Australia's National
Science Agency

Global Power System Transformation

Interim report of 2023/24 research topic progress

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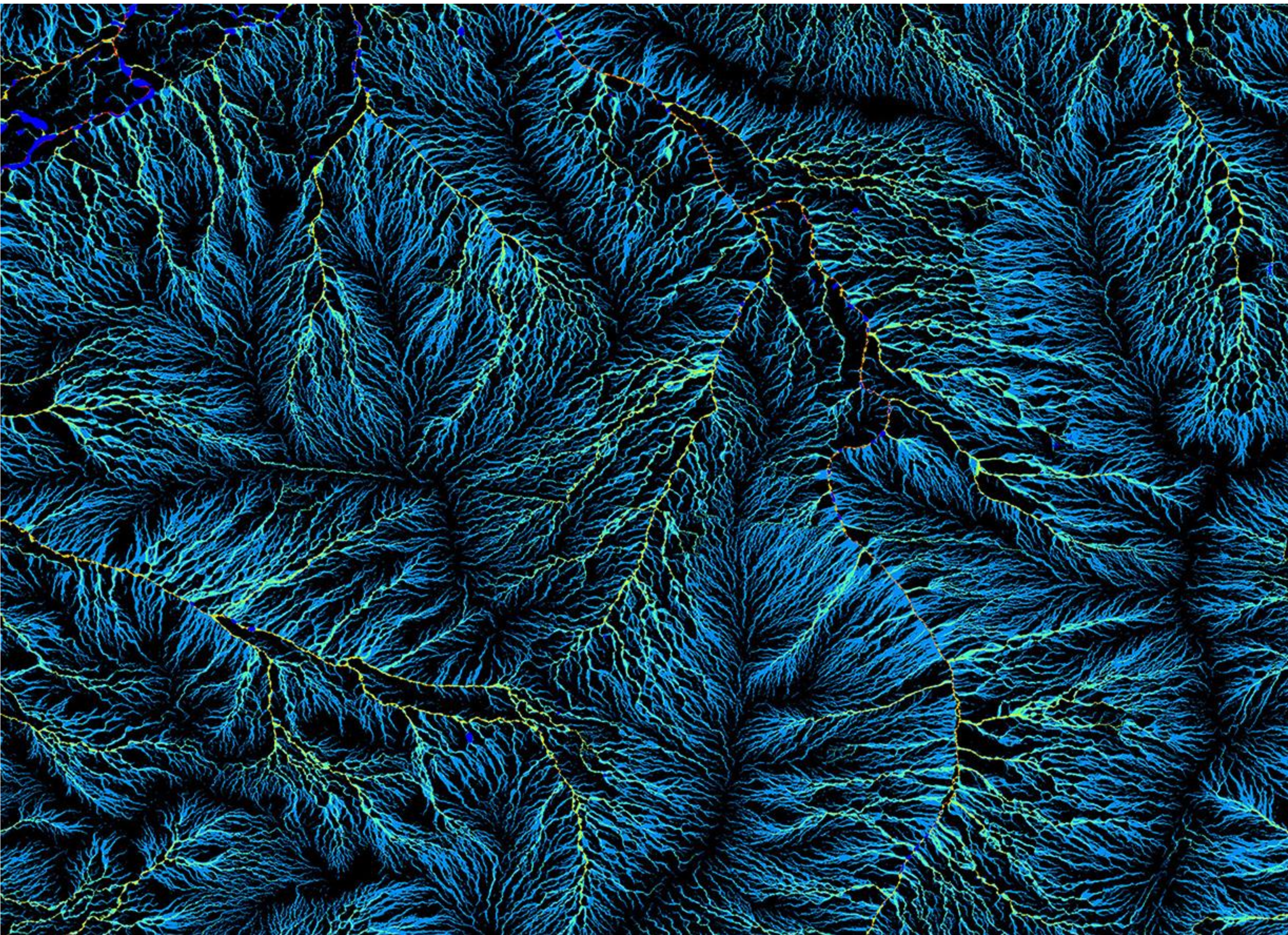

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Executive summary

This report has been prepared by GHD Advisor in their role as CSIRO GPST Research Plan program management support. It summarises the progress, insights, and achievements of eight CSIRO funded Global Power System Transformation (GPST) research projects carried out during 2023. The eight funded projects are a continuation of energy sector application research initiated by CSIRO during 2022, and represent the second year of implementation of the CSIRO GPST Research Roadmap published in 2021.

The CSIRO supported research is strategically targeted to enhance energy section research that will support stable acceleration of the energy transition underway in Australia, and globally.

The information used to present this summary report has been provided by the research organisations appointed by CSIRO to lead each of the eight research topics of the CSIRO GPST Research Roadmap.

This report specifically seeks to present key information on each research project with the objective to:

- Define the critical need for this research to support the acceleration of the energy transition underway in Australia, and globally.
- Establish clearly what has been done in the research topic to the end of 2023, since commencement in May 2023.
- Summarise what is scheduled to be completed in each research topic until contract end in April 2024.
- Place the current stage of research in the CSIRO Research Plan that was developed for each research topic.
- Suggest any changes or adaptation to the original research roadmap published in 2021 as a result of influencing factors such as research outcomes, advances in relevant technology, or energy policy and regulation changes.
- Recommended high priority future work for this topic for the next round of research scheduled for 2024/25.

The outlined information has been collected to prepare this interim report, which may be used by CSIRO to:

- Get a succinct update on research progress that will assist CSIRO to evaluate requirements and prepare the next stage of research planned to commence in July 2024.
- Prioritise tasks for future stages of the CSIRO GPST Research Plan based on outcomes and successes of Stage 3.
- Estimate budgetary requirements for critical next stage research and secure future funding for the continuation of the CSIRO GPST research program.
- Assist discussions with DCCEEW, DFAT, and other government departments to outline the critical importance of this energy research to assist Australia's energy transition.

In reviewing the detailed progress reports submitted by the eight research organisations in December of last year, we observe that generally all research topics are progressing according to the 2021 Research Plan. Some notable insights of the research progress to date include:

- Continuing risk is due to delay in accessing critical, but highly confidential, data and information from AEMO required for some research topics i.e., PSCAD wide area network model for Topic 5 and accessibility to AEMO operational data hosting servers for Topic 3. At time of writing these matters were being progressed, but have required extensive time to resolve.

- Research conducted by all eight project teams is reasonably aligned with the original 2021 produced Research Plan. There appears to have been some reprioritising of critical tasks within some projects driven by efficiency goals (e.g., assessment tool development in Topic 2), system operator needs (e.g., AEMO use case assessment in Topic 7, and D-motor load testing focus of Topic 8), and/or technology and policy drivers (e.g., increased focus on DER and hydrogen impacts on transmission planning).
- At least half the projects have had personnel changes, which does create some lag as new researchers get up to speed on the topic and tasks. This is not unexpected as most of the university based researchers are PhD candidates and Masters students. However, the project leads of each project has remained the same and hence disruptions have been minor.

Noteworthy is that some projects that may be marginally delayed in completion due to dependence on confidential data and information that must be provided by AEMO. Due to the sensitive nature of this data there are contractual and accessibility matters that have taken longer than expected and introduced unforeseen delays. Future research would be well advised to commence request for information at a very early stage to avoid delays.

1 Introduction

The implementation of the CSIRO sponsored Global Power System Transformation Research Roadmap[1] (The *Research Plan*) commenced in May 2023 with one research project selected for each of eight focus areas (Table 1). There was no successful research project appointed for Topic 6.

The 2023/24 research is Stage 3, with Stage 1 being the development of the program itself during 2021, and Stage 2 building on this research during 2022/23. Subsequent years of research will be referred to as Stage 4, Stage 5 etc.

Table 1: 2022/23 CSIRO GPST Roadmap Research projects

#	GPST Research Topic	Research Project	Contracted Research organisation
1	Inverter design	Transient stability enhancement of IBR dominated grids in the presence of grid forming inverters	Monash University (supported by EPRI)
2	Stability tools and methods	Analytical methods for determination of stable operation of IBRs in a future power system	Electrical Power Research Institute (EPRI) (supported by Monash University)
3	Control room of the future	Applications of machine learning for power system applications	EPRI
4	Planning	Flexible planning methodologies to improve the robustness of infrastructure investment decision making.	University of Melbourne
5	Restoration and black start	The role of inverter-based resources during system restoration	Aurecon
6	Services	No researcher appointed.	No researcher appointed.
7	Architecture	Power System Architecture	Strategen
8	Distributed Energy Resources	Dynamic Operating Envelopes	University of Melbourne
9	DER and stability	DER and stability	University of New South Wales

The contracted research projects are scheduled to be completed by 30 April 2024. However, for some projects, a longer than expected contract negotiation caused these to commence later. Additionally, difficulty in accessing confidential information and/or systems meant some project tasks were delayed. Consequently, several projects may not be finalised until after the April 2024 end date. However, any time extensions granted, will be subject to CSIRO consideration of the criticality of outstanding research and the

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

importance of wrapping Stage 3 research on time to commence the next stage of all research topics concurrently.

To commence the next round of funding for the 2024/25 GPST research , CSIRO has requested the researcher to provide advice that addresses the following matters:

- Overall research topic and project overview and objective as described in the 2021 CSIRO GPST research plan.
- Research completed by 15 December 2023 as part of the Stage 3 implementation of the *Research Plan*.
- Outstanding Stage 3 research activities to be completed by 30 April 2024.
- Progress against the full program outlined in the 2021 CSIRO GPST research plan.
- Relevance of the undertaken research to the Australian energy industry.
- Recommendations for future work as part of Stage 4 to be conducted during 2024/25.

This report summarises the key points of the researchers' advice provided as an interim progress report on 15 December 2023, particularly regarding future research recommendations and the alignment of these recommendations with the original *Research Plan*. This summary contains key points of the researcher progress submissions. The full reports are available on the CSIRO GPST Teams site[2].

[2] https://csiroau.sharepoint.com/:f:/r/sites/CSIROG-PSTCoordinationStage3-GHDCoordination/Shared%20Documents/GHD%20Coordination/Interim%20reports?csf=1&web=1&e=Vehl94

2 Advanced inverter applications

2.1 Topic 1: Transient stability enhancement

Monash University (MU), with the support of Electric Power Research Institute (EPRI), are researching to improve the transient stability of networks dominated by Inverter-Based Resources (IBR) during faults and subsequent fault recovery. Focus of their research is analysing the different grid forming inverters (GFMI) and their influence on stability and how IBR control systems can be improved to increase their and the overall network's stability.

For Stage 3 of the research plan Monash University (MU) is conducting research and analysis to enhance the transient stability of grid forming inverters (GFMI). To achieve this, research efforts are focused particularly on improvements to current limiters (CL), which are crucial for GFMIs to ensure the devices operate within their thermal capability. While CLs are critical for protecting the GFMI from overcurrent, such limiting can also adversely affect stability.

Secondary to this year's research is a further function of GFMI that allows these devices to compensate voltage unbalances that are caused by unsymmetrical faults. GFMIs achieve this by injecting negative sequence current during such faults. However, such negative sequence current injection can also adversely impact GFMI transient stability if not balanced against the necessary positive sequence current necessary to support system voltages during faults.

Monash have broken down the various research stages of Stage 3 are follows:

- Task 1: Continuing the expansion of transient stability analysis developed in Stage 2 to encompass various expanded network topologies that more resemble existing physical networks.
- Task 2: Development of a tool specifically designed for conducting transient stability analysis for multi-IBR systems.
- Task 3: Analyse the impact of negative sequence (NS) current injections from IBRs on their transient stability; findings of this work will be presented in a technical white paper.
- Task 4: Investigation of the transient stability of CL GFMI control implementation in non-Battery Energy Storage System IBRs, particularly wind turbine generators.

With the completed and in-progress research, Stage 3 further advances the following tasks of the CSIRO GPST *Research Plan* for Topic 1[3]:

- Task 1: Frequency stability[4]
- Task 3: Interaction mitigation and oscillation damping[5]
- Task 4: Protection and reliability[6]

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[3] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-1-Inverter-design-Final-Report-with-alt-text-2.pdf

[4] Ibid 2, Section 4.1.1.1.

[5] Ibid, Sections 4.1.3.1, 4.1.3.2, 4.1.3.3.

[6] Ibid, Sections 4.1.4.1, 4.1.4.2, 4.1.4.3.

- Task 5: Trending topics[7]

Task 4 above forms the majority of the Stage 3 MU research, while the other tasks are progressed through assessment of the developed control systems and the analysis of the interaction of multiple IBR using the conceptualised advanced techniques. The current work forms the second year of research implementation, builds on last year's Stage 2 research, and is scheduled to be completed by 30 April 2024. The status of the *Research Plan* Tasks expected by MU at the end of Stage 2 is shown in Table 2.

Table 2: Overall research progress for the Topic 1 tasks in comparison to the full program defined in the Roadmap.

	TASK	Stage 3 (23/24) Progress
1	**Frequency Stability**	
1.1	Defining the response of GFLIs and GFMIs for a credible contingency	
1.2	Control of ESS based on the capability of the energy source to provide various frequency services	
1.3	Coordinated/distributed control of BESSs for frequency control	
2	**Voltage stability**	
2.1	Investigation of IBR reactive power provision capabilities against the backdrop of losing synchronous machines	
2.2	Interactions between synchronous machine AVR, GFMI AVR and GFLI in providing reactive power support	
3	**Interaction Mitigation and Oscillation Damping**	
3.1	Identifying the nature of oscillations in IBR-dominated grids	
3.2	Standardising the models of IBRs[8]	80%
3.3	Modelling, analysis, control and coordination of IBRs for oscillation damping	30%
4	**Protection and reliability**	
4.1	IBRs effect on existing protection systems	
4.2	Enhancing IBR response during and subsequent to faults	60%
4.3	Assessment and enhancement of IBRs reliability	70%
4.4	Cyber-secure inverter design for grid-connected applications	
5	**Trending Topics**	
5.1	Developing alternative control methodologies for GFMIs	20%
5.2	Grid-forming capability for HVDC stations and wind and solar farms	50%
5.3	AI in IBRs control	

Future work for Topic 1 recommended by MU to further progress high priority tasks 4.1, 4.2, and 6.2 include:

- Investigate the transient stability of the GFMIs under various fault profiles, including varying the number of faulted phases, fault duration and impedance.
- Extension of transient stability analysis considering various fault profiles across different network topologies, including radial and intermeshed systems.

[7] Ibid, Section 4.1.5.

[8] The stability assessment tool has been incorporated into Task 4.3 instead of the shared task with Topic-2 since the Topic 1 tool doesn't involve any dynamic simulation (except for validation purposes) and its primary function is to provide stability assessment capability for larger systems.

- Investigate efficient real-time transient instability detection methods (TID) for enhanced power system analysis, quick decision-making, and improved grid reliability.
- Investigate the impact of system conditions, including load level, load type, grid strength, and generation mix, on the TS and operation of GFMIs with NS controls. Task 4.2?

The objective of the above tasks is focused on protection and reliability, as well as exploiting synergies with research Topic 2, which also investigates advanced inverter matters, albeit from a small disturbance perspective. The two topics can be considered complimentary.

MU and EPRI highlight the importance of research in this area of advanced inverter applications assessment in and Australian context being driven by the significant development of renewable energy zones (REZ) anticipated according to AEMO's Integrated System Plan. The REZ developments are likely to be in radial network configurations and located far from the remaining synchronous generators. Therefore, stability issues may inevitably emerge in such regions. This research effort is aimed at establishing a simple framework that would allow an accurate analysis and estimation of transient stability margins of large IBR-clusters that constitute REZ regions, thereby supporting the network service providers and the network operator in maintaining a stable and secure grid, which is becoming more and more crucial as the penetration of IBRs in the NEM gradually increases.

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

The Australian power system has experienced a rapid and sustained growth in the share of solar, wind, and energy storage connecting to the transmission and distribution systems. The share of such IBR is expected to continue growing over the foreseeable future, as indicated in AEMO's Integrated System Plan. One aspect important for ensuring stable operation of the current and future Australian power system is evaluating the system stability and stability margin in the small signal domain, considering the IBRs connected to the system.

The Australian power system's first experience of the potential small signal or oscillatory instability that can occur in IBR dominated grids was observed in the West Murray region of Victoria as far back as 2020[9]. Since that time the interconnection of IBRs has more than tripled and with the development of several REZ in NSW and likely in other states, it is important to develop means of assessing and managing stability resulting from adverse oscillatory behaviour between IBR control systems.

The task of managing small signal stability is exacerbated because of the large number of different system operating points that can occur throughout the day and throughout the year, varying with network arrangements, demand, and generation dispatch. In the previous Stage 2 of Topic 2 research, a time series power flow analysis of the synthetic network of the National Electricity Market (NEM) area was performed, where the network voltage profile was optimized for 24 power flow cases representing future high penetration of IBRs to assess the impact of the system operating point on the stability in the form of short circuit assessment and dynamic simulation involving IBRs. At the same time, two different methods for estimating the IBR impedance characteristics at any operating point were developed and these estimated impedances were used in a small network to evaluate stability.

In this Stage 3 research, EPRI (supported by MU) has focused on:

[9] https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/west-murray-zone-power-system-oscillations-2020--2021.pdf

- Extensively testing the two methods for IBR impedance estimation at any operating point and selecting the most effective method to be applied for the ongoing analysis of this research.
- Studying the stability of a large transmission network using blackbox IBR models and a multifrequency representation of the network.
- Assessing the role of IBR unit constraints such as current limiting on the stable operation and stability margin of the system.

The research conducted by EPRI during 2023/24 progresses the following tasks of the CSIRO GPST Topic 2 *Research Plan*[10]:

- Task 1: Stability margin evaluation[11]
- Task 2: Small signal stability screening methods[12]

To achieve the required research by the completion date of 30 April 2023, EPRI have:

- Developed a blackbox inverter model for testing purposes to assess the performance of the impedance estimation methods developed. The blackbox model was able to seamlessly transfer between the two software platforms used in this project, MATLAB/Simulink and PSCAD, which will improve efficiency and ensure accuracy of the overall project studies.
- Evaluated the performance of two impedance prediction algorithms that can be used to assess blackbox inverter models, one based on analytical prediction and one on data driven methods. The researchers identified that the analytical method performed better when presented with the same training data of operating points and was selected as the method to be applied for remainder of the project.
- Conducted small-signal analysis of smaller simpler network systems, in order to test the selected methodology, compare this with time-domain simulations, and establish most of the procedure necessary for the full study of the NEM system to be carried out in future research.

To complete the outstanding work planned for Stage 3 of Topic 2 research, EPRI will over the next three months:

- Finalise the ongoing debugging and benchmarking of the synthetic NEM network small signal model against time domain simulations for next stage research.
- Add IBR models (both whitebox and blackbox) to the small signal analysis – for a small two area system. The EMT and fundamental frequency model responses will then be compared for accuracy.
- Utilise the developed network small signal model to identify critical nodes of the network by evaluating the proximity to a stability margin boundary, and study/develop the associated metrics for performance assessment.
- Extend the analysis to characterise the behaviour of the small signal network model across a variety of operating points, and the compare approaches for stability assessment using the model of the entire network and a two-port network equivalent.

[10] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-2-Stability-Tools-and-Methods-Final-Report-with-alt-text-2.pdf

[11] Ibid 7, Table 1, Topic 1.

[12] Ibid, Table 1, Topic 2.

- Identify the impact of IBR current limit over a 24-hour period on the performance of the analytical method impedance prediction algorithm as well as the small signal stability will be assessed.

Progress of the CSIRO *Research Plan* for Topic 2 against the tasks carried out in the 2023/24 work is shown in Table 3. Also included in the Topic 2 research are three medium and two low priority tasks, these are not shown below but can be viewed in the section of the *Research Plan* covering Topic 2.

Table 3: Expected progress for the Topic 2 research activities considered in the initial research plan by the end of the 2023/24 period and forecast for the 2024/25 period

	TASK	Stage 3 (23/24) Progress	Stage 4 (24/25) estimate
	Critical		
1	Stability margin evaluation	50%	75%
2	Small signal stability screening methods	50%	75%
3	Voltage stability boundary		
4	Voltage control, recovery, collapse		
	High		
5	Online identification of system strength		
6	Monitoring inertia in real time		
7	Modelling and model validation		
8	Voltage and reactive power management	25%	
9	Real time simulators		
10	Critical contingency identification		
11	Real time contingency analysis		
12	Protection system operation and coordination		

EPRI has initially described both tasks 1 and 2 of Table 3 as each requiring a three-year research program[13]. However, based on present progress it is more likely that four years will be required. Continuation of tasks 1 and 2 for the 2024/25 period, as recommended by EPRI, would therefore be expected to complete the two most critical tasks in the list.

Recommendations for future research of the high priority tasks 1 and 2 provided by EPRI is in line with the research plan, and includes:

1. Improvement of the impedance estimation algorithms by identifying such nonlinear limits/regions of operation and corresponding operating points needed for an accurate impedance model.
2. Study the features of IBRs critical to be represented in a blackbox model for obtaining a near-accurate estimated impedance.
3. Develop a multiple frequency network equivalent model for a large network such as the synthetic NEM network for operating point stability assessment.
4. Future discussions on the topic can also bring in inverter OEMs and commercial software vendors to help streamline the process of industry adoption of small signal stability assessment.

[13] Ibid, Table 5.

3 Grid Development

3.1 Topic 4: (Power System) Planning

The transition to a fully decarbonised energy system is spearheaded by the increasing uptake of variable renewable energy (VRE) and distributed energy resources (DER), the electrification of different sectors, and the large-scale adoption of low-carbon fuels such as green hydrogen. Developing the aforementioned technologies is a challenging task exacerbated by the increasing uncertainty around *what* and *how much* of each technology will connect to the electrical transmission system, as well as *when* and *where*. Energy system planners are thus faced with the task of striking a good compromise between the cost-effectiveness of a deeply decarbonised energy system and the need for ensuring day-to-day operational security, reliability and resilience against high-impact low-probability (HILP) events, which are particularly challenging to model and capture in traditional planning methodologies.

In this project, The University of Melbourne (UoM) addresses several fundamental issues associated with Topic 4, "Planning" of the CSIRO-GPST roadmap[14], particularly in the context of energy systems integration. Specifically, UoM aim to examine and assess, from a techno-economic perspective:

- Impact and benefits of integrating DER, sector-coupling, and storage technologies in low-carbon energy infrastructure planning, under different sources of uncertainty.

- Among other studies, the project seeks to determine the option value of operational flexibility provided by DER, hydrogen electrolysers, and the inherent storage capability of hydrogen pipelines (*linepack*[15]) in supporting system operation and displacing or delaying investments in transmission infrastructure.

- Moreover, to deal with the inevitable computational challenges that emerge from modelling the complexity of the operation of power systems, clustering and optimisation techniques are explored to identify methodological options for the identification of representative periods to use in the planning process and determine how these techniques could inform on the procedures adopted by the Australian Energy Market Operator (AEMO) in their integrated system plan (ISP).

The project aims to comprehensively represent and analyse the influence of incorporating operational flexibility from DER, hydrogen electrolysers and options for hydrogen transmission and storage infrastructure within the expansion planning problem under multiple uncertainties. UoM's main objective is to evaluate planning strategies and the impact of flexible technologies in making robust and forward-thinking investments, thereby reducing planning risks and regrets. This provides valuable insights into the current decision-making processes undertaken by different stakeholders and informs the next steps in methodological developments in this topic. The specific tasks of the Stage 3 Topic 4 UoM led project and their links to the planning roadmap are:

A. Analyse pertinent representative period selection (e.g., days, weeks, months, or years) techniques in the planning process through big data classification algorithms. (Planning roadmap: Research project R2S1P1).

[14] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-4-Planning-Final-report_with-AltText-2.pdf

[15] The linepack is the amount of pressured gas stored in a pipeline.

B. Identify and quantify the value of the operational flexibility that different types of storage, demand-side (including DER), and sector-coupling (particularly hydrogen electrolysers) technologies could provide in displacing or delaying transmission investments and enhancing resilience to extreme events. (Planning roadmap[2]: projects R5S2P1, R5S2P2 and R5S3P2. Interactions with projects R4S2P3 and R5S1P1).

C. Model and numerically assess the potential benefits from integrated electricity-hydrogen infrastructure design and relevant long-duration storage options in optimal integrated infrastructure planning under deep, long-term uncertainty. (Planning roadmap[2]: research project R5S1P1).

D. Quantify the resilience benefits that different types of storage, DER, hydrogen technology and transmission infrastructure could provide against different types of extreme events, including Dunkelflaute periods and prolonged outages of conventional generators and interconnectors. (Planning roadmap[2]: research project R3S3P3. Interactions with project R5S3P2).

Of the four tasks undertaken in this Stage 3, UoM had by late December 2023 completed the first two, with the four months of project time remaining dedicated to completion of:

- Task C (sector coupling and new technologies):
    - determine the best options for whole-system expansion when dealing with alternative energy infrastructure, particularly hydrogen, to provide insights into the benefits and risks of adopting a fully electric energy transmission system or a more integrated electricity-hydrogen one.
    - study the potential “option value” of pro-active hydrogen infrastructure investment, including its potential role in providing resilience to various climate-driven events through electrolyser demand flexibility and deep storage options.
- Task D (resilience and network outages):
    - perform sensitivity analysis to better understand the impact of modelling network infrastructure outages on investment recommendations and the influence of diverse methodological approaches for representing scheduled and non-scheduled events within the scenario tree employed in the stochastic planning framework.The currently underway work thus addressed the tasks of the research plan related to research program 1 of Topic 4, while also laying foundations to others, such as program 4 that investigates “decision making”.
    - Based on the documented progress, the project is well on track and UoM has completed the first two tasks of their contracted research. We expect completion of the remaining tasks of risk analysis, resilience assessment, and new technology to be by 30 April 2023. The status of the key tasks by this date are shown in Table 4.

On completion of the Stage 3 tasks, UoM expects overall progress against the Topic 4 research Roadmap to be advanced against all critical topics. GHD note that while progression against the overall Roadmap appears aligned, the initial timelines for some of the tasks that make up the research programs may be somewhat skewed due to re-prioritising and/or resourcing e.g., focus was placed on progressing R2: Power system operation, meaning that R1: Long-term uncertainty remained at the Stage 2 state of completion. As part of the final report UoM will be requested to refresh the Roadmap timelines and resource requirements to inform future work.

Table 4: Expected progress for the Topic 4 research activities considered in the initial research plan by the end of the 2023/24 project period

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

The project is relevant to Australia's transmission planning processes, and AEMO has been a proactive supporter of the research, providing information and feedback throughout. While the 2023/24 Stage 3 builds on the initial power system planning research conducted during Stage 2 further work in line with the highest priority tasks of the research plan is recommended by UoM in subsequent stages of the Research Plan to increase value from future energy infrastructure investment decisions, including:

- Task 1: Deep dive into the modelling and assessment of integrating distribution and transmission network planning within the expansion planning process.[16]
- Task 2: Analyse the potential economic and operational benefits of better integrating gas and electricity infrastructure planning.[17]
- Task 3: Leverage advanced mathematical algorithms to optimise the computational efficiency and enhance the performance of long-term planning frameworks.[18]

3.2 Topic 7: System Architecture

Designed as traditional linear supply chains, however, our legacy power systems have often been deeply 'siloed'. Many professionals working, for example, in the distribution sector have required only limited or no interaction with the bulk power system, and vice versa. By contrast, these ultra complex systems are now experiencing a profound transformation, ultimately requiring them to become far more dynamically interdependent. Occurring at unprecedented scale and pace, this requires new ways of thinking and working together that are far more holistic, inclusive, and integrative.

Establishing a sound architectural framework, cognisant of the required performance envelop of the system through to 2050 is of critical and foundational relevance Australia's transforming and future electric power systems.

[16] Ibid 12, pg. 49, R4S2P3, R4S3P1, R5S2P1, R5S3P1

[17] Ibid, pg. 47, R3S3P3, R5S1P1.

[18] Ibid, pg. 45, R2S1P1.

The objective of the Topic 7 Stage 3 research is identifying appropriate future power system architectures[19] for coordinating new technology capabilities, regulatory approaches, market design, and the distribution/transmission interface in a highly distributed, variable renewable energy-based system.

The research aligns with the Action Research Plan developed in Stage 1[20], which was informed by a review of over twenty projects and initiatives in the United States, the United Kingdom and Australia. This analysis aimed to identify and recommend an integrated and adaptive combination of 'best practice' methodologies and activities suitable for application in Australia. In Stage 2, global best practice methodologies were 'road tested' in the development of a Reference Architecture aligned with AEMO's 2050 Step Change Scenario. This Reference Architecture included an integrated set of artefacts as outlined in Figure 1 below.

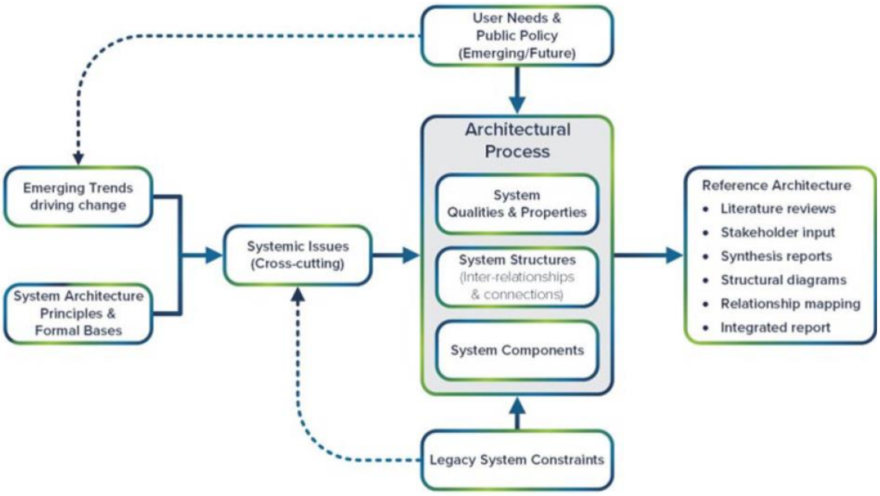

Figure 1: Reference Architecture Development Process

In Stage 3, Energy Catalyst has expanded the application of architectural tools, with a practical focus on immediate priorities for the NEM, SWIS and DKIS. This work only partially covers the detailed architectures stage of work presented by Energy Catalyst in their 2022/23 Stage 2 report as next steps (Figure 2).

[19] Power system architecture endeavours to describe the underlying design and structure of the electricity system – how its components and its participants are organised and interact. Topic 7 notes four distinct and interactive layers within their definition of the PSA discipline: power flow, operational control, market transactions, and information/data exchange.

[20] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-7-Power-System-Architecture-Final-Report-with-alt-text.pdf

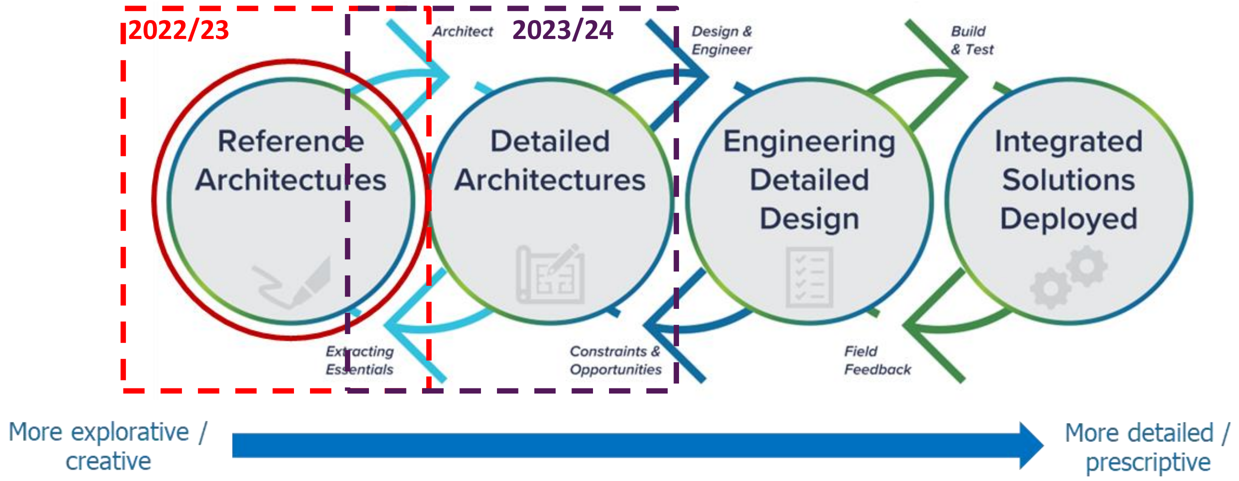

Figure 2: Progress of Topic 7 research against the 2021 Research Roadmap tasks

Instead a majority of the research effort has been on establishing, maturing, and testing the formal methodologies for making architectural choices, with a focus on developing AEMO issues maps (use cases) including:

- Emergency DPV Curtailment – focused on the management of Minimum Operational Demand (MOD) and including considerations regarding the mass-scalability of Dynamic Operating Envelopes (DOE);
- Operational Forecasting of DER/CER - including initial consideration of entity roles and responsibilities; and,
- DER/CER Scheduling – including initial consideration of entity roles and responsibilities, DSO models, communications routings, and structural cyber-security vulnerabilities.

Similarly, efforts have been applied to build architectural maps for whole-system oriented demonstration projects to learn and understand how different aspects of the energy system interact, including:

- AEMO / AusNet - Project EDGE
- Western Power - Project Symphony
- Ausgrid - Project Edith

Architectural mapping of these use cases and demonstration projects provide input to the Model Based System Engineering (MBSE) and development of functional layer building blocks on a Dassault Systems – CATIA Magic[21] Product-line software platform.

The tasks of the research has hence been adapted to include four tasks that progress the detailed architectural mapping, albeit at a more measured pace that allows for the development of tools and methodologies:

- Phase 1 – project initialisation including information gathering and stakeholder engagements
- Phase 2 – project inputs through analysis of MBSE software applications, use case analysis, and assessment of demonstration projects
- Phase 3A – Architectural mapping and analysis of targeted issues, including MBSE mapping of key GPST Stage 2 architectures

[21] https://memko.com.au/software/catia/catia-magic/

- Phase 3B – Exploration and co-design of detailed architectural process involving stakeholder engagement and detailed architecture design

Initial phases 1 and 2 of Stage 3 are completed or close to completion. These represent the preparatory works, and in Stage 3 and 4 is where Energy Catalyst is proposing to develop the above noted AEMO use cases, using MBSE software representations. Specifically, this includes:

- how the "architectural objectives" associated delivering these Functional Requirements are defined;
- how these Functional Requirements might manifest across the four functional layers set out in the PSA Network of Structures; and
- some consideration of staged uplift over time starting from current capability – loosely, from shorter term measures to manage today issues, that can appropriately evolve and scale to meet the step change we expect to see.

Progress against tasks is aligned with the projected milestones, with status of completion shown below.

Table 5: Overall research progress for the Topic 7 tasks in comparison to the full program defined in the Roadmap

Task	Status at 15 December 2023
1.1. Detailed project workplan and statement of deliverables	100%
1.2. Workshop workplan and statement of deliverables with CSIRO & AEMO	100%
1.3. Workshop workplan and statement of deliverables with International Expert Panel (IEP)	100%
1.4. Incorporate enhancements in detailed project workplan and statement of deliverables	100%
2.1. Analysis of Model Based Systems Engineering (MBSE) software applications	100%
2.2. User-friendly PSA information for senior stakeholders	Final draft
2.3. Research architectural inputs for Australia's more whole-system oriented demonstration projects	100%
2.4. Research current status of the three target issues agreed with AEMO and collaboratively engage on their baseline Functional Requirements draft report	In progress
3.1. Collaboratively engage with AEMO to jointly develop an initial model for DER/CER categorisation and DSO/DNSP functional requirements	In progress
3.2. MBSE-based mapping of two key G-PST Stage 2 architectures and Australia's more whole-system oriented demonstration projects	In progress
3.3. Analyse and report learnings relevant to targeted NEM issues	0%
3.4. Multi-stakeholder Engagement	0%
3.5. Multi-stakeholder Co-design of Detailed Architecture process	0%

4 Power System Operation

4.1 Topic 3: Control room of the future

EPRI are conducting research on the GPST Topic 3 Control Room of the Future (CROF). The original 2021 roadmap for Topic 3 outlined pathways for innovation around a set of key pillars, with focus on Data and Software Applications, and Human Factors and Operator Interactions.

The CSIRO CROF stage 2 work in 2022/23 began work on the elements of the roadmap with focus on the CROF research pillars for data and control room applications. The aim was to work on aspects of artificial intelligence and machine learning (AI/ML) for real time power system operations applications, given the long gestational period of development. This work involved close interaction between EPRI, Royal Melbourne Institute of Technology (RMIT) and AEMO to identify a methodology for developing machine learning projects, data and use cases, and to build a prototype proof of concept application for use on real AEMO data. The stage 2 project was completed in 2023 and the report on the project is available publicly on the CSIRO website. [22]

The framework and proof of concept development work from stage 2 is being continued in the Stage 3 project in 2023/24. EPRI are again partnering with RMIT and AEMO to continue the research. The focus remains on the data pillar of the original 2021 roadmap, with a new focus on operational models and how the process for model validation could be improved in the operational domain.

The Stage 3 project comprises three main tasks:

1) Machine learning applications and use case methodology.
2) Exploration of language and text-based machine learning and knowledge-based systems in system operations.
3) Network and generator model validation processes and systems.

Objectives and progress in each of these tasks during the 2023/24 period are as follows, with a relative state of completion expected at the end of the Stage 3 research period listed in Table 6.

Machine learning applications:

This work involves continuation of the stage 2 work with deployment of a prototype directly on AEMO systems using AEMO data. The sub tasks for the project are below:

(a) Prototype deployed at AEMO for at least one use-case on alarm management.
(b) Completed investigation into machine learning for constraint management use case.
(c) Experimentation and analysis with actual AEMO datasets

Deliverables for task 1 include:

- Prototype code suitable for public release, including non-proprietary sample demonstration data to show that the prototype functions properly, and instructions on how to use the tool(s).

[22] Topic 3 Control Room of the Future Stage 2 Report: https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Final-Reports/Topic-3-GPST-Stage-2.pdf

- Brief technical report(s) or presentations for each of above, or inclusion in final report

Exploration of language and text-based machine learning:

This task involves exploration of possible use cases for large language models in the system operations domain. Given this is emerging technology it is unclear what or if it could be potentially useful for system operators. The sub tasks are:

(a) A prototype developed by the project team based on textual information, or a knowledge-based task that is suitable for public release, instructions on the tool(s) demonstration on either a publicly available data set or a non-proprietary data set that can be released with the prototype.

(b) Experimentation and analysis against any available public datasets.

Deliverables for this second task are a brief technical report(s) or presentation for all activities above, or inclusion in final report

Network and generator model validation

This task involves engaging with modelling subject matter experts in AEMO to define a methodology for automatically validating the accuracy of a model using high-speed data recorders. The sub tasks are:

(a) Identified 2-3 models for study inclusion based on priority, complexity, and ease of access as defined by AEMO.

(b) Initial investigation on standardization framework for model validation. Brief progress report on above exploratory work, or inclusion in final report.

The deliverable for this third task is a final report that should include a proposed development pathway for how the validation tools might be developed into a final product to be integrated within a power system operations company.

The Topic 3 project and overall research are at an early stage and has been delayed by necessary AEMO confidentiality and cybersecurity frameworks that protect the sensitive information related to power system operation. Access of the information required specific contracts to be executed between AEMO and EPRI, and AEMO and RMIT. This has meant the researchers were not able to access the information directly and had to work through the AEMO experts, whose time and availability has been limited. Consequently, progress has been slow to date. Execution of these contracts was affected in January 2024, such that the remainder of the project time is expected to see more results and completion of critical works. However, there are many outstanding activities still left to be completed, including:

- Completion of labelling on a large set of identified incidents, such as for 6-12 months to facilitate ML model training.
- Access to the real AEMO system to develop and deploy the ML models for incident detection and discrimination.
- Testing of ML model on test datasets from the four main datasets.
- Build a user interface for the prototype for displaying output information to the operator based on the output of the ML model for incident detection.
- Access to the real AEMO system to develop and deploy the LLM model for interaction with the datasets.
- Development of the methodology for model validation for an asset with high-speed recording.
- Development of the framework for automated model validation, based on the manual model validation framework.

EPRI, RMIT and AEMO expect many if not all to be reasonably progressed or even completed by end of Stage 3.

Table 6: Overall research progress for the Topic 3 tasks in comparison to the full program defined in the Roadmap

Task	Status at 15 December 2023
Machine learning applications and use case methodology.	30%
Exploration of language and text-based machine learning and knowledge-based systems in system operations.	30%
Network and generator model validation processes and systems.	20%

4.2 Topic 5: Blackout and system restoration

Power system restoration is the process by which a system can be restarted following a blackout, such as occurred in South Australia in 2016. Traditionally, restoration has relied on the presence of synchronous generators such as gas turbines, hydro power stations, and even coal fired generators. However, as the energy transition sees many of our traditional generating systems being retired, a risk is emerging of the means to restart the network in the absence of synchronous machines, and which technologies can replace these current restoration sources.

Topic 5 of Australia's Global Power System Transformation (G-PST) Research Roadmap[23] expands the understanding and enhancements of system restoration capabilities in National Electricity Market (NEM). It focuses on investigating the performance, capabilities and limitations of different types of grid-forming and grid-following inverters with respect to black start capability and restoration support in power systems with a high share of inverter-based resources (IBR), expanding on previous research completed in 2022/23 on Topic 5. Investigation will be made on:

(a) system restart and restarted island operation simulations with no synchronous generators online;

(b) power system analysis of the role of synchronous generators and condensers when combined with GFMI BESS and other factors such as distributed energy resources (DER) and resynchronisation of restarted islands.

The response of each restart option and factors influencing its performance is assessed with the use of detailed vendor-specific electromagnetic transient (EMT) simulation models using PSCAD software.

This work utilises a network model of the North Queensland Power System reflecting locations of existing system restart ancillary service (SRAS) providers and a future renewable energy zone (REZ) inclusive of wind, solar, battery and Flexible AC Transmission System (FACTS) devices. This is a confidential AEMO model to which access is restricted. This confidentiality has required new contracts to be put in place between AEMO and Aurecon to allow access for this year's research. Additionally, extra requirements have been put in place by AEMO's Cybersecurity team that has further complicated the issuing of the model to Aurecon. As of early January 2024, the contracts had been signed, but the cybersecurity approval had not been issued, meaning that Aurecon has not yet received the current AEMO model.

However, with contracts signed, it is possible to use last the North Queensland model Aurecon received in 2022/23, although this model does not contain some of the critical information Aurecon additionally required e.g., composite load models including DER representations and dynamic reactive power sources

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

such as Static Var Compensators. Notably, the composite load models have now been accessible, meaning work has progressed further.

In the absence of the current PSCAD model, Aurecon has progressed with the information presently available, including detailed vendor-specific EMT simulation models of each black-start technology type, to focus on the use of grid forming inverters (GFMI) Battery Energy Storage Systems as a black start device, and their capability to energise neighbouring network to restart nearby grid following (GFLI) devices which can further support the restart process.

Relying on the ability of a GFM BESS to restart a single GFL generator, studies expanded on the number and total MVA capacity of GFL devices restarted and supported by a single GFM BESS black-starter. Emphasis was placed on expanding understanding of stable restart scenarios supported by a black start GFM and attempting to identify stability boundaries of restarted islands. Current work has not identified a clear stability limit yet but has provided three material insights:

- MVA ratio between GFM BESS black start device and a variety of GFL wind and BESS devices is viable upwards of 1:7.5. That is, a 100 MVA GFM BESS black start device can support a restarted island inclusive of various GFL support devices up to 750 MVA.
- Larger support device to black start provider MVA ratios may be prone to fault ride through (FRT) restrike behaviour on some support devices with their system normal settings. This is due to the lower short circuit ratio (SCR) and increased voltage sensitivity, rendering existing FRT thresholds as too restrictive.
- Black start providers need not be the main provider of frequency control in a restarted island. Studies have shown that a GFL BESS support device with frequency control enabled can provide the majority of frequency control in a restarted island, facilitating a GFM BESS black start provider to sit near 0 MW output and act as a swing machine to manage transient disturbances within the island.

While overall progress is slightly behind schedule due to delays in receiving critical information, there are a number of outstanding activities in Topic 5, that have either commenced and are in progress, or are to commence and be completed by the end of the research period. These include:

- IBR device related studies to be finalised to assess impact of different IBR on network stability and resilience, identification of stability limits of equipment during restoration, and IBR control system parameter impacts on islanded network stability.
- Assess the need for different performance standards for IBRs between system intact and system restoration.
- Assess the need for any additional performance requirements for grid-forming IBRs, or a more detailed specification of existing technical requirements, i.e., what grid-formation means in the context of system restart.
- Optimal placement of grid-forming black start IBR considering the proximity to load centers, synchronous generation power stations, and non-black start generator areas.
- Synchronising two or more restarted islands in an IBR dominated or 100% IBR power system.
- Impact of the presence of DER in stabilising load that is picked up as the system is progressively restored.
- Power system technical requirements that consolidate both the network and generation, and their interactions
- Dynamic performance success criteria during system restoration in terms of rise time, settling time, damping and magnitude of the network response in an IBR dominated or 100% IBR power system.

Consequently, while good progress is evident, there are a number of slightly behind schedule tasks. However, Aurecon envisages that if the model is provided much if not all will be completed.

Progress of the tasks according to the Aurecon prepared CSIRO 2021 *Research Plan* and contracted Stage 3 research are shown in Table 7, where progress status is based on timely receiving of all outstanding AEMO PSCAD models.

Table 7: Expected progress for the Topic 5 research activities considered in the initial research plan by the end of the 2023/24 period

	RESEARCH TASK	Anticipated 2023/24 Progress Status
1	**Inverter-based resources**	
1.1	Grid Following Inverters (GFLI)	80%
1.2	Grid Forming Inverters (GFMI)	80%
1.3	Distributed Energy Resources (DER)	80%
1.4	The role of synchronous generators and condensers in an IBR dominated power system	65%
2	**Network impact**	
2.1	Impact on control systems	30%
2.2	Impact on protection systems	30%
2.3	Assessing the need for modifications	
3	**Tools and techniques**	
3.1	Power system modelling and simulation tools	20%
3.2	Decision support tools for control centers	
4	**Technical and regulatory requirements**	
4.1	Technical and regulatory requirements	80%
5	**End-to-end system restoration**	
5.1	Restoration from transmission network	45%
5.2	Restoration from distribution network	
5.3	Commissioning and model validation tests for end-to-end black start capability	
5.4	Representative example of end-to-end system restoration in power systems with high share of IBR	100%

Aurecon's recommendations for future work are also aligned with the CSIRO GPST Topic 5 *Research Plan*:

- The treatment of GFMI and GFLI IBR during system restoration, with consideration to their required operating reserves, operating modes, and droop settings[24]
- Impact on network control and protection systems, including a detailed assessment of emergency control schemes and static reactive power compensation equipment[25]
- Power system modelling and simulation tools, and the inclusion of protective relays into the analysis[26]
- Power system technical requirements[27]

[24] Ibid 21, pg. 24, Table 7-2, sub-topic (I).

[25] Ibid, pg. 24, Table 7-2, sub-topic (II).

[26] Ibid, pg. 24, Table 7-2, sub-topic (III).

[27] Ibid, pg. 24, Table 7-2, sub-topic (IV).

- End-to-end power system restoration, including top-down, bottom-up restoration, and hybrid restoration techniques[28]

[28] Ibid, pg. 24, Table 7-2, sub-topic (V).

5 Distributed Energy Resources

5.1 Topic 8: Distributed Energy Resources

Australia is leading the world in the adoption of rooftop solar PV with almost one in three houses having the technology. Rooftop solar PV has already achieved the mark of generating 14% of the total Australia's electricity demand. This and other distributed energy resources (DERs) such as batteries and electric vehicles are creating opportunities to homes and businesses to save or even make extra money. Savings are achieved by reducing energy bills while extra money can be made through aggregators, who bundle DERs to participate in the electricity market run by the Australian Energy Market Operator (AEMO). The challenge, however, is to enable homes and business to make the most of their DERs while ensuring the integrity of the existing electricity distribution infrastructure (the 'poles and wires').

To tackle this challenge, Distribution Network Service Providers across Australia are gearing up to offer their customers flexible connection agreements known as operating envelopes (or dynamic operating envelopes). These operating envelopes (OEs) can be used to orchestrate the bidirectional flows from DERs whilst ensuring the integrity of the poles and wires. However, DNSPs in different States and Territories are likely to calculate and allocate OEs differently, given that they have different monitoring infrastructures at the distribution level, particularly in terms of smart meters and availability of network models. Therefore, it is important for DNSPs and, ultimately, to AEMO, to understand the spectrum of potential benefits and drawbacks of using the different OEs.

The project "Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia" is carried out by UoM and funded by CSIRO as part of the Stage 3 of the "Australian Research for Global Power Systems Transformation (G-PST)" for Topic 2[29]. This research phase builds on Stage 2, which successfully demonstrated that for single low voltage (LV) network i.e., a single neighbourhood, full electrical network models and full monitoring of customers (i.e., 100% smart meter penetration) are not necessarily needed to calculate adequate OEs. Simpler OE implementations that require very limited knowledge of the low voltage (LV) electrical network (to which residential customers are connected to) and very limited monitoring have great potential to be good enough to solve excessive voltage rise/drop and asset congestion within the LV network.

Building on the four OE implementations developed during Stage 2 – which are the Ideal OE, Asset Capacity OE, Asset Capacity & Critical Voltage OE, and Asset Capacity & Delta Voltage OE – the current Stage 3 research is:

- Assessing the implications of large-scale OE calculations in terms of accuracy, necessary algorithmic adaptations, and computational requirements.
- Providing guidance on data-driven techniques that can enhance their electrical modelling processes.
- Providing guidance on forecasting techniques for OEs.

UoM in their Stage 3 research is expanding the application of OEs from single LV feeders to multiple neighbourhoods represented as a parallel arrangement of multiple LV feeders and distribution transformers connected to a high voltage supply point. This grows the single feeder application studied in

[29] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-8-DERs-Final-Report_with_alt_text-2.pdf

Stage 2 to more extensive and realistic distribution system arrangements. In doing so it also considers the interaction between parallel feeders particularly related to thermal limitations and over voltages.

The research objectives have been divided across eight succinct tasks, aligned with the Topic 8 research roadmap:

1) Assessment of the performance of the four OE implementations of stage 2 when used for integrated HV-LV networks (i.e., multiple neighborhoods).
2) Design of improved OE calculations/implementations considering both HV and LV networks.
3) Implementation and assessment of the redesigned OE calculations for integrated HV-LV networks.
4) Recommendations to DNSPs and AEMO on the use of the improved calculation of OEs for integrated HV-LV networks.
5) Qualitative assessment of data-driven techniques that can enhance DNSPs electrical modelling processes.
6) Qualitative assessment of forecasting techniques for operating envelopes.
7) Prepare final report and presentation.
8) Share algorithms and data with CSIRO and AEMO.

At this stage of research, this project is demonstrating that OEs can be effectively quantified across a large area consisting of multiple LV feeders e.g., implemented at a high voltage (HV) supply point, hence informing AEMO on the extent to which DERs could be utilised by aggregators. AEMO could use this information to estimate the minimum demand on a given area, which would help them with the planning of the power system operation. Moreover, the forecasting necessary for OEs can significantly help with forecasts at transmission voltage levels, thus also helping AEMO to have a more accurate forecasts to plan power system operation and generator dispatch ahead. Some notable findings made by UoM on the implementation of OEs across multiple LV feeders simultaneously noted that:

- Multiple neighbourhoods (multiple distribution transformers) require OEs simultaneously, which can further exacerbate voltage and thermal issues. This makes it necessary to consider the interactions among LV networks and the HV feeder which, in turn, require adaptations to how OEs are calculated.
- Outcomes to date note that thermal issues (HV transformer capacity) associated with multiple neighbourhoods can be resolved, but not voltage ones unless using the ideal OE. While providing high accuracy the ideal OE also comes at highest cost.
- The asset capacity & critical voltage OE has a reasonable compromise between accuracy and cost. It solves thermal problems on transformers for any penetration of flexible customers. Although it does not always solve thermal problems at head of feeders due to some simplifications, it reduces the issues for medium-high penetration of flexible customers.
- The asset capacity & critical voltage OE reduces numerous voltage problems for low-medium number of flexible customers penetration. It also release almost the same amount of energy that the ideal OE releases (which releases the most). All of this without the need of electrical network models and with limited monitoring.

UoM advises that all contracted Stage 3 work will be completed by 30 April 2024. In the absence of more detailed information being available from UoM, we have assumed that relative progress aligns with the individual short-term research task length of the *Research Plan* for Topic 8 generally being three years.

Table 8: Expected progress of UoM's research for the 2021 CSIRO Topic 8 research activities by the end of the 2023/24 period

	RESEARCH TASK	Anticipated 2023/24 Progress Status
	Very High Priority	
RQ0.1	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)?	60%
RQ1.3	What is the role of DER standards in concert with the future orchestration of DERs?	30%
RQ4.1	What are the minimum requirements for a DER-rich distribution network equivalent model to be adequate for its use in system planning studies?	30%
RQ5.1	What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?	60%
RQ5.2	What are the necessary considerations of establishing a distribution-level market (for energy and services)?	30%
	High Priority	
RQ1.1	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?	50%
RQ1.2	For each DER control approach, what is the most adequate decision-making algorithm (solution method)?	50%
RQ3.1	What are the most cost-effective ancillary services that can be delivered by DERs considering the expected technological diversity and ubiquity of DERs?	
RQ4.2	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	
RQ2.1	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%

This project so far is demonstrating that the OEs developed for individual neighborhoods – as considered in stage 2 – are not as effective to solve issues, particularly voltage ons, when OEs are used across multiple neighbourhoods. It is also demonstrating that OEs developed when considering integrated HV-LV networks (multiple neighbourhoods simultaneously) work better. However, further research is needed with respect to other aspects. This includes two main streams of work:

- Implications of Australian PV inverter Volt-Watt and Volt-var requirements on the effectiveness of OEs. This stream of work relates to RQ 1.3 of the Australia's G-PST Research Roadmap.
- HV-level quantification of aggregated OEs considering rural and urban HV feeders as well as forecast. This stream of work relates to RQ 4.1 of the Australia's G-PST Research Roadmap.

These additional tasks would further expand on the proposed research plan for Topic 8.

The adequate orchestration of DERs can ensure a future in which every house in Australia can have solar photovoltaics and electric vehicles and, ultimately, help Australia meet our 2030 renewable targets in the most cost-effective way. The concept of Operating Envelopes is one that is already being adopted in Australia as it can help orchestrating DERs whilst ensuring network integrity (the 'poles and wires') by providing time-varying export and import limits at the connection point of customers (or DERs). In fact, the export part of operating envelopes has already been approved by the AER [3] to be offered by DNSPs to customers that would like to have a variable flexible export limit instead of the fixed one (which is default today). Some DNSPs are already offering this new type of connection to their customers [4, 5] while others are preparing accordingly.

UoM states that The knowledge being developed by this project is not only important to Australia, but to many other countries since the increase in the DER adoption is happening worldwide. Therefore, Australia is in a strong position to share its knowledge and lead collaborations with research institutions from other countries and thus help in the world's energy transition.

5.2 Topic 9: DER and stability

The integration of distributed energy resources (DERs) such as solar PV systems, battery energy storage systems (BESS), electric vehicle chargers, and flexible loads into distribution networks introduces complexities in network management. This transformation necessitates advanced and accurate toolsets for network operators and market responsible entities like AEMO, TNSPs, and DNSPs in Australia and globally. These tools must not only accurately represent the power system's state at any given time and location but also adapt to the evolving demands of the network. The detailed modelling of these devices is critical, as they exhibit complex behaviours during power system disturbances and in steady states, necessitating informed operational and planning decisions by System Operators to ensure a stable and resilient power system.

Current simulation and modelling approaches, particularly involving DERs and intelligent loads such as air conditioners and heat pumps, fall short in capturing the complexities of real-world conditions. Major challenges in the operation of DER in LV networks involves:

(a) inconsistencies with standards' requirements,

(b) varied responses to grid disturbances,

(c) differences across inverters from different manufacturers and

(d) differences between models and actual inverter behaviour.

These inconsistencies directly affect the accurate representation of systems, especially ones that are in the early stages of growth within LV networks, such as BESS, hybrid PV/BESS systems, EVs, and smart loads. Further, this gap highlights the importance of experimental validation of simulations to ensure model accuracy and reliability.

GPST Stage 2's experimental testing revealed significant discrepancies in the responses of DER, BESSs, EVs, and various loads to grid disturbances compared to distributed PV inverters. These findings emphasize the need for public access to testing results for BESS, EVs, and smart loads to confidently integrate them into network models. The researchers supported by AEMO have noted that comprehensive testing of DER and smart loads is therefore essential as it facilitates ongoing DER deployment without resorting to overly conservative power system operation, prevents unnecessary network investment, enhances the network's capacity to accommodate DER, and ensures that modelling tools evolve in tandem with grid operations and standards.

Stage 3 research for Topic 9 are aligned with the research priorities established in the CSIRO GPST *Research Plan*[30]:

- Development of standardized inverter test procedure for both DER, BESS, hybrid energy systems (HESS – combined PV and BESS with up to three different operating modes), and load types.
- Testing of DER, BESS and HESS according to test methods compliant with AS 4777.2020.
- Inverter reconnection testing that maps the voltage levels and time delay with which DER are reconnected to the grid following disconnection. Such behaviour modelling is important for AEMO to consider in restarting procedures, as well as transient system responses to disturbances.
- Testing of flexible loads commonly found in consumer households.

While the test procedures will optimise the time spent testing each system, whether load or DER, the additional models developed using the results of these tests will further update and refine the composite load models that are used by system operators to assess power system stability.

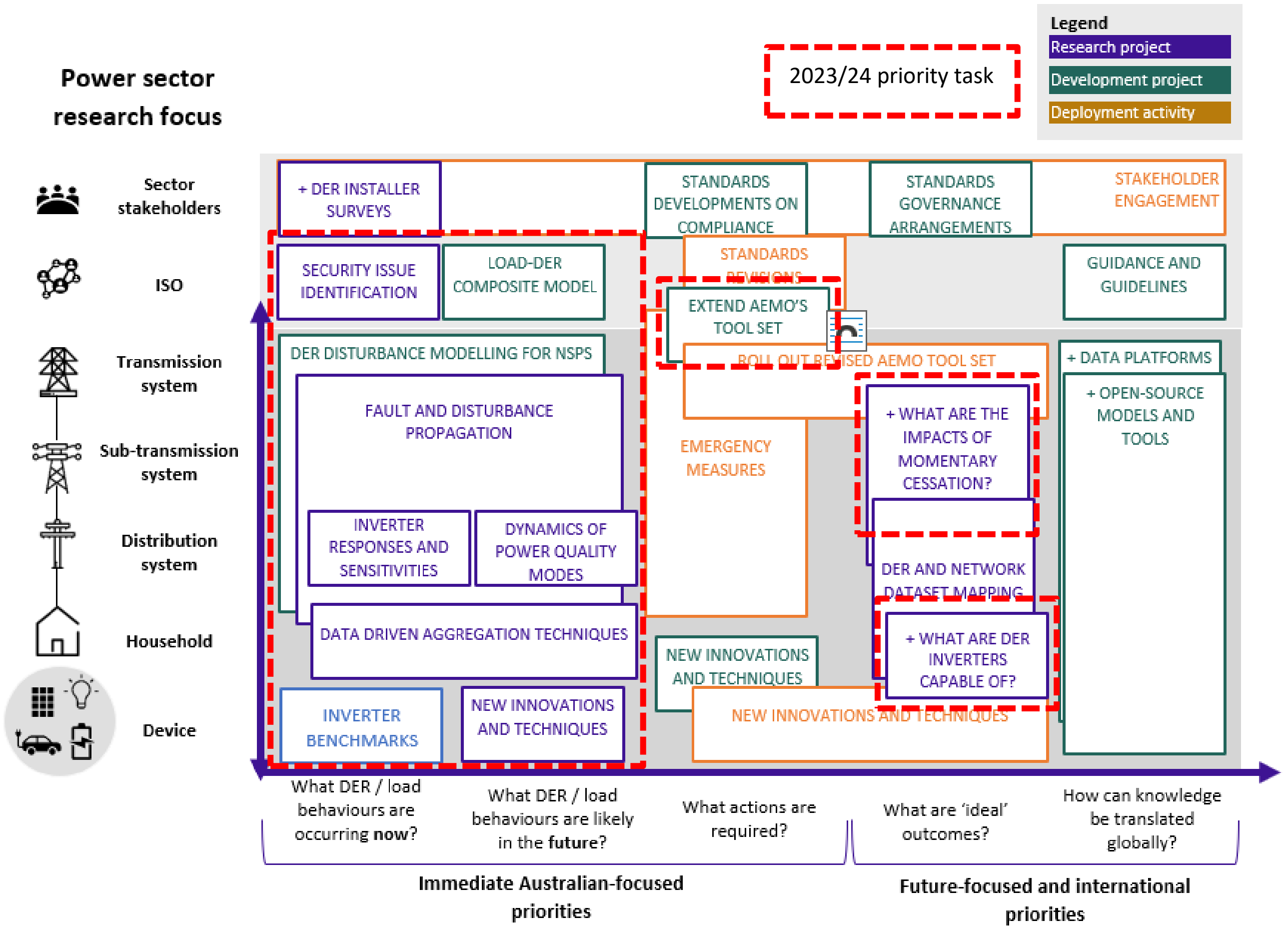

Figure 3: Relevance and regional prioritisation of Topic 9 research tasks

The key tasks carried out by UNSW are aligned with immediate Australian-focused research priorities documented in the Topic 9 *Research Plan*, such as inverter benchmarking, development of load-DER composite models, and DER disturbance modelling[31]. UNSW reports that these tasks make up the research plan priorities as shown in Figure 3, marked by the red dashed outline.

[30] https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-9-DER-and-Stability-Final-Report-with-alt-text.docx

[31] Ibid, pg. 41, Figure 14.

By mid-December 2023, UNSW and UoW reported successful completion and progressing of a number of high priority research tasks, including:

- Development of streamline test procedures for DER, BESS, HESS, inverter driven loads, and motor loads.
- Successful testing of nine DER, BESS and HESS inverters. The researchers also engaged with the OEM to resolve discrepancies between their test results and inverter behaviour and those obtained by the manufacturer.
- UNSW have completed roughly two thirds of the reconnection testing of some 50 inverters. Tests include black start restoration when the inverter starts the first time with nominal frequency and voltage, and inverter behaviour in face of declining voltages.
- Motor D load testing by UoW to assist AEMO with refinement of the CMPLDW model used in AEMO system operations, has included fifteen non-inverter domestic loads such as washing machines, air conditioners, and fridges. Tests have included a range of stall, sag, and restart tests. Results of this research have already led to significant refinements in the parameters used by AEMO in their load model representation.
- Three different EVs have also been tested to understand the behaviour of these new and expanding load types.

UNSW and UoW expect to successfully to complete outstanding tasks of the Stage 3 research by the end of the research period on 30 April, including the following:

The main activities scheduled for the next 6 months of the project are the following:

- Complete BESS and HESS testing in different modes.
- Continuation of reconnection testing of remaining 30+ inverters.
- Identifying the point on wave disturbance effect on the PV inverters.
- Continuation of Load Testing with EV load and analysis of the load testing results.
- Update of the project website with the PV and BESS results.
- Expansion of the project website with load testing results.

Future work recommended by UNSW for the future research in this topic as part of Stage 4 research includes:

- **PV inverters** - Conduct advanced wave disturbance analysis on residential PV inverters, focusing on testing point on wave (POW) disturbance analysis on the fleet of residential PV inverters to grid disturbances, informing future updates to standards, and informing ongoing development of dynamic models representing distributed PV.
- **BESS/hybrid inverters** - Further testing of the responses of the fleet of BESS and hybrid inverters to grid disturbances, examining compliance with AS/NZS4777.2:2020, informing development of dynamic models representing distributed BESS.
- **Weak Grids**: Establish the laboratory configuration to illustrate a weak grid scenarios for LV networks, aiming to comprehend the behaviour of residential PV, Hybrid, and BESS inverters in a weak grid conditions.
- **Parallel Inverter Connection**: Investigate the response of inverters when connected in parallel under various grid disturbances.

- **Loads** – Surveying and testing of further residential and commercial loads in order to better tune and improve dynamic load models. Load models remain the largest source of uncertainty in NEM dynamic models.
- **Industrial loads** – Surveying industrial and commercial load sites to understand load composition, any relevant protection on site, and test behaviour of various load types during disturbances
- **EVs** – Testing of EV charging infrastructure to understand responses during disturbances. This will inform development of suitable performance standards for EVs with regards to impacts on grid stability. It will also inform development of dynamic power system models for EVs.
- **Larger capacity inverters** - Develop laboratory facilities capable of testing MW size inverters. These are one of the biggest growth areas, and behaviour in disturbances is poorly understood.
- **Grid Restoration Strategies:** Explore the role of DERs in grid restoration post high-impact events, focusing on optimizing DER contributions to enhance system resilience.
- **Aggregation of Distributed Energy Resources:** Explore strategies and technologies for effectively aggregating DERs including the development of algorithms and control systems for real-time management and optimization of DER aggregates.