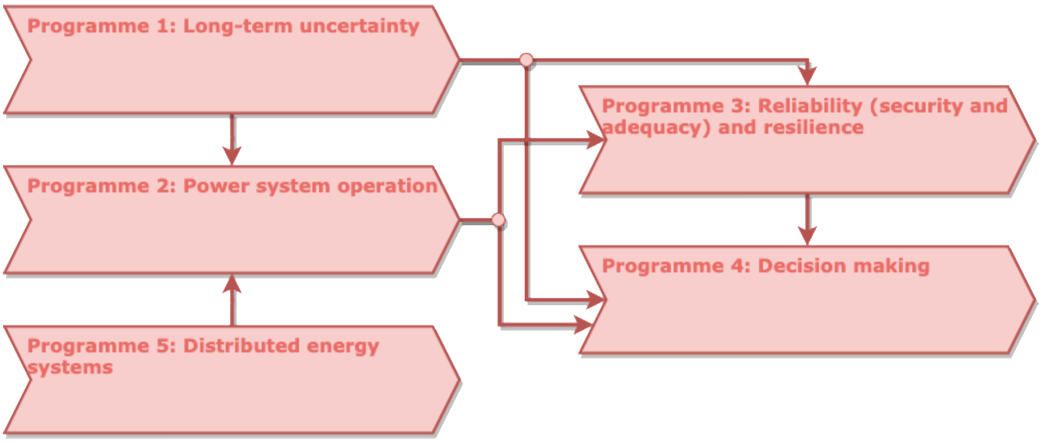


Figure 24: Interactions between research tasks of the Topic 4 research

Within each program the researchers have identified multiple research streams, and one or more projects within each stream. For Stage 2, the tasks identified as most critical to initiate and progress include:

1. Identify the optimal infrastructure investment solutions, and their optionality value, yielded by an adaptive, flexible plan based on multi-stage stochastic planning.
2. Assess the robustness of a transmission plan based on deterministic approaches such as least-worst weighted regret (LWWR) analysis relative to flexible planning.
3. Quantify the investment risk associated with deterministic and stochastic methodologies and possible options to model and control investment risk.
4. Propose suitable methodologies to assess and quantify the value of different infrastructure investment options in providing resilience to HILP events.
5. Assess and compare the value of investment in alternative technologies, like DER and hydrogen as a means to defer investment-intensive assets.

Completion of these tasks has progressed Topic 4 research as shown in Figure 25.

PROGRAMME	STREAM	PROJECT	CODE	Project	Progress
Long-term Uncertainty	Scenario development for planning studies	Modelling long-term uncertainty in power system planning with the consideration of HILP events (adequacy and security) and critical operation conditions	R1S1P3	Ongoing	15%
Decision Making	Metrics, objectives and risk modelling of different stakeholders	Modelling competing objectives, sources of risk, and risk appetite of different stakeholders in power system planning. Determination of metrics to value cost and risk	R4S1P1	Ongoing	25%
		Modelling investment flexibility in power system planning decision making by enhancing the decision structure and the representation of scenario trees	R4S2P2	Ongoing	50%
Distributed Energy Systems	Multi-energy systems	Modelling the impact and flexibility embedded in the interactions between power systems and other energy systems for planning studies	R5S1P1	Ongoing	10%

Figure 25: Research projects within Topic 4 progressed during Stage 2

6.1.5 Topic 5: Black starting and system restoration

As part of the Stage 2 effort of Topic 5, Aurecon has progressed critical tasks with the research roadmap developed for black start and restoration. Of the five overarching areas of system restoration research, Stage 2 has successfully progressed four, as shown in Table 5.

Table 5: Progress of Topic 5 research against the 2022 Research Roadmap tasks

	RESEARCH TASK	Completion progress
1	**Inverter-based resources**	**50%**
1.1	Grid Following Inverters (GFLI)	50%
1.2	Grid Forming Inverters (GFMI)	83%
1.3	Distributed Energy Resources (DER)	*Future Stages*
1.4	The role of synchronous generators and condensers in an IBR dominated power system	65%
2	**Network impact**	0%
2.1	Impact on control systems	*Future Stages*
2.2	Impact on protection systems	*Future Stages*
2.3	Assessing the need for modifications	*Future Stages*
3	**Tools and techniques**	**10%**
3.1	Power system modelling and simulation tools	20%
3.2	Decision support tools for control centers	*Future Stages*
4	**Technical and regulatory requirements**	**15%**
4.1	Technical and regulatory requirements	15%
5	**End-to-end system restoration**	**20%**
5.1	Restoration from transmission network	25%
5.2	Restoration from distribution network	*Future Stages*
5.3	Commissioning and model validation tests for end-to-end black start capability	*Future Stages*
5.4	Representative example of end-to-end system restoration in power systems with high share of IBR	50%

6.1.6 Topic 6: Services

The NEM, just like other modern power systems, uses a range of essential system services to manage the power system voltages, power system frequency, relying on other critical quantities such as inertia and system strength. Stage 2 research of Topic 6 has focused on power system frequency , with the progress made shown in Table 6. Future stages of Topic 6 will expand the research into other areas of essential system services, while concurrently further work in power system frequency management and control also will be needed.

Table 6: Progress of Topic 6 research against the 2022 Research Roadmap tasks

	RESEARCH TASK	Completion progress
1	What system services are needed to maximise the benefits of stakeholders and to achieve an at least cost transition?	
1.1	How should services be coordinated across the transmission and distribution levels?	*Future Stages*
1.2	What tariff settings can produce a sustainable power grid transformation, promoting demand response mechanisms and encouraging peak load mitigation?	*Future Stages*
2	Are **frequency support services** suitably configured to achieve the long-term interests of electricity stakeholders?	60%
2.1	What type of resources and configurations are more efficient for FFR provision?	60%
2.2	Virtual inertia in existing (or future) wind farms	60%
3	What services are needed to achieve the **technical requirements** of Australia's future power grid to maintain?	10%
3.1	The necessity for and the requirements of expanding frequency and voltage support services to the distribution grid in Australia need further studies.	15%
3.2	There is an appetite to unlock flexibility, either by way of matching customer needs with Variable Renewable Energy (VRE), or providing a new level of system preparedness through applications such as virtual power plants (VPPs).	15%
3.3	Flexibility, an attribute on top of all services, needs standalone research in the Australian grid.	*Future Stages*
4	Are **voltage support services** suitably configured to achieve the long-term interests of electricity stakeholders?	0%
4.1	How should voltage support services be differentiated across the generation, transmission and distribution sectors of the grid?	*Future Stages*
4.2	What opportunities for voltage support services arise through the uptake of new disruptive technologies	*Future Stages*
5	What **metrics** should be used to define services in IBR dominated grids?	20%
5.1	How should current metrics be re-defined to measure the impact of new technologies and services?	25%
5.2	What new metrics should be introduced to assess quality of service of IBR driven distributed supply and demand on frequency and voltage control, and black-start performance.	25%
5.3	How flexibility measures, such as the flexibility chart and Insufficient Ramping Resource expectation, can help in dynamic monitoring of the Australian grid flexibility?	*Future Stages*
5.4	Is there a requirement to introduce an inertia market in Australia?	25%

6.1.7 Topic 7: Power System Architecture

Power system architecture is a complex and evolutionary field of research, and Strategen has progressed along the research roadmap of Topic 7 in developing a reference architecture structure, a first step in the work required (Figure 26). Successfully completed, and contained within this initial stage are four distinct parts, critical to the overall reference architecture development:

1. Customer and societal objectives for future power systems
2. Emerging trends that are diving change in GW-scale power systems

3. Systemic issues that impede progress and require architectural interventions
4. Emerging system structures derived from mapping the 'as built' architecture settings to accommodate a 'Step Change' type of future.

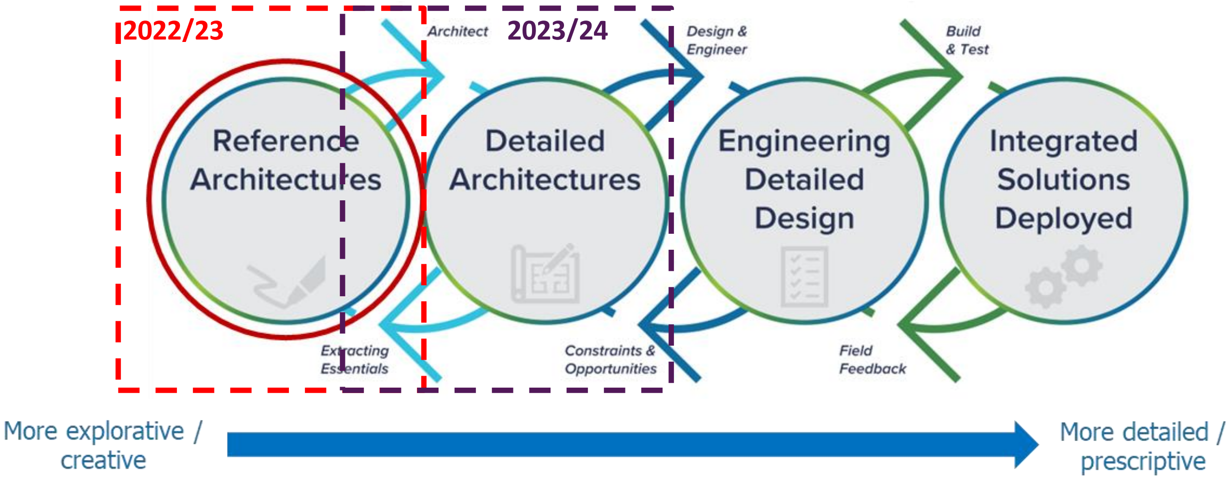


Figure 26: Progress of Topic 7 research against the 2022 Research Roadmap tasks

6.1.8 Topic 8: Using OEs to orchestrate DERs

The research roadmap of Topic 8 identified ten research questions that would be addressed over the duration of the program. During Stage 2, these have progressed as shown in Table 7.

Table 7: Progress of Topic 8 research against the 2022 Research Roadmap tasks

	RESEARCH TASK	Completion progress
	Very High Priority	**23%**
0.1	What data flows (DER specs, measurements, forecasts, etc.) are needed to ensure AEMO has enough DER/net demand visibility to adequately operate a DER-rich system in different time scales (mins to hours)?	22%
1.3	What is the role of DER standards in concert with the future orchestration of DERs?	25%
4.1	What are the minimum requirements for a DER-rich distribution network equivalent model to be adequate for its use in system planning studies?	*Future Stages*
5.1	What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?	25%
5.2	What are the necessary considerations of establishing a distribution-level market (for energy and services)?	20%
	High Priority	**40%**
1.1	For each of the potential technical frameworks for orchestrating DERs in Australia (e.g., based on the OpEN Project), what is the most cost-effective DER control approach to deal with the expected technological diversity and ubiquity of DERs?	40%
1.2	For each DER control approach, what is the most adequate decision-making algorithm (solution method)?	50%
3.1	What are the most cost-effective ancillary services that can be delivered by DERs considering the expected technological diversity and ubiquity of DERs?	*Future Stages*

4.2	What is the minimum availability of ancillary services from DERs at strategic points in the system throughout the year and across multiple years?	30%
	Medium Priority	**40%**
2.1	For each of the potential technical frameworks for orchestrating DERs and the corresponding decision-making algorithms, what is the most cost-effective communication and control infrastructure?	40%

6.1.9 Topic 9: DER and Stability

Figure 27 shows an overview of the Topic 9 research program and how the proposed research and development schedule and topics offers can support practical deployment of DER. The figure also highlights the key areas that have been covered as part of Stage 2 (darker shading indicates greater coverage in Stage 2), with a particular focus on:

- Inverter Responses and sensitivities
- Dynamics of Power Quality Modes,
- Fault and disturbance propagation,
- Extension of the AEMO toolset,
- Input to development and validation of the Load-DER composite model,
- Roll-out of the revised AEMO toolset, and
- Engagement with stakeholders.

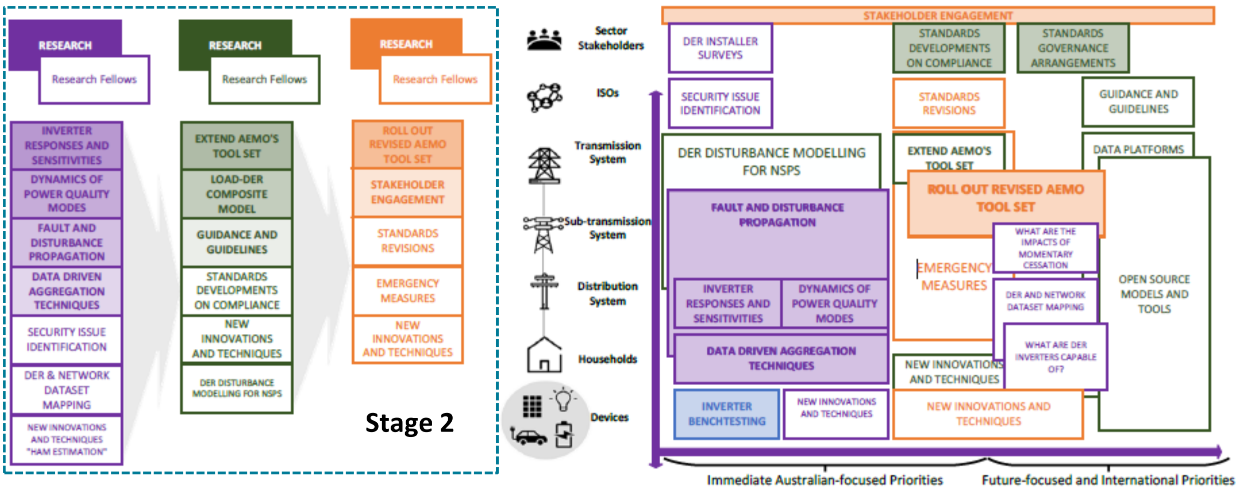


Figure 27: Research Topics and alignment of Stage 2 research

The following summarises the progress that was completed as part of Stage 2 against the first of five research questions identified in Section 3.2 of the Topic 9 research roadmap.

1. *What pilot studies must be performed on the network to better understand the behaviour of DER to grid disturbances?*

   - **Continuous testing of DPV inverters (100%)**. With the extensive tests completed at UNSW over the past 4 years and the open release of the testing procedure, we consider this aspect complete. However, continuous testing is required to ensure that newer DPV inverters meet requirements.
   - **Testing of BESS and HESS (50%)**. Testing of 5 devices demonstrated issues with responses when exposed to grid disturbances. The testing procedure is released but additional tests are required to provide adequate input to load modelling in RMS and

EMT models.

- **Testing of EVs (10%)**. The complexities introduced by EV charging infrastructure and EVs requires further testing, especially as EVs are expected to drive major load growth in distribution networks. Testing of 2 EV chargers and 1 EV do not provide sufficient results for load modelling.
- **Testing of loads (40%).** Additional testing is required for loads that correspond to Motor types A, B and C of the CMPLDW load models. Load coincidence or diversity factor also needs to be accounted for.
- **Validation against observations in the networks (20%).** Preliminary work has been undertaken, but additional model development is required.

7 Future Research

7.1 Next steps: Priority research tasks

The CSIRO Australian G-PST Research Roadmap recognises that the research required to lead the way in accelerating the decarbonisation of our energy sector and integrating renewable energy into electricity networks is a long term investment. It is critical to address high priority matters first and retain the agility to resolve emerging ones. Indeed, many of the research questions being addressed will be answered only after multi-year projects. Consequently, the Roadmap envisages several stages of research that will each support the ultimate goals.

This report has provided a summary of the first year of research investment, the second stage of the Roadmap. The researchers of the Stage 2 projects submitted an interim report in December 2022, in which they were asked to recommend suitable future research focus areas, based on their progress and insights gained over the first seven months of their work. In many instances the areas of research proposed continued the research tasks commenced in Stage 2. However, there were also some examples of expansion of the original roadmap. This is to be expected. It reflects the rapid change, and the accelerated learning underway in this changing environment.

Already the third stage continues research in the four identified broad areas and nine research topics, including some of the priority projects described in the following.

7.1.1 Topic 1: Advanced inverter design

Apart from the studies that have been completed or planned to be completed in this project presented above, future studies and directions for the third stage of the CSIRO Research Roadmap (Q2 2023 and onwards) are suggested below.

1. Extension of the APRC for a wider interconnected multi-IBR system, beyond the five devices considered during Stage 2.
2. Investigation on impacts of negative-sequence current reserve on transient stability of GFMI.
3. Extension of the transient stability analysis for wide area multi-IBR systems.
4. Tuning/design guidelines for IBR.
5. Further enhancement of current limiters to improve stability during transient events.
6. Grid-forming inverter applications to wind and solar farms to enhance stability.

7.1.2 Topic 2: Analytical tools and methods

As a new research area, in addition to the topic of determining analytical functions of stability for black box models, , real-time tools should be developed to assess the stability margins of grid-connected inverters by considering not only the normal operations of the power system but also abnormal operations (e.g., during faults and unbalanced events). More precisely, future research opportunities include addressing the following concepts:

1. Determination of the region of convergence of an operating point
2. Modularisation of the analytical stability functions that allow for easy system reconfiguration

3. Development of tools that can automate the process developed to date
4. Discrimination between small signal and large signal stability challenges
5. Development of a process to update the analytical functions when the black box models undergo a change due to firmware updates in the actual product in the field
6. Evaluation of compatibility of derived analytical stability functions with existing commercial simulation tools

7.1.3 Topic 3: Control Room of the Future

The work commenced in Stage 2 is expected to continue to completion, further investigating the use of ML methods to analyse operational alarm data and assist operator decision making.

Based on the methodologies developed to detect alarm spike, chatter, and pattern mapping, one use case has been examined. Further data sets and use cases should be developed to verify the useability of the models and methods. Further optimisation of the methods is also a priority matter.

7.1.4 Topic 4: Power system planning

Power system planning research should continue to build on the results and insights of Stage 2 and progress further high priority tasks, such as:

1. Identifying the value of demand side flexibility, including and especially DER, from the perspective of transmission planning (research program 5 of the Topic 4 Roadmap),
2. Improving the modelling of dynamic security constraints, specifically those related to frequency control and system strength issues, to better capture the value of new types of electricity storage systems, demand response and transmission options in addressing those issues (research program 2),
3. Assessing the benefits of sector coupling and long-term storage options in the provision of reliability and resilience (research programme 3), based on the methodologies developed to assess resilience using stochastic planning, and the modelling requirements to include hydrogen assets in the decision portfolio.

7.1.5 Topic 5: Black start and system restoration

The recommendation of future work is consistent with the original research plan proposed in 2021, thereafter the most critical items were included in the 2022-2023 research plan and pursued. The list below includes recommended priority items to be addressed as part of the 2023-24 research work.

1. The treatment of inverter-based resources during system restoration including Large-scale IBR and distributed energy resources (DER).
2. Impact on network control and network element protection systems on effective system restoration.
3. Power system modelling, simulation and testing of GFMI and GFLI.
4. Defining power system technical requirements during system restoration, including, but not limited to dynamic reactive support plant performance and DER response.

5. Assessing bottom-up restoration techniques such as using optimal placement of GFMI black starter IBR, the use of various storage technologies as stabilising loads, or synchronising two or more power islands.

7.1.6 Topic 6: Services

The research of Stage 2 has focused on the technical aspects of power system frequency control. The researchers have recommended a continued effort be made in this area, including tasks such as:

1. Studying the requirements for FCAS regionalisation to determine the optimally needed FCAS in each power region based on both market and dynamic responses during events.
2. Developing methods to coordinate the response from FCAS sources within a power region and across power regions, including assessing opportunities for controls to activate FCAS locally by making the controller smart enough to recognise if the event is within the power area or not.
3. Studying the RoCoF ride-through capabilities of synchronous generators and other network elements to answer the following questions:
   (a) What levels of RoCoF can existing synchronous generators in the NEM ride-through?
   (b) What are the various mechanisms that could lead to tripping/disconnection?
   (c) Apart from synchronous generators, are there any other elements in the power system that might exhibit unusual behaviour or tripping in response to high RoCoF?

7.1.7 Topic 7: Power system architecture

Topic 7 research during Stage 2 has culminated in the development of a reference architecture, identifying emerging issues, requirements, stakeholder and societal expectation. To now progress to a detailed architecture design, the researchers recommend that subsequent stages consider development of the detailed architecture by progressing two tasks in parallel:

1. Demonstrate the practical benefits of applying PSA disciplines to the following five topics in a whole-of-system and medium-longer term architectural manner:
   (a) Whole-system Demand-side Flexibility (DSF),
   (b) Dynamic Operating Envelopes (DOE) and capacity allocation fairness in a unified manner,
   (c) Management of Minimum Operational Demand (MOD),
   (d) Identification of hidden structural cyber-security vulnerabilities, and
   (e) Relevant Distribution System Operator (DSO) models.
2. Work collaboratively with CSIRO and AEMO, and a diverse range of stakeholders, to co-design a subsequent full Detailed Architecture process involving multi-stakeholder participation.

7.1.8 Topic 8: Using OEs to orchestrate DERs

The Stage 2 work of Topic 8 has advanced numerous high priority tasks of the research roadmap. The researcher recommendation was to continue these tasks to completion over the next stage and to additionally consider two more tasks:

1. Forecasting for OEs in advance of near real-time, i.e., hours ahead, through development of spatially granular forecasts. Such forecasts should capture both the active and reactive power

behaviours of consumers as well as voltages, at specific locations hours ahead, using advanced techniques that exploit available data including features associated with demand and DERs (e.g., temperature, solar irradiance, etc.) while using a limited volume of historical data.
2. Consideration of network and operational factors to capture the effectiveness of alternative OE approaches when applied to alternative types of distribution networks (alternative topologies, impedances, customer categories, etc.).

7.1.9 Topic 9: DER and stability

Topic 9 has advanced the testing of battery energy storage systems, hybrid energy storage systems, many form of household loads and EV charging stations. This has improved the accuracy of AEMO's composite load models. To continue to improve the load and DER models used for power system planning, operation, and general analysis, further tasks are recommended by the researchers, including:

1. Development of time-domain aggregated models.
2. Development of frequency-domain aggregated impedance models.
3. Extended testing of DER, BESS, and Hybrid PV/BESS inverters, focusing on BESS and HESS under grid disturbances.
4. Identification of worse than expected effects and vulnerable DER.
5. Examination of the impact of external control devices on DER response.
6. Extended testing of EVs and smart loads, emphasising power electronics converters, air conditioners, and heat-pumps.
7. Evaluation of interactions between smart loads and DER, and investigation differences between on-board EV chargers and converter-based charging infrastructure.
8. Assessment of the system restoration response of DER, ESS, and EVs in a low inertia environment with limited synchronous generation.
9. Extended testing of motor types A, B, and C, including water pumps and commercial refrigerator systems.
10. Continued engagement with OEMs to identify opportunities for improvement in available firmware, commissioning processes and remote capabilities.

7.2 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 two 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.

There is a substantial body of work still ahead, and although expressions of interest for Stage 3 closed in May 2023, 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

8 The power system research ecosystem

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

- the AEMO Engineering Roadmap to 100% Renewables[18] and
- the AEMO Operations Technology Roadmap (OTR)[19].

These two initiatives 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 the need to operate 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 placed side-by-side apparent links are easily observed (Figure 28). Having a common focus is the driver for continued and close cooperation between CSIRO and AEMO 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://aemo.com.au/en/initiatives/major-programs/operations-technology-program/operations-technology-roadmap

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

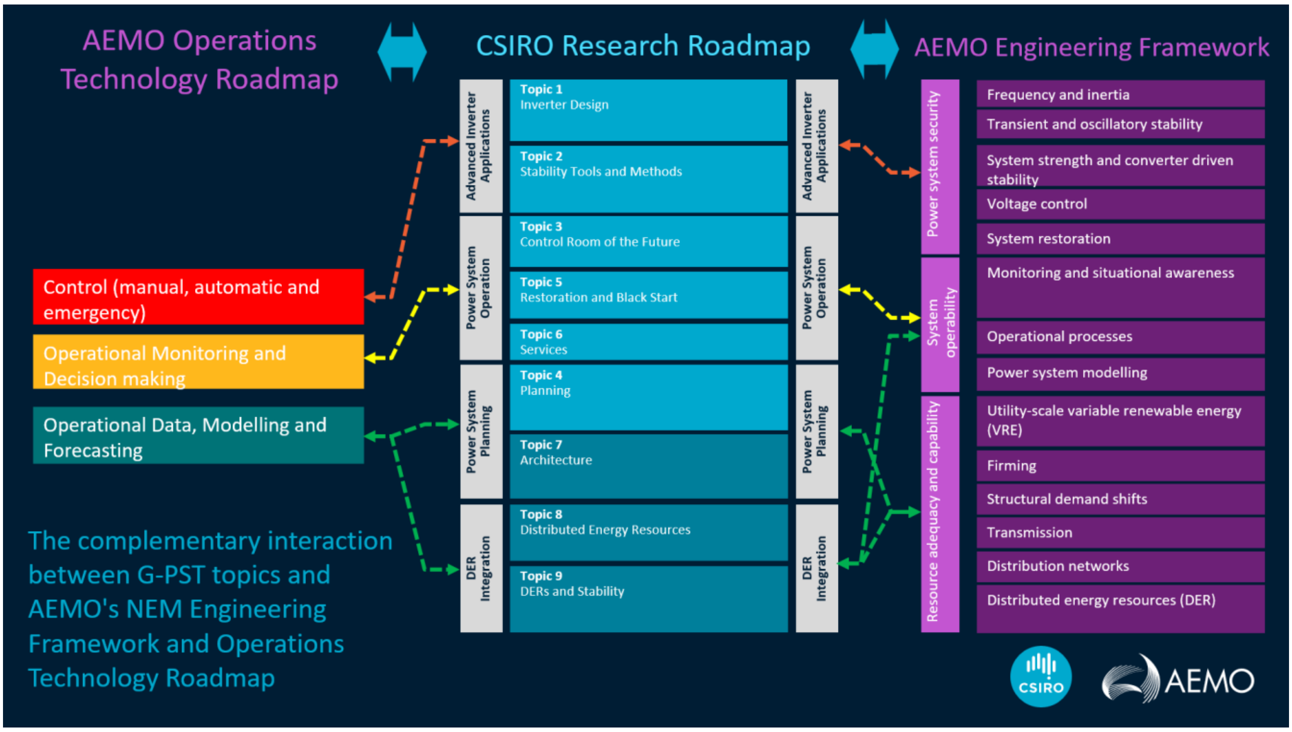

Figure 28: Alignment of the CSIRO Research Roadmap and AEMO's Operations Technology Roadmap and the Engineering Framework

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

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