# Power System **Planning**

## Australian Research Plan for CSIRO-Global Power System Transformation Consortium

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# Executive Summary

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Energy Market Operator (AEMO) have jointly initiated a research program in partnership with several research institutions to contribute to the Global Power System Transformation (G-PST) consortium. The program is aimed at developing research plans for the whole Australia and beyond which address the highest value imminent or potential challenges faced by different stakeholders in the path of the decarbonising the power system. The aim is to identify both where research is needed to address Australia's unique challenges, and where Australian researchers can make unique contributions to meeting global challenges.

In the broader context of the G-PST activities, the University of Melbourne has been commissioned by CSIRO to develop the Australian research plan on the topic *"power system planning"*. Planning practices have traditionally adopted deterministic approaches to represent the long-term drivers of system expansion, historically mainly associated with annual load growth, with relatively simplified representations of system operation. However, the increasing operational and technological complexity of power systems, as well as the uncertainty in future system, market and policy developments, are diminishing the effectiveness of traditional approaches. The operation of low-carbon systems dominated by renewables and distributed energy resources (DERs) and with increasing coupling with other energy sectors calls for new modelling requirements and tools. Long-term uncertainty is increasingly influenced by factors, including emerging technologies and business models, policy environments, and climate change, that all represent daunting challenges to system reliability and resilience. More sophisticated and flexible representations of the possible futures are needed, along with new decision-making frameworks and tools to deliver plans that optimise outcomes across multiple scenarios. New metrics and methodologies are needed that account for the technical and economic risks faced by multiple stakeholders during the energy transition. The interface between power systems and other energy systems and sectors (i.e., gas, hydrogen, transport) also needs to be properly designed to capture the impact of and flexibility created by multi-energy systems and sector coupling in planning studies.

Substantial research is needed to define the frameworks that lay the foundation for low-carbon power and energy system planning. In this regard, the effort undertaken in this project draws on a wide range of issues identified by industry stakeholders and the research community. A large issue slate prompts a range of questions; which ones are distinct, which overlap? What are the dependencies? How can we be confident we are not missing something critical? Which issues are of greatest value – and to which stakeholders? When are insights needed to best benefit industry? How do priority issues best translate into a practical research plan? And, where and how does this plan leverage our collective strengths to meet Australia's unique challenges and make a significant and distinctive contribution to global power system transformation?

This project has systematically responded to each of these questions with the support and continuous feedback of key industry stakeholders, research providers, and of course the CSIRO. To be more specific, using 15 research questions provided by the G-PST Agenda as the foundation, a list of 119 research questions have been established, which have then been distilled in 36 research projects. Then, the projects are aligned in 16 research streams within five cohesive research programmes:

1. **Long-term uncertainty**: Methodologies and models to define uncertainties and risks in the representation of future power systems

2. **Power system operation**: Models and tools needed to assess and quantify the technical and economic performance of the system, also considering computational efficiency
3. **Reliability (security and adequacy) and resilience**: Methodologies and models to assess the system reliability and resilience under various uncertain or extreme conditions. Definition and design of metrics to assess techno-economic performance in power system planning under uncertainty
4. **Decision making**: All the elements (e.g., metrics, risk appetites, objectives of stakeholders) associated with the design and interactions of modules and tools to determine flexible investments in power system planning under uncertainty
5. **Distributed energy systems**: Models for evaluating demand side flexibility, impacts and flexibility embedded in the interactions between power system and other energy systems (i.e., gas, hydrogen), and assessing adequacy and resilience contribution from DERs in planning studies

This research plan expands on the scope of the G-PST agenda to meet a broader range of challenges of unique importance to Australian industry stakeholders, including for instance modelling of climate change impact and development of frameworks and architectures for decision-making under uncertainty. The plan also articulates the potential impact of the proposed research, evaluates the capabilities of Australian research institutions to deliver it, and highlights the potential of this research to make a significant contribution to the G-PST agenda. Finally, the plan is pragmatically structured to best leverage local expertise and deliver high value to industry and society, with actionable insights within the next five years.

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# 1 Introduction

## 1.1 Background

The electric power system is considered the backbone of modern energy supply systems because of the increasing electrification of different sectors (e.g., heating/cooling, transportation) and the subsequent interdependency between it and other energy systems (e.g., gas, hydrogen). Additionally, the power system plays a crucial role in the low-carbon transition due to the potential for fossil fuel power stations (e.g., coal plant, gas turbine) to be replaced with renewable energy resources (e.g., solar, wind). In fact, increasing renewable penetration in power system is deemed to be one of the most important measures in tackling climate change and achieving carbon neutrality. However, the increasing electrification of energy demand and the renewable integration uptake on the generation side brings challenges, uncertainties, and risks to both the short-term operation and the long-term planning of power system.

Although a substantial increase of generation capacity is expected in the future to meet the rising demand, the temporal and spatial disparity of renewable output and demand is creating operation conditions that will impact the reliability of power systems. Furthermore, shifts across fuel sources (e.g., replacing coal plant with cleaner and more flexible sources such as gas generators) will have an impact on the supply chain that needs to be carefully assessed also from the point of view of reliability. At the same time, climate change is increasing the frequency and severity of extreme events such as storms and bushfires which put system resilience to the test.

Different measures are being taken to maintain system reliability and resilience, such as the deployment of battery energy storage systems (BESS) and pumped hydro storage to increase system flexibility. Network reinforcement is also required to alleviate network congestion and enable a low-cost, reliable supply when the need to transfer substantial amounts of energy across the system increases. Network reinforcement will then help to reduce the curtailment of renewable generation and address the spatial and temporal diversity of supply, particularly for large-scale wind/solar farms which are usually located away from load centres and the thermal power plants they replace. A secure and unrestricted network connection for renewable power plants is essential so that market-driven investments for renewable energy can continue in the future.

The decisions on whether, when and how to reinforce the transmission network have an enormous impact on the efficient development of the system. They are complex in nature, due to the regulated nature of the transmission assets (investment risks cannot be distributed by the interaction of market forces) and the sheer size of techno-economic interactions between system components. Thus, the frameworks that address this complex decision process must continually evolve to meet the new system challenges. On the one hand, the assets used for network reinforcement often have a long lifetime and high upfront costs. Therefore, the decision-making framework is often required to demonstrate the adequate identification and consideration of long-term uncertainties and risks in the process to determine investments recommendations. This is becoming increasingly important when facing rapidly changing scenarios for technology developments on the generation side, such as distributed energy resources (DERs) including inverter-based resources (IBRs) which are fundamentally changing the operation conditions of the system. On the other hand, the solutions for alleviating network congestions are no longer limited to traditional network-based assets (e.g., transmission lines and transformers). Flexible assets such as batteries and other technologies such as synchronous condensers to deal with inertia and system strength issues are also being considered to deal with constraints. These assets usually have a substantially lower deployment lead time compared to network-based assets, and they can simultaneously provide multiple services to support system reliability. More importantly, they can also help unlock investment flexibility in transmission planning. This refers to their capacity to provide value in a wider range of operation conditions until relevant uncertainties have unfolded to justify the large expenditures associated to network reinforcements, hence reducing the overall investment risk.

The definition of high-performance decision-making frameworks capable of incorporating all these elements is essential for the present and the future of the power system. Many of the components inside the planning framework require further study to understand the underlying challenges of future power systems; also, extensive research is needed to define the methodologies needed to identify and optimise the portfolio of investments that can address these challenges.

## 1.2 Energy Transition Goals

Decarbonisation of our economy is now recognised as a crucial global goal if we are to avoid the most serious consequences of extreme climate change. For the energy sector in Australia, the goal is to achieve this decarbonisation while considering the National Electricity Objectives (NEO):

“*to promote efficient investment in, and efficient operation and use of, electricity services for the long term interests of consumers of electricity with respect to:*

- *price, quality, safety and reliability and security of supply of electricity*
- *the reliability, safety and security of the national electricity system.*"

Australia has immense and increasingly low-cost renewable energy resources across the country, which have led to a fast growth of residential rooftop PV installation in National Electricity Market (NEM) and Wholesale Electricity Market (WEM) in last ten years. On top of the high penetration of distributed IBRs, large-scale renewable energy projects are also connecting to the system, helping to decarbonise Australia’s energy system. Federal and states governments have set up various incentive schemes and renewable energy zones (REZs) to provide exclusive economic and infrastructure support to potential renewable energy projects. Essentially, renewable technologies are and will be playing a central role in the future of Australian energy sector.

As highlighted above, to maintain system security and reliability and provide resilience, an appropriate decision-making framework is needed to guide the investment decisions in power system planning. Traditionally, such planning frameworks have relied on deterministic tools to perform cost-benefit analysis, which may fail to adequately capture the long-term uncertainties in the power system planning problem. Such deterministic approaches may also lead to under or over investment in the transmission network, which would result in higher electricity costs for consumers. Additionally, the modelling of system operation employed in these tools is often very simplified, which might be inadequate to capture the challenges of future systems with deep penetration of renewables, DERs and IBRs.

All the previous elements call for a research plan aimed to explore the new tools, metrics and decision-making frameworks for planning in response to a rapid change of technology mix in future low-carbon power system.

## 1.3 A way forward

Australia must meet the challenges of our future energy transition in a way that is timely, effective – and balances the needs and objectives of the future grid's manifold power system stakeholders. Our context (in terms of infrastructure, operational, regulatory and policy dynamics) and geography and climate present unique and in some cases urgent challenges. These are challenges we must and can meet, by leveraging the best talent from industry and its research providers in collaborative research focused on the highest impact, time-critical issues. Our collaborative research community is already at the leading edge of global thinking on the challenges of power systems planning. The plan laid out in this document reflects the needs, aspirations and priorities of industry stakeholders as well as insights from its research collaborators. It sets an agenda for collaboration that leverages our strengths to meet Australia's unique challenges, maximise value for all energy system stakeholders – and make a significant contribution to the transformation of power systems across the globe.

# 2 Methodology

The objective of this effort is to provide the Australian Power Systems Planning community with a plan that,

a) is strongly supported by that community,
b) effectively leverages its capabilities, and
c) delivers timely and useful insights and tools that
    a. meet Australia's unique needs, as well as, where possible,
    b. significantly and distinctively advance global capabilities.

As noted in the summary, there is no shortage of potential issues to address, based on inputs from industry stakeholders and the research community. Again, as noted, this prompts a range of questions; which are distinct, which overlap? What are the dependencies? How can we be confident we are not missing something critical? Which issues are of greatest value – and to which stakeholders? When are insights needed to best benefit industry? How do priority issues best translate into a practical research plan? And, where and how does this plan leverage our collective strengths to meet the above objectives?

Our methodology systematically responds to these challenges as the balance of this section explains.

## 2.1 Research plan scope

The scope of this project encompasses planning for all aspects of power systems – with some limitations laid out below. This means that the research activities presented do not only consider transmission[1] planning. The research plan is structured as a set of research activities that power system stakeholders in Australia (and potentially other countries in the context of the G-PST consortium) would undertake in order to address in a timely manner the system challenges of the coming decade. The breadth of these challenges is represented through a set of key research questions on power system planning, which are introduced in section 3.4 and the full list of research questions is presented in Appendix A.

The scope of this research plan is defined with the following **assumptions** and **exclusions**, which may lead to certain **limitations** as explained below:

- **Assumptions**: The research plan prioritises the research activities needed in the context of Australia's power systems, which have some unique features, such as high penetration of IBRs, a largely radial grid topology at transmission level and an extremely long transmission network. Most of the research outcomes, however, are still expected to be applicable to system planning in other countries around the world.

- **Exclusions**: The research plan will not consider research questions about specific aspects of distribution network planning. It will also not include specific questions about modelling planning decisions within other sectors like gas or hydrogen. However, the influence of these sectors and the distribution network are considered in the research questions about system planning, that is, the relevant interfaces with the system and the interaction between sectors will be reflected in the analysis and assessed in an aggregated, equivalent manner.

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[1] For example, although AEMO's ISP only produces decisions for transmission (interconnectors), it does have a stage where a combined generation and transmission expansion plan is run.

- **Limitations**: The prioritisation of the research questions and plan is based on multiple rounds of engagements with relevant stakeholders and their perception of the current challenges. However, the priorities of different stakeholders might change in the future due to rapid changes in the technology mix and potential policy and regulation adjustments. As different research packages in the research plan are also coupled with each other to a certain extent, and delays on some research activities might hinder others, it will be essential to re-calibrate the research plan at least biennially. This is discussed both below and in the risk assessment section.

### 2.1.1 Research plan structure

A research plan, at a national level, is a strategic endeavour that aims to describe the steps a country needs to take to accomplish specific **outcomes and goals** within a specific period of time with constrained resources. This naturally leads to the need to **prioritise actions** based on their potential value and an understanding of when new insight will be of most value to industry. In order to be effective, a research plan needs clearly defined **milestones**, and ideally also performance indicators, to track the progress towards achieving the specific project goals. Another fundamental aspect of an effective research roadmap is continuing **stakeholder engagement**, to maintain alignment of activity with impact objectives, maximise the practical value of deliverables and build commitment to their subsequent application. While this project is focused on articulating a high impact research agenda's success will be determined by the effectiveness of research processes. We know that best outcomes will result from close collaboration that effectively leverages talent and insight from industry and its research providers, and actively aligns research activities and deliverables with industry needs.

Figure 1 presents the building blocks of a research plan. The following describes the methodological aspects of each of the blocks:

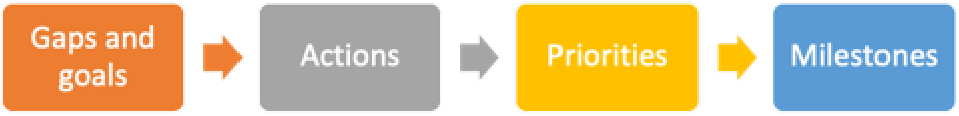

*Figure 1. Building Blocks of Research Plan*

- Gaps and goals: in the context of a research plan, the goals correspond to a comprehensive set of clear research questions that need to be answered. The questions must be constructed in a way that they will describe the gaps between current capabilities and future needs. At the same time, it should be possible to determine straightforwardly if the questions have been successfully answered. Each research question (goal) aims to address gaps in knowledge; these gaps include understanding the role of different technologies, system modelling, solution methodologies, scenario representation, etc.
- Actions: from a research perspective, the actions correspond to the activities conducted to effectively answer the research questions. The research plan is structured around 3 levels of activities, namely, research programmes, research streams and research projects. A programme is a collection of streams, and a stream is a collection of projects. This approach enables the most effective allocation of topics and resources among incumbent research institutions. If the research plan has been conceived with a strong stakeholder engagement (validation), and if it reaches the right audiences, it will thus naturally promote the development of the research activities within the country. In the context of such a national research plan, actions might also include the support of specific research through a range of funding mechanisms (scholarships, research projects, creation of centres, etc.).
- Priorities: both goals and actions must be prioritised to address the gaps and questions that are most valuable and urgent. This is based on stakeholder inputs and the authors'

perspectives. These priorities are reflected in the research plan through the position of the different research projects in the timeline and the resources assigned to each of them, highlighting the milestones connected to the expected research outputs associated with the pressing gaps under consideration.

- Milestones: considering that the research plan potentially covers a long horizon (10 years starting in 2023[2]), it is relevant to establish a series of milestones that will allow tracking progress in addressing the research gaps and optimise the focus, effectiveness, and resource allocation for continuing research. To be clear, the plan focuses on delivering practical insights of high relevance and value to industry in the first half of this planning horizon.

The importance of milestones and in-project feedback mechanisms cannot be over-stated. While directionally the aim may be to establish a 10-year plan – to paraphrase, "no research programme survives sustained contact with reality unchanged". Many factors drive the industry need for new insight – and they are all changing fast. It's also impossible to predict the insights and new challenges that will emerge as a result of our collective research. What's critical is to focus on delivering insight we know industry values highly – as soon as possible, and if necessary, incrementally. Application of that and other planning insights and tools will itself reveal new opportunities and challenges. Continuing industry engagement in and feedback to every individual research project is essential to ensure activities and outcomes are actively aligned with highest value industry needs. And at the programme level, the overall agenda needs to flexibly adapt to ever-evolving industry challenges. In short, the structure of the programme and the execution of the projects within it must be actively driven by the needs and timeframes of industry – not the research community.

### 2.1.2 Research plan development

Our development methodology systematically transforms a large but unstructured issue slate assembled from myriad sources into a rigorously structured plan that, based on their feedback, best represents industry needs and priorities. This transformation is achieved in four phases that successively distil highest value challenges and is sketched in Figure 2:

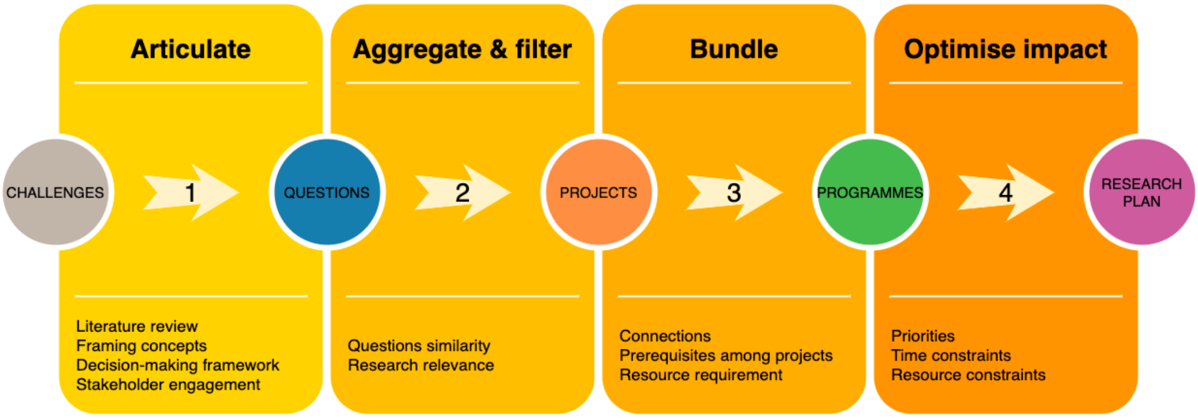

*Figure 2. Research plan development phases*

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[2] The activities of the roadmap start in year 2023 to allow for a period of coordination, sourcing of funding and allocation of activities to the institutions in charge of developing the research.

### Articulate phase

This phase addresses the questions:

- What are the issues that are considered important by Australian industry and research stakeholders, and by the international power systems community, and
- How can we know we are not "missing something important", in particular in terms of future industry dynamics?

We have met these challenges through

a) a process combining systematic stakeholder engagement and targeted reviews of relevant academic literature and industry technical reports (including of course G-PST sources), and
b) the development of a range of frameworks that reflect the underlying structure and dynamics of the industry and power system planning specifically – and their application to rigorously explore the issue space to identify potentially significant issues that may be missed by the first step

This work has drawn heavily on the contributions of stakeholders, both to capture issues and to develop and refine the framing concepts used to build confidence that the overall issue slate is, in terms of material issues, comprehensive. This issue slate, articulated as a set of "raw" research questions, is the output of this phase.

### Aggregate and filter phase

This phase addresses the questions:

- Of our initial issue set, which are in-scope and for those that are, which are unique or tightly related?
- Which resulting issues have the potential to deliver material industry impact? And
- How do the issues in this filtered set translate into discrete research projects?

Our process responded by:

a) Semantic analysis that identified the focus and intent of each element of our issue set
b) Grouping of tightly related issues and articulation of their collective intent as a distinct issue
c) Consolidation of the issues that have the potential to deliver material industry impact
d) Translation of the substance of the consolidated research question set into research projects defined and scoped to address them

This resulted in a set of discrete research projects that address specific topics of interest which, collectively comprehensively reflects the slate of issues captured or generated by this project.

### Bundle phase

This phase addresses the questions:

- Where are there synergies or dependencies across the defined project set?
- What programme structure best supports these linkages?
- What are the resource implications?

Project linkages may emerge for several reasons. Projects may focus on issues where natural overlaps with related but distinct projects offer potential synergies as each is pursued. i.e., there is the natural potential for "productive intellectual ferment" through the active exchange of ideas in tackling a similar challenge. It’s also likely that projects with these characteristics will draw on distinct pools of research expertise. Obviously too, projects may depend on the insights from others in order to progress, or need to deliver insights to dependants.

We have responded to these challenges by:

a) Identifying project dependencies and synergies that may result from projects tackling deeply related but distinct challenges, from leverage of related expertise and alignment with related stakeholders
b) Estimating project resource requirements
c) Sequencing of projects based on dependencies
d) Bundling of individual projects into:
    a. Streams, representing groups of projects that deliver distinctive, deeply related end products, and
    b. Programmes, representing groups of streams that draw from related expertise and have distinct stakeholders.

The result is an overall research plan structured with programmes, streams and projects, supported by an articulation of their dependencies and an estimate of associated resources.

**Optimise impact phase**

This phase addresses the questions:

- When are research deliverables needed in order to maximise their value for industry? And
- How does that translate into a feasible research timeline?

There is a “time value” for all research outputs. Certainly, there is such a thing as “too late”, where deliverables are no longer relevant because industry just sources other solutions. It’s also true that industry needs in some cases to have established a range of pre-requisites before new tools and insights can be applied. The sequencing and duration of projects needs to reflect what is feasible to deliver in this time window. Research project timeframes certainly don’t linearly compress with additional resources. High-quality research resources are scarce – so the aim must be to apply them against the “critical path” set of issues that maximise industry impact.

Achieving this is hardly an exact science, but by establishing effective feedback mechanisms with industry stakeholders, any imbalances in the initial profiles of activity will be quickly addressed. Importantly, we do not believe it is in most cases possible to ascribe value to research projects with deliverable timeframes beyond five years. This doesn’t mean there are not going to be massively valuable insights needed in that timeframe – only that it is impossible to plausibly define them now. We have established timelines for the overall research plan by:

a) Developing some understanding of the optimal delivery time windows for each project and stream based on a combination of stakeholder inputs and team experience
b) Iteratively optimising the balance of resources, pragmatic project durations and deliverable “time value”

This results in a timeline of activities for each research programme that in aggregate aims to maximise the delivery of actionable, high-value insight well within the next five years. The timeline also identifies the need for stream and programme milestones that provide the feedback needed to maximise impact and maintain alignment of the agenda and activities with industry needs.

## 2.2 Framework for analysis of power system planning

### 2.2.1 Framing concepts

Framing concepts articulate the underlying structure and dynamics of the issue space we are addressing in order to enable their systematic exploration. These frameworks are an essential vehicle for building a common understanding of emerging challenges across all stakeholders and building confidence that all dimensions of the issue space are rigorously tested for material issues.

Our overarching conceptual logic explores the Power System Planning issue space in three main categories, namely Input/Output, Model and Decision-making framework. These categories describe the main components of any power system planning platform[3], and, as it is presented in Figure 3, they are further broken down into a total of 7 key areas. Each of these represents umbrella concepts that are at the core of any of the research questions presented in the plan.

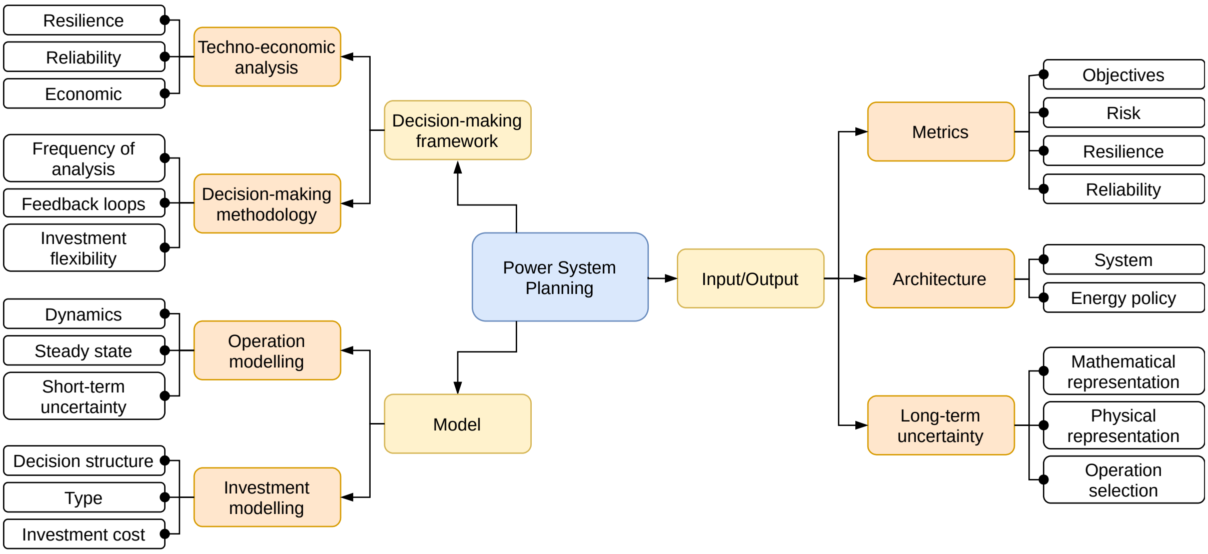

*Figure 3. Framing concepts tree for power system planning*

Figure 3 presents the top 4 levels of depth of a logic tree with many additional layers, all of which contribute to the systematic exploration of the issue space, but which are collapsed in the exhibit for clarity. In the following sections the further explores 7 umbrella areas.

**Area 1: Architecture** (I/O category)

The architecture domain refers to both the physical system and the policies (energy and climate) that give shape to the supply chain of electricity in Australia.

The physical system is represented by the technology types (generators, transmission, storage, VPPs, etc.), their technical features (rating, availability, dynamic behaviour, etc.) and their cost parameters. Also, the system is described by its topology, which includes the location of assets and the balancing areas that might exist in the system. International interconnectors and the specific interfaces with other energy systems are also elements that are included in this category.

The energy policy layer is the other fundamental element under the architecture umbrella. It includes the description of the market principles and the regulations guiding the operation and investment decisions. It also considers all the standards that define the underlying technical requirements and the quality of the products being traded through the system. Environmental policy (e.g. emissions targets)

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[3] Platform here refers to any structure whose objective is to conduct power system planning. For instance, it includes any methodology and/or software package conceived to plan the future power system.

and technology policy (e.g. hydrogen electrolysers) are some of the specific frameworks included within the energy policy architecture.

**Area 2: Long-term uncertainty** (I/O category)

All the elements associated with the definition of the future are covered in this area. It includes the mathematical representation of the uncertainty, comprising the definition of uncertainty sets, and their interaction/sampling to form scenarios and scenario trees (and in case their probability).

The physical representation of uncertainty refers to the specific power system variables and processes subject to uncertainty in the long term; this includes the description of all parameters that are affected by the uncertainty and the effects that the uncertainty can have on the system.

The selection of the operating conditions that best represent the future is also included under this umbrella. In practical terms, this corresponds to the selection of the specific periods in the future that are needed to describe the operation of the system: this can include the representation of all hourly periods of operation within the planning horizon, or a subset of them aiming to reduce the computational burden. Whatever strategy is selected to represent the periods relevant to describe the future operation of the system, it will always include the definition of the values associated with the uncertain variables.

**Area 3: Operation modelling** (Model category)

This area refers to the models used to describe the operation of the power system. It includes the realm of dynamic models needed to represent the transient behaviour of the system, the models representing steady-state conditions of the system and the uncertain elements that impact the operation in the short term.

The mathematical description of the transient behaviour of frequency, voltage, current, among other variables, fall within the dynamic models needed to perform security analysis of the system. The mathematical description of technical aspects of the system, like power flows, unit commitment, reserve requirements, among other aspects generally used to quantify the economic behaviour of the system, are classified under steady-state models. Both in the dynamic and steady-state realms, the sources of short-term uncertainty correspond to the potential contingencies (credible, non-credible and “indistinct”, such as loss of distributed DERs) the system can experience and the deviations of expected output of renewable energy sources and load.

**Area 4: Metrics** (I/O category)

Any attempt to quantify the techno-economic performance of the system involves the definition of a set of metrics and indicators that can allow the comparison and analysis of different system conditions, investment plans, operation strategies, etc.

The natural application of metrics is in the context of the definition of the objective function for different optimisation problems that are needed in power system planning. For example, objective functions include the minimisation of expected costs or the minimisation of the worst regret; naturally, the metrics and indicators used in the objective function can also include technical quantities, like emissions, volume of renewables, lost load, etc. Other metrics relevant in power system planning may include those associated with risk quantification (variance, conditional-value-at-risk, etc.), which also can be used both for technical and economic assessments and enable the ability to represent the risk appetite of the planner and stakeholders in the outcomes.

The quantification of the technical performance of the system demands for metrics capable to describe system reliability[4] and resilience. Since the new and future challenges of the system are substantially different from those experienced in the past, the right metrics to describe system security, adequacy, flexibility, and resilience are an open research area.

**Area 5: Techno-economic analysis** (Decision making category)

Any decision-making framework for power system planning will involve a series of analyses aiming to evaluate the techno-economic performance of the system under different configurations and conditions. The range of analyses spans from reliability and resilience assessments to economic quantifications of the operation of the system. In general, all these analyses are based on bespoke operational models built upon the concepts presented in Area 3.

Typically, existing planning frameworks include environmental, adequacy and security studies, the assessment of optimal dispatch of the system, and the analysis of all previous outcomes together to determine the optimal path of development of the system. The new challenges in the system require further resilience and flexibility assessments, and a deeper understanding of the contributions of different technologies and specific assets (location, sizes) towards achieving a reliable, resilient, and environmentally responsible system.

**Area 6: Investment modelling** (Model category)

Planning an efficient future power system under deep uncertainty requires a healthy set of investment options that can help the system to adapt to future needs and challenges. This area covers the concepts associated with the structure of investment decisions and how they are accommodated within the specific structure of the planning methodology; the specific underlying operation models for each investment option are contemplated under the elements presented in Area 3.

One fundamental element behind investment modelling is the specific investment options under consideration, either individual technologies (transmission, generation, storage, synchronous condensers, etc.) to be installed in specific areas of the system or commercial solutions (demand response, intertrips, etc) to be implemented in the system as needed. The magnitude and timing of capital expenditures and the capital cost of each option are a fundamental part of this description.

The other central concept in investment modelling is the way investment decisions are organised. The standard option is to consider a single decision that represents the moment the option becomes active which should at least consider the lead time needed to deploy the assets in the system. Each investment can have a richer set of investment decisions representing the reality of an engineering project (real options): the project potentially can be stopped, its size can change, the activities included in the lead time can be split into incremental decisions, etc. A larger set of decisions increases the flexibility an investment option can provide to the system that faces deep uncertainties.

**Area 7: Decision-making methodology** (Decision making category)

This area includes all the elements associated with the general procedures that define the decision-making framework. The outermost layer of the framework involves the definition of frequency of plan review and the stakeholders that are involved in its direct development.

The inner workings of the planning framework are also described in the methodology, specifying the algorithmic steps to arrive at the decision. These include, amongst other things: the interactions and feedback between different techno-economic analyses, the definition of the structure of the problem

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[4] In this report the concept of reliability is used to describe the joint set of requirements involving security and adequacy objectives aimed to guarantee the transient and steady-state capacity of the system to serve load.

to capture investment flexibility (includes the definition of scenario and investment decision structure), the selection of decision metrics.

### 2.2.2 Bottom-up design for decision-making framework

As has been indicated in Figure 3, the seven primary investigative areas fall under three logical categories; “inputs/outputs” (i.e., architecture, long-term uncertainty, metrics), “models” (e.g., operation, investment) and “decision-making framework” (i.e., techno-economic analysis, decision-making methodology). These categories relate to the functional modules which carry out different tasks required in power system planning, such as technical analysis (i.e., security, adequacy, resilience), economic assessment (i.e., operational cost evaluation) and decision-making (i.e., investment options selection). System planning relies on the effective modelling of the complex real-world dynamics and interactions of multiple types of systems (operations, technology, economics and more) within multiple, complex and time-varying external constraints (market supply and demand, economic return objectives, regulatory frameworks and environmental and climate variables) to meet similarly complex performance demands. Decision-making methodologies can be characterised by the presence (or absence) and performance characteristics of the modules used to do all these things and the interactions between them. This approach provides a robust and flexible framework for understanding, comparing and evaluating decision-making methodologies. In addition to enabling systematic comparison of different planning methodologies, it also helps detect aspects of the methodologies that create risks or have the potential for material improvement.

Figure 4, represents and describes the elements that, together, allow for the comprehensive characterisation of individual planning modules. The connection graph between these element nodes across a planning model, collectively defines its topological architecture. For instance, a module requires inputs (marked as “Inputs” block in Figure 4) to determine the parameters of power system simulation/optimisation, such as technology parameters (e.g., ramping rates of generators, minimum stable generation levels, etc.), network topology and market operation rules. The objectives of optimisation and metrics used to assess system performance are also defined for each module and contained in the “Metrics” block shown in Figure 4. The “Methods” block indicates the methods and procedures to adequately perform different analyses within the module. The relevant information of “Methods” block is from techno-economic analysis and decision-making methodology areas which were shown in Figure 3. The outputs of a module may, for example, include decisions on generation expansion (e.g., generation portfolio, technology mix), recommendations of network reinforcements (e.g., transmission lines construction) and values of metrics related to system performances on technical, environmental and economic aspects as shown in Figure 4.

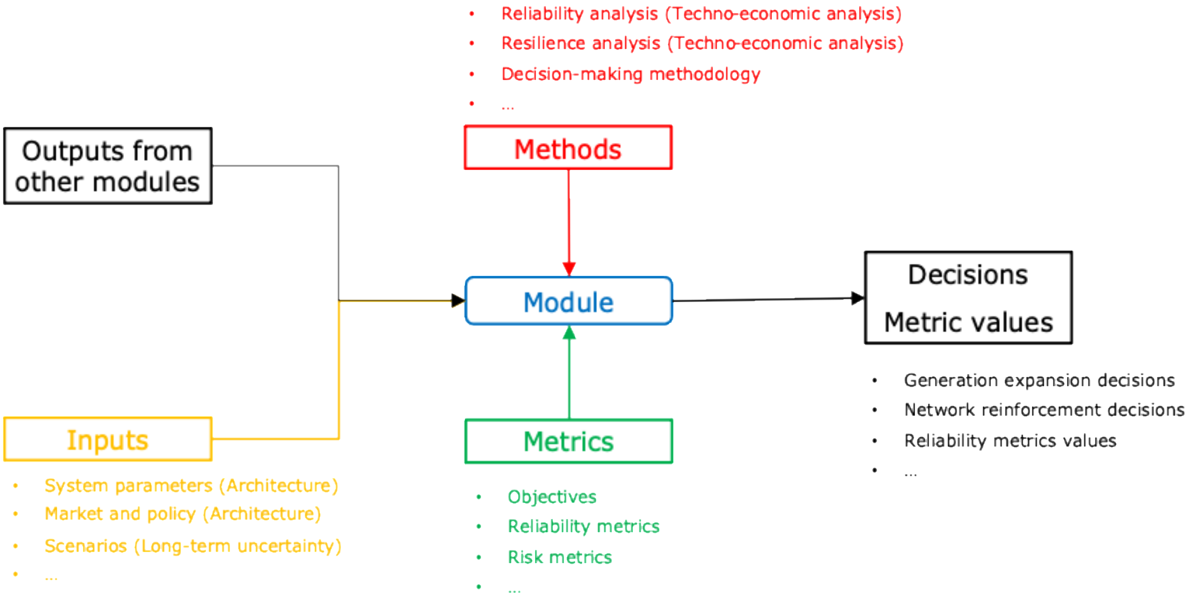

*Figure 4. Elements related to a module, with associated information contained in them*

As mentioned above, different technical and economic analyses will be performed within each module to derive the values of specific metrics and make investment decisions accordingly. These analyses have been classified into three categories: "Dynamics test", "Adequacy and flexibility tests" and "Economic assessment" as shown in Figure 5. The dynamics test examines the potential issues on power system stability by following relevant methods and simulated with electromagnetic transients (EMT) tools (e.g., PSCAD, DIgSILENT). The adequacy and flexibility tests are used to evaluate the power system performance on balancing supply and demand under various system conditions. The adequacy and flexibility tests need to be run by using system operation models, such as unit commitment or economic dispatch models. The economic assessment also relies on system operation models, while the outputs of the economic assessment are economic metrics, such as annual operational cost, marginal prices of energy and reserve markets.

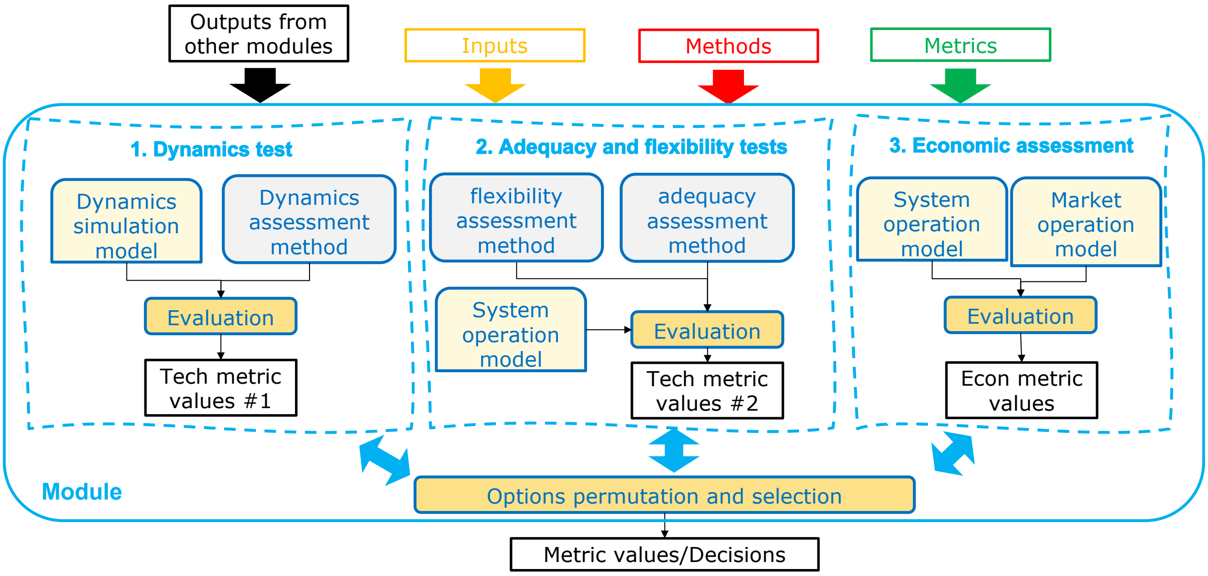

*Figure 5. Configuration of technical and economic analyses inside a module*

Depending on the module's tasks, different analyses may be performed multiple times within the same module. For example, when making network investment decisions, the technical and economic benefits of different investment options need to be evaluated independently. This process is called "options permutation" in Figure 5. Then, investment decisions can be made by comparing the results of options permutation, while the values of relevant metrics will also be taken as the outputs of the module.

As discussed at the beginning of this section, the module concept is a tool that enables the characterisation, evaluation and comparison of arbitrarily complex models. The illustration of multi-module framework for decision-making methodology is shown in Figure 6. This multi-module design is used to reflect the "divide and conquer" approach that is widely adopted by system operators around the world in power system planning. For instance, most power system planning practices will perform a generation expansion study ahead of transmission planning. For instance, National Grid ESO (NGESO) would publish its Future Energy Scenario (FES) before Network Options Assessment (NOA) [1]. The generation expansion part predicts the evolution of generation portfolio and demand, which is in turn used to generate scenarios for the transmission planning study.

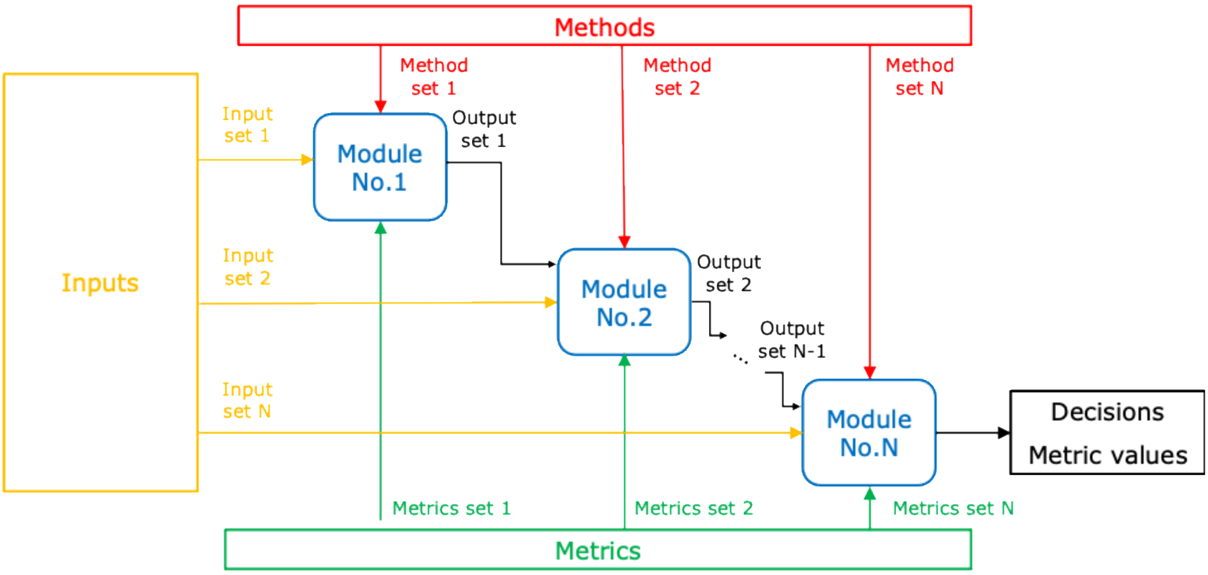

*Figure 6. Multi-module framework for decision-making methodology in power system planning*

The decision-making methodology of AEMO's Integrated System Plan can be concisely characterised by the multi-module framework depicted in Figure 7. In ISP, AEMO firstly performs generation expansion and transmission planning with low-granularity inputs and generate scenarios in the first module. The scenarios are fed into the second module called "time-sequential analysis" which performs dynamic tests and economic assessments with high granularity inputs. This module generates the system operational cost in the planning horizon when applying different reinforcement options. Finally, the operational costs across different scenarios are passed into the last module which uses least-worst regret to select the investment options to be recommended in ISP.

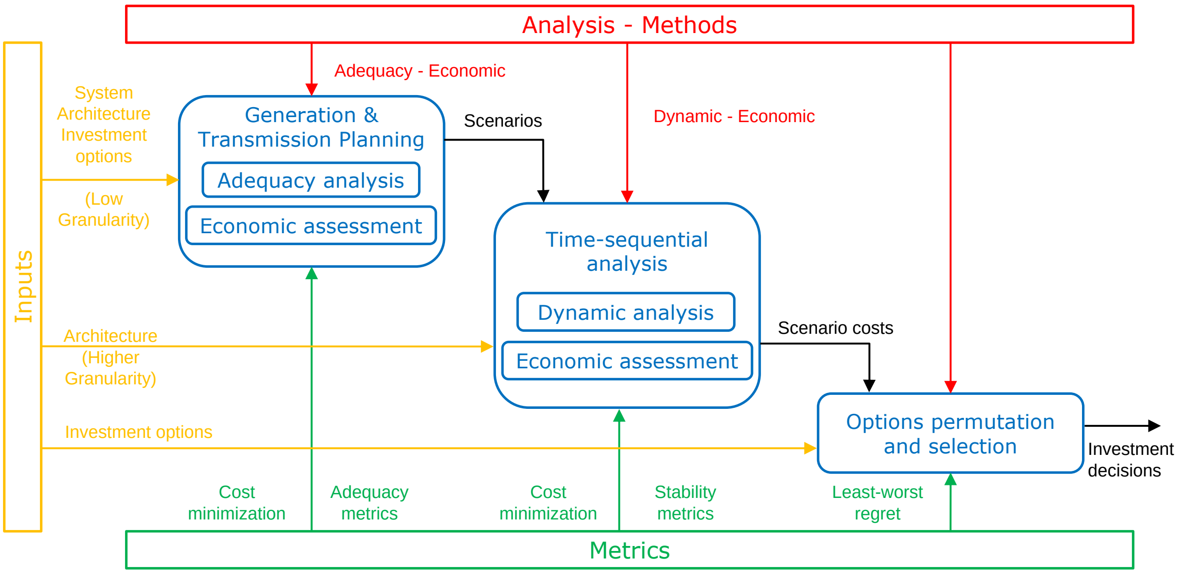

*Figure 7. AEMO's decision-making methodology of Integrated System Plan 2022*

Other decision-making methodologies in power system planning, such as NGESO's NOA, can also be represented with the multi-module framework. The generality of the multi-module framework allows the visualisation and comparison of different decision-making methodologies on a consistent basis. Such comparison can help to identify the missing components in the existing methodologies. Additionally, better interactions between different technical and economic analyses can be explored to achieve a more efficient and effective decision-making process in power system planning.

## 2.3 Research Questions Refinement

We systematically both expanded and refined our set of research questions through the following process steps:

1) We translated the content discussed in the stakeholder interviews into research questions.
2) We proposed additional research questions based on related research.
3) The issue set was consolidated from the above and the research questions identified in the CSIRO's G-PST Request for Information (RFI) document.
4) Issues were classified within the most relevant of the seven defined research areas (Section 2.2.1). Each question has one primary area and one secondary area if applicable.
5) Duplicate questions were consolidated.
6) Issues were rated based on stakeholder feedback as of "high", "medium" or "low" priority.
7) Issues were further examined to identify whether they have high relevance to other topics in the CSIRO's G-PST program.
8) Five or more research questions that reflect both "high" priority and highest impact potential were selected from each area and marked as key research questions.

The key research questions were used to develop the final research plan after feedback from further stakeholders engagement and coordination with CSIRO and G-PST.

# 3 Plan Development

## 3.1 Current Solutions

In the context of power system planning, current solutions correspond to the decision-making frameworks, techno-economic analyses and models used by power system planners to make investment decisions. This section introduces a comparison of global decision-making frameworks and then the observations on the unique demands on and characteristics of Australia's planning approaches.

### 3.1.1 Global experiences

Power system planning frameworks are currently heavily influenced by the development of climate change, energy policy, growth of new technologies and evolution of new business models. All these components are complex and have many associated uncertainties. The following presents the main uncertainty sources influencing power system planning with a special focus on methodologies used for transmission expansion planning (TEP); transmission is the scope for planning in most countries, since transmission investments are regulated, and the timely development of reinforcement is essential for the optimal operation of the future power system. The review on uncertainty in optimal power system planning conducted by CIGRE [2] was the first step of this analysis. The following key uncertainty factors have been identified for planning processes:

1. **RES penetration and load growth** are fundamental sources of long-term uncertainty in all the countries under consideration, however, China considers the increasing penetration of RES in a deterministic way.
2. **Generation fleet** evolution has been widely acknowledged as a key source of uncertainty by all six network planners that have been reviewed, but only AEMO and EirGrid have made advanced considerations on the impact of the evolving generation mix, for instance by setting new frequency response requirements and inertia constraints, limiting the maximum output of the largest generator to reduce contingency size, etc.
3. **Investment costs** may directly influence the decision to proceed with a specific transmission option. Methodologies generally consider the evolution of investment costs; however, most planning regulatory frameworks do not reflect the economic costs, risks and benefits of a more complex structure.
4. **New technologies and commercial solutions**, such as batteries and demand response, although there are relevant technology deployments in France, the UK, Australia and Ireland, are not necessarily considered as a relevant source of uncertainty in all countries.
5. **Regulatory and policy environments** are commonly reflected in the scenario design process, which will influence the modelling of the operation or the structure of the techno-economic analyses. For example, policies on decarbonisation can be reflected in the future conditions of the system through different input variables, such as high renewable energy penetration level, electrification of different sectors, decommission of coal plants, etc.

The current planning practices of six countries were analysed [2]–[11]. Table 1 summarises the uncertainty factors currently being considered (highlighted in green), or which are part of the scenarios but are not considered as an uncertainty factor (highlighted in yellow). The variables highlighted in red are not specifically considered in the definition of scenarios.

Scenarios allow planners to model different assumptions about uncertain variables and their correlations. This approach is currently used by most system planners around the world to model the uncertain future [2]. It provides a balance between investigating a broad range of possible futures and maintaining the technical consistency (correlation of variables) necessary to produce insightful analysis.

*Table 1. Long-term uncertainty factors considered by different countries*

| **Uncertainty factor** | **Australia** | **UK** | **Ireland** | **China** | **Chile** | **France** |
|---|---|---|---|---|---|---|
| **Load growth** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **RES growth** | 🟩 | 🟩 | 🟩 | 🟨 | 🟩 | 🟩 |
| **Generation mix** | 🟩 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| **New commercial solutions** | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 |
| **Technology Investment cost** | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 |
| **Regulatory environment** | 🟩 | 🟩 | 🟩 | 🟥 | 🟨 | 🟩 |

*green: uncertain variable; yellow: deterministic variable; red: not considered

The number of scenarios used in ten selected countries is listed in Table 2. Most planners prefer to use less than five scenarios to represent plausible futures, e.g., envisaging nuclear or coal plants retirement, increase of DERs penetration, electrification of heating and transport, etc. The number of scenarios under scrutiny has a great impact on the workload of the planner, which in general has very tight deadlines and limited resources to produce the investment recommendations. Importantly, none of the countries listed in Table 2 explicitly considers weighting scenarios in their CBA process, as there is no explicit probability assigned to the scenarios used in the planning.

*Table 2. Number of scenarios used in transmission planning in ten selected countries ([2], [3], [7], [9], [11]–[16])*

| **UK**[5] | **France** | **China** | **Chile** | **Australia**[6] | **Ireland** | **Switzerland**[7] | **Belgium** | **Germany** | **Italy**[8] |
|---|---|---|---|---|---|---|---|---|---|
| 4(1) | 3 | 1 | 5 | 5+5 | 3 | 2(4) | 3 | 3 | 1+2 |

In some cases, system planners build scenarios or perform further studies to represent (technical and economic) sensitivities around core scenarios. For example, AEMO has developed several specific sensitivities around the baseline scenarios to represent very specific events that can greatly affect system conditions (e.g., early decommission of specific units) [8]. For example, Terna uses additional scenarios to represent and evaluate different sensitivities [13]. National Grid is currently using a probabilistic load flow approach in the security assessment of a specific scenario, to add robustness in the analysis of the transfer capability of the system with/without proposed transmission reinforcements, as this scenario is the one with the highest network stress among all four scenarios under consideration. In Swissgrid's Strategic Grid 2025 proposal [14], two marginal scenarios are built to check the long-term robustness of reinforcement options proposed in the two core scenarios, whilst the two marginal scenarios are not used to identify any additional network reinforcement requirement.

Given the complexity and uncertainties of both technical and economic analysis associated with scenario-based planning, some system operators have also considered reducing the number of scenarios that are evaluated. For example, the Chilean SO has decided to decrease the number of

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[5] Only the "Two Degrees" scenario is used in the security transfer capability assessment of NOA.

[6] Five sensitivities are built to represent the sensitivity of policy and risks faced by the Australian National Electricity Market.

[7] Two marginal scenarios are constructed to test the robustness of reinforcement options.

[8] Two scenarios are built to represent the sensitivity of the core scenario instead of reflecting the expected future.

scenarios from five to three from 2020, while EirGrid has removed the “Slow-Progress” scenario from its Tomorrow’s Energy Scenarios 2019[9].

Other than identifying existing uncertainty factors and scenarios in several countries, the technical details of the planning models used by the seven countries we have analysed are listed in Table 3. The table highlights different aspects of the techno-economic analyses and decision processes considered to be common practice worldwide.

As shown in Table 3, the planning horizon used in different countries is generally in the range of 15 to 20 years, except for Swissgrid which only defines a transmission expansion plan for the next 10 years. However, Swissgrid would then perform a technical analysis against the robustness of its reinforcement options for a 20-year horizon.

The time granularity of simulation varies from 15 minutes to a few hours across different countries. One practice to be highlighted is that both Chile and Australia use load block techniques in different parts of the methodology which can reduce simulation time steps by clustering several time periods, but only for the periods with similar demand levels rather than adopting it with a fixed time length. This action can increase computational efficiency; however, since the time correlation is lost in the construction of the load blocks, it can affect the accuracy of the results if there is a high proportion of time-dependent elements like storage, or if unit-commitment constraints are binding in the operational decisions. Another strategy used to reduce the computational burden is to represent the operation through typical days or typical weeks; China and Chile perform simulations using typical days of each month and then scale them up to represent transfer volumes variation or annual operational cost.

Additionally, with regards to the modelling of system operation, some countries use simple economic dispatch, while other countries adopt unit commitment analysis to better capture the technical characteristics of conventional generators (minimum up- and down-time, start-up/shut-down activities, etc.). The technical constraints of system operation also vary in the simulation performed by different planners. In terms of modelling of the network, the maximum flows of individual transmission lines are typically calculated according to thermal, voltage and fault-clearing standards, then the results are mapped as numerical constraints in economic-dispatch/unit-commitment. However, static transfer capability is used by State Grid in its economic dispatch process. With regards to ancillary services, most countries model these as aggregated spinning reserves through derating online plant capacity, while AEMO also models the requirement of minimum inertia level due to RoCoF, which can be crucial for low-inertia system operation.

In the context of the security assessments, countries perform the analysis at least at peak demand. For example, Chile does not only perform Winter/Summer peak snapshots but also analyses specific snapshots that are likely to be associated with maximum levels of power transfer across relevant corridors. As seen in Table 3, most countries perform the security analysis at various demand levels to mimic different system operating conditions besides the peak snapshot. In addition, the UK comprehensively covers network security criteria in the analysis. On the other hand, other system operators perform extra tests such as reactive power management and frequency stability assessment, like in the case of AEMO. The security assessment behind each reinforcement is not run for every year in the planning horizon; planners use different sampling periods varying from every 2-3 years by National Grid up to every 10 years by State Grid and Swissgrid.

*Table 3. International practice of technical modelling characteristics in TEP process ([[2]–[4], [6]–[12], [13]–[19]]*

| | | **Countries** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **UK (National Grid)** | **France (RTE)** | **China (State Grid)** | **Chile (CEN)** | **Australia (AEMO)** | **Ireland (EirGrid)** | **Switzerland (Swissgrid)** |
| **Economic assessment** | **Software** | BID3 | ANTARES | SPER | OSE2000 | PLEXOS | - | - |
| | **Resolution and timescale** | 3-6h (up to 1 hour); whole year | Hourly; whole year | 15 mins to hourly; typical day in each month | Few hours (8 blocks per day; typical weekday/ weekend in each month | Few hours (few load blocks); from snapshot to whole year | Hourly; whole year | N/A |
| | **Operational model** | Economic dispatch | Unit commitment | Economic dispatch | Economic dispatch | Simplified unit commitment | Economic dispatch | Economic dispatch |
| **Security assessment** | **Software** | DIgSILENT/POUYA | CONVERGENCE | PSD-BPA | DIgSILENT | PSS/E | PSS/E, DSA | - |
| | **Year sampling frequency** | Every 2-3 years | - | One in next 5-10 years and one in next 10-15 years | Every year | Every 5-7 years | Every 5 years | Every 10 years |
| | **Timescale and sampling frequency** | Winter peak snapshot; every 3 years | Snapshots; *Not available* | Snapshots; every typical year | Peak demand snapshots; every year | Peak/low demand snapshots; every year | Peak and other demand snapshots; *Not available* | Peak congestion snapshots; every 10 years |
| | **Constraints** | ▪ Voltage<br>▪ Thermal<br>▪ N-1/N-1-1/N-D<br>▪ Fault outage | ▪ Voltage<br>▪ Thermal<br>▪ N-1/N-1-1/N-D<br>▪ Fault outage | ▪ Voltage<br>▪ Thermal<br>▪ N-1/N-1-1/N-D<br>▪ Fault outage | ▪ Voltage<br>▪ Thermal<br>▪ N-1/N-1-1/N-D<br>▪ Fault outage | ▪ Voltage<br>▪ Thermal<br>▪ N-1/N-1-1/N-D<br>▪ Fault outage<br>▪ Frequency stability | ▪ Voltage<br>▪ Thermal<br>▪ N-1/N-1-1/N-D<br>▪ Fault outage | - |
| | **Reliability index** | LOLE | LOLE LOLP EENS | EENS | EENS | EENS | - | - |

### 3.1.2 Australian experience

AEMO's ISP process covers a decision horizon of 20 years and includes the effect of distributed energy resources (DERs), virtual power plant (VPP), grid-scale generation, energy storage systems (ESS), high voltage transmission, the gas system, hydro resources, and the electrification of transport. The next ISP, that is ISP 2022, is also considering the effect of hydrogen in the power system, as opposed to ISP 2018 and 2020 considered neither hydrogen nor nuclear energy. The structure of the decision-making framework for the ISP 2022 is presented in Figure 8 (also see Figure 7).

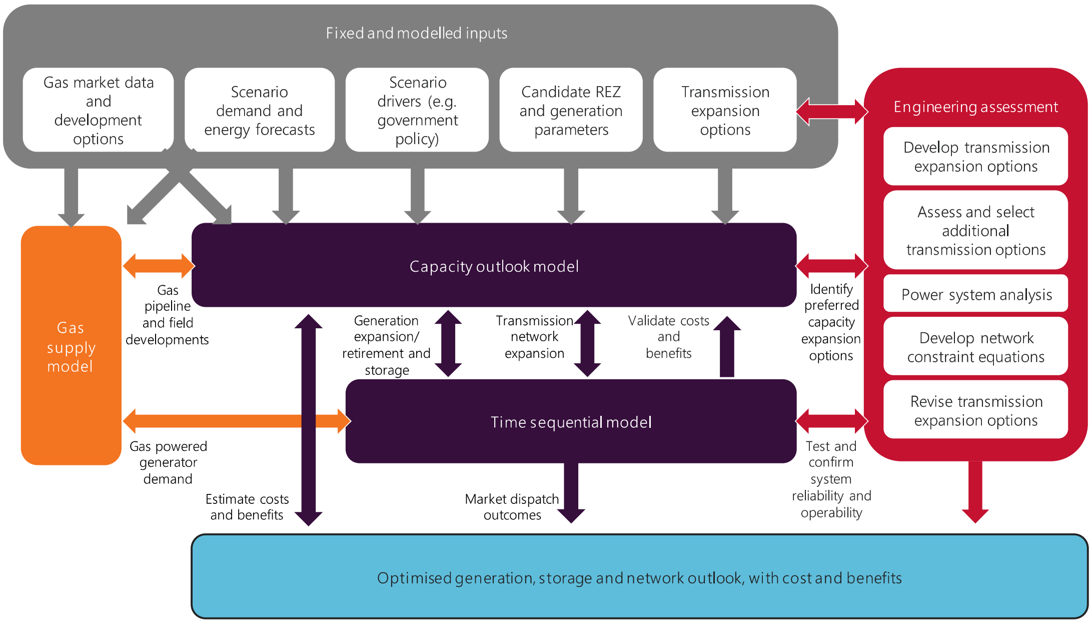

*Figure 8. ISP 2022 decision making framework as presented in* [20]

The ISP addresses the power system needs for reliability, security, public policy objectives and their supporting system standards. The transmission expansion decisions necessary to leverage the transition from a coal-fired generation dominated system to a low-carbon, low-inertia system dominated by VRES and DER are made using a minimum cost and least worst regret approach.

To determine the optimal transition path for the system, the ISP models the future through a set of 5 scenarios (see Figure 9) that are characterised by varying load levels (LOAD) and supply profiles (VRES and DER), energy storage parameters and investment costs, the behaviour of the gas and electricity markets, etc. Figure 9 illustrates how each scenario balances the decentralisation and decarbonisation objectives (energy policy) by providing a reference to the level of DER, LOAD, and VRES. On top of the 5 scenarios, the methodology considers additional sensitivities on relevant system projects, such as earlier retirement of generators, delays in large pumped-hydro storage, closure of large industrial loads (smelters), etc.

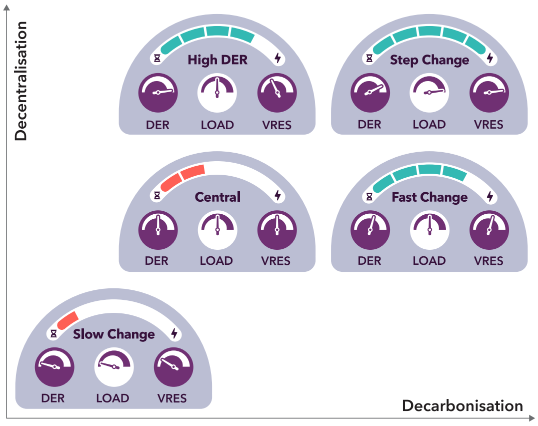

*Figure 9. ISP Scenarios (Source:* [21]*)*

The methodology aims to find the least cost development path for each scenario and sensitivities separately. Each deterministic least cost development path is determined using a generation and transmission expansion model (using the proprietary software PLEXOS, see Table 3) resulting in hourly dispatch outcomes that are then tested for security criteria (fault levels, dynamics, voltage compliance, etc.) using proprietary software PSS/E (Table 3). Then, based on those results it determines the least-regret development path across all scenarios.

In [21] AEMO states that least worst regret is preferred over the expected cost minimisation since it inherently considers the adapted plans rather than locking a single view of the future for each scenario. [21] also highlights the fact that the least worst regret does not need to ascribe probabilities to the corresponding scenarios. In order to account for scenario weights, in the methodology description for ISP 2022 [20] the least worst regret approach has been extended to the so-called least worst *weighted* regret approach originally proposed by the authors of this report for National Grid ESO in Great Britain.

## 3.2 Industry Activities

A collection of major studies, projects, policies, and standards in the energy sector of Australia is provided below as the basis and guidance for the research plan.

- ***Independent Review into the Future Security of the National Electricity Market – Blueprint for the Future (Finkel Review)*** [22]**:** This 2017 independent review, headed by Australia's Chief Scientist Dr Alan Finkel AO, provided the COAG Energy Council with a roadmap for ensuring the reliability (adequacy and security) of the national energy market (NEM) via proper system design/control and modification of governance.

- ***NEM Electricity Statement of Opportunities (ESOO)*** [23]***:*** The ESOO conducts a reliability assessment of the NEM over a 10-year outlook period against the reliability standard and interim reliability measure specified in NER clause 3.9.3C, as well as AEMO's Reliability Forecast under the Retailer Reliability Obligations (RRO).

- ***Reliability Standard Implementation Guidelines*** [24]***:*** The Reliability Standard Implementation Guidelines describe how AEMO applies the reliability standard across all of its reliability procedures, including the methodology and assumptions used in the reliability assessment conducted by ESOO.
- ***2020 System Strength and Inertia Report*** [25]***:*** The outlook for system strength and inertia in the National Electricity Market (NEM) over the next decade has been evaluated by AEMO. In

this report, AEMO notes that there are growing indications that projected system strength in Queensland, New South Wales, and Victoria may be inadequate in the near future if certain circumstances occur. Similarly, projected inertia in Queensland may be insufficient.

- ***Network Support and Control Ancillary Services (NSCAS) Review*** [26]***:*** The NSCAS framework is one of the mechanisms established by the National Electricity Rules (NER) for AEMO to manage power system security and reliability, and it is part of a broader cooperative system planning process between AEMO and transmission network service providers (TNSPs). Based on the requirement of the framework, AEMO needs to assess the system requirements and NSCAS gaps to keep the system operating within an acceptable security and reliability level. TNSPs are expected to procure services or other solutions to fill the declared gap, otherwise AEMO will use reasonable endeavours to acquire necessary NSCAS itself.

- ***Projected Assessment of System Adequacy (PASA)*** [27]***:*** The Projected Assessment of System Adequacy or PASA is the principal method of forecasting the adequacy of the power system to stay within the reliability standard. AEMO prepares PASA in three timeframes:

    1) *Pre-Dispatch PASA* covers the next trading interval until the end of the next trading day
    2) *Short Term PASA* covers 6 trading days from the end of the trading day covered by the most recent pre-dispatch schedule with a half-hourly resolution
    3) *Medium Term PASA* (MT PASA) covers 24 months from the Sunday after the day of publication with a daily resolution

- ***Mechanisms to Enhance Resilience in The Power System – Final Report*** [28]***:*** AEMC has proposed a number of modifications to the power system's security framework in this report to assist the market operator, AEMO, in managing the risks of extreme events and "indistinct" events. The study recommends that AEMO conducts an annual review to identify emerging risks in the power system in six key areas: frequency, voltage, inertia, system strength, the prevalence of distributed energy resources, and the functioning of special protection systems. This report also recommends general provisions in the regulations to allow AEMO the option to prioritise system security obligations when the spot market is halted. AEMC has developed a proposal on rule changes to implement the recommendations made in this report.

- ***General Power System Risk Review (GPSRR***) [29]: AEMC issued a final decision and final rule on 3 June 2021 to adopt a comprehensive General Power System Risk Review (GPSRR) in place of the current Power System Frequency Risk Review (PSFRR). An annual assessment will be conducted by AEMO, in cooperation with network service providers (NSPs), to identify and evaluate threats to the security of the power system that it believes are likely to cause cascading outages or significant supply disruptions.

- ***AEMO Real-time Simulator Project*** [30][31]***:*** AEMO awarded a contract to the Canadian-based company Opal-RT to develop a real-time digital simulator for analysing the NEM's power system dynamic performance. The simulator is expected to have the capability of simulating and analysing large-scale power systems at near-real-time speeds using accurate electromagnetic models of IBRs to assist RES integration analysis and threats (e.g., bushfires and storms) management in the power system. The simulator will be built in a digital twin platform with cloud-based access for researchers and developers.

- ***ACOLA – Australia's Energy Transition Plan (The Research Plan)*** [32]***:*** The *Research Plan* aims to identify research gaps and advocate research priorities for a successful Australian energy transition to nett zero carbon emissions (by 2050), with the goal of informing the direction, allocation, and quantity of research funding in Australia. This will direct the actions of research funders, businesses, and researchers involved in the national energy transition, encouraging research that complements current strengths and avoids duplication. The Research Plan will be updated on a regular basis and created in collaboration with stakeholders to ensure that it stays relevant during the energy transition (nominally 30 years).

- ***Integrated System Plan (ISP) – AEMO***[33]**:** The Integrated System Strategy (ISP) is a comprehensive plan for the evolution of the National Electricity Market (NEM) for the next two decades and beyond. It aims to develop a cost-effective, reliable, and resilient energy system capable of achieving any emissions trajectory set by policymakers while maintaining a manageable level of risk. It takes full use of the possibilities presented by current and expected breakthroughs in Distributed Energy Resources (DERs), large-scale generation, networks, and linked sectors such as gas and transportation. AEMO released the first National Electricity Market (NEM) Integrated System Plan (ISP) in 2018, which will be revised every two years.

- ***Renewable Integration Study (RIS)*** [34]***:*** RIS is the first step in a multi-year plan to keep the system reliable in future NEM, with a large proportion of renewable resources. This Stage 1 RIS study explores the difficulties in keeping the power system reliable when the system is operating with high instantaneous penetrations of wind and solar production, based on the projections made in ISP.

- ***AEMO Engineering Framework*** [35]: AEMO Engineering Framework is the next step in a multi-year plan to provide an integrated roadmap for the NEM. It advances on the earlier RIS Stage 1 phase. To go beyond the RIS, the Engineering Framework takes a wider view and acknowledges existing industrial operations. The goal of the Engineering Framework is to help facilitate a conversation to identify potential future operating circumstances for the NEM power system, as well as to consolidate a shared perspective of the present work ongoing to adapt the system and existing paths for participation.

- ***Regulatory Investment Tests for Transmission (RIT-T)*** [36]**:** TNSPs perform transmission regulatory investment tests (RIT-T) on prospective transmission network and non-network projects. AEMO's ISP may meet some of the obligations for the initial stages of RIT-T tests for major transmission argumentations according to AEMC's rule, but TNSPs are still required to complete the process. RIT-T aims to identify the credible alternative that maximises the present value of nett economic gain to all market participants involved in the production, consumption, and transportation of electricity.

- ***Electricity Sector Climate Information (ESCI) project*** [37]***:*** The ESCI project aims to construct a database of anticipated future climate scenarios. ESCI will offer downscaled climatic data, including temperature, wind, rainfall, stream flows, solar radiation, and bushfire weather risk. The datasets provided by the ESCI project can be used as input for the electricity sector in assessing the risk posed by climate change and extreme weather events to investments, system reliability.

- ***Technology Investment Roadmap*** [38]***:*** The roadmap will assist Australia in prioritising investments in emerging and developing low-emission technologies based on the specified short-, medium-, and long-term goals. It will serve as a foundation for establishing economically feasible stretch objectives for high-priority technology compared with high-emission technologies published annually. This Roadmap will be supplemented by the Low Emissions Technological Statements. Each statement will give an update on global technology advances and allow the Government to adjust its investment portfolio accordingly while remaining committed to Australia's long-term goal to achieve net-zero emission by 2050.

- ***Data Strategy Consultation*** [39]**:** The Energy Security Board (ESB) has published a public consultation document on a new NEM data strategy, which was one of the recommendations from the Finkel Review.

- ***Australia's National Hydrogen Strategy*** [40]***:*** The plan describes a method to scale up the national hydrogen economy, which includes a series of nationally coordinated activities for government, business, and the community, with the goal of positioning Australia as a significant worldwide exporter by 2030. QLD, WA, TAS and VIC have established their own hydrogen industry strategies at state level in response to the national hydrogen strategy [41]–[44].

- ***ESB-Post 2025 Market Design Project*** [45]***:*** This project aims to identify the challenges faced by NEM design in transition to a low-carbon power system. Four areas are identified as the priority challenges to be addressed:

    1) Resource adequacy
    2) Essential system services and scheduling mechanisms
    3) Unlocking demand-side participation
    4) Transmission and access

- ***Victoria's Climate Change Strategy*** [46]***:*** Victoria's Climate Change Strategy is a strategic plan to achieve net-zero emissions and climate resilience in Victoria by 2050. Every five years, the Victorian government must release a new climate change plan, which sets the intermediate goals for the state's statutory long-term aim of net-zero emissions by 2050, and outlines how it will achieve these targets.

- ***Tasmania Climate Action Plan (Climate Action 21)*** [47]***:*** Climate Action 21 has set the Tasmanian Government's agenda for action on climate change through to 2021. It reflects the Tasmanian Government's commitment to addressing the critical issue of climate change and articulates how Tasmania will play its role in the global response to climate change.

## 3.3 Stakeholder engagement

We have engaged a wide range of stakeholders from Australia, the UK and the US through online meetings. These include system operators (SO), transmission network service providers (TNSP), distribution network service providers (DNSP), and regulator/policy makers[9].

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[9] Specific aspects of the summary of stakeholder engagement meetings might eventually be kept confidential and not included in the final deliverable report, depending on their feedback on this draft report.

The details of the meetings are summarised as follows:

### 3.3.1 Australian Energy Market Commission (AEMC)

- **Relevance**: Australian energy market policymaker/regulator
- **Summary**: The main outcomes and emerging priorities from the discussions with AEMC are:
    - Modelling the impact of climate change on power system planning, particularly on investment uncertainty and risk
    - Evaluating system resilience when facing extreme events and the relevant policies needed to encourage investments to enhance system resilience
    - Achieving an efficient outcome when balancing market-driven investments and regulated network investments

### 3.3.2 Australian Energy Market Operator-NEM

- **Relevance**: System operator of National Electricity Market
- **Summary**: The main outcomes and emerging priorities from the discussion with AEMO are:
    - Improving the representation of long-term uncertainty in power system planning
    - Modelling the interaction between power system and other energy systems (e.g., gas, hydrogen) and impacts from other sectors decarbonising (transport, steel, etc).
    - Representing the risk profiles of different stakeholders in power system planning problem

### 3.3.3 Electric Power Research Institute (EPRI)

- **Relevance**: Project leader of other topics in the CSIRO G-PST program
- **Summary**: The main outcomes and emerging priorities from the discussion with EPRI are:
    - Modelling the operation of new technologies (e.g., DERs, batteries) and their potential risks to system security in power system planning
    - Leveraging machine learning and artificial intelligence techniques for applications in power system planning

### 3.3.4 Western Power

- **Relevance**: TNSP and DNSP of Western Australia
- **Summary**: The main outcomes and emerging priorities from the discussion with Western Power are:
    - Capturing the interaction and conflict between distribution and transmission networks in planning
    - Determining the optimal mix of network and non-network solutions in power system planning
    - Identifying the benefits of one investment to different stakeholders and designing a fair cost recovery scheme of the investment

### 3.3.5 Australian Energy Market Operator-WEM

- **Relevance**: System operator of Wholesale Electricity Market
- **Summary**: The main outcomes and emerging priorities from the discussion with AEMO are:
    - Methods and models needed in dealing with long-term uncertainty in power system planning
    - Quantifying the potential risk introduced by new technologies (i.e., DERs) in power system short-term operation and long-term planning
    - Developing the ideal governance structure in the power system to timely respond to the emerging challenges

### 3.3.6 AusNet

- **Relevance**: One of the DNSPs and the TNSP in Victoria
- **Summary**: The main outcomes and emerging priorities from the discussions with Ausnet are:
    - Developing models for IBR and building EMT tools for network analysis
    - Using data-driven approaches to improve the network management

### 3.3.7 National Grid ESO

- **Relevance**: System operator in Great Britain
- **Summary**: The main outcomes and emerging priorities from the discussion with NGESO are:
    - Integrating the generation expansion and transmission planning or creating feedback loops between them
    - Increasing the modelling granularity with the consideration of computational complexity
    - Valuing the externalities of reinforcement options in the costs and benefits analysis

### 3.3.8 Tesla

- **Relevance**: Participant in the NEM and energy and services provider via new technologies
- **Summary**: The main outcomes and emerging priorities from the discussion with Tesla are:
    - Determining the necessary adjustments of policy and market rules in a low-carbon power system
    - Developing a consistent model of battery operation used by different stakeholders for benefits evaluation

### 3.3.9 Powerlink

- **Relevance**: TNSP of Queensland
- **Summary**: The main outcomes and emerging priorities from the discussion with Powerlink are:
    - Developing models and tools to analyse network operation under minimum load condition
    - Evaluating the impact of high penetration of grid-forming IBRs to power system short-term operation and long-term planning
    - Developing methodology to guide proactive investment to respond to rapid change of technology mix

### 3.3.10 TasNetworks

- **Relevance**: TNSP of Tasmania
- **Summary**: The main outcomes and emerging priorities from the discussion with TasNetwork are:
    - Evaluating the incremental cost of hosting capacity for IBRs
    - Investigating the roles of market-driven investments and centralised planning in achieving carbon neutrality
    - Modelling the operation of large-scale loads (i.e., electrolysers) in power system planning

## 3.4 Research Questions

119 research questions have been identified as a result of systematic analysis and stakeholder engagement. All research questions in each of the seven core areas are tabulated below by ID based on their primary area categorisation. The secondary area (SA) of each question and the other G-PST topics that each question may relate to are also listed where applicable. The full questions list is attached in Appendix A. All research questions in Appendix A have been linked to one or multiple projects, which are further elaborated in section 4.1. Table 4 illustrates research questions from each area that were repeatedly discussed in the stakeholder engagement.

There is some overlap of the scope of the challenges addressed by different questions. However, the full Appendix A list represents the direct inputs from stakeholders and G-PST sources with only the minimal edits needed to improve clarity. At this point in the process, no merge or discard of the questions has been performed to retain their originality, as many of them reflect unique research priorities or practical issues raised by individual stakeholders mentioned in section 3.3.

*Table 4. Important research questions in each area*

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| **Area 1: Architecture** | | | |
| **A1-1** | In the context of DERs visibility in power system planning, what data is necessary to accurately model various levels/paradigms of DERs control including influence on UFLS schemes? | **DER** | **A3** |
| **A1-2** | How to geographically map renewable capacity installation availability vs technical and nontechnical constraints, and what are these constraints? | | **A3** |
| **A1-7** | What techniques are needed to identify the regions that are most vulnerable to different kinds of disruptive weather events, including heatwaves, bushfires, duststorms, etc? | | **A5** |
| **A1-14** | In the context of dealing with the challenges faced by future power systems, what reliability standards are needed and how should they be assessed? | | **A4** |
| **A1-19** | What are the roles of market-driven investments and centralised planning in achieving different policy targets (e.g., carbon neutrality)? | | |
| **A1-22** | In the context of ensuring system reliability and resilience through service provision, should stakeholders be incentivised to contribute or mandated to comply, and how do you design these incentives and mandates? | | |
| **Area 2: Long-term Uncertainty** | | | |
| **A2-1** | What system conditions (e.g, peak demand, minimum demand, low inertia level) should be considered in the scenarios used in network planning? | | |
| **A2-2** | How to include high impact low probability events in scenario tree representation (and in the underlying operational models)? | | |
| **A2-3** | When building the scenarios that represent the long-term uncertainty in the system, how should we represent the probability distribution of the relevant uncertain variables, in particular for the penetration of new technologies like IBRs and DERs? | | |
| **A2-4** | What are the limitations and advantages of using deterministic scenarios in the context of power system planning? | | |
| **A2-5** | Is the scenario-based approach the best way to represent long-term uncertainty in power system planning? | | |
| **A2-6** | In the context of scenarios for long-term planning, how are scenarios themselves influencing the decision making as opposed to and in conjunction with the methodology? | | **A7** |
| **Area 3: Operation Modelling** | | | |
| **A3-2** | In the context of system security paradigm, what are the advantages and limitations of using probabilistic security criteria and risk-based criteria, how to model them efficiently? | | **A1** |
| **A3-4** | How to represent the impact of DER integration and demand electrification in operation models used for transmission network planning? | | **A1** |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| **A3-6** | How to model demand and its embedded flexibility in different sectors (i.e., electrification of heating and transportation, industrial processes, hydrogen production, etc.)? | | **A1** |
| **A3-11** | What kind of dynamic modelling is needed for IBR to ensure the robustness of security analysis? | | **A5** |
| **A3-14** | What are the requirements for stability analysis tools in systems which have a large portion of grid-forming inverters and other new technologies such as virtual synchronous machines? | | |
| **A3-16** | How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high renewable energy future (wind, solar, demand-side flexibility)? | | |
| **A3-21** | To what extent can the operation of the system be simplified without impacting the investment decisions? What are the parameters of different resources (e.g., minimum up and down times) and the system operation characteristics (e.g., unit commitment) that may be simplified? What mathematical models are most suitable for these simplifications? | | |
| **A3-26** | How to incorporate different constraints (thermal, voltage and stability) into network modelling in a computation-efficient way? | | |
| | **Area 4: Metrics** | | |
| **A4-1** | How to measure the performance of transmission and distribution network assets under extreme weather conditions (such as bushfires, floods, strong gusts, heat waves, etc.)? | | **A5** |
| **A4-2** | What metrics are required to identify long-term scarcity of capacity? | | |
| **A4-3** | What metrics are required to evaluate the contribution of large-scale storage, hybrid plants (e.g., PV-plus-storage) and virtual power plants to resource adequacy? | | |
| **A4-4** | What are the right metrics to measure reliability and resilience? | | |
| **A4-5** | What are the metrics needed to measure the environmental impact of investment options? | | |
| **A4-6** | What are the metrics needed to quantify the potential impact of voltage issues due to the decline of net demand? | | |
| | **Area 5: Techno-economic Analysis** | | |
| **A5-1** | How does the integration of IBRs and DERs impact the risk profile of the power system, particularly in high impact, low probability events? | | **A1** |
| **A5-4** | How to model the increasing bushfire risk and assess its impact on supply resilience of transmission and distribution networks? | | **A1** |
| **A5-5** | How to explicitly model the uncertainty and risk created by climate change in power system planning? | | **A2** |
| **A5-16** | What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables? | | |
| **A5-17** | What features need to be added to long-term planning methods and studies to consider other reliability services (e.g., flexibility) in addition to traditional resource adequacy and deliverability? | | |
| **A5-18** | What studies are required to evaluate the contribution of large-scale storage, hybrid plants (e.g., PV-plus-storage) and virtual power plants to resource adequacy? | | |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| **A5-21** | How to combine transmission and generation infrastructure investment to enhance system resilience? | | |
| **A5-24** | How should sufficient black-start capability and the performance and integrity of the protection system be modelled in long-term reliability studies? | **Black start** | |
| **Area 6: Investment Modelling** | | | |
| **A6-1** | How shall the investment in demand response be modelled in power system planning? | | |
| **A6-3** | How to exploit the value of investment optionality when facing long-term uncertainty? | | |
| **A6-4** | What type of decision structure for new assets is the one that strikes the right balance between investment flexibility and additional information needed from transmission owners? | | |
| **A6-5** | How to model the risk for not delivering investment options on time? | | |
| **A6-6** | How to deal with the discrepancy between asset lifetime and planning time horizon? | | |
| **Area 7: Decision Making Methodology** | | | |
| **A7-1** | How to model competing objectives and risk appetites of different stakeholders in power system planning? | | **A1** |
| **A7-3** | In the context of determining the optimal mix of network and non-network solutions in power system planning, what methodologies and tools are needed for a consistent comparison of these solutions? | | **A3** |
| **A7-4** | In the context of increasing electrification and growing IBR and DER penetrations, what additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments? | | **A5** |
| **A7-5** | How to integrate reliability and resilience assessments into transmission planning in a trackable manner? | | **A5** |
| **A7-6** | How to include investment optionality into the decision-making framework of power system planning? | | **A6** |

# 4 The Research Plan

Projects are the building blocks of the proposed research program and plan. Each of the issues deemed by stakeholders to be of highest priority has been translated into specific research project definitions. The scope of research activities identified is broad and includes; developing mathematical modelling and analysis tools, performing parametric studies and designing consistent methodologies. We have further filtered and aggregated research questions to design research projects that effectively address what may be one or a cluster of research questions. Projects are then, based on consideration of internal and external G-PST dependencies, impact potential and resourcing, further linked, sequenced and grouped to deliver a comprehensive and pragmatically implementable research plan that delivers high value and implementable insight and tools to industry within the next five years.

## 4.1 Research projects

There are 119 research questions identified in section 3.4, which are associated with the power system planning regime and which are reflected in one or more aspects of this research plan. When defining research projects, research questions related to high impact actionable issues have been distilled into projects based on the following principles:

- "Distil and conquer" approach is adopted when defining projects. One research question may be linked to multiple projects, while one research project may be (partially) addressing multiple research questions;
- The objectives of individual projects should be distinct from each other so that research overlap can be minimised;
- The maximum length of any individual project should be 4 years to ensure deliverables are delivered in competitively relevant timeframes and that resource levels and activity maintain alignment with industry needs.

As a result of this process, 36 projects have been defined with the full list of research projects shown in Appendix B. The following are illustrative:

Project 1: **Modelling long-term uncertainty in power system planning with the consideration of HILP events (adequacy and security) and critical operation conditions**

Linked research questions:

- ⇔ What system conditions (e.g., peak demand, minimum demand, low inertia level) should be considered in the scenarios used in network planning?
- ⇔ How to include high impact low probability events in scenario tree representation (and in the underlying operational models)?

Project 2: **Modelling the steady-state operation of the system considering the trade-offs between computational efficiency and model precision (e.g., identifying the right spatio-temporal granularity, technology and market representation, network reduction)**

Linked research questions:

- ⇔ How to determine reserve requirements for different types of contingencies, in particular in systems with high DER and IBR penetration?
- ⇔ How to evaluate the trade-off between computational complexity and modelling details within operation models in power system planning?

- How to develop a network modelling methodology that can seamlessly and consistently capture the performance of the assets at different spatial levels (i.e., inter-region, intra-region) in power system planning?
- What are the electricity consumption sectors that can provide demand response and what are the technical and non-technical constraints that can limit their demand response capability?
- To what extent can the operation of the system be simplified without impacting the investment decisions? What are the parameters of different resources (e.g., minimum up and down times) and the system operation characteristics (e.g., unit commitment) that may be simplified? What mathematical models are most suitable for these simplifications?
- How to conduct voltage management under low demand conditions?

Project 3: **Methodologies and tools to integrate reliability (security and adequacy) and resilience assessments into the decision-making process with tractability considerations and a process-oriented structure**

Linked research questions:

- In the context of dealing with the challenges faced by future power systems, what reliability standards are needed and how should they be assessed?
- How to capture the trade-off between system investment costs and technical performance (security, adequacy and resilience)? (Such as the marginal benefits of investing in additional storages (e.g., batteries, pumped hydro storage, etc.) on system reliability and resilience)
- What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables?
- How to improve the computational efficiency of tools for technical analysis in power system planning?
- How should sufficient black-start capability and the performance and integrity of the protection system be modelled in long-term reliability studies?
- In the context of increasing electrification and growing IBR and DER penetrations, what additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments?

## 4.2 Research programmes and streams

The 36 defined research projects are the fundamental building blocks of the research plan. They are however related by their issue dependencies, the expertise needed to deliver them and their stakeholders. These relationships guide their alignment within research **streams** and **programmes** that will enable both the most effective leverage of combined talent of industry and its research providers and stakeholder-aligned performance governance.

This next level of alignment and aggregation results in 5 research programmes managing 16 research streams (subdivided within programmes) as summarised in Table 5:

*Table 5. Programmes and streams in the research plan*

| *Programme* | Stream |
|---|---|
| *Long-term uncertainty* | Scenario development for planning studies |
| | Climate change impact on individual power system components performance |
| | Uncertainty in policy and market developments |
| *Power system operation* | Steady-state operation modelling |
| | System dynamics modelling for planning purposes |
| | Security constraints formulation |
| *Reliability (security and adequacy) and resilience* | Reliability and resilience metrics |
| | System-level impact of climate change |
| | Credible and non-credible contingencies |
| | Characteristics on DER/IBR response to different events |
| *Decision making* | Metrics, objectives and risk modelling of different stakeholders |
| | Methodologies for decision-making under uncertainty |
| | Interdependence of power system planning (transmission, distribution, generation) |
| *Distributed energy systems* | Multi-energy systems and electrification |
| | Distributed energy markets and demand-side flexibility |
| | Distributed energy resources impact on planning |

Each stream addresses specific research topics and is constituted from one or more of the projects listed in Appendix B. A brief introduction of every stream and the research projects under each stream is added in Appendix C. The following illustrates how challenges particularly highlighted by stakeholders have translated into three streams:

- **Scenario development for planning studies** under research programme 1 "*long-term uncertainty*"

  This stream covers the development of scenarios that may significantly impact the planning output, including evolving generation and DERs portfolio and demand, HILP events and critical operation conditions representation, and the uncertainty created sector coupling.

- **Steady-state operation modelling** under research programme 2 "*power system operation*"

  This stream focuses on those research questions aiming to improve the steady-state operation models used in the context of power system planning. This involves streamlining the steady-state models to make them as computationally efficient as possible, while also representing all the binding constraints to guarantee a feasible outcome. Some topics included within this stream includes the consideration of reactive power, imperfect competition and back start capabilities in the models representing the future power system.

- **Methodologies for decision-making under uncertainty** under research programme 4 "*decision making*"

  This stream is chiefly concerned with the structure of an ad-hoc decision-making methodology capable to coordinate all needed techno-economic analyses in an accurate and tractable structure that can be solved by a team of people in a reasonable period of time. This includes the capacity to make complex decisions on network and non-network assets and integrate reliability and resilience analysis in the decision-making process.

After bundling the projects into streams and programmes, we have also mapped the **interactions** between projects, streams and programmes. The interactions are used to indicate the potential interactions required to facilitate the effective exchange of research outcomes among projects. Explicitly considering these interactions in the development of a research plan can help to improve the plan's practicality. The interactions between research programmes are shown in Figure 10. The projects in "long-term uncertainty" and "distributed energy systems" programmes are generally used to build the inputs of modelling, which only has outflow interactions. The "decision making" programme has the most inflow interactions because it needs to gather all the results of technical and economic assessments to make various decisions in power system planning.

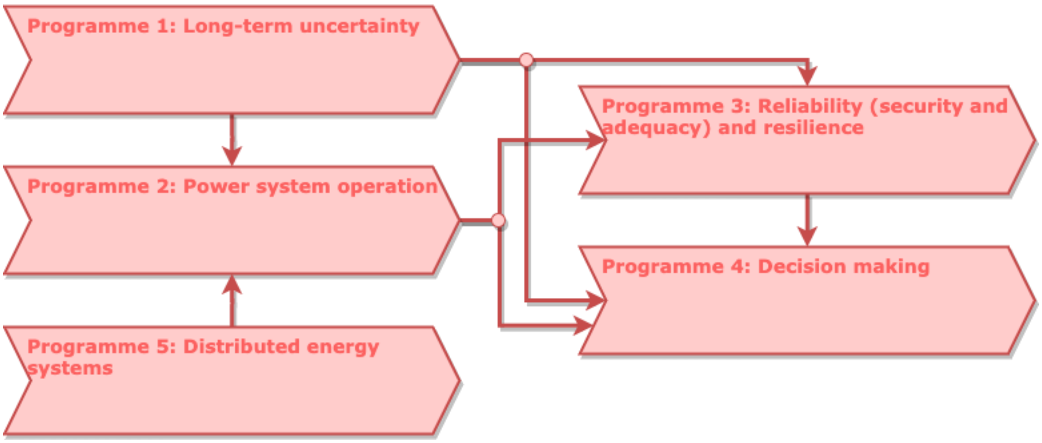

*Figure 10. Interactions between research programmes*

Within every research programme, the interactions at stream and project levels are also mapped. An example is shown in Figure 11, which shows the interactions of all streams in research programme 1 and the interactions between projects within the stream of "Scenario development for planning studies".

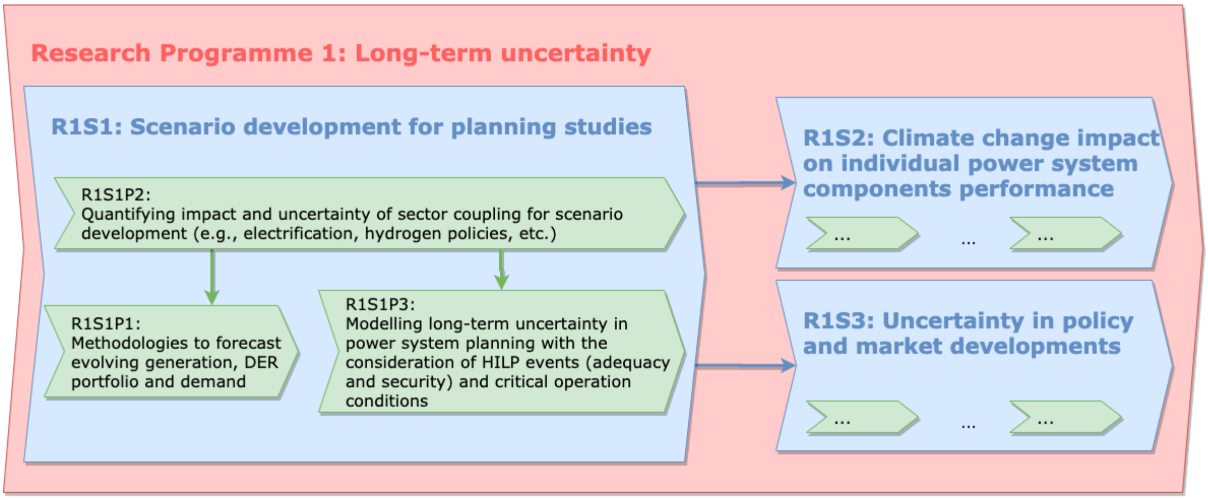

*Figure 11. Interactions at stream and project levels in research programme "long-term uncertainty"*

The description of all interactions is attached in Appendix D. The interactions are summarised in a table format with a connection matrix. The resulting connectivity graph is used in planning resource allocations over time. For example, the interactions of the streams shown in Figure 11 (blue arrows) are illustrated in Table 6. The projects in the row header provide input for the projects displayed in the column header. In this case, the output (research outcomes) of stream “Scenario development for planning studies” will provide inputs for streams “Climate change impact on individual power system components performance” and “Uncertainty in policy and market developments”, therefore two cells are filled with dot to reflect such interactions in Table 6.

*Table 6. Stream interactions in research programme 1 “long-term uncertainty”*

| *Interactions* | | ***Input*** | | |
|---|---|---|---|---|
| | | *Scenario development for planning studies* | *Climate change impact on individual power system components performance* | *Uncertainty in policy and market developments* |
| ***Output*** | *Scenario development for planning studies* | | • | • |
| | *Climate change impact on individual power system components performance* | | | |
| | *Uncertainty in policy and market developments* | | | |

## 4.3 Research plan development

After identifying all research projects and relevant interactions mentioned in sections 4.1 and 4.2, the assembly of the research plan is based on consideration of:

- Research priorities
- Resource requirements
- Risk mitigation strategies
- Australian research capabilities

Of them, the research priority, resource requirement and risk mitigation strategy will have direct effects on the timeline design. An evaluation of Australian research capabilities helps to suggest the most effective alignment of the research plan programs with the participants from Australian research institutions.

### 4.3.1 Research priorities

The objective of this effort is to articulate a research plan that delivers industry timely, high-value insight and goals. Projects have been sequenced and prioritised to do so. Priorities are evaluated against a range of factors, such as:

- Research interactions
- Research impact potential
- Delivery dates
- Other G-PST topics interaction
- Stakeholder engagement

#### *4.3.1.1 Research interactions*

The interactions introduced in section 4.2 are one of the factors used to determine project priority. For example, as seen in Figure 11 and Table 9 from Appendix D, the project *R1S1P2* should feature a higher priority than *R1S1P1* and *R1S1P3,* because it produces research outcomes to support the research agenda of the other two research projects. Additionally, the research priority of the projects in R1S1 may be higher than the projects in R1S2 and R1S3 because the research outcome of R1S1 is used as input for R1S2 and R1S3, as shown in Table 6 above.

#### *4.3.1.2 Research Impact potentials*

Several factors contribute to the impact potential of research. We have attempted to assess value based on the relative potential impact of the research on the economics of the whole power system. In the case of cost, this can be understood as the potential impact in the category due to a better-informed decision. There are four factors we have considered in contributing to the research impact potential, which are:

- **CAPEX**: investment cost on power system assets
- **OPEX**: system operational cost
- **Reliability**: research impact potential related to security, adequacy and flexibility
- **Resilience**: research impact potential related to resilience

In the CAPEX and OPEX categories, we estimated potential impact over a decade, in four ranges 0-1%, 1-5%, 5-10% and >10% of total economic cost. Under Reliability and Resilience categories, three levels of the potential impact over a decade are considered, which are 0-20%, 20-60%, >60%. The research impact potential is assessed at the stream level and hypotheses are assigned to each stream based on our experience on relevant industry projects and extensive literature reviews.

#### *4.3.1.3 Delivery dates*

Other than research impact potential, the delivery date requirement is another criteria for prioritising research streams. There are two time-related categories that need to be determined:

- "**Highly useful from**": This indicates the earliest timeframe in which industry is likely to be able to leverage emerging insights.
- "**Less relevant after**": If the research under this stream is completed after this date, the benefits to power system planning would reduce substantially.

Our hypotheses on the research impact potential and delivery timeframes for each research stream are attached to Appendix E.

#### *4.3.1.4 G-PST topics interactions*

The interactions with other G-PST topics are also considered after discussing with the corresponding project leaders. 16 out of 36 projects proposed in topic 4 link to other G-PST topics, while every G-PST topic has at least one project linked here. The linked projects are mentioned as follows:

For topic 2 "**Stability tools**",

- *R1S1P3* – "Modelling long-term uncertainty in power system planning with the consideration of HILP events (adequacy and security) and critical operation conditions". The research carried in Topic 2 would require the snapshots developed in project *R1S1P3* to indicate different system operating conditions to be analysed in stability studies.
- *R2S2P2* – "Developing models, stability analysis methodologies and test conditions for future power systems under different portfolios of grid-forming and grid-following IBRs". The stability tools and methods developed in the research plan of Topic 2 would be used in this project.

For topic 3 “**Control room**”,

- *R3S3P1* - “Identifying credible and non-credible contingencies, including indistinct events, for different system states (e.g., using machine learning techniques) aiming to reduce the size of planning studies”. The research carried out in Topic 3 would require relevant tools to be used to classify and determine the impact of different types of contingency events, while some of the typical contingency events can be selected and used in project *R3S3P1* for planning studies.

For topic 5 “**Restoration and black start**”,

- *R2S3P2* - “Identifying black start requirements of future power systems and the black start capabilities of new technologies. Modelling black start services in power system planning”. How to model (simplified) black start services in planning studies requires research inputs from topic 5.

For topic 6 “**Services**”,

- *R4S1P3* - “Designing the optimal schemes (e.g., mandatory, market-incentivized, hybrid) for service provision to maintain system reliability and resilience”. This project requires the research outcomes of topic 6 to provide the characteristics of services in future power systems, which can be further analysed in this project to indicate the optimal schemes to procure such services.
- *R5S2P1* - “Identifying the sources and availability of demand-side flexibility, quantifying its aggregated profile, and determining its representation as an investment option in power system planning”. This project will also rely on the technical requirement of services provided from topic 6 so that the categories of service provision with demand-side flexibility can be identified, which can be further developed as investment decisions.

For topic 7 “**Architecture**”, two projects under streams “Uncertainty in policy and market developments” in our topic have clear linkages with research carried in topic 7. This requires topic 7 to provide potential market designs of future power systems so that such designs can be modelled and integrated into the decision-making framework of power system planning.

- *R1S3P1* – “Quantifying the Impact and modelling the interactions between market developments and system planning (e.g., capacity markets)”
- *R1S3P2* – “Quantifying the impact of carbon pricing and other externalities on planning”

For topic 8 “**Distributed energy resources**”, there are five projects in topic 4 linked to topic 8. In topic 4, the relevant projects mainly investigate the impact and potential benefits brought by the integration of DERs and IBRs when planning power systems. Increasing DERs penetration may result in system contingencies happening more frequently with a larger imbalance which will be investigated in project *R3S3P2*. The high penetration of DERs may also require more detailed consideration on the demand side other than modelling load growth in power system planning. For example, more complicated investment decisions on distribution network assets and the uncertainty of DERs growth need to be integrated into planning studies as seen in project *R4S3P1*. Then, the last three projects (*R5S2P2, R5S2P3, R5S3P1*) focus on modelling the behaviour of DERs for planning studies. All these projects require the research outcomes of topic 8, which will have more detailed modelling of DERs behaviours and then discussion needs to be held to decide how to convert these models developed in topic 8 into the ones used by the research in topic 4. The relevant projects are:

- *R3S3P2* - “Profiling power system risks under various contingencies and indistinct events for future low-carbon grid with high penetration of IBR/DERs”.
- *R4S3P1* - “Modelling investment decisions (including demand response) at distribution network level and determining the methodologies to integrate them in power system planning”.
- *R5S2P2* - “Modelling distributed energy systems (e.g., DERs, VPPs) operation and determining the data required to represent their operation (considering short-term uncertainty) for planning studies”.
- *R5S2P3* - “Developing equivalent models to represent the aggregated dynamic behaviour of distributed IBRs for planning studies”.
- *R5S3P1* - “Modelling the impact of high DERs penetration on power system planning

For topic 9 “**System security with high DER penetration**”, there are three projects in our topic linked to the research carried in topic 9, which are mainly focused on evaluating the response behaviour of DERs and IBRs when facing system contingencies and extreme events, and additionally how DERs can contribute to system reliability and resilience. The relevant projects are:

- *R3S4P1* - “Modelling and analysing the impact on planning from IBR (including and in particular batteries) response to credible contingencies and high impact low probability (HILP) events”
- *R3S4P2* - “Modelling and analysing the impact on planning from DERs (including DERs aggregations as microgrids, VPPs, etc.) and distribution network assets response to credible contingencies and high impact low probability (HILP) events”
- *R5S3P2* - “Modelling and analysing the contribution of DERs to system reliability (security and adequacy) and resilience

Ideally, the timeline arrangement of the “cross-topic” projects should be associated with the research plans developed in other G-PST topics. This interactive design enables the research outcomes can be delivered on time to support projects in other topics, or related research in two G-PST topics can be carried simultaneously to enable a “closed-loop” interaction. However, the research plans of other G-PST topics are not ready yet. Therefore, in the research plan of topic 4 “planning”, the projects associated with other G-PST topics will be labelled as high priority ones and completed at their earliest convenient date. A further adjustment can be made by CSIRO or project coordinator to achieve a more consistent design of research plans across all G-PST topics.

#### 4.3.1.5 Stakeholder engagement

Highlighting potential stakeholder engagement can improve the executability of the research plan by indicating which industry partners should be included in each project. Five types of potential stakeholders are identified for this research plan, namely system operator (SO), transmission network service provider (TNSP) and distribution network service provider (DNSP), regulator and generation company (GenCo). The key stakeholder engagement is considered at stream level and our hypotheses on stakeholder engagement are shown in Appendix F.

### 4.3.2 Resource requirements

The resource requirement of a research plan is defined as relevant personnel needed each year. The measurement unit of resource requirement is the full-time equivalent (FTE) of a researcher with 5 years of relevant research experience. The resource equivalence of a PhD student may be considered as 0.5 FTE per year. Resources are needed at three levels:

- **Governance**
  *The monitoring and quality control of projects, streams, programmes and the overall plan. This must draw on both senior, deep subject matter expertise, and senior industry stakeholders that are, together, the ultimate arbiters of the quality and value of research activity and outputs.*
- **Problem-solving and project leadership**
  *The objective of the research projects of this plan is to deliver insights and tools of maximal value to industry. The quality of problem-solving leadership – in particular, its continuing alignment of ideas and activity with this objective – will determine the ultimate impact of each project. Project management is of course important, ensuring that front-line resources are effectively developed and managed to deliver timely, high-value outcomes. The two things are quite distinct. It is not uncommon for industry research projects to fail to deliver timely outcomes because of poor project management. It is more common for them to fail to deliver fantastic impact – because of the lack of industry-value focused problem-solving leadership. While project management is a deterministic process, problem-solving leadership demands peak collaborative problem-solving skills and deep subject matter expertise. The former can be delegated to mid-level personnel, the latter depends on the active leadership of the best and most experienced (and scarce) research leaders.*
- **Frontline researcher**
  *This refers to those for whom the project is their principal research activity.*

The success of all these projects depends on continuous deep collaboration between industry and its research providers – the latter including academia, CSIRO and other commercial research services providers. We expect the best projects will include dedicated personnel at all of the above levels and, at a minimum in governance and the front line of research. The latter is particularly important. Research providers need direct, intimate access to industry insight and experience to understand its issues, its value drivers, and how deliverables need to be architected to enable industry stakeholders to exploit their full potential. Industry needs a deep internal understanding of how insights have emerged, how emerging insights and tools may be best deployed – and why there are compelling reasons to do so. This, perhaps frivolously, can in engineering terms be thought of as "impedance matching"; ensuring research maximises the value of research deliverables relative to their theoretical business potential and then minimising the "translational losses" as they are adopted by industry.

We hope these observations catalyse next-step implementation planning and resourcing that is resolutely grounded in maximising industry impact. Our resource estimates are enumerated in terms of front-line research services providers. We however expect that project business cases reflect resource demands across stakeholders that enable effective collaboration, problem-solving leadership and governance.

Table 7 sketches this concept, where the aggregate resource demand is a multiple of our estimate of frontline research provider demand.

*Table 7. Activity components in research plan*

| *Activity (in FTE, not cost)* | Industry | Research providers |
|---|---|---|
| *Governance* | $X_i$ | $X_{rp}$ |
| *Problem-solving and project leadership* | $Y_i$ | $Y_{rp}$ |
| *Frontline researcher* | $Z_i$ | $Z_{rp}$ |

Figure 12 illustrates our directional expectations for the resources required at each of the discussed project levels. Some project management administrative tasks may be shared across streams and programmes, where they are managed by research providers. We expect this to be the case for governance. High-quality problem-solving leadership however is less project-scale variant – making small projects typically much less efficient for a given quality of output. This is taken into consideration when scoping projects.

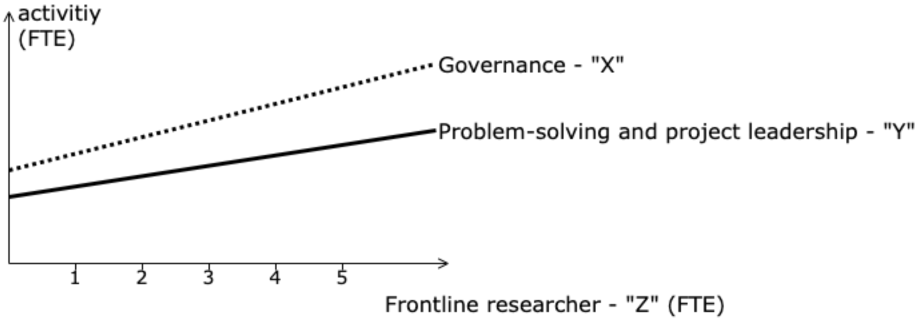

*Figure 12. Resource requirement of governance and project leadership in relation to frontline researcher*

Our hypotheses on the frontline researcher provider resource requirements (in FTE) for each project are laid out in Appendix B. The aggregate is 84 FTE over ten years, with, consistent with the impact focus, most deployed in its first half. Overall resource demands and costs are not within the scope of this project to consider.

### 4.3.3 Risk mitigation

Integrating risk mitigation measures into the research plan is essential, particularly considering that the plan is dealing with "burning" challenges, such as climate change. Relevant research will happen across the world in the next few years, which may advance part of the research plan without other researchers' knowledge at first hand. At the same time, any shift of industry focus (due to rapid technology change) or government policy adjustment may make much of an established research plan invalid and redundant. Therefore, a flexible and adjustable research plan is needed to respond to:

- Emerging insights from other research institutions on the world
- External factors that change the scope or objectives of existing projects (e.g., regulatory adjustment)
- The emergence of new challenges and consequently new research questions

The flexibility of a research plan is mainly contributed by a pre-defined contingency plan and periodical review. The contingency plan allows project delays to be dealt with smoothly. The periodical review can realign the activities in the research plan with evolving industry needs. To execute such periodical review, an advisory board also needs to be established to oversee such review process. To be more specific, there is a range of actions that will be applied in this research plan development as part of the risk mitigation strategy, as follows:

- **Contingency plan:** Adding an extra 0.5 FTE to every project when building a timeline for the research plan in anticipation of project delays
- **Periodical review:**
  - Performing an annual review by the governance board to add new information regarding the latest research development in the industry and academia, which allows project leaders to integrate such research advancement into their project.
  - Establishing milestones at intervals of two years and asking the advisory board to review and update the remaining research plan by adding, deleting or revising projects and their corresponding timeline.

### 4.3.4 End-products

This project delivers both a structured research plan and an estimate of the frontline resources needed to pursue it. The research plans at project/stream level for the five research programmes are shown in Figure 13-Figure 17 respectively. All projects are coded to improve the visibility of the timeline and interactions, while the name of the project can be found in Appendix B. Each project is expected to be executed in the allocated FTE levels (i.e., 0.5, 1, 1.5 or 2), which in the case of research institutions may correspond to teams composed by researchers of different seniority, whose aggregated commitment to the project results in the associated FTE level. The "height" of the project block in Figure 17 reflects such pace, such as 0.5 FTE/year for R1S2P1 and 2 FTE/year for R1S1P1. There are four important factors highlighted in Figure 17-Figure 17 as follows:

- Timeline and resource requirement of individual projects
- Interactions between projects and streams
- Stakeholder engagement
- Involvement with other G-PST topics

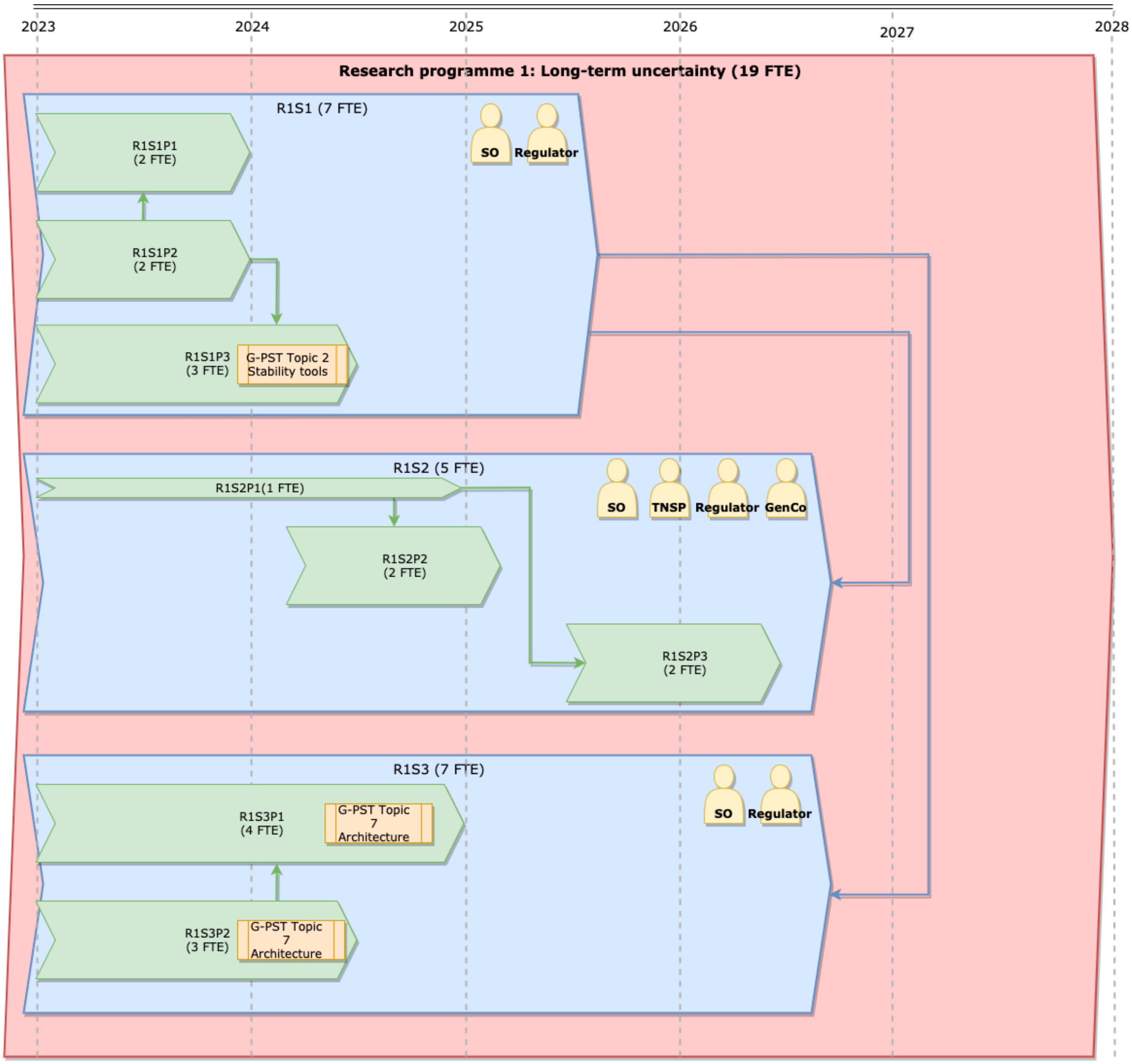

*Figure 13. Research plan at project and stream level under research programme 1 "Long-term uncertainty"*

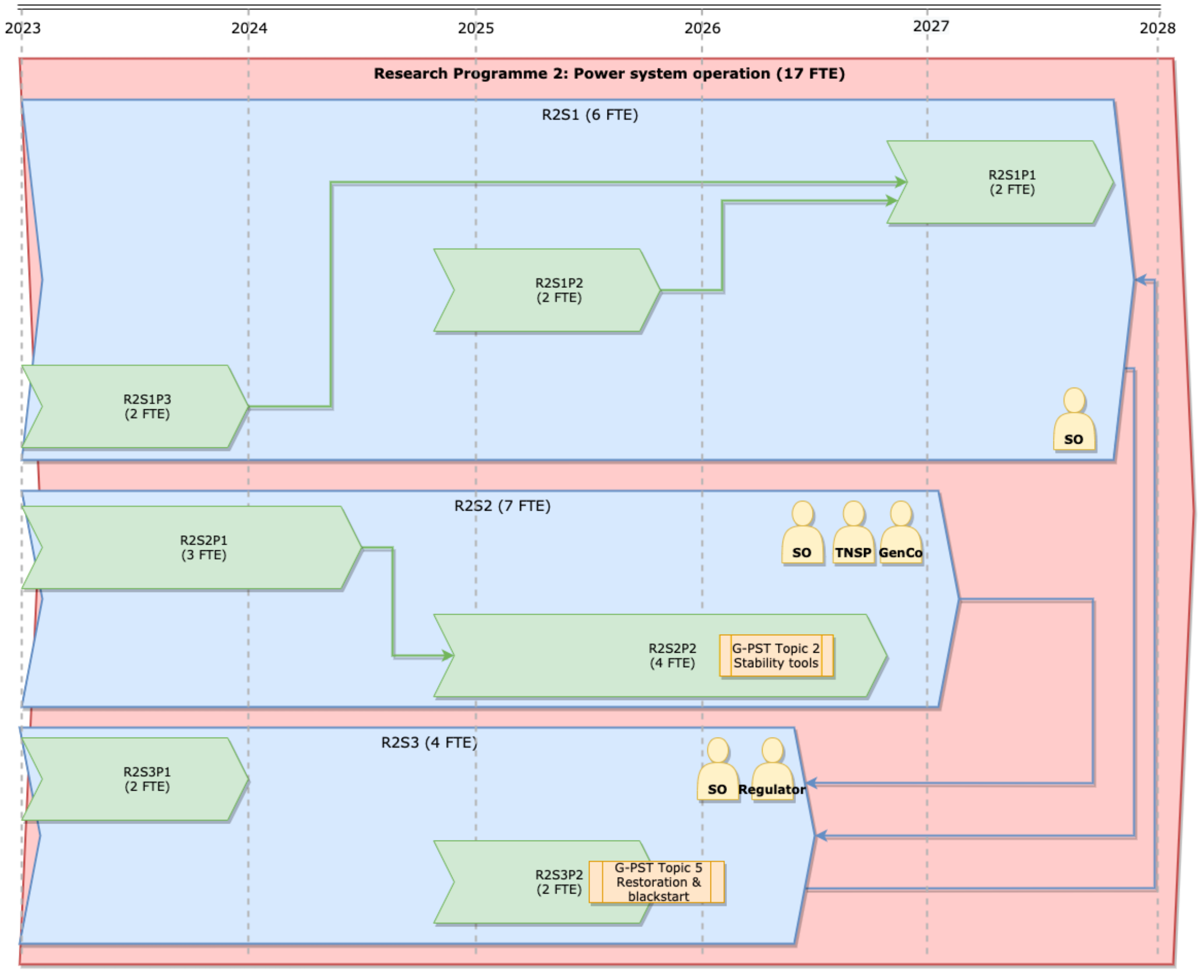

*Figure 14. Research plan at project and stream level under research programme 2 "Power system operation"*

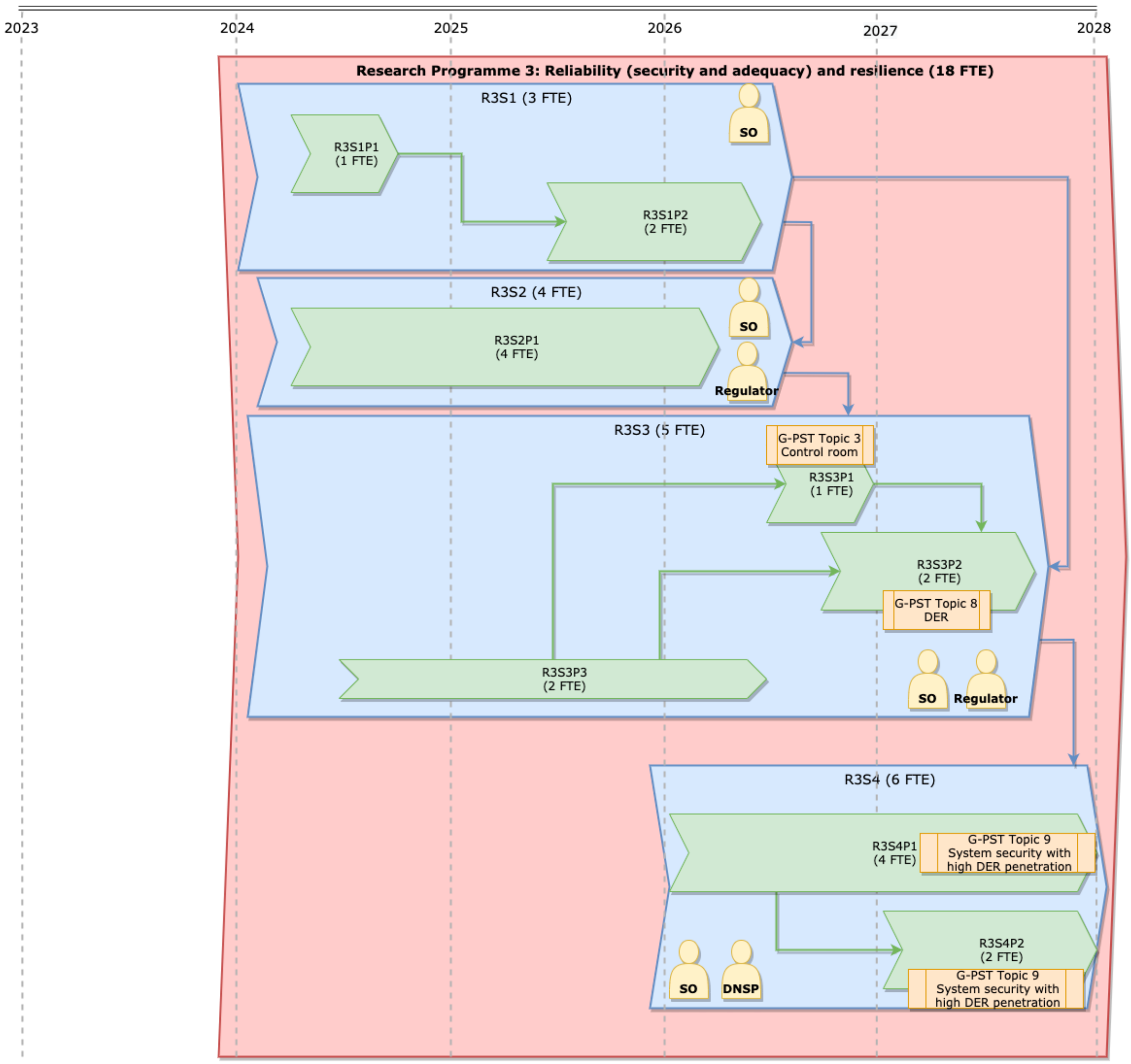

*Figure 15. Research plan at project and stream level under research programme 3 "Reliability (security and adequacy) and resilience"*

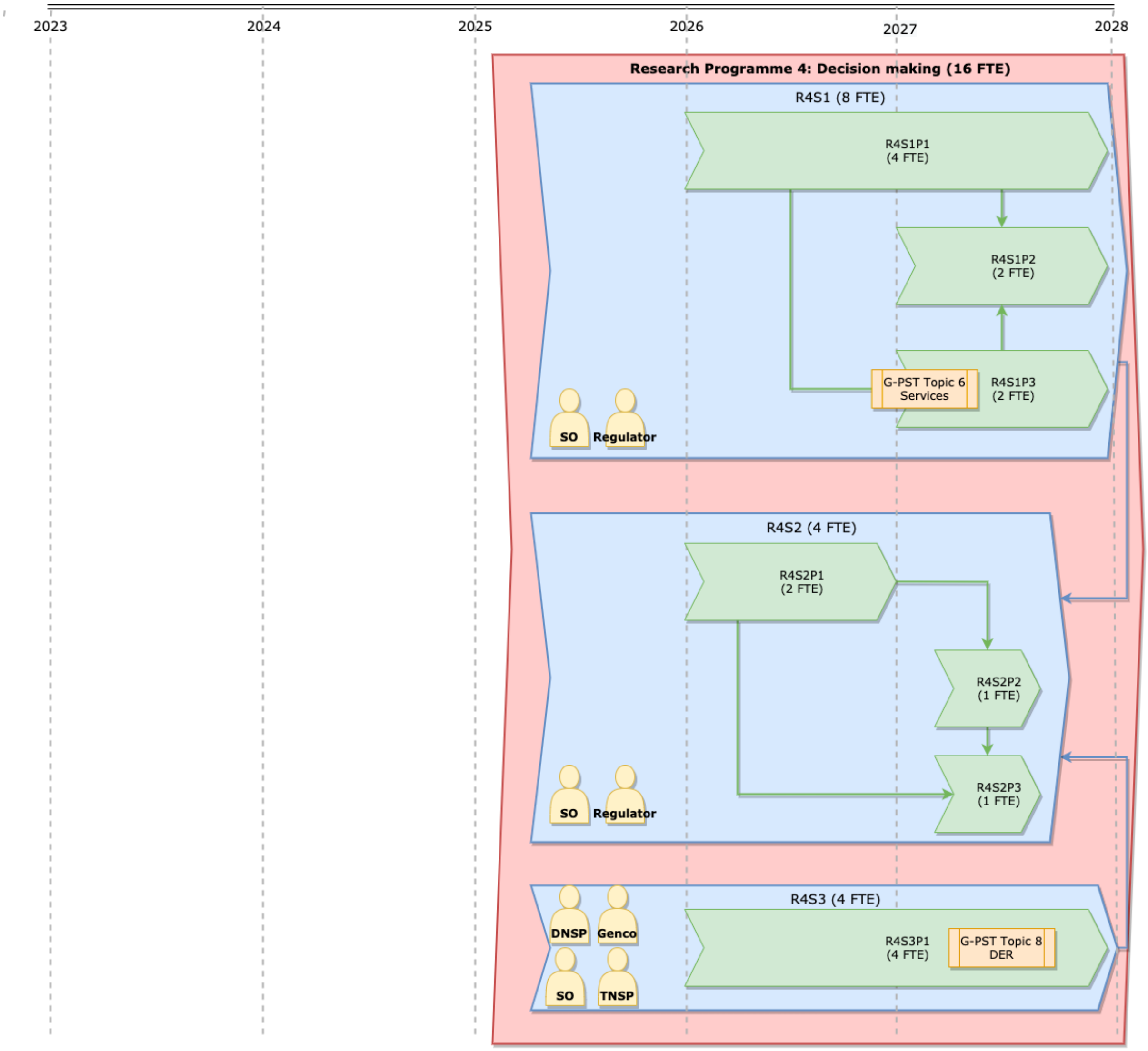

*Figure 16. Research plan at project and stream level under research programme 4 "Decision making"*

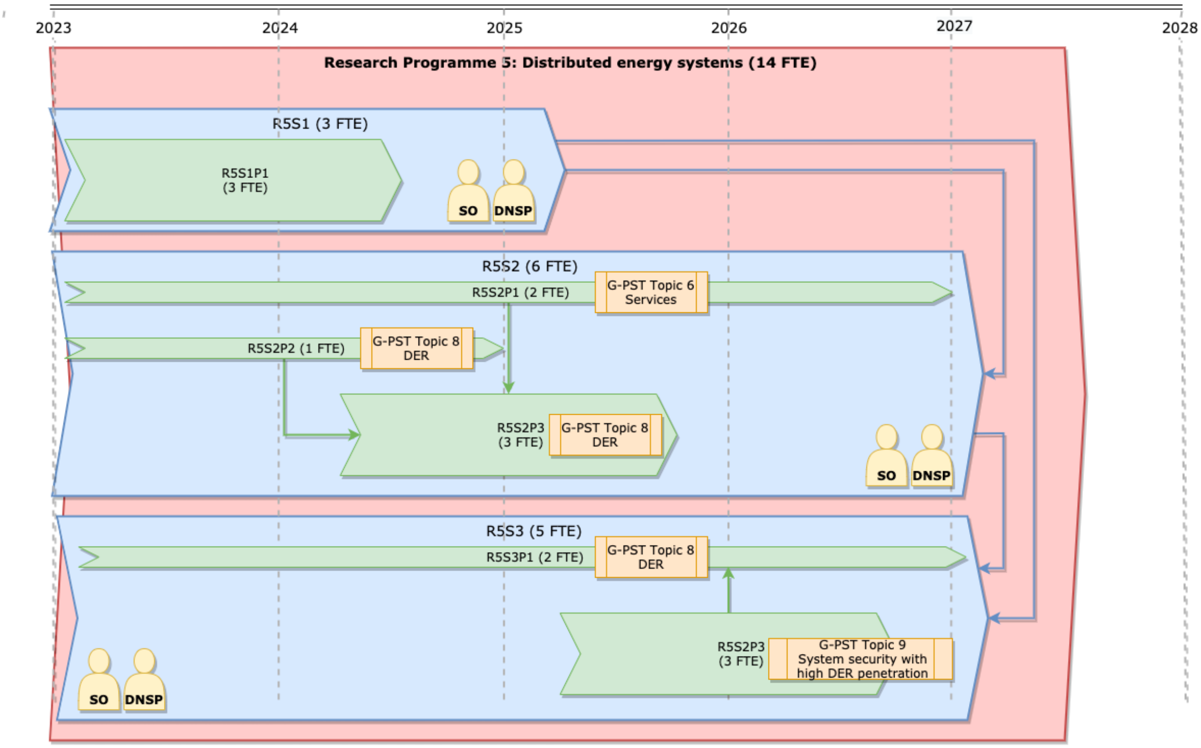

*Figure 17. Research plan at project and stream level under research programme 5 “Distributed energy systems”*

Each plan also provides an overview of resource allocation between research programmes, each of which is expected to be led by individual research service providers. This part of the research plan covers:

- Resource requirements of each research programme across a decade
- Interactions between research programmes
- Periodical review milestones (annually by the governance board and biennially by the advisory board)

For periodical reviews, when there is a coincidence of annual review and the major milestone, the annual review would take precedence, as shown in Figure 18. Resources are front-loaded in order to maximise the impact in the first 5 years. The insight developed in this period will build an understanding of the challenges that would drive further high-value research in next 5 years.

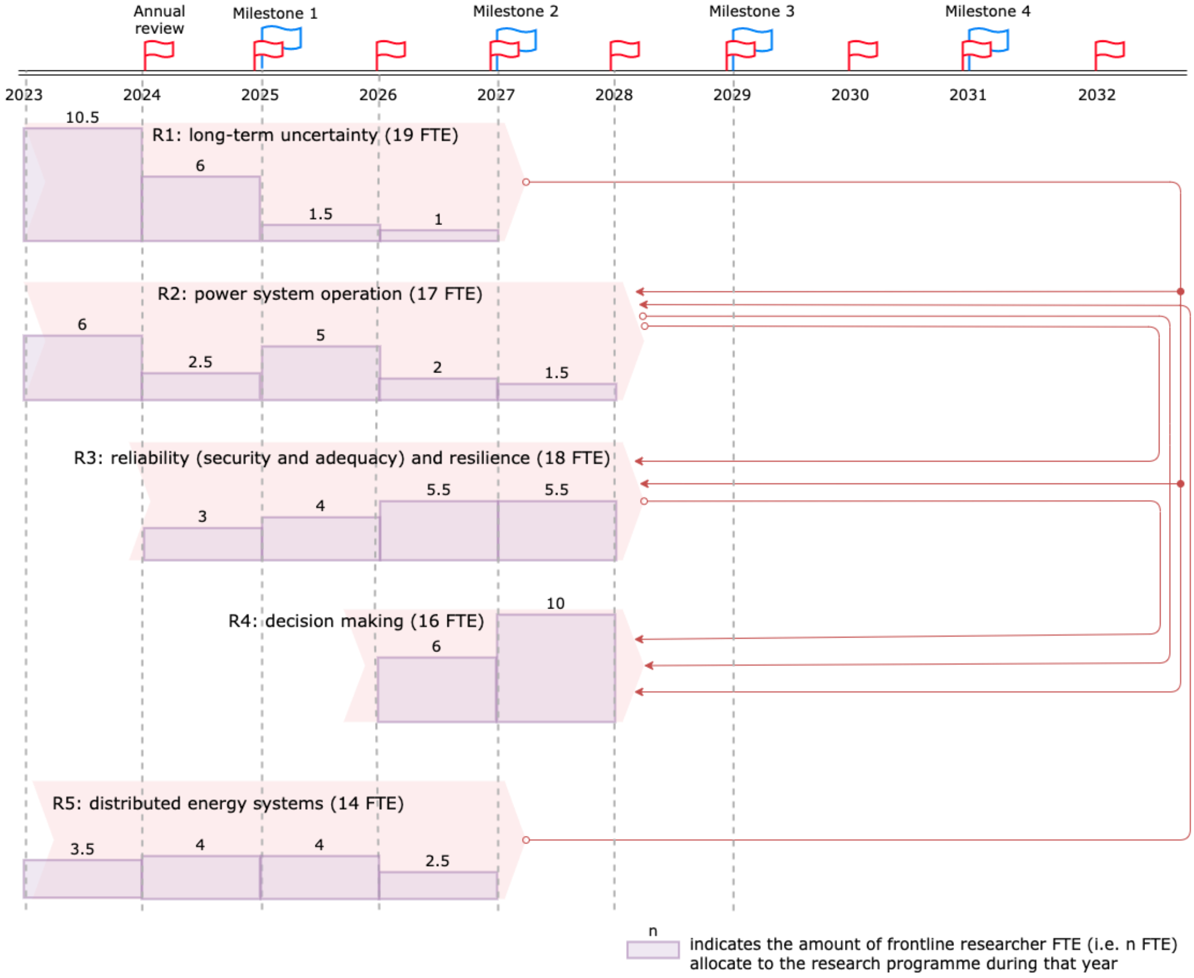

*Figure 18. Research plan at research programme level*

### 4.3.5 Australian research capability

In the domain of power system planning, we believe that Australian research institutions are fully capable of conducting the programmes described in this research plan. Based on recent research activities and outputs, which are driven by local industry needs the Australian research providers have demonstrated "leading" research capability on at least 4 streams out of 16 streams defined in this research plan.

For the "Scenarios development for planning studies" stream, Integrated System Plan (ISP) published by AEMO biennially may be considered as a leading exercise in the world which considers the highest number of scenarios to drive decisions, as shown in the system planning practices reviewed in Table 2. The diversity of the scenarios is also substantial, which even covers potential development of green hydrogen industry in Australia.

When dealing with the stream of "Climate change impact on individual power system components performance", Australian research institutions should also be considered as leaders in the subject. For example, the Electricity Sector Climate Information (ESCI) project [37] has comprehensively investigated the impact of climate change, extreme weather and temperatures on the performance of power system assets.

Regarding "Credible and non-credible contingencies", Australian industry partners and regulators have published various relevant reports. "Mechanisms to Enhance Resilience in The Power System" [28] published by AEMC created a clear framework to define distinct and indistinct events leading to stability issues. AEMO's "General Power System Risk Review (GPSRR)" has expanded the scope of frequency risk review from single contingency to cascading failure and major supply disruption events.

For "Distributed energy markets and demand side flexibility", there are projects like "ESB-Post 2025 Market Design Project" which covers unlocking demand-side flexibility to provide system services, which can also be used to deal with long-term uncertainty in power system planning.

The research capability of Australian institutions on other streams is at least at "parity" level. International collaboration is also desirable to accelerate the execution of the research plan and share the research outcome with global communities. For more details about our research capability assessment see Appendix F.

## 4.4 From G-PST agenda to Australian Research plan

In the G-PST Inaugural Research Agenda [48], the "planning" topic had 15 research questions. These "core" questions were used as the compass while navigating through the plethora of possible power system planning challenges, linking them to planning frameworks and proposing relevant research questions. For instance, the G-PST questions laid the foundation for developing the framing concept tree shown in Figure 3. After extensive discussions with stakeholders and literature review, the number of research questions increased from 15 to 119, as shown in Appendix A. Among these questions, there are high-level ones that set up contexts for creating practical research questions later, such as:

> "*45. How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high renewable energy future (wind, solar, demand-side flexibility)?*"

and practical ones, like the following one discussed when engaging with AEMO and NGESO:

> *"To what extent can the representation of the operation of the system be simplified without impacting the investment decisions? What are the parameters of different resources (e.g., minimum up and down times) and the system operation characteristics (e.g., unit commitment) that may be simplified? What mathematical models are most suitable for these simplifications?"*

There may be overlaps of the challenges addressed by different questions; solving some practical questions may be a prerequisite to answer other high-level questions. However, we have decided to follow the principle that "*priority will not be assigned to questions, but there will be prioritised projects which link to multiple questions".*

Starting from 15 G-PST agenda questions, and then expanding to 119 research questions, and subsequently creating 36 research projects, we have not only drilled down and distilled the questions from G-PST agenda but also expanded the **agenda's scope** considering Australian (and international) stakeholders' feedback. Then, we also evaluated the **research impact potential** of projects and the **Australian research capabilities** available to address these research projects. Figure 19 maps the profile of projects against three factors mentioned above:

- **GPST agenda relationship**:
    - **Only in GPST Agenda**: Project solely links to the questions listed in G-PST Agenda [48]
    - **Overlay with GPST Agenda**: Project links to both G-PST and stakeholder-proposed questions. The value on x-axis is calculated as the number of stakeholder-proposed questions divided by the total number of linked questions
    - **Scope not covered by G-PST Agenda**: project only links to questions proposed by stakeholders

- **Impact potential**: Calculated with the four indicators of research impact potential mentioned in section 4.3.1.2
- **Australian research capability**: Identified in section 4.3.5

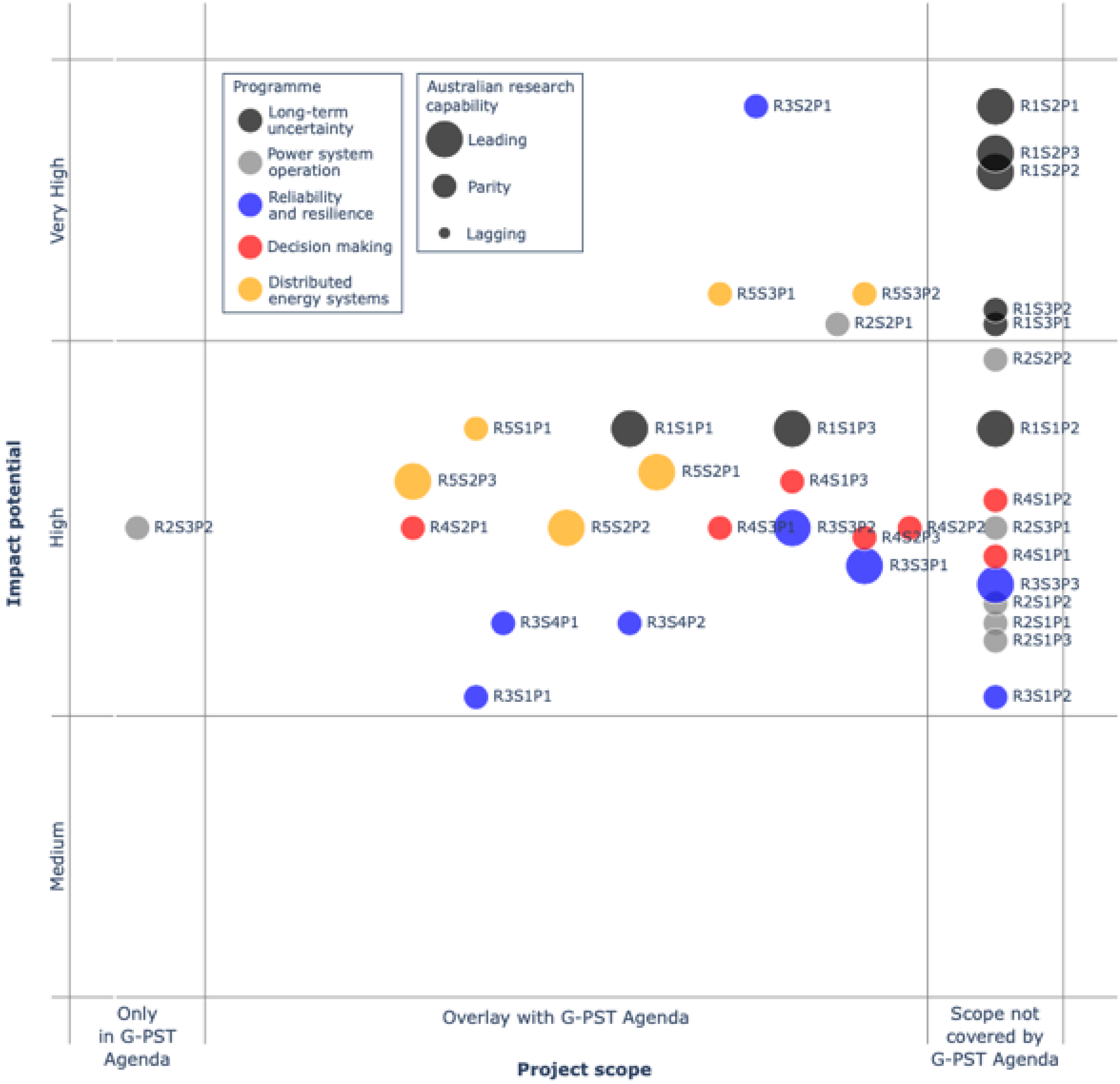

*Figure 19. GPST scopes, Australian impact potential and research capability of research projects*

Figure 19 shows the projects that go beyond the scope of G-PST Agenda, mainly in the area of power system operation and long-term uncertainty. There are also projects which were specifically driven by G-PST, such as R2S3P2 about considering black-start requirement in planning studies.

In summary, the G-PST agenda has provided a strong foundation to systematically explore the challenges ahead, which has been augmented, consolidated and reviewed with the support of local stakeholders. The resulting plan robustly and comprehensively reflects the needs and priorities of Australian industry - while also expanding and contributing to the global agenda.

# 5 Recommendations

With very significant input and help from industry and its research providers, this project has assembled the issues and challenges that represent the state of the art – and the state of industry needs – in the domain of power systems planning. It has, based on iterative assessment and review by industry and research peers, systematically distilled this into a practical research plan to address the most time-critical and valuable of those challenges. The resulting plan, to the extent that it effectively leverages the best talents of industry and its research partners, has the potential to materially assist the Australian power system industry in meeting its unique challenges – and unlock significant new value for its stakeholders. And it has the potential to make a distinctive and substantial contribution to the ability of the global power system industry to meet the complex challenges of the coming energy transition.

This plan has been developed with and for the benefit of Australia's key power industry stakeholders. We hope that, as a consequence of their deep involvement, those stakeholders see their needs and priorities compellingly reflected in the focus, sequencing and timing of the proposed projects. And that the research services provider community recognise the potential for this plan to leverage their strengths to make a significant contribution to the evolution of the industry, both locally and globally. Hence, our recommendation is that the next steps in the development of the full project and, later on, in its delivery, actively involve industry stakeholders as key partners.

We hope and expect that our plan will provide an objective and productive foundation for future discussions about where future investment in research collaboration should be made. Meeting the challenges addressed in this plan has the potential to unlock significant new value for our country. The sooner we are all begun on this task – with an urgent focus on industry impact – the more of this potential will be realised.

Our final recommendation is that what we provided here, rather than a static document, should be considered a dynamic, flexible and adaptable plan. As such, in order to be actioned, it will require further developments with the support of industry and in concert with the other topics and research providers that are part of the broader project. We will of course be very happy to contribute to these further developments for what we can.

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# Appendix A : Research questions list

## Area 1: Architecture

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A1-1<br>**(GQ.46)** | In the context of DER visibility in power system planning, what data is necessary to accurately model various levels/paradigms of DER control including influence on UFLS schemes? | DER | A3 |
| A1-2 | How to geographically map renewable capacity installation availability vs technical and nontechnical constraints, and what are these constraints? | | A3 |
| A1-3 | How to consider the environmental aspect in power system planning? | | A7 |
| A1-4 | What is the right methodology to determine the decommission decisions of the existing generators in generation expansion? | | A7 |
| A1-5 | HVDC and phase-shifting transformers are currently quite rare in Australia, what roles are they and other Flexible AC Transmission Systems (FACTS) devices likely to play in the future? | | |
| A1-6 | In the context of technologies available for network support/reinforcement, what are their technical strengths and commercial maturity and how can they be represented in power system planning? | | |
| A1-7 | What techniques are needed to identify the regions that are most vulnerable to different kinds of disruptive weather events, including heatwaves, bushfires, duststorms, etc? | Stability tools and methods | A |
| A1-8 | Which technical capabilities should be acquired by DERs to maximise their system integration? | DER | |
| A1-9 | How does the aging of generation and transmission assets impact their efficiency and fragility? | | |
| A1-10 | How to model the operation of new technologies (e.g., DER, VPP, hydrogen electrolyser) in network planning? | | A3 |
| A1-11 | What is the right structure for regulated return on investment for new transmission assets? | Architecture | |
| A1-12 | What is the ideal governance structure to timely respond to the challenges faced by low-carbon power systems? | Architecture | |
| A1-13 | What should be the specifications of IBR control modules to avoid malfunctions and unexpected tripping? | Inverter design | |
| A1-14 | In the context of dealing with the challenges faced by future power systems, what reliability standards are needed and how should they be assessed? | Architecture | A4 |
| A1-15 | In the context of future power systems, what are the markets needed to valuate services provided by different technologies? | Services | |
| A1-16 | What are the relevant policy changes needed to allow the provision of network support services by batteries at all system levels? | Services | |
| A1-17 | How to value the externalities of reinforcement options? | | |
| A1-18 | What are the technical requirements for each individual technology to guarantee the reliability of future power systems? | Architecture | |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A1-19 | What are the roles of market-driven investments and centralised planning in achieving different policy targets (e.g., carbon neutrality)? | Architecture | |
| A1-20 | What is the market design that promotes the penetration of technologies needed to get to a zero-carbon power system? | Architecture | |
| A1-21 | What are those electricity consumption sectors that can provide demand response and what are the technical and non-technical constraints that can limit their demand response capability? | | A3 |
| A1-22 | In the context of ensuring system reliability and resilience through service provision, should stakeholders be incentivised to contribute or mandated to comply, and how do you design these incentives and mandates? | | |

## Area 2: Long-term uncertainty

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A2-1<br>**(GQ.47)** | What additional load and resource forecasting models are necessary to account for electrification of the transportation and building sectors? | | |
| A2-2 | How to include high impact low probability events in scenario tree representation (and in the underlying operational models)? | | |
| A2-3 | When building the scenarios that represent the long-term uncertainty in the system, how should we represent the probability distribution of the relevant uncertain variables, in particular for the penetration of new technologies like IBRs and DERs? | | |
| A2-4 | What are the limitations and advantages of using deterministic scenarios in the context of power system planning? | | |
| A2-5 | Is scenario-based approach the best way to represent long-term uncertainty in power system planning? | | |
| A2-6 | In the context of scenarios for long-term planning, how are scenarios themselves influencing the decision making as opposed to and in conjunction with the methodology? | | A7 |
| A2-7 | What system conditions (e.g, peak demand, minimum demand, low inertia level) should be considered in the scenarios used in network planning? | | A7 |

## Area 3: Operational modelling

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A3-1<br>(**GQ.41a**) | How to model the operation of RES in black start plan? | Black start | |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A3-2<br>**(GQ.45)** | How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high renewable energy future (wind, solar, demand-side flexibility)? | | |
| A3-3<br>**(GQ.50)** | What are appropriate aggregate DER models and methods for inclusion in transmission-level modelling? | | A5 |
| A3-4 | How to represent the impact of DER integration and demand electrification in operation models used for transmission network planning? | Architecture | |
| A3-5 | How to model the DERs operation and provision of ancillary services in power system planning? | | A1 |
| A3-6 | How to model demand and its embedded flexibility in different sectors (i.e., electrification of heating and transportation, industrial processes, hydrogen production, etc.)? | Architecture | A1 |
| A3-7 | How to model the interaction between the power system and other energy systems (i.e., gas, hydrogen) in power system planning? | | A1 |
| A3-8 | How to use available data in a meaningful way to build models/tools for DER operation? | DER/Stability | A1 |
| A3-9 | How to accurately model and account for DER in power system planning, particularly for capturing its role in system reliability and resilience? | | A5 |
| A3-10 | What is the role of other systems, particularly gas (and in the future possibly hydrogen storage), in adequacy and resilience assessment? | | A5 |
| A3-11 | What kind of dynamic modelling is needed for IBR to ensure the robustness of security analysis? | DER/Stability | A5 |
| A3-12 | In the context of system security paradigm, what are the advantages and limitations of using probabilistic security criteria and risk-based criteria, how to model them efficiently? | | |
| A3-13 | How to determine reserve requirements for different types of contingencies, in particular in systems with high DER and IBR penetration? | Architecture | A5 |
| A3-14 | What are the requirements for stability analysis tools in systems which have a large portion of grid-forming inverters and other new technologies such as virtual synchronous machines? | Stability | A5 |
| A3-15 | How to evaluate the trade-off between computational complexity and modelling details within operation models in power system planning? | | A7 |
| A3-16 | How may system security paradigms (e.g. N-1) evolve in a world where high-impact, low-probability weather events are becoming more likely? | Architecture | A1 |
| A3-17 | What are the options (e.g., standalone microgrids) being considered to enable resilience in the power system? | | |
| A3-18 | How to develop a network modelling methodology which can seamlessly and consistently capture the performance of the assets at different spatial levels (i.e., inter-region, intra-region) in power system planning? | | |
| A3-19 | Should agent-based models be used to study market operation in power system planning? | | A7 |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A3-20 | How should system security criteria be adapted to incorporate high impact low probability events? | | A1 |
| A3-21 | To what extent can the operation of the system be simplified without impacting the investment decisions? What are the parameters of different resources (e.g., minimum up and down times) and the system operation characteristics (e.g., unit commitment) that may be simplified? What mathematical models are most suitable for these simplifications? | | |
| A3-22 | What kind of dynamic models are needed in network planning? | | |
| A3-23 | Can generic dynamic models (as opposed to manufacturer's models) of the elements provide the right representation of the system's transient performance? How do you develop these models? | DER | |
| A3-24 | Is it feasible to achieve a dynamic representation that is both comprehensive and computationally efficient to extensively simulate wider voltage behaviour in the network? | Stability | |
| A3-25 | What are the categories of contingency events that need to be considered in power system planning? | | |
| A3-26 | How to incorporate different constraints (thermal, voltage and stability) into network modelling in a computation-efficient way? | | |
| A3-27 | How to model storage operation to reflect its benefits in multi-service provision in power system planning? | | |
| A3-28 | What alternative approaches can be used to avoid the reliance on a full system representation in the context of EMT simulations? | Architecture | |
| A3-29 | In the context of the economic assessment of investment options that provide multiple services, how should the sources of value of each technology be represented in the operation, what time granularity is needed and what modelling tools should be used? | | |
| A3-30 | What are the options to absorb excessive reactive power under low demand conditions? | | |
| A3-31 | How to conduct voltage management under low demand conditions? | | |
| A3-32 | What are the tools needed to forecast and quantify the potential voltage issues due to the decline of net demand? | | |

### Area 4: Metrics

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A4-1<br>**(GQ.38a)** | What metrics are required to identify long-term scarcity of capacity? | High | |
| A4-2<br>**(GQ.44a)** | What metrics are required to evaluate the contribution of large-scale storage, hybrid plants (e.g., PV-plus-storage) and virtual power plants to resource adequacy? | High | |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A4-3 | How to measure the performance of transmission and distribution network assets under extreme weather conditions (such as bushfires, floods, strong gusts, heat waves, etc.)? | High | A5 |
| A4-4 | What are the right metrics to measure reliability and resilience? | High | |
| A4-5 | What are the metrics needed to measure the environmental impact of investment options? | High | |
| A4-6 | What are the metrics needed to quantify the potential impact of voltage issues due to the decline of net demand? | Medium | |

### Area 5: Techno-economic analysis

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A5-1<br>**(GQ.37)** | What additional probabilistic planning methods and tools are necessary for planning a power system with a high share of IBRs and in particular, variable renewable energy resources? | | |
| A5-2<br>**(GQ.38b)** | How to identify long term scarcity of capacity to maintain reliability? | | |
| A5-3<br>**(GQ.39)** | What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables? | a5-18 | |
| A5-4<br>**(GQ.41b)** | How should sufficient black-start capability and the performance and integrity of the protection system be modelled in long-term reliability studies? | Black start | |
| A5-5<br>**(GQ.42)** | What features need to be added to long-term planning methods and studies to consider other reliability services (e.g., flexibility) in addition to traditional resource adequacy and deliverability? | | |
| A5-6<br>**(GQ.43)** | How to capture the trade-off between system investment costs and technical performance (security, adequacy and resilience)? (Such as the marginal benefits of investing in additional storage (e.g., batteries, pumped hydro storage, etc.) on system reliability and resilience) | a5-11 | A4 |
| A5-7<br>**(GQ.44b)** | What studies are required to evaluate the contribution of large-scale storage, hybrid plants (e.g. PV-plus-storage) and virtual power plants to resource adequacy? | | |
| A5-8<br>**(GQ.49)** | What additional planning models and methods are needed to plan for a system that can withstand expected or unexpected lulls in the weather driving much of the resource mix, e.g. an extended wind drought? | | |
| A5-9<br>**(GQ.51)** | What models and methods are necessary to quantify the need and requirements for long duration energy storage? | | |
| A5-10 | How to address the system security and stability issues associated with the integration of IBRs? | Architecture | A3 |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A5-11 | How to value the service provision from DERs in support of system reliability and resilience? | | A4 |
| A5-12 | How to quantify the risks introduced by DER integration (e.g., indistinct events) in power system planning? | | A4 |
| A5-13 | How to determine the value of customers' reliability and resilience? | | A4 |
| A5-14 | how to incorporate DER in system security and resilience evaluation for planning studies, given their potential tripping risk following transmission level contingencies? | | A3 |
| A5-15 | How to model the increasing bushfire risk and assess its impact on supply resilience of transmission and distribution networks? | | A1 |
| A5-16 | How to explicitly model the uncertainty and risk created by climate change in power system planning? | | A2 |
| A5-17 | What are the potential roles of ML/AI application for contingency analysis and scenarios screening in power system planning? | | A2 |
| A5-18 | Is it necessary to model the time-dependent characteristic of storage for resilience and reliability analyses in power system planning? | | A3 |
| A5-19 | How will power system infrastructures derating (due to aging) impact system reliability and resilience? | | |
| A5-20 | How to evaluate the cost to increase the IBRs hosting capacity of the network from a whole system perspective? | | |
| A5-21 | How to combine transmission and generation infrastructure investment to enhance system resilience? | | |
| A5-22 | how to improve the computational efficiency of tools for technical analysis in power system planning? | | A3 |
| A5-23 | How to determine the optimal location of batteries to maximise the benefits to the system? | | A7 |
| A5-24 | What could be the optimal distribution network management strategies in preparation and response to extreme weather conditions? | Architecture | A3 |
| A5-25 | What kind of studies are needed to identify the benefits of one investment option to different stakeholders? | | |
| A5-26 | How does the integration of IBRs and DERs impact the risk profile of the power system, particularly in high impact, low probability events? | | A1 |
| A5-27 | How to use data-driven approaches to improve outage management (and security in general) in distribution networks? | Control room/Stability tools | A3 |

## Area 6: Investment modelling

| ID | Question | G-PST topic | SA |
|---|---|---|---|
| A6-1 | How shall the investment in demand response be modelled in power system planning? | | |
| A6-2 | What are the investment strategies (e.g., anticipatory investment) that better deal with long-term uncertainty? | | |
| A6-3 | How to exploit the value of investment optionality when facing long-term uncertainty? | | |
| A6-4 | What type of decision structure for new assets is the one that strikes the right balance between investment flexibility and additional information needed from transmission owners? | | |
| A6-5 | How to model the risk for not delivering investment options on time? | | |
| A6-6 | How to deal with the discrepancy between asset lifetime and planning time horizon? | | A7 |
| A6-7 | In the context of the definition of investment options, is it better to define the characteristics of the reinforcement a priori or let the transmission owners propose options based on given requirements? | | A7 |

## Area 7: Decision-making methodology

| ID | Question | G-PST topic | SA |
|---|---|---|---|
| A7-1<br>**(GQ.40)** | In the context of increasing electrification and growing IBR and DER penetrations, what additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments? | | A5 |
| A7-2<br>**(GQ.48)** | What changes can be incorporated into the transmission planning process to accommodate new drivers of uncertainty in electricity demand (e.g., large load growth due to electrification or low net load growth due to increased use of DER)? How should the component of flexible demand be modelled in planning studies, particularly looking at it from the uncertainty lens? | | A2 |
| A7-3 | In the context of determining the optimal mix of network and non-network solutions in power system planning, what methodologies and tools are needed for a consistent comparison of these solutions? | | A3 |
| A7-4 | How to model competing objectives and risk appetites of different stakeholders in power system planning? | | A1 |
| A7-5 | How to integrate reliability and resilience assessments into transmission planning in a trackable manner? | | A5 |
| A7-6 | How to include investment optionality into the decision-making framework of power system planning? | | A6 |
| A7-7 | What is the right frequency (for instance biennially like in Australia, or annually like in the UK) to revise investment decisions and analyse new options in power systems? | | |

| ID | Question | G-PST topics | SA |
|---|---|---|---|
| A7-8 | How to perform a comprehensive search of the space of investment options in the context of power system planning? | | |
| A7-9 | How to use investment optionality to efficiently respond to the rapid change of technology mix? | | |
| A7-10 | How to integrate the planning decisions of distribution networks into the decision-making methodology of transmission network planning? | | A3 |
| A7-11 | How to achieve an efficient outcome when planning a system with both market-driven and regulated investments? | | |
| A7-12 | What are the advantages and limitations of decoupling the generation of scenarios from the investment decisions on network reinforcements? | | |
| A7-13 | How to create an optimal portfolio of batteries and hydro-pump storage? | | |

# Appendix B : Research projects

| *Code* | **Projects** | **Linked questions** | **Resource requirement (FTE)** |
|---|---|---|---|
| *R1S1P1* | Methodologies to forecast evolving generation, DER portfolio and demand | *A1-(1(G46),4)*<br>*A2-(1(G47),3,4,5)*<br>*A7-(10(G48))* | 2 |
| *R1S1P2* | Quantifying impact and uncertainty of sector coupling for scenario development (e.g., electrification, hydrogen policies, etc.) | *A1-10* | 2 |
| *R1S1P3* | Modelling long-term uncertainty in power system planning with the consideration of HILP events (adequacy and security) and critical operation conditions | *A1-(13)*<br>*A2-(2,7)*<br>*A5-(8(G49))* | 3 |
| *R1S2P1* | Modelling of climate change for power system planning purposes (different types of events, spatio-temporal representation, probabilities, correlation, etc.) | *A1-(2,7)* | 1 |
| *R1S2P2* | Modelling the impact of extreme (high/low) temperatures on conventional generation, RES output, network components, demand, etc. | *A1-(3,7)* | 2 |
| *R1S2P3* | Modelling of asset failure under extreme weather conditions, fragility curve of individual component, common mode failure and cascading failure characteristics, etc. | *A1-(3,7)* | 2 |
| *R1S3P1* | Impact and interactions between market developments and system planning (e.g., capacity markets) | *A1-(11,12,16, 19,20)* | 4 |
| *R1S3P2* | Impact of carbon pricing and other externalities on planning | *A1-(3,17)*<br>*A4-(5)* | 3 |
| *R2S1P1* | Modelling the steady-state operation of the system considering the trade-off between computational efficiency and model precision (e.g., identifying the right spatio-temporal granularity, technology and market representation, network reduction) | *A3-(13,15,18,21,31)* | 2 |
| *R2S1P2* | Quantifying reactive power requirement and modelling its provision in power system planning (minimum demand) | *A3-(30,31,32)*<br>*A4-(6)* | 2 |
| *R2S1P3* | Quantifying the impact of imperfect competition in the operational and planning decisions of future power systems | *A3-(19)* | 2 |
| *R2S2P1* | Dynamic modelling of new technologies (e.g., storage, electrolyser) and its representation in power system planning | *A3-(11,22,23,27)*<br>*A5-(9(G51))* | 3 |
| *R2S2P2* | Developing models, stability analysis methodologies and test conditions for future power systems under different portfolios of grid-forming and grid-following IBRs | *A3-(11,14,22,23,28)* | 4 |
| *R2S3P1* | Representing steady-state and dynamic security constraints (e.g., voltage, frequency, thermal, system strength) into the steady-state operation model used in power system planning | *A3-(12,16,20,24,26)* | 2 |

| *Code* | **Projects** | **Linked questions** | **Resource requirement (FTE)** |
|---|---|---|---|
| *R2S3P2* | Identifying black start requirements of future power systems and the black start capabilities of new technologies. Modelling black start services in power system planning | *A3-(1(G41.a))*<br>*A5-(4(G41.b))* | 2 |
| *R3S1P1* | Developing new metrics to quantify the benefits to reliability and resilience associated with the investment in new system assets | *A4-(1(G38.a),2(G44.a),4)*<br>*A5-(2(G38.b),20)* | 1 |
| *R3S1P2* | Quantifying the value of differentiated reliability and resilience for different customer groups | *A5-(13)* | 2 |
| *R3S2P1* | Assessing the reliability and resilience of power system considering the impact of climate change and extreme weather conditions (e.g., bushfires, high/low temperature, storms) on its infrastructure/components | *A3-(16)*<br>*A4-(3)*<br>*A5-(15,16,24,3(G39),8(G49))* | 4 |
| *R3S3P1* | Identifying credible and non-credible contingencies, including indistinct events, for different system states (e.g., using machine learning techniques) aiming to reduce the size of planning studies | *A3-(2(G45),25)*<br>*A5-(14,17,27,12)* | 1 |
| *R3S3P2* | Profiling power system risks under various contingencies and indistinct events for future low-carbon grid with high penetration of IBR/DERs | *A3-(2(G45))*<br>*A5-(2(G38.b),12,15,18,19,24,26)* | 2 |
| *R3S3P3* | Modelling the impacts and benefits of other infrastructure and sector coupling (e.g., gas, hydrogen) on power system reliability and resilience | *A3-(10)*<br>*A5-(11)* | 2 |
| *R3S4P1* | Modelling and analysing the impact on planning from IBR (including and in particular batteries) response to credible contingencies and high impact low probability (HILP) events | *A3-(2(G45),17)*<br>*A5-(3(G39),5(G42),7(G44.b),10, 20)* | 4 |
| *R3S4P2* | Modelling and analysing the impact on planning from DERs (including DER aggregations as microgrids, VPPs, etc.) and distribution network assets response to credible contingencies and high impact low probability (HILP) events | *A3-(9,2(G45),17)*<br>*A5-(5(G42),7(G44.b),9,11)* | 2 |
| *R4S1P1* | Modelling competing objectives, sources of risk (e.g., project construction delays), and risk appetite of different stakeholders (e.g., system operators, transmission owners) in power system planning. Determination of metrics to value cost and risk. | *A5-(25)*<br>*A6-(5)*<br>*A7-(4)* | 4 |
| *R4S1P2* | Developing a consistent decision-making framework to coordinate market-driven (e.g., generation) and regulated (e.g., transmission) investments while considering reliability | *A5-(21)*<br>*A6-(7)*<br>*A7-(3,7,8,11,12)* | 2 |
| *R4S1P3* | Designing the optimal schemes (e.g., mandatory, market-incentivized, hybrid) for services provision to maintain system reliability and resilience | *A5-(7(G44.b))* | 2 |

| *Code* | **Projects** | **Linked questions** | **Resource requirement (FTE)** |
|---|---|---|---|
| *R4S2P1* | Methodologies and tools to integrate reliability (security and adequacy) and resilience assessments into the decision-making process with tractability considerations and a process-oriented structure | A1-(14)<br>A5-(1(G37),2(G38.b),3(G39), 4(G41.b),5(G42), 6(G43),22)<br>A7-(5) | 4 |
| *R4S2P2* | Modelling investment flexibility in power system planning decision making by enhancing the decision structure (e.g., real options) and the representation of scenario trees to deal with deep uncertainties (e.g., rapid technology change) | *A2-(6)*<br>*A5-(1(G37))*<br>*A6-(2,3,4,6)*<br>*A7-(6,9)* | 2 |
| *R4S2P3* | Methodologies and tools to incorporate the assessment of non-network solutions value streams in the network expansion problem aiming to capture flexibility through capital-intensive investment deferral | *A1-(15)*<br>*A5-(9(G51),23)*<br>*A6-(1)*<br>*A7-(3,13)* | 1 |
| *R4S3P1* | Modelling investment decisions (including demand response) at distribution network level and determining the methodologies to integrate them in power system planning | *A6-(1)*<br>*A7-(1(G40),10)* | 1 |
| *R5S1P1* | Modelling the impact and flexibility embedded in the interactions between power systems and other energy systems (e.g., gas, hydrogen) for planning studies | *A2-(1(G47))*<br>*A3-(6,7)*<br>*A7-(1(G40),2(G48))* | 3 |
| *R5S2P1* | Identifying the sources and availability of demand side flexibility, quantifying its aggregated profile, and determining its representation as an investment option in power system planning | *A1-(21)*<br>*A3-(6,8)*<br>*A7-(1(G40),2(G48))* | 2 |
| *R5S2P2* | Modelling distributed energy systems (e.g., DERs, VPPs) operation and determining data requirement to represent their operation (considering short-term uncertainty) for planning studies | *A1-(1(G46))*<br>*A3-(3(G50),4,5,8)*<br>*A5-(1(G37))*<br>*A7-(4(G40),10)* | 1 |
| *R5S2P3* | Developing equivalent model to represent the aggregated dynamic behaviour of distributed IBRs for planning studies | *A3-(3(G50))*<br>*A5-(1(G37))*<br>*A7-(10)* | 3 |
| *R5S3P1* | Modelling the impact of high DERs penetration on power system planning | *A3-(9)*<br>*A5-(12,14,23)*<br>*A7-(1(G40),2(G48))* | 2 |
| *R5S3P2* | Modelling and analysing the contribution of DERs to system reliability (security and adequacy) and resilience | *A1-(1(G46),21)*<br>*A3-(5,10,27)*<br>*A5-(11)* | 3 |

# Appendix C : Research streams explanation and projects

1. Research programme 1 “*long-term uncertainty*”
   1.1. **Scenario development for planning studies**

   This stream covers the development of scenarios that may significantly impact the planning output, including evolving generation and DERs portfolio and demand, HILP events and critical operation conditions representation, and the uncertainty created sector coupling.

      - Methodologies to forecast evolving generation, DERs portfolio and demand
      - Quantifying impact and uncertainty of sector coupling for scenario development (e.g., electrification, hydrogen policies, etc.)
      - Modelling long-term uncertainty in power system planning with the consideration of HILP events (adequacy and security) and critical operation conditions

   1.2. **Climate change impact on individual power system components performance**

   This stream aims at assessing the risk that climate change presents to critical power system infrastructures (fragility and capacity) so that the impacts of climate change on power systems can be assessed and, where practicable, mitigated.

      - Modelling of climate change for power system planning purposes (different types of events, spatio-temporal representation, probabilities, correlation, etc.)
      - Modelling the impact of extreme (high/low) temperatures on conventional generation, RES output, network components, demand, etc.
      - Modelling of asset failure under extreme weather conditions, fragility curve of individual components, common-mode failure and cascading failure characteristics, etc.

   1.3. **Uncertainty in policy and market developments**

   This stream quantifies the impact and interactions between market developments and system planning (e.g., capacity markets), with consideration of the impact of various externalities in planning.

      - Impact and interactions between market developments and system planning (e.g., capacity markets)
      - Impact of carbon pricing and other externalities on planning

2. Research programme 2 “**Power system operation**”
   2.1. **Steady-state operation modelling**

   This stream focuses on those research questions aiming to improve the steady-state operation models used in the context of power system planning. This involves streamlining the steady-state models to make them as computationally efficient as possible, while also representing all the binding constraints to guarantee a feasible outcome. Some topics included within this stream includes the consideration of reactive power, imperfect competition and back start capabilities in the models representing the future power system.

      - Modelling the steady-state operation of the system considering the trade-offs between computational efficiency and model precision (e.g., identifying the right spatio-temporal granularity, technology and market representation, network reduction)
      - Quantifying reactive power requirement and modelling its provision under different operation conditions (e.g., minimum demand) in power system planning
      - Quantifying the impact of imperfect competition in the operational and planning decisions of future power systems

2.2. **System dynamics modelling for planning purposes**

Power system dynamics modelling represents a rich area of study in the context of the future power system. In particular, the elements of power system dynamics that are of special interest for planning purposes include the dynamic modelling of new technologies and how to efficiently include them in planning studies and the definition and development of tools capable to address the study of transient behaviour of the system under high penetration of inverter-based technologies.

- Dynamic modelling of new technologies (e.g., storage, electrolyser) and its representation in power system planning
- Developing models, stability analysis methodologies and test conditions for future power systems under different portfolios of grid-forming and grid-following IBRs

2.3. **Security constraints formulation**

The objective behind this research stream is to translate the transient behaviour of the system into operating envelopes that can be used in the context of the steady-state operation models to guarantee that the dispatch of the system is not only optimal from an economic point of view but also feasible from a technical perspective.

- Representing steady-state and dynamic security constraints (e.g., voltage, frequency, thermal, system strength) into the steady-state operation model used in power system planning
- Identifying black start requirements of future power systems and the black start capabilities of new technologies. Modelling black start services in power system planning

3. Research programme 3 "**Reliability (security and adequacy) and resilience**"

3.1. **Reliability and resilience metrics**

This stream covers the definition and design of metrics to assess techno-economic performance in power system planning under uncertainty.

- Developing new metrics to quantify the benefits to reliability and resilience associated with the investment in new system assets
- Quantifying the value of differentiated reliability and resilience for different customer groups

3.2. **System-level impact of climate change**

In this stream, research targets the assessment of the reliability and resilience of power systems considering the impact of climate change and extreme weather conditions (e.g., bushfires, high temperature, storms) on its infrastructure/components.

- Assessing the reliability and resilience of power system considering the impact of climate change and extreme weather conditions (e.g., bushfires, high/low temperature, storms) on its infrastructure/components

3.3. **Credible and non-credible contingencies**

This stream identifies and analyses relevant contingencies and indistinct events under different system states and quantifies their impact on system reliability and resilience, considering high-RES penetration level and increasing sector coupling in future power system.

- Identifying credible and non-credible contingencies, including indistinct events, for different system states (e.g., using machine learning techniques) aiming to reduce the size of planning studies

    - Profiling power system risks under various contingencies and indistinct events for future low-carbon grid with high penetration of IBR/DERs
    - Modelling the impacts and benefits of other infrastructure and sector coupling (e.g., gas, hydrogen) on power system reliability and resilience

3.4. **Characteristics on DER/IBR response to different events**

Modelling the DER/IBR response strategies during HILP events, credible/non-credible contingencies and indistinct events and analysing the benefits and limitations of different DER/IBR response strategies.

- Modelling and analysing the impact on planning from IBR (including and in particular batteries) response to credible contingencies and high impact low probability (HILP) events
- Modelling and analysing the impact on planning from DERs (including DERs aggregations as microgrids, VPPs, etc.) and distribution network assets response to credible contingencies and high impact low probability (HILP) events
- Modelling competing objectives, sources of risk (e.g., project construction delays), and risk appetite of different stakeholders (e.g., system operators, transmission owners) in power system planning. Determination of metrics to value cost and risk.

**4.** Research programme 4 "**Decision making**"

4.1. **Metrics, objectives and risk modelling of different stakeholders**

Integrating market-driven and regulated investment decisions in a consistent decision framework lies at the core of this research stream. This includes the description of competing objectives, sources of risk and risk appetites of different stakeholders when planning the system.

- Modelling competing objectives, sources of risk (e.g., project construction delays), and risk appetite of different stakeholders (e.g., system operators, transmission owners) in power system planning. Determination of metrics to value cost and risk.
- Developing a consistent decision-making framework to coordinate market-driven (e.g., generation) and regulated (e.g., transmission) investments while considering reliability
- Designing the optimal schemes (e.g., mandatory, market-incentivized, hybrid) for services provision to maintain system reliability and resilience "

4.2. **Methodologies for decision-making under uncertainty**

This stream is chiefly concerned with the structure of an ad-hoc decision-making methodology capable to coordinate all needed techno-economic analyses in an accurate and tractable structure that can be solved by a team of people in a reasonable period of time. This includes the capacity to make complex decisions on network and non-network assets and integrate reliability and resilience analysis in the decision-making process.

- Methodologies and tools to integrate reliability (security and adequacy) and resilience assessments into the decision-making process with tractability considerations and a process-oriented structure
- Modelling investment flexibility in power system planning decision making by enhancing the decision structure (e.g., real options) and the representation of scenario trees to deal with deep uncertainties (e.g., rapid technology change)

        - Methodologies and tools to incorporate the assessment of non-network solutions value streams in the network expansion problem aiming to capture flexibility through capital-intensive investment deferral

    4.3. **Interdependence of power system planning (transmission, distribution, generation)**

    This research stream focuses on determining the value of modelling investment decisions at distribution level and, if this proves possible and efficient, integrating those decisions on a single decision-making framework for the whole system.

        - Modelling investment decisions (including demand response) at distribution network level and determining the methodologies to integrate them in power system planning

5. Research programme 5: “**Distributed energy systems**”

    5.1. **Multi-energy systems and electrification**

    This stream explores the modelling of flexibility embedded in the interactions between power systems and other energy systems (i.e., gas and hydrogen), and consequently using such flexibility for grid support services and represented in power system planning.

        - Modelling the impact and flexibility embedded in the interactions between power systems and other energy systems (e.g., gas, hydrogen) for planning studies

    5.2. **Distributed energy markets and demand-side flexibility**

    The research in this stream is aimed at identifying the data required to capture the aggregated behaviour of distributed energy systems so that models can be developed to quantify demand-side flexibility and the utilisation of such flexibility for different ancillary services in the context of power system planning.

        - Identifying the sources and availability of demand-side flexibility, quantifying its aggregated profile, and determining its representation as an investment option in power system planning
        - Modelling distributed energy systems (e.g., DERs, VPPs) operation and determining data requirements to represent their operation (considering short-term uncertainty) for planning studies
        - Developing equivalent model to represent the aggregated dynamic behaviour of distributed IBRs for planning studies

    5.3. **Distributed energy resources impact on power system planning**

    This stream focuses on evaluating the response behaviour of DERs and IBRs when facing system contingencies and extreme events, and additionally how DERs can contribute to system reliability and resilience.

        - Modelling the impact of high DERs penetration on power system planning
        - Modelling and analysing the contribution of DERs to system reliability (security and adequacy) and resilience

# Appendix D : Research streams and projects interaction

*Table 8. Stream interactions in research programme 1*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R1S1 | R1S2 | R1S3 |
| **Output** | R1S1 | | ● | ● |
| | R1S2 | | | |
| | R1S3 | | | |

*Table 9.Project interactions in stream "Scenario development for planning studies"*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R1S1P1 | R1S1P2 | R1S1P3 |
| **Output** | R1S1P1 | | | |
| | R1S1P2 | ● | | ● |
| | R1S1P3 | | | |

*Table 10.Project interactions in stream "Climate change impact on individual power system components performance"*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R1S2P1 | R1S2P2 | R1S2P3 |
| **Output** | R1S2P1 | | ● | ● |
| | R1S2P2 | | | |
| | R1S2P3 | | | |

*Table 11.Project interactions in stream "Uncertainty in policy and market developments"*

| | Interactions | **Input** | |
|---|---|---|---|
| | | R1S3P1 | R1S3P2 |
| **Output** | R1S3P1 | | |
| | R1S3P2 | ● | |

*Table 12. Stream interactions in research programme 2*

| | Interactions | ***Input*** | | |
|---|---|---|---|---|
| | | *R2S1* | *R2S2* | *R2S3* |
| ***Output*** | *R2S1* | | | ● |
| | *R2S2* | | | ● |
| | *R2S3* | ● | | |

*Table 13. Project Interactions in Stream "Steady State Operation Modelling"*

| | Interactions | ***Input*** | | |
|---|---|---|---|---|
| | | *R2S1P1* | *R2S1P2* | *R2S1P3* |
| ***Output*** | *R2S1P1* | | | |
| | *R2S1P2* | ● | | |
| | *R2S1P3* | ● | | |

*Table 14. Project Interactions in Stream "System dynamics modelling for planning purposes"*

| | Interactions | ***Input*** | |
|---|---|---|---|
| | | *R2S2P1* | *R2S2P2* |
| ***Output*** | *R2S2P1* | ● | |
| | *R2S2P2* | | |

*Table 15. Project Interactions in Stream "Security constraints formulation"*

| | Interactions | ***Input*** | |
|---|---|---|---|
| | | *R2S3P1* | *R2S3P2* |
| ***Output*** | *R2S3P1* | | |
| | *R2S3P2* | ● | |

*Table 16. Stream Interactions in Research Program 3*

| | Interactions | **Input** | | | |
|---|---|---|---|---|---|
| | | R3S1 | R3S2 | R3S3 | R3S4 |
| **Output** | R3S1 | | | ● | ● |
| | R3S2 | | | ● | ● |
| | R3S3 | | | | ● |
| | R3S4 | | | | |

*Table 17. Project interactions in stream "Reliability and resilience metrics"*

| | Interactions | **Input** | |
|---|---|---|---|
| | | R3S1P1 | R3S1P2 |
| **Output** | R3S1P1 | | ● |
| | R3S1P2 | | |

*Table 18. Project interactions in stream "Credible and non-credible contingencies"*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R3S3P1 | R3S3P2 | R3S3P3 |
| **Output** | R3S3P1 | | ● | |
| | R3S3P2 | | | |
| | R3S3P3 | ● | ● | |

*Table 19. Project interactions in stream " Characteristics on DER/IBR response to different events"*

| | Interactions | **Input** | |
|---|---|---|---|
| | | R3S4P1 | R3S4P2 |
| **Output** | R3S4P1 | | |
| | R3S4P2 | ● | |

*Table 20 Stream interactions in research program 4*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R4S1 | R4S2 | R4S3 |
| **Output** | R4S1 | | ● | |
| | R4S2 | | | |
| | R4S3 | | ● | |

*Table 21. Project interactions in stream " Metrics, objectives, and risk modelling of different stakeholders "*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R4S1P1 | R4S1P2 | R4S1P3 |
| **Output** | R4S1P1 | | ● | ● |
| | R4S1P2 | | | |
| | R4S1P3 | | ● | |

*Table 22. Project interactions in stream " Methodologies for decision-making under uncertainty"*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R4S2P1 | R4S2P2 | R4S2P3 |
| **Output** | R4S2P1 | | ● | ● |
| | R4S2P2 | | | ● |
| | R4S2P3 | | | |

*Table 23. Stream interactions in research program 5*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R5S1 | R5S2 | R5S3 |
| **Output** | R5S1 | | ● | ● |
| | R5S2 | | | ● |
| | R5S3 | | | |

*Table 24. Research project interactions in stream " Distributed energy markets and demand side flexibility "*

| | Interactions | **Input** | | |
|---|---|---|---|---|
| | | R5S2P1 | R5S2P2 | R5S2P3 |
| **Output** | R5S2P1 | | | ● |
| | R5S2P2 | | | ● |
| | R5S2P3 | | | |

*Table 25. Research project interactions in stream " DER impact on planning "*

| | Interactions | **Input** | |
|---|---|---|---|
| | | R5S3P1 | R5S3P2 |
| **Output** | R5S3P1 | | |
| | R5S3P2 | ● | |

# Appendix E : Planning research program questions [48]

37. What additional probabilistic planning methods and tools are necessary for planning a power system with a high share of IBRs and in particular, variable renewable energy resources?

38. What studies and metrics are required to identify long term scarcity of capacity to maintain reliability?

39. What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables?

40. What additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments in a paradigm of increasing electrification and growing IBR and DER penetrations?

41. How should sufficient black-start capability and the performance and integrity of the protection system be modelled in long term reliability studies?

42. What features need to be added to long-term planning methods and studies to consider other reliability services in addition to traditional resource adequacy and deliverability?

43. How can system security be balanced against lower costs for operation and investment?

44. What studies and metrics are required to evaluate resource adequacy with hybrid plants (e.g. PV-plus-storage) and virtual power plants?

45. How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high renewable energy future (wind, solar, demand side flexibility)?

46. What mechanisms are necessary to accurately model and account for DER in planning exercises to ensure a reliable power system is being planned? What data is necessary to accurately model various levels/paradigms of DER control, including influence on under frequency load shedding schemes?

47. What additional load and resource forecasting models are necessary to account for electrification of the transportation and building sectors?

48. What changes can be incorporated into the transmission planning process to accommodate new drivers of uncertainty in electricity demand (e.g., large growth due to electrification or low growth due to increased use of DER)?

49. What additional planning models and methods are needed to plan for a system that can withstand expected or unexpected lulls in the weather driving much of the resource mix, e.g. an extended wind drought?

50. What are appropriate aggregate DER models and methods for inclusion in transmission-level modelling?

51. What models and methods are necessary to quantify the need and requirements for long duration energy storage?

# Appendix F : Research impact potentials, delivery dates and stakeholder engagement of different research streams

*Table 26. Research impact potentials, delivery dates of research streams under programmes 1 and 2*

| ***Programme*** | **Stream** | **CAPEX** | **OPEX** | **Reliability** | **Resilience** | **Highly useful from** | **Loss of relevance** |
|---|---|---|---|---|---|---|---|
| *Long-term uncertainty* | Scenario development for planning studies | >10% | 1-5% | >60% | >60% | 2025 | 2033 |
| | Climate change impact on individual power system components performance | 1-5% | 1-5% | 20-60% | >60% | 2025 | 2029 |
| | Uncertainty in policy and market developments | >10% | >10% | <20% | <20% | 2025 | 2033 |
| *Power system operation* | Steady-state operation modelling | 1-5% | 1-5% | >60% | >60% | 2025 | 2033 |
| | System dynamics modelling for planning purposes | 1-5% | 1-5% | <20% | 20-60% | 2025 | 2033 |
| | Security constraints formulation | <1% | <1% | >60% | >60% | 2025 | 2029 |

*Table 27. Research impact potentials, delivery dates of research streams under programmes 3, 4 and 5*

| *Programme* | Stream | CAPEX | OPEX | Reliability | Resilience | Highly useful from | Loss of relevance |
|---|---|---|---|---|---|---|---|
| *Reliability (security and adequacy) and resilience* | Reliability and resilience metrics | >10% | 1-5% | >60% | >60% | 2025 | 2033 |
| | System level impact of climate change | 1-5% | 1-5% | <20% | <20% | 2025 | 2033 |
| | Credible and non-credible contingencies | <1% | 1-5% | 20-60% | >60% | 2025 | 2029 |
| | Characteristics on DER/IBR response to different events | 1-5% | 1-5% | <20% | 20-60% | 2029 | 2033 |
| *Decision making* | Metrics, objectives and risk modelling of different stakeholders | >10% | 1-5% | <20% | 20-60% | 2029 | 2033 |
| | Methodologies for decision-making under uncertainty | 1-5% | 1-5% | 20-60% | 20-60% | 2029 | 2033 |
| | Interdependence of power system planning (transmission, distribution, generation) | >10% | 1-5% | <20% | 20-60% | 2025 | 2029 |
| *Distributed energy systems* | Multi-energy systems and electrification | >10% | 5-10% | <20% | <20% | 2029 | 2033 |
| | Distributed energy markets and demand side flexibility | 1-5% | 5-10% | <20% | 20-60% | 2029 | 2033 |
| | DER impact on planning | 1-5% | 5-10% | <20% | 20-60% | 2029 | 2033 |

*Table 28. Stakeholder engagement of research streams under programmes 1 and 2*

| ***Programme*** | **Stream** | **System operator (SO)** | **Transmission network service provider (TNSP)** | **Distribution network service provider (DNSP)** | **Regulator** | **Generation company (GenCo)** |
|---|---|---|---|---|---|---|
| *Long-term uncertainty* | Scenario development for planning studies | • | | | • | |
| | Climate change impact on individual power system components performance | • | • | | • | • |
| | Uncertainty in policy and market developments | • | | | • | |
| *Power system operation* | Steady-state operation modelling | • | | | | |
| | System dynamics modelling for planning purposes | • | • | | | • |
| | Security constraints formulation | • | | | • | |
| *Reliability (security and adequacy) and resilience* | Reliability and resilience metrics | • | | | | |
| | System level impact of climate change | • | | | • | |
| | Credible and non-credible contingencies | • | | | • | |
| | Characteristics on DER/IBR response to different events | • | | • | | |

*Table 29. Stakeholder engagement of research streams under programmes 3, 4 and 5*

| ***Programme*** | **Stream** | **System operator (SO)** | **Transmission network service provider (TNSP)** | **Distribution network service provider (DNSP)** | **Regulator** | **Generation company (GenCo)** |
|---|---|---|---|---|---|---|
| *Decision making* | Metrics, objectives and risk modelling of different stakeholders | • | | | • | |
| | Methodologies for decision-making under uncertainty | • | | | • | |
| | Interdependence of power system planning (transmission, distribution, generation) | • | • | • | | • |
| *Distributed energy systems* | Multi-energy systems and electrification | • | | • | | |
| | Distributed energy markets and demand side flexibility | • | | • | | |
| | DER impact on planning | • | | • | | |

# Appendix G : Australian research capability

| ***Programme*** | **Stream** | **Research capability** |
|---|---|---|
| *Long-term uncertainty* | Scenario development for planning studies | Leading |
| | Climate change impact on individual power system components performance | Leading |
| | Uncertainty in policy and market developments | Parity |
| *Power system operation* | Steady-state operation modelling | Parity |
| | System dynamics modelling for planning purposes | Parity |
| | Security constraints formulation | Parity |
| *Reliability (security and adequacy) and resilience* | Reliability and resilience metrics | Parity |
| | System level impact of climate change | Parity |
| | Credible and non-credible contingencies | Leading |
| | Characteristics on DER/IBR response to different events | Parity |
| *Decision making* | Metrics, objectives and risk modelling of different stakeholders | Parity |
| | Methodologies for decision-making under uncertainty | Parity |
| | Interdependence of power system planning (transmission, distribution, generation) | Parity |
| *Distributed energy systems* | Multi-energy systems and electrification | Parity |
| | Distributed energy markets and demand side flexibility | Leading |
| | Distributed energy resources impact on planning | Parity |