Investment Planning Under Uncertainty

Lessons from the Australian Energy System

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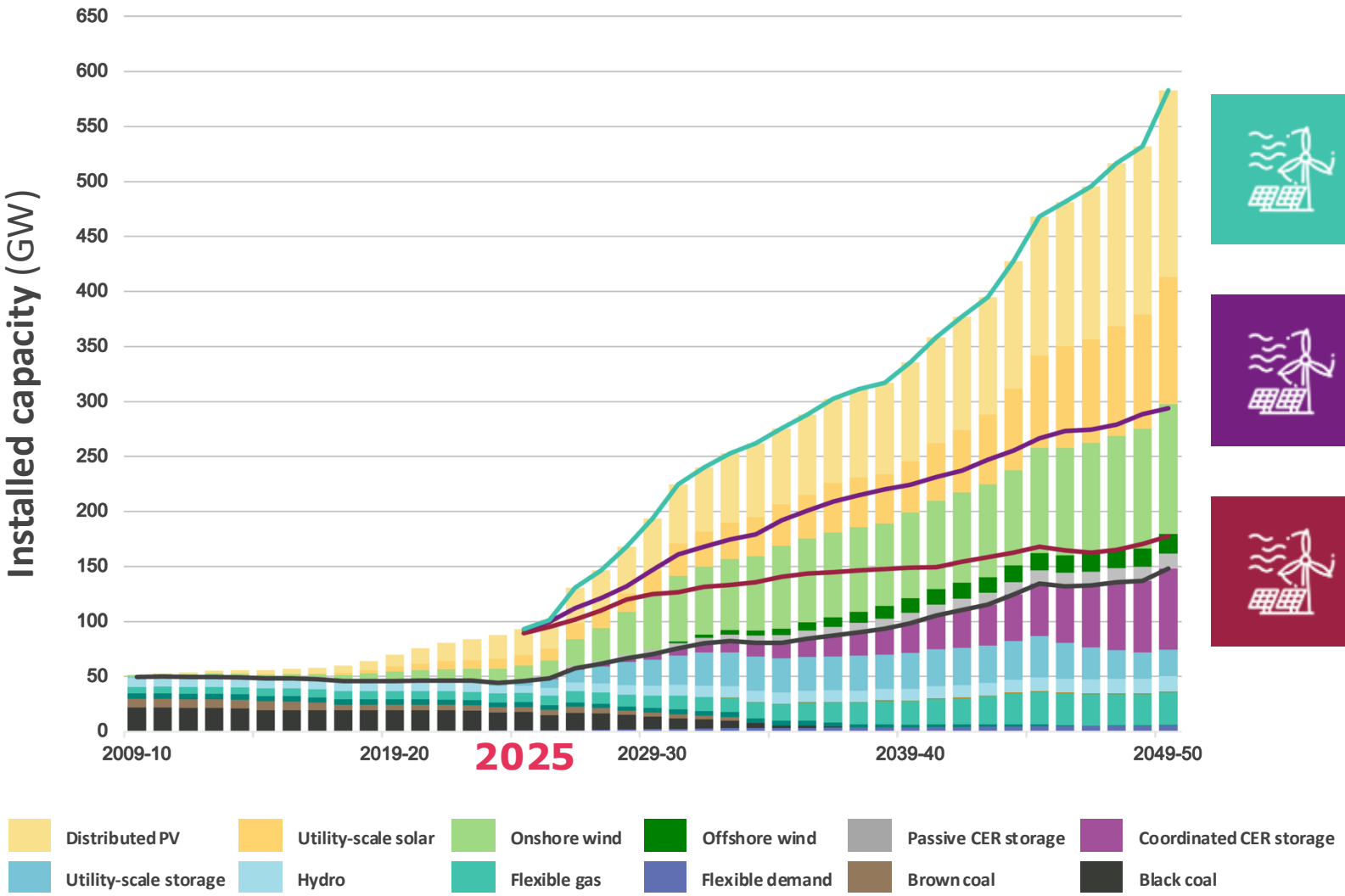
EPICS Centre International Workshop, Newcastle, Australia

January 2026

Planning future low-carbon energy systems

Expected installed capacity - *Australian east-coast electricity system*



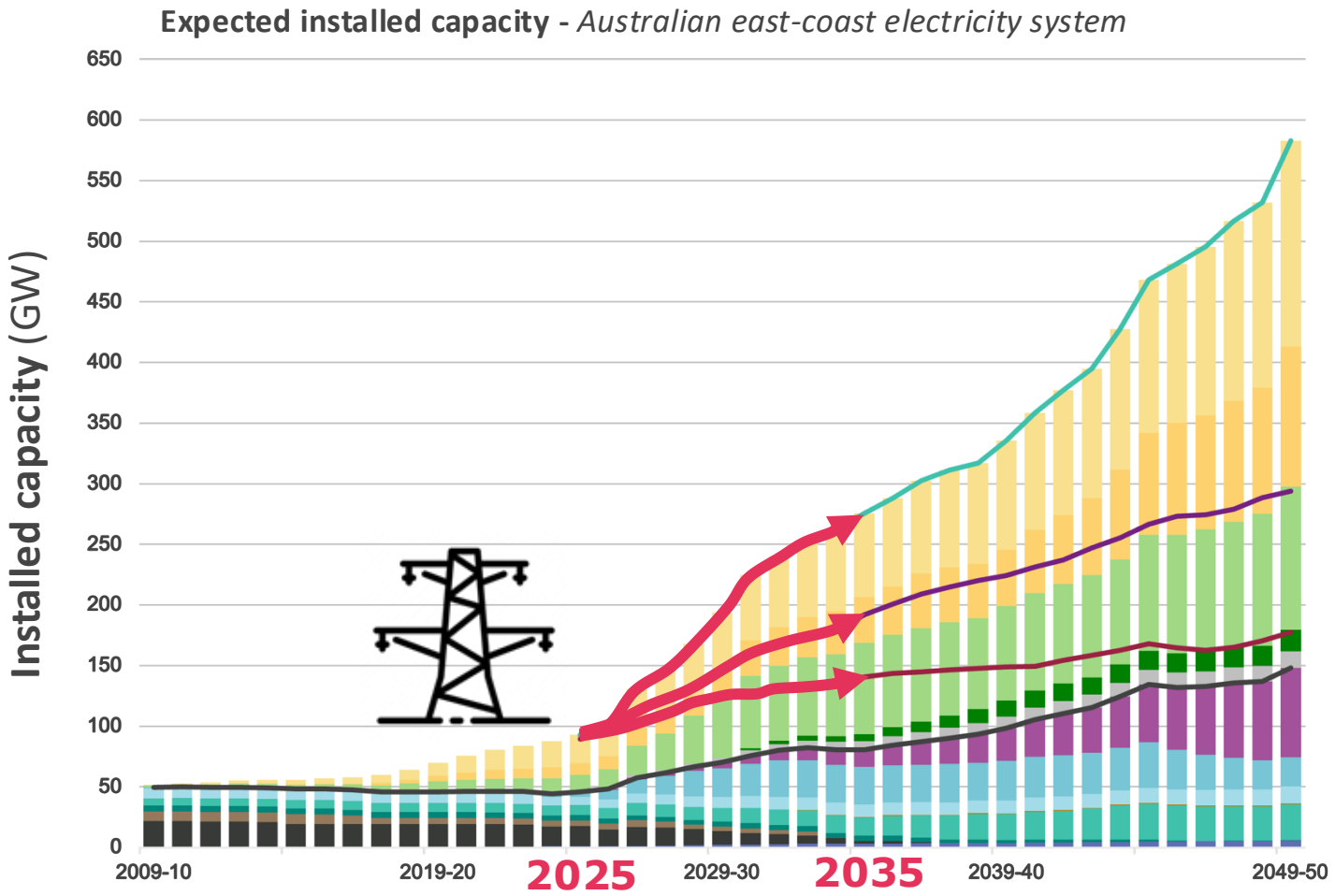
System pathway #3
Green energy exports

System pathway #2
Step change

System pathway #1
Progressive change

Source: Australian Energy Market Operator (AEMO), 2024 Integrated System Plan

Planning future low-carbon energy systems



System pathway #3
Green energy exports

System pathway #2
Step change

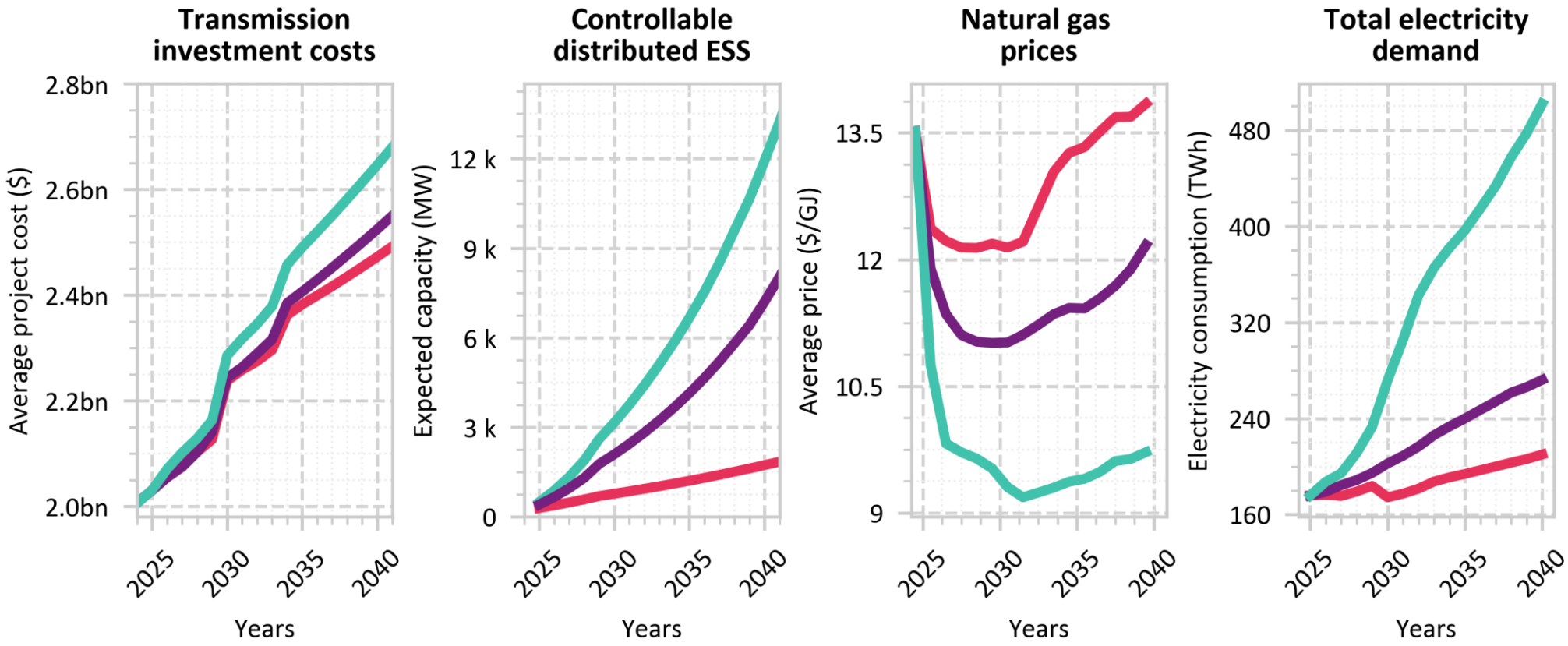
System pathway #1
Progressive change

Long-term **uncertainty** is inevitable, but **investment decisions** cannot be postponed

Source: Australian Energy Market Operator (AEMO), 2024 Integrated System Plan

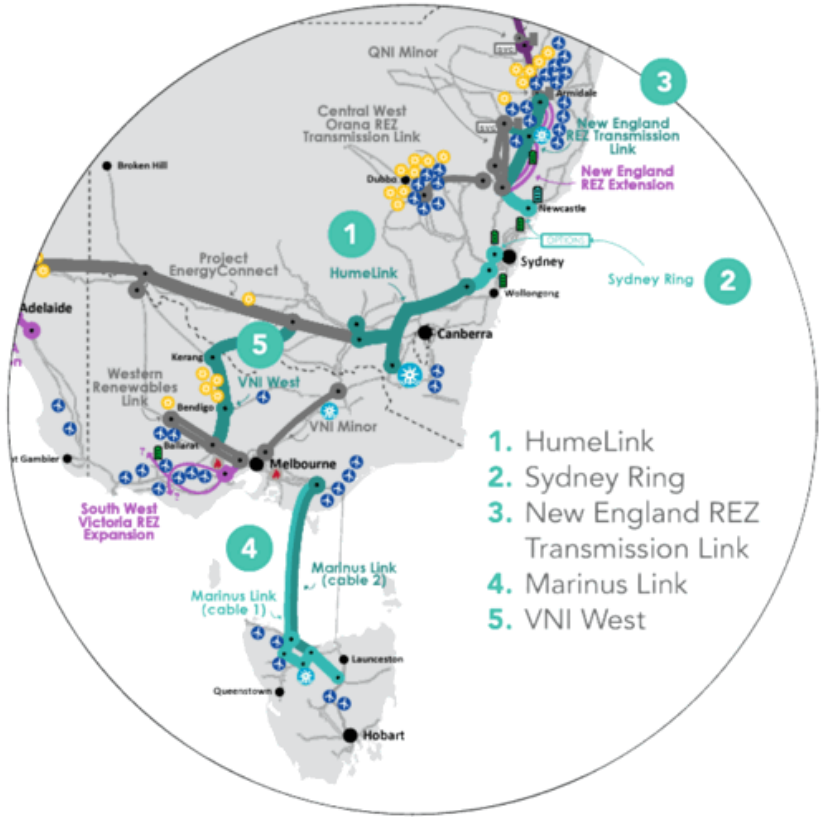
Infrastructure planning under multi-dimensional uncertainties

What future do we plan for?



Source: Australian Energy Market Operator (AEMO), Integrated System Plan (ISP)

Infrastructure planning under multi-dimensional uncertainties



Long-term uncertainty
Technical and economic uncertainties

Uncertainty across systems and networks
Un

→ *Planning risks!*

U
Climate-induced and ELR-driven uncertainties

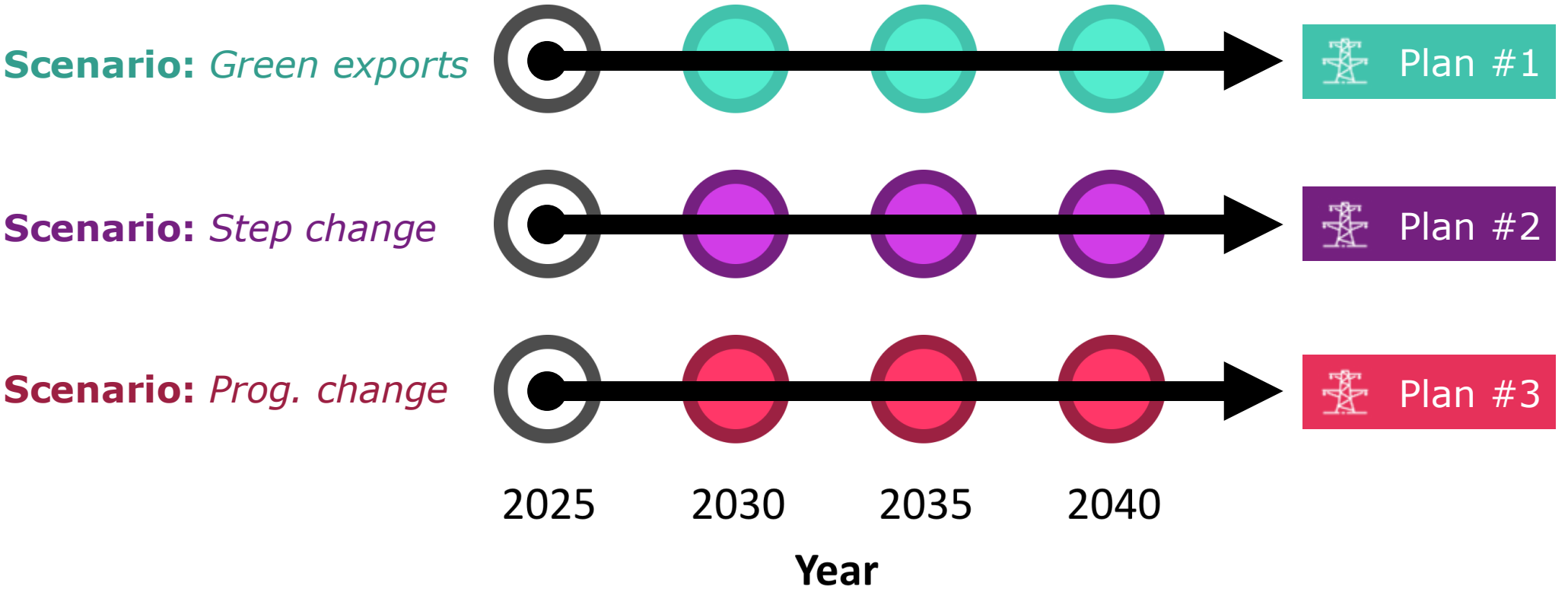
Greater computational complexity
Bigger and more complex planning models

How can we support decision-makers in **de-risking investment plans** against an **uncertain** future?

ELR: Energy-limited resources

Addressing uncertainty in infrastructure planning

Standard (deterministic) planning practices



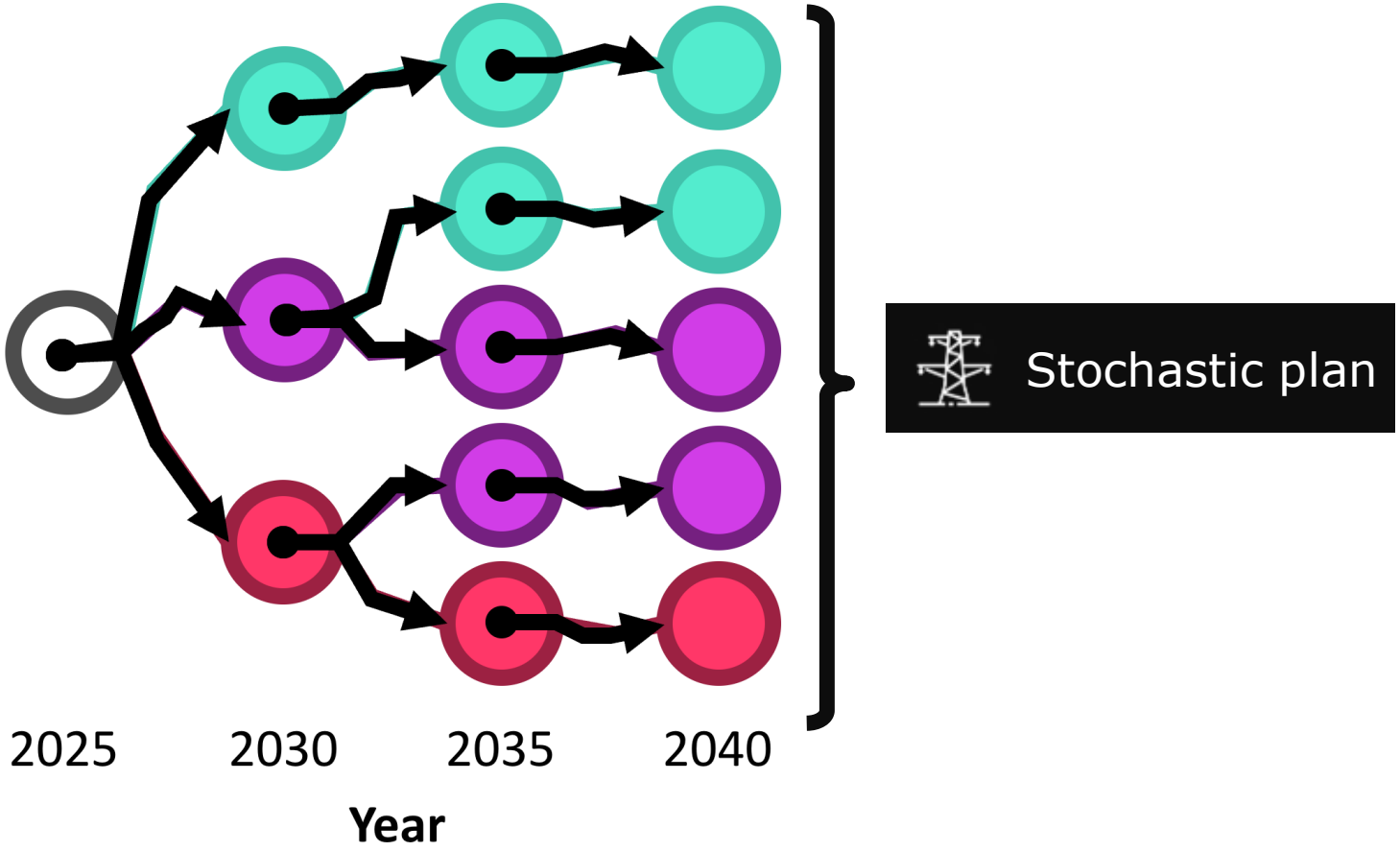
Investment plans are made assuming **the future is perfectly known**

Are we sure that a plan will work if the scenario **does not materialises?**

R. M
smart grid technologies, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 375, no. 2100, Aug. 2017, doi: 10.1
B. M
systems, *Electric Power Systems Research*, vol. 212, Nov. 2022, doi: 10.1016/j.epsr.2022.108470.

Addressing uncertainty in infrastructure planning

The stochastic planning approach

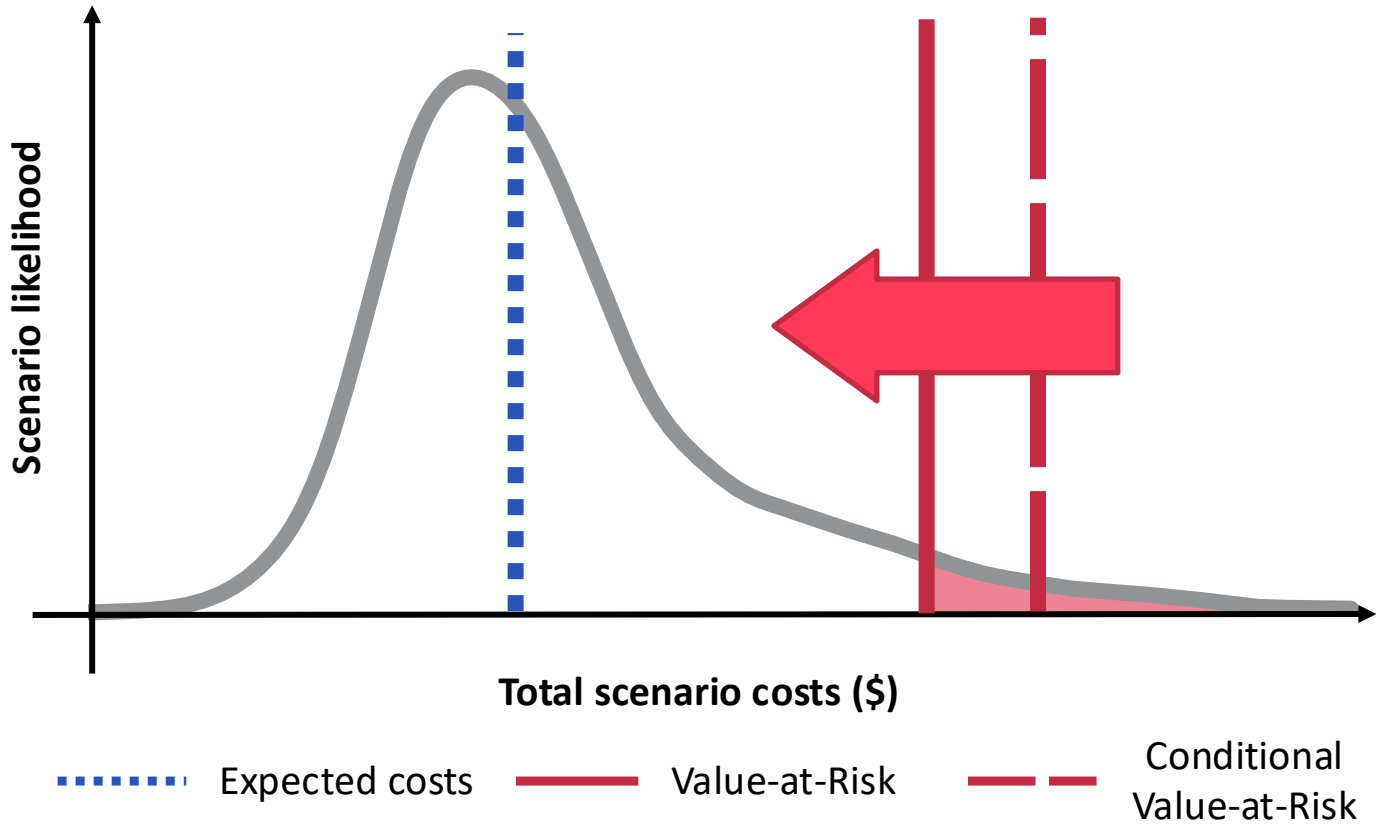


We can develop an *adaptive* plan that is **robust** across scenarios

R. More ***nd*** ***smart g*** doi: 10.1098

B. Moya, R. Moreno, S. Püschel-Løvengreen, A. M. Costa, and P. Mancarella, ***"Uncertainty representation in investment planning of low-carbon power systems,"*** *Electric Power Systems Research*, vol. 212, Nov. 2022, doi: 10.1016/j.epsr.2022.108470.

Incorporating "*Risk management*" in energy system planning



It is possible to allow *investors* and *planners* manage their **risk** appetites!

S. Püschel-Løvengree… …GRE Science and *Engineering*, vol. 31,

P. Apablaza, S. Püsch… ***…nd risk-aware low-carbon power syste…*** …0.

Uncertainty-aware system planning

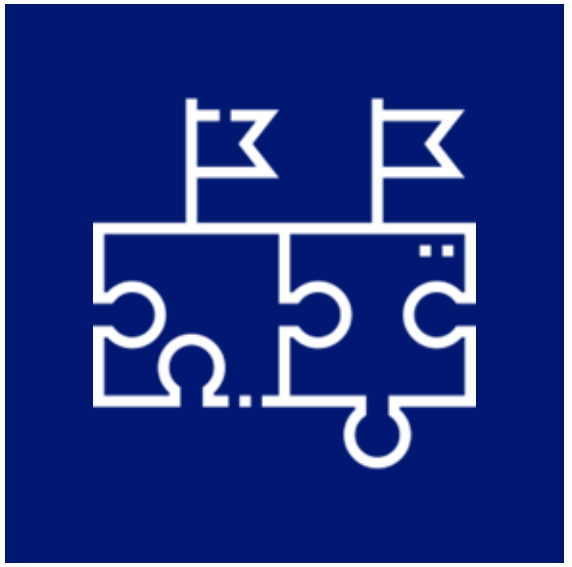
Stochastic planning methodology

Scenario-tree-based Stochastic plan

Ensures investment feasibility across all scenarios

Operation & investment techno-economic model

Accounts for the system physics, reliability, investment and running costs



Scalable solution strategy

Makes the large-scale model tractable, unlocking unique insights

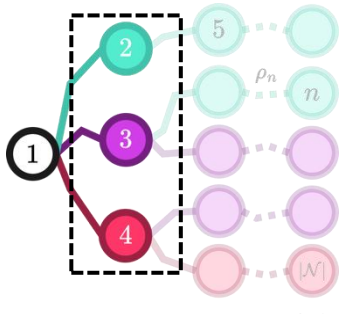
P. Apablaza, S. Püschel-Løvengreen, R. Moreno, S. Mhanna, and P. Mancarella, ***"Assessing the impact of DER on the expansion of low-carbon power systems under deep uncertainty,"*** *Electric Power Systems Research*, vol. 235, p. 110824, Oct. 2024, doi: 10.1016/j.epsr.2024.110824.

P. Apablaza, S. Püschel-Løvengreen, R. Moreno, and P. Mancarella, ***"Valuing distributed energy resources flexibility in an uncertain and risk-aware low-carbon power system planning context,"*** *Sustainable Energy, Grids and Networks*, vol. 43, Sep. 2025, doi: 10.1016/j.segan.2025.101850.

Uncertainty-aware system planning

Scalable solution strategy for multi-stage problems

Dantzig-Wolfe decomposition



Column generation & sharing

$\{\boldsymbol{\pi}_n, \boldsymbol{\mu}_n\}$ Dual "*prices*"
Quality of the column

Master problem

"Orchestrator"

$$\min_{\boldsymbol{X}^{\text{inv}},\lambda} \sum_{n\in\mathcal{N}} \rho_n \left(\boldsymbol{c}_n^{\text{inv}} \boldsymbol{X}_n^{\text{inv}} + \sum_{j\in\mathcal{K}_n} \lambda_{n,j} \boldsymbol{c}_n^{\text{op}} \widehat{\boldsymbol{X}}_{n,j}^{\text{op}} \right)$$

Investment chronology	$\sum_{j\in\mathcal{K}_n} \lambda_{n,j} \widehat{\boldsymbol{Z}}_{n,j} \le \sum_{h\in\mathcal{P}_n} \boldsymbol{X}_h^{\text{inv}} \quad [\boldsymbol{\pi}_n]$
Convex combination	$\sum_{j\in\mathcal{K}_n} \lambda_{n,j} = 1; \lambda_{n,j} \in \{0,1\} \quad [\boldsymbol{\mu}_n]$
Investment integrality	$\boldsymbol{X}_n^{\text{inv}} \in \mathbb{Z}^+$

Subproblem

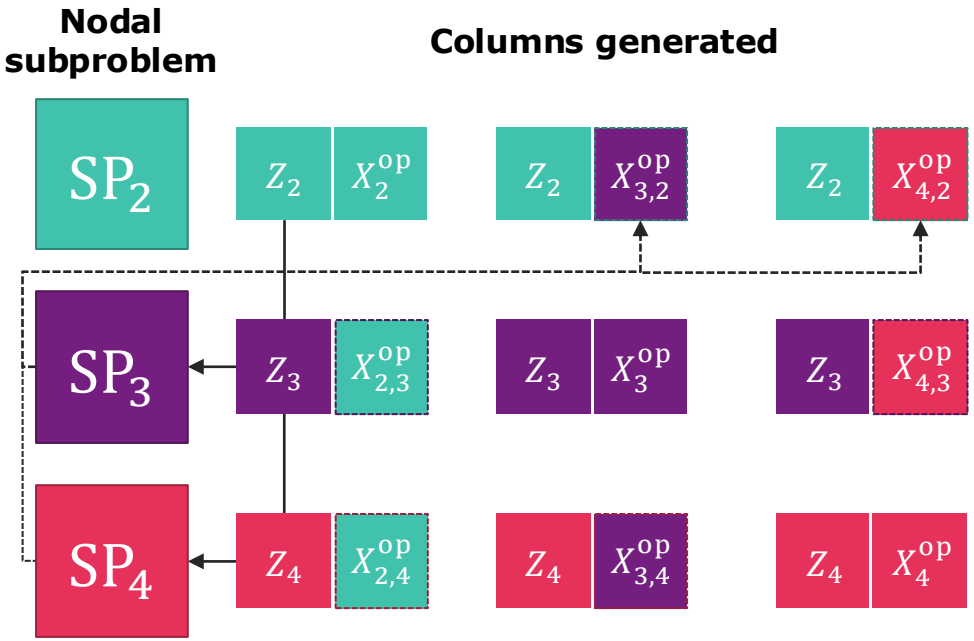
Investment—operation in node n

$$\min \rho_n \boldsymbol{c}_n^{\text{op}} \boldsymbol{X}_n^{\text{op}} - \boldsymbol{\pi}_n^{\mathsf{T}} \boldsymbol{Z}_n - \boldsymbol{\mu}_n$$

System operation	$\boldsymbol{X}_n^{\text{op}} \in \mathcal{X}_n^{\text{op}}$
Investment feasibility	$\boldsymbol{A}_n \boldsymbol{X}_n^{\text{op}} \le \boldsymbol{U}_n \boldsymbol{Z}_n$ $\boldsymbol{Z}_n \le \overline{\boldsymbol{Z}}_n$

…

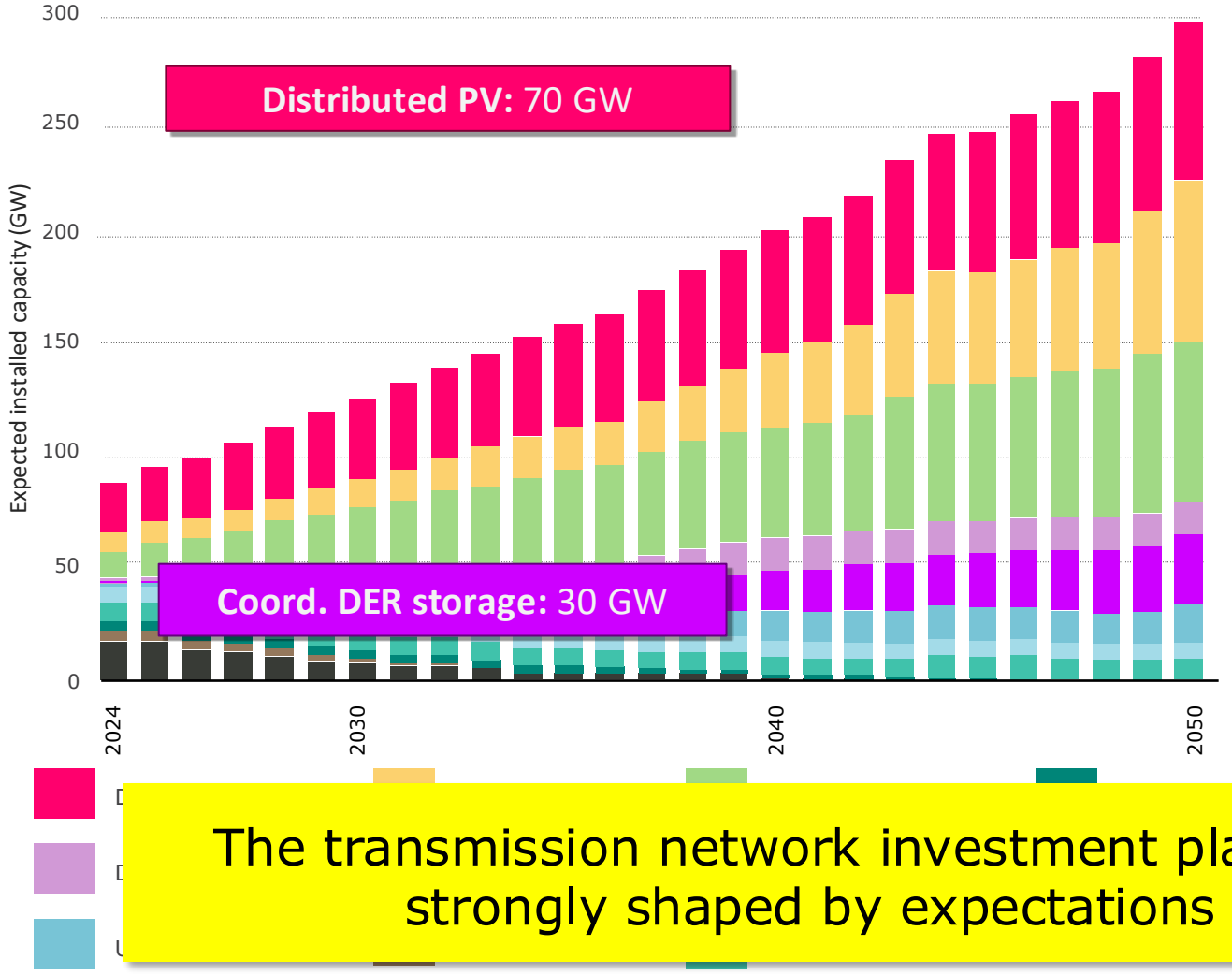
$\{\widehat{\boldsymbol{Z}}_n, \widehat{\boldsymbol{X}}_n^{\text{op}}\}$ Columns



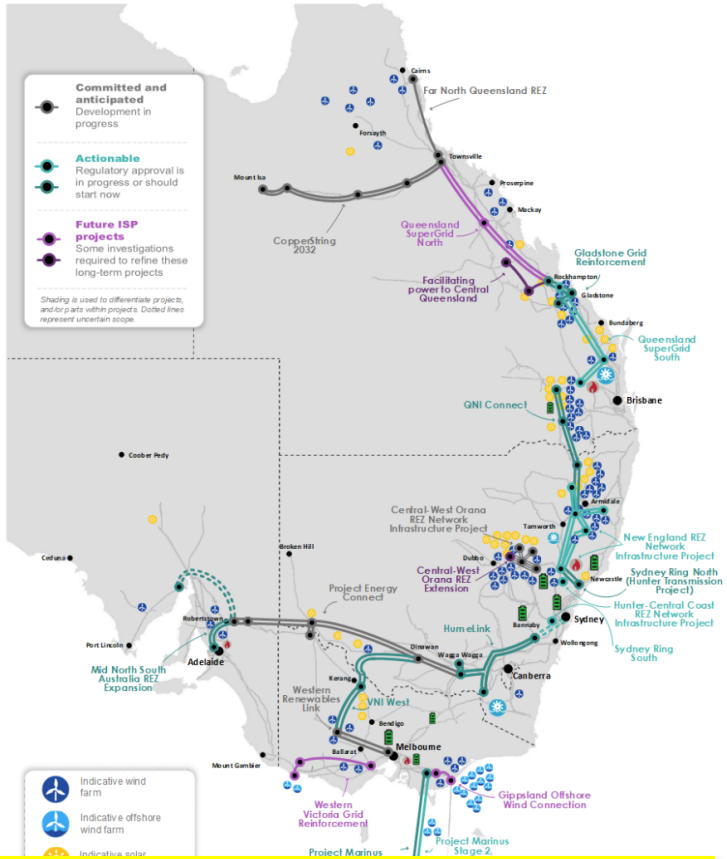
The value of DER and impacts of uncertainty across networks

Expected installed capacity

*Australian east-coast electricity system – **Step Change scenario***



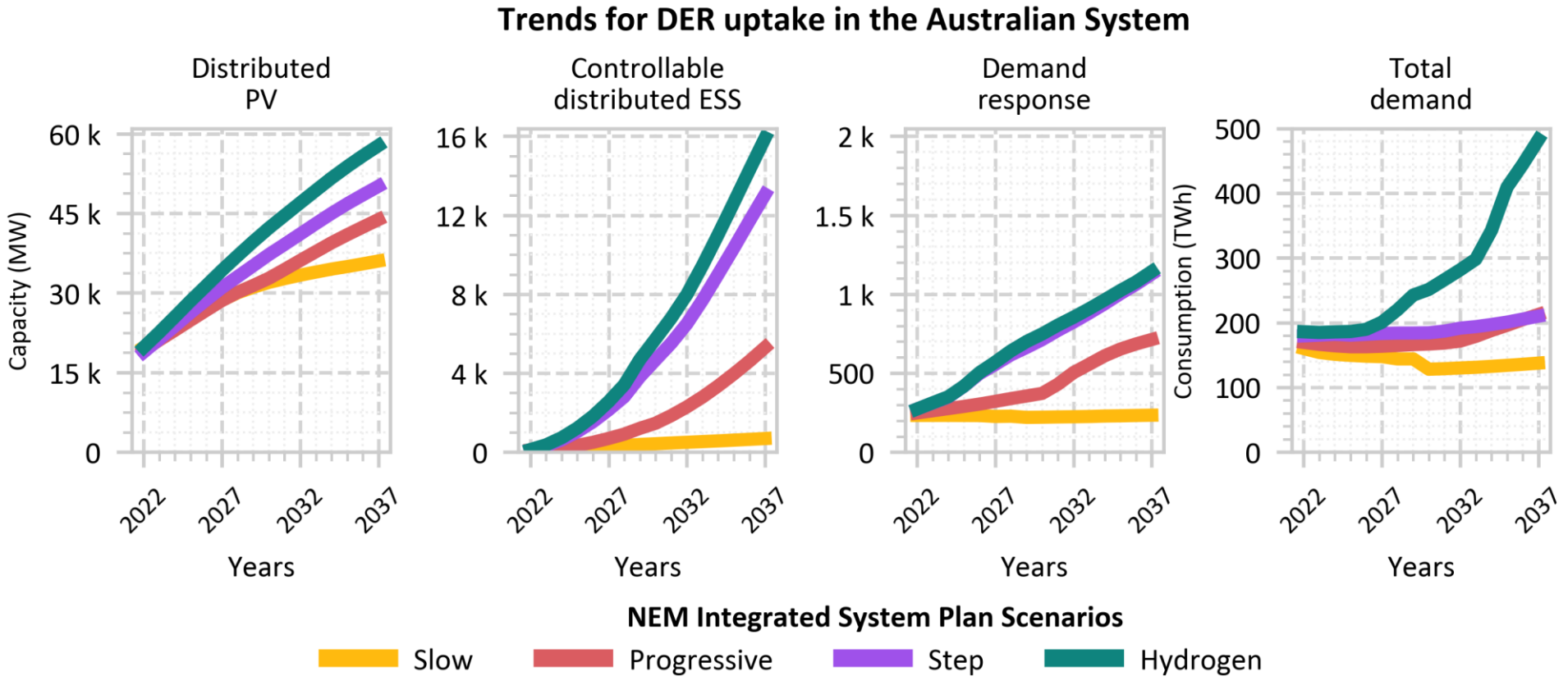
Transmission network investment plan



The transmission network investment plan for the Australian system is strongly shaped by expectations of **DER development**

Source: Australian Energy Market Operator (AEMO), Integrated System Plan (ISP)

The value of DER and impacts of uncertainty across networks

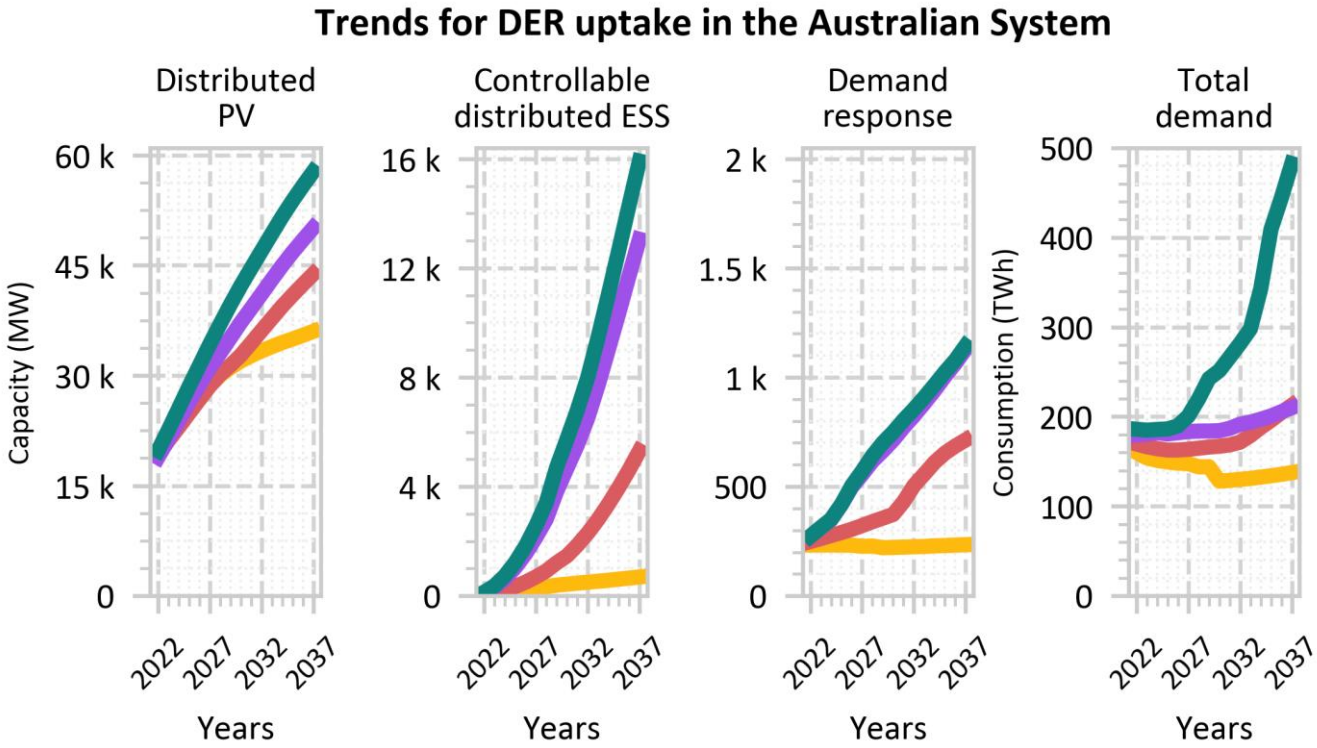


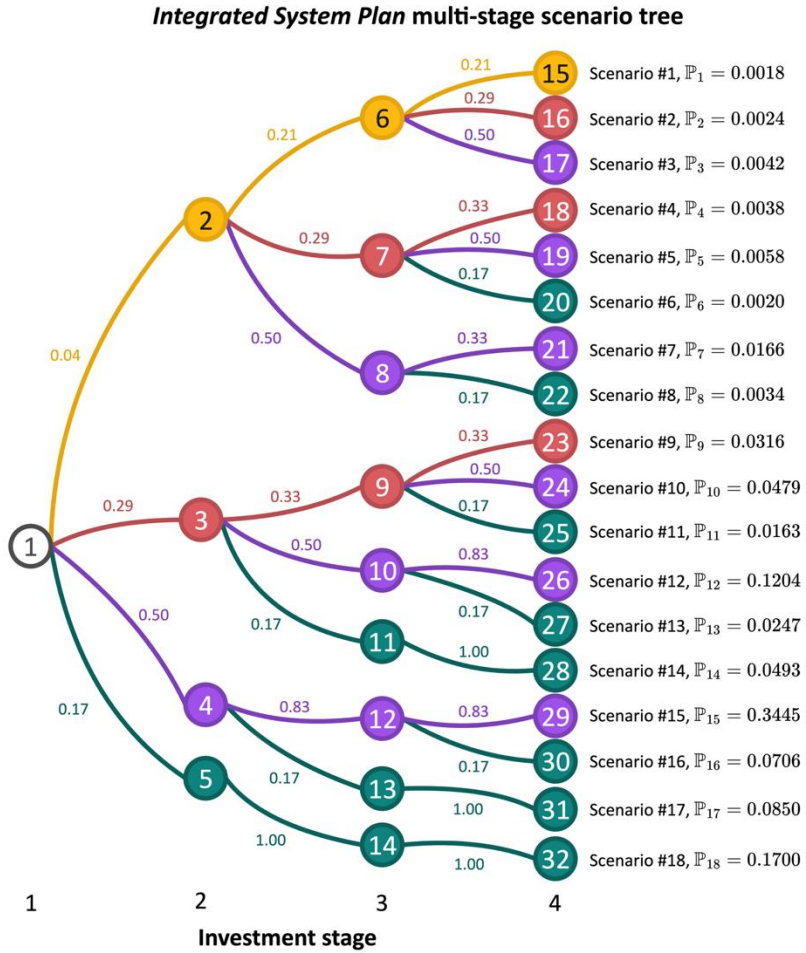
To avoid over- or under-estimations, the value of **DER flexibility**, **must** be assessed through **uncertainty-aware planning**

Source: Australian Energy Market Operator (AEMO), Integrated System Plan (ISP)

The value of DER and impacts of uncertainty across networks

Uncertainty representation





B. Moya, R. Moreno, S. Püschel-Løvengreen, A. M. Costa, and P. Mancarella, ***"Uncertainty representation in investment planning of low-carbon power systems,"*** *Electric Power Systems Research*, vol. 212, Nov. 2022, doi: 10.1016/j.epsr.2022.108470.

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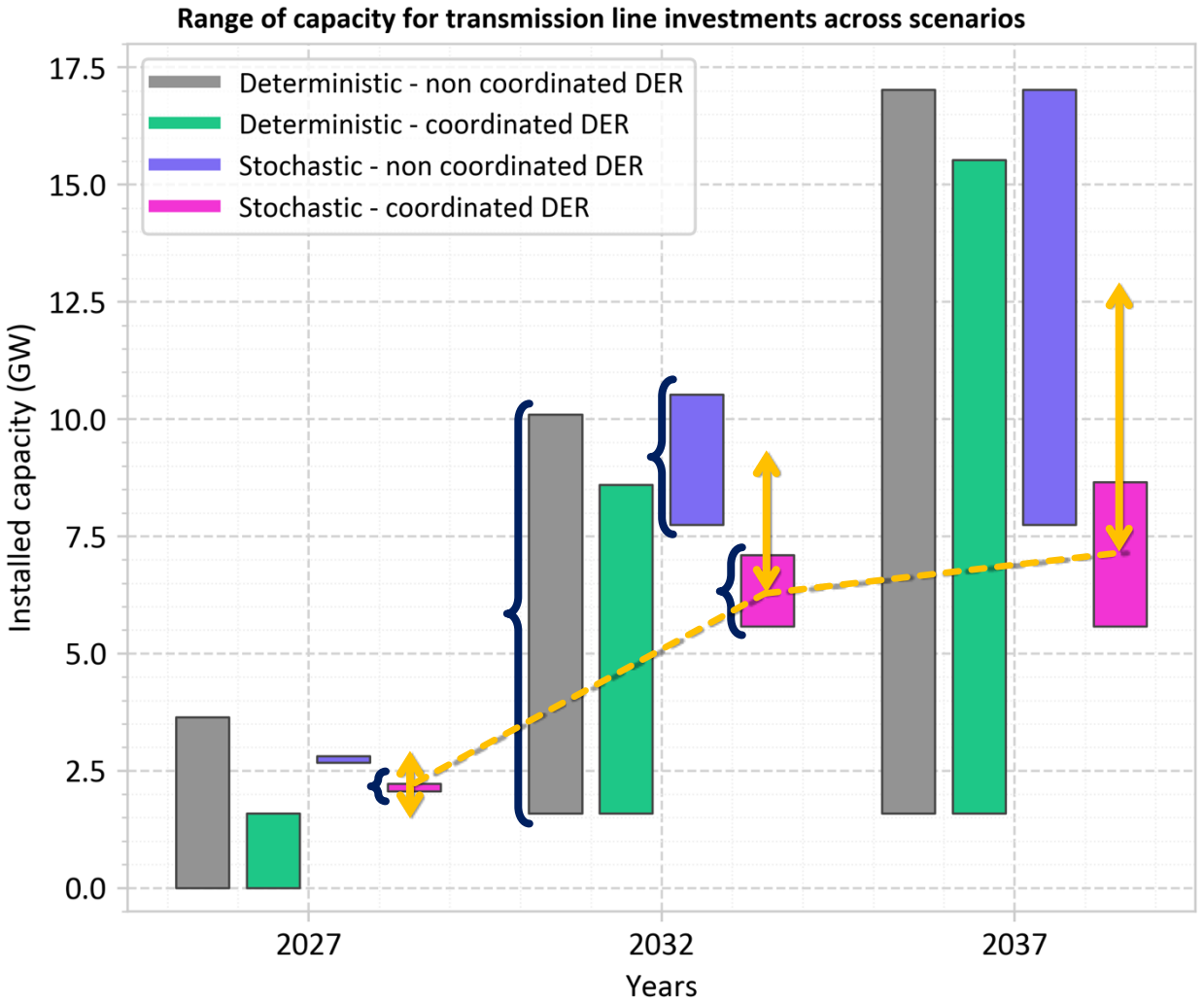
The value of DER and impacts of uncertainty across networks

*Deterministic versus stochastic planning – **Investment decisions***

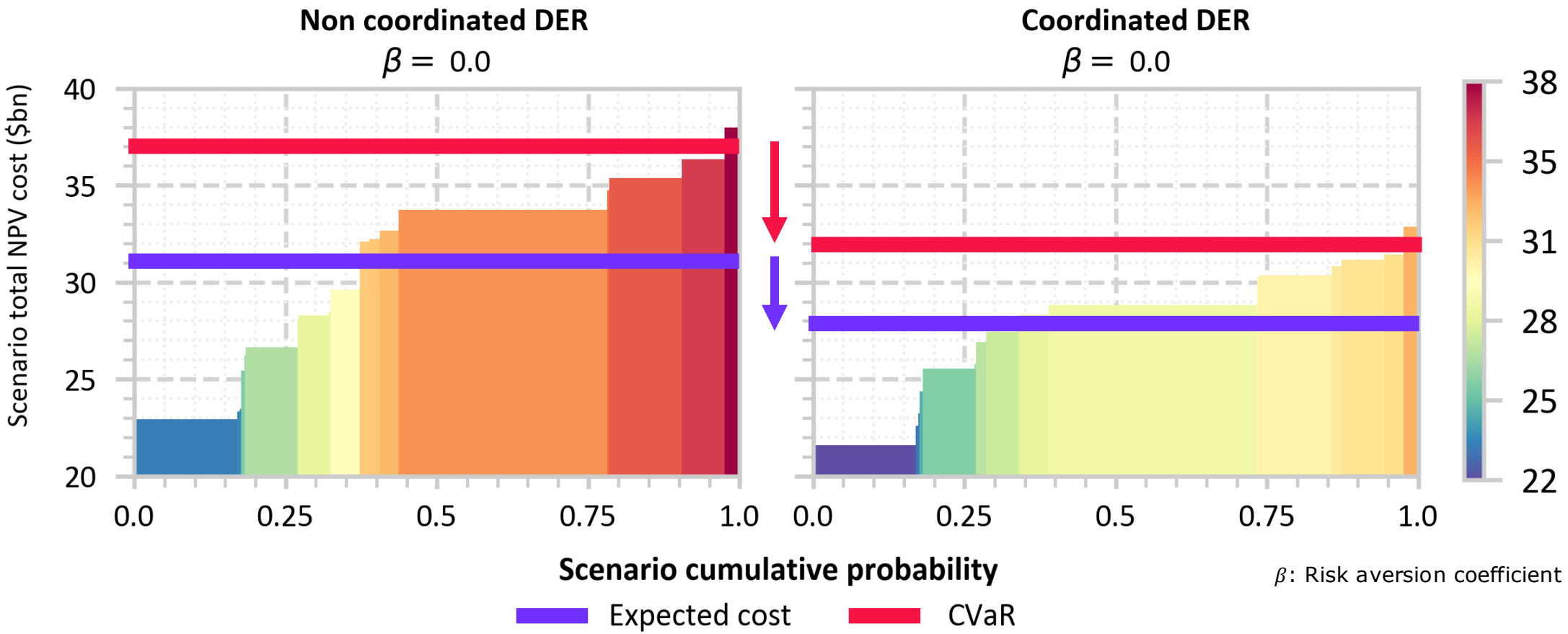


- Stochastic uncertainty-aware planning:
  - Allows for obtaining a ***single plan*** for ***today's investments***, even against **many future scenarios**
  - Investment plan exhibits **less investment risk**
  - DER coordination reduces investment uncertainty → **risk-hedge** value
  - A **clearer, robust long-term investment plan** can be developed

P. Apablaza, S. Püschel-Løvengreen, R. Moreno, S. Mhanna, and P. Mancarella, ***"Assessing the impact of DER on the expansion of low-carbon power systems under deep uncertainty,"*** *Electric Power Systems Research*, vol. 235, p. 110824, Oct. 2024, doi: 10.1016/j.epsr.2024.110824.

The value of DER and impacts of uncertainty across networks

Capturing de-risking capabilities of DER coordination



*DER coordination **shifts down** and **narrows** the economic performance profile of the system*

*Billion-dollar savings in **expected cost** as well as in **risk***

P. Apablaz … ***low-carbon power system planning context,*** *Sustainable Energy, Grids and Networks*, vol. 43, Sep. 2025, doi: 10.1016/j.segan.2025.101850.

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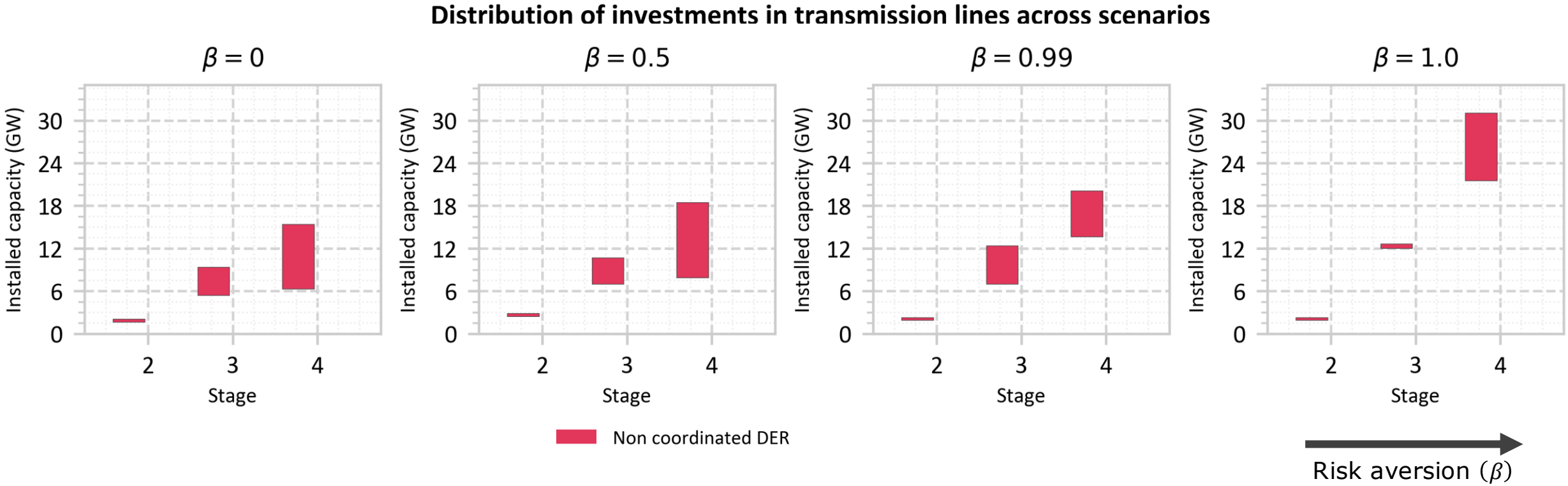

Higher degrees of risk aversion require additional network investments

P. Apablaza, S. Püschel-Løvengreen, R. Moreno, and P. Mancarella, ***"Valuing distributed energy resources flexibility in an uncertain and risk-aware low-carbon power system planning context,"*** *Sustainable Energy, Grids and Networks*, vol. 43, Sep. 2025, doi: 10.1016/j.segan.2025.101850.

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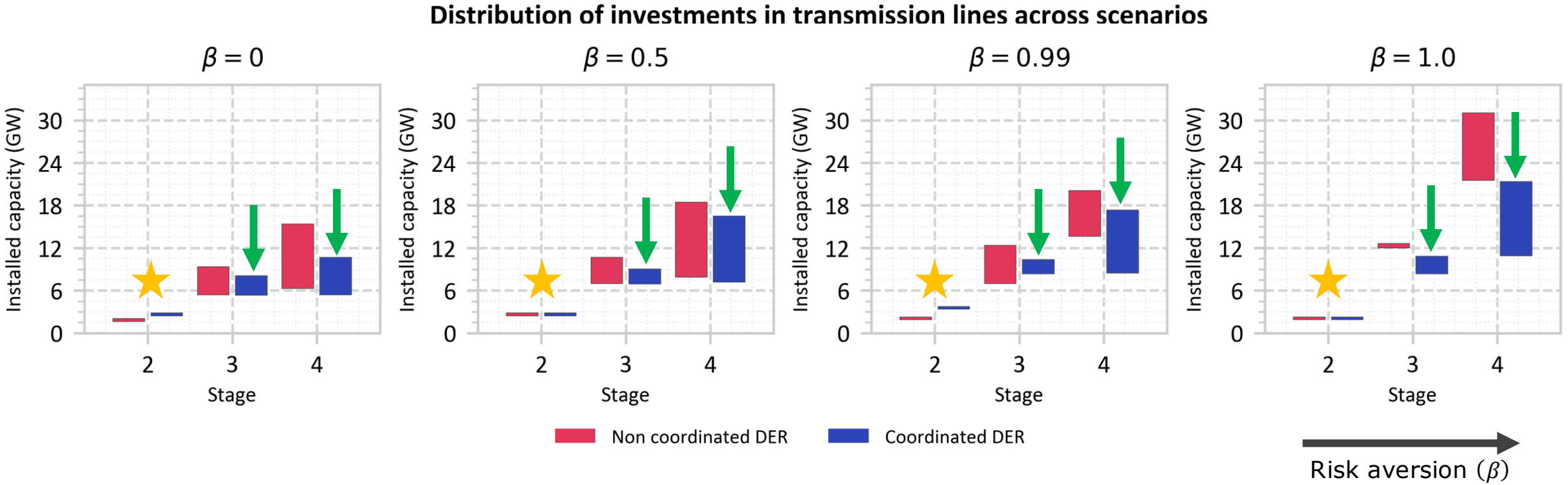


***Anticipatory network investments** are **required** to ensure DER coordination benefits in later stages*

*DER coordination is a **de-risking** strategy for transmission investment planning*

P. Apablaza, S. Püschel-Løvengreen, R. Moreno, and P. Mancarella, ***"Valuing distributed energy resources flexibility in an uncertain and risk-aware low-carbon power system planning context,"*** *Sustainable Energy, Grids and Networks*, vol. 43, Sep. 2025, doi: 10.1016/j.segan.2025.101850.

Planning integrated energy systems

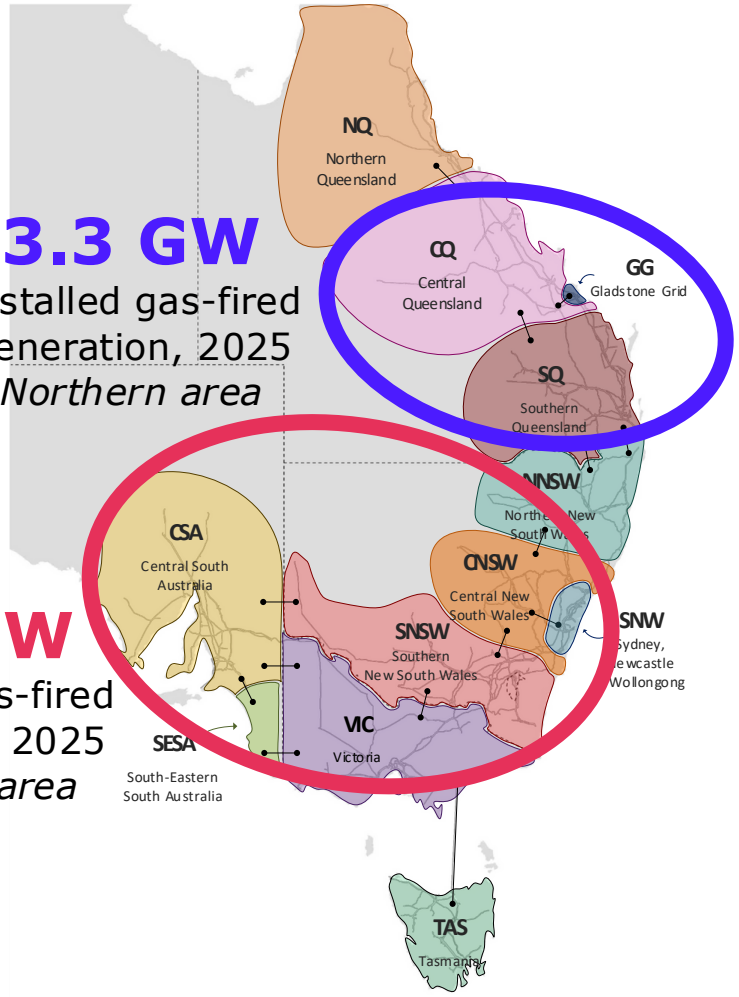
Where and when to prioritise infrastructure investments?

*"With coal retiring, renewable energy connected with transmission and distribution, firmed with storage and **backed up by gas-powered generation** is the **lowest-cost way** to supply electricity to homes and businesses as Australia transitions to a net zero economy."* – AEMO 2024 ISP

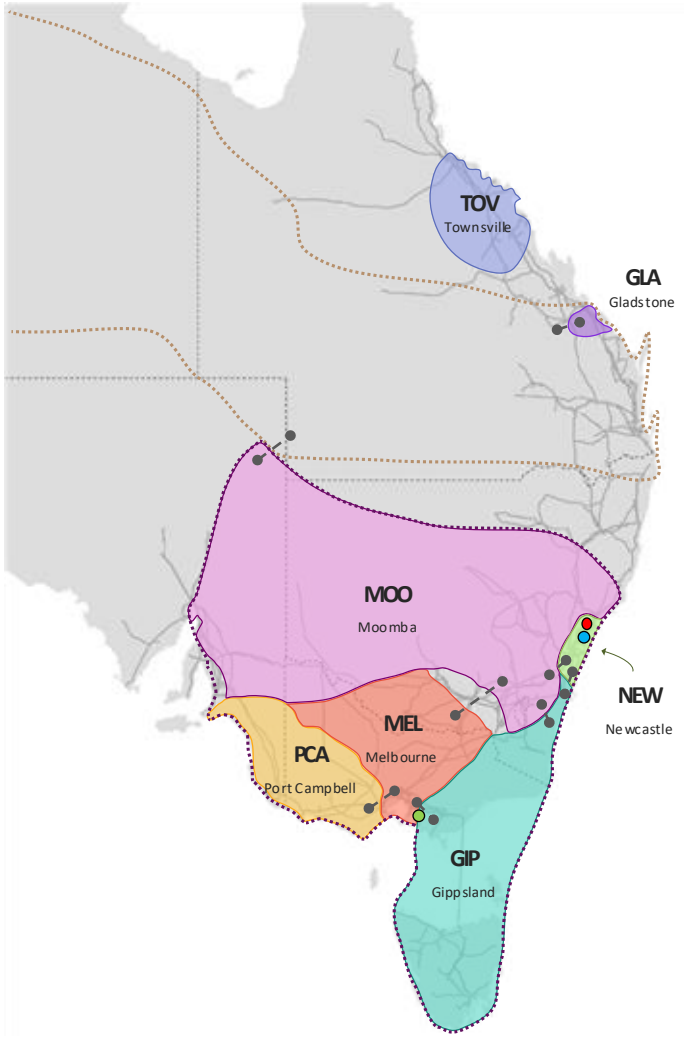
3.3 GW
Installed gas-fired generation, 2025
Northern area

8.9 GW
Installed gas-fired generation, 2025
Southern area

East-Coast Electricity System



East-Coast Gas System

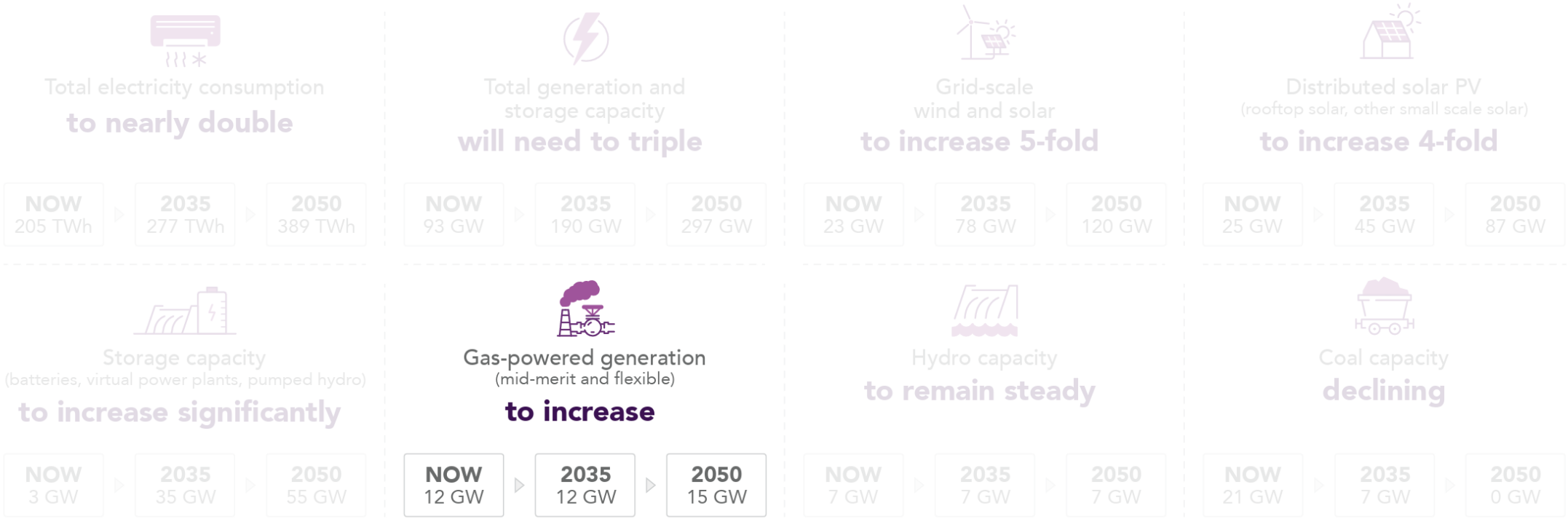


Sources:
Australian Energy Market Operator (AEMO), 2024 Integrated System Plan (ISP) & 2025 Gas Infrastructure Options Report

Planning integrated energy systems

Where and when to prioritise infrastructure investments?

Expected energy transition to 2050 ('Step Change' scenario)



Sources:
Australian Energy Market Operator (AEMO), 2026 Draft Integrated System Plan (ISP), December 2025

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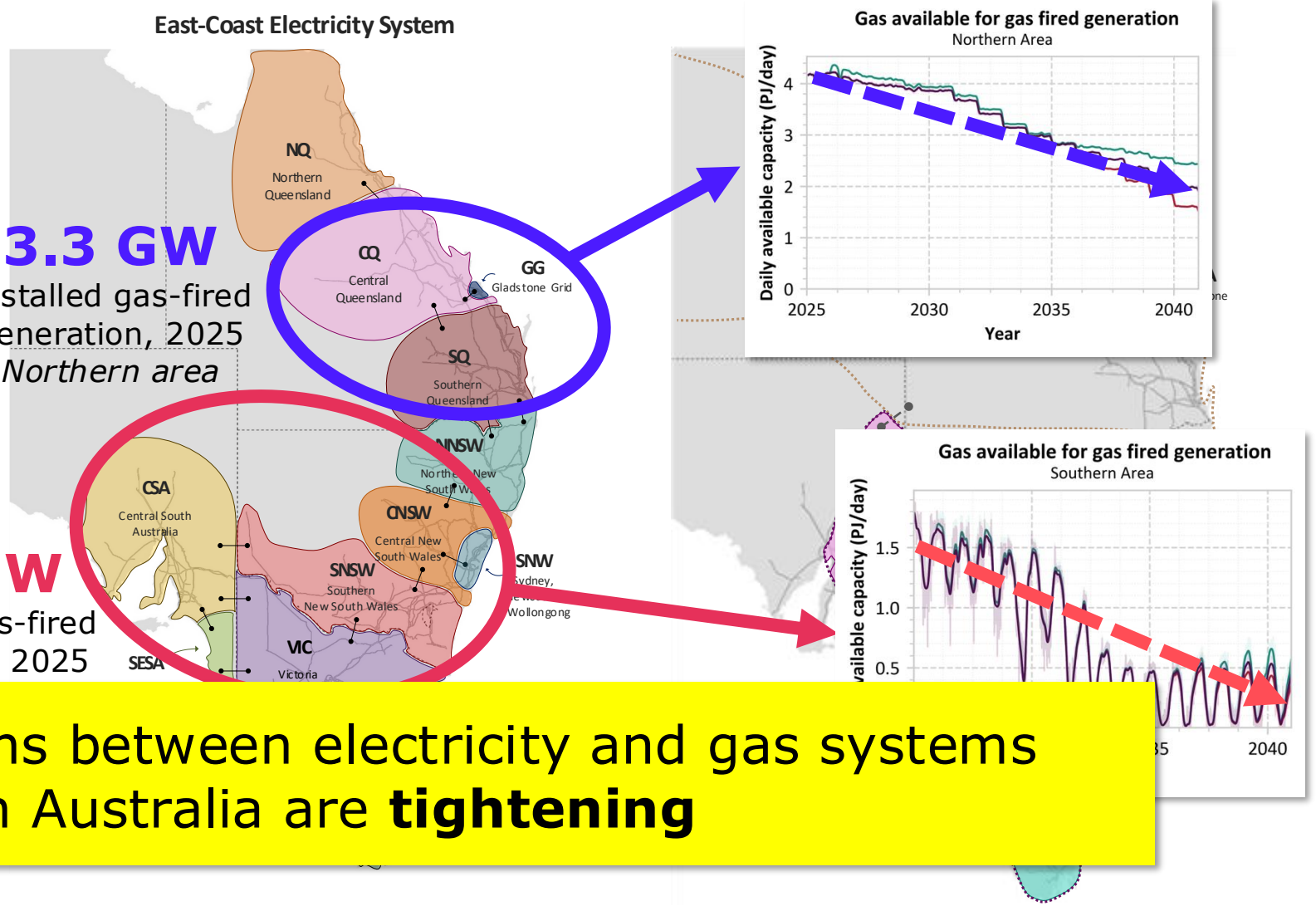
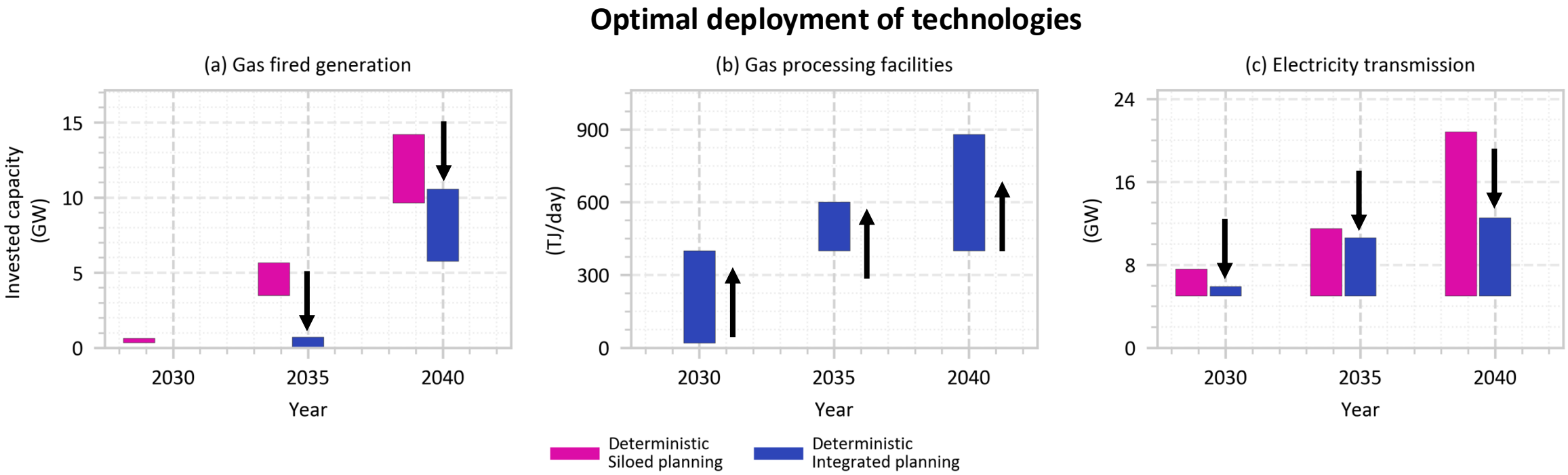


The interactions between electricity and gas systems in Australia are **tightening**

Sources:
Australian Energy Market Operator (AEMO), 2024 Integrated System Plan (ISP) & 2025 Gas Infrastructure Options Report

Planning integrated energy systems

Where and when to prioritise infrastructure investments?

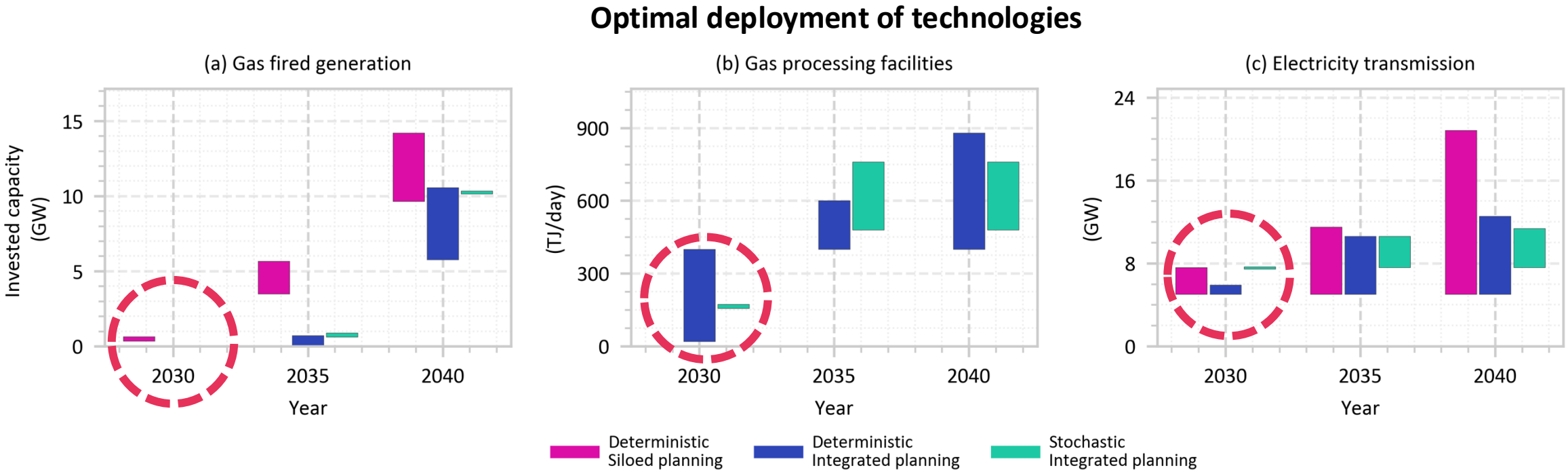


"Siloed" planning: generation and transmission required, with prevalence of **adequacy** and **investment risks**

Integrated planning between electricity and gas systems reveals a strategic **investment pathway**

Planning integrated energy systems

Where and when to prioritise infrastructure investments?



"Siloed" planning: generation and transmission required, with prevalence of **adequacy** and **investment risks**

Integrated planning between electricity and gas systems reveals a strategic **investment pathway**

When uncertainty is accounted for, investments become **actionable**, and therefore, **much less risky**

Key takeaways

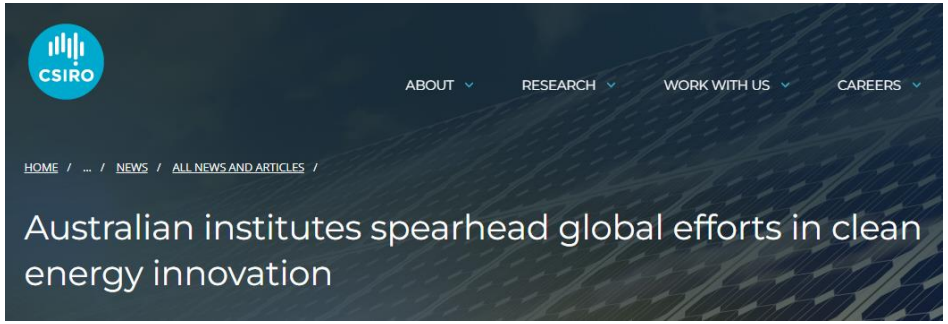
- A stochastic, risk-aware planning philosophy would enable planners to:
  - Capture and mitigate the risks posed by long-term uncertainties
  - Control risk preferences
  - Facilitate the identification of technologies with de-risking potential
  - Support the development of robust investment strategies
- DER coordination is a **de-risking** strategy for large-scale transmission planning, both in terms of **costs** and **investment decisions**
- **Coordinated investments** across electricity and gas systems are a more efficient, coherent and less risky investment pathway
- Deterministic planning is less suitable for revealing the **benefits of flexibility** and system integration, as well as the underlying **cost-risk trade-offs**

Always open for collaborations!

☺

New Global Research Centre to provide EPIC clean energy boost

The new Electric Power Innovation for a Carbon-Free Society (EPICS) Centre will address challenges in clean energy production and storage.



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https://www.csiro.au/en/news/All/News/2023/September/Australian-institutes-spearhead-global-efforts-in-clean-energy-innovation

https://www.unimelb.edu.au/newsroom/news/2023/september/new-global-research-centre-to-provide-epic-clean-energy-boost

For further reading!

- R. Moreno, A. Street, J. M. Arroyo, and P. Mancarella, ***"Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies,"*** *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 375, no. 2100, Aug. 2017, doi: 10.1098/rsta.2016.0305.
- B. Moya, R. Moreno, S. Püschel-Løvengreen, A. M. Costa, and P. Mancarella, ***"Uncertainty representation in investment planning of low-carbon power systems,"*** *Electric Power Systems Research*, vol. 212, Nov. 2022, doi: 10.1016/j.epsr.2022.108470.
- S. Püschel-Løvengreen, S. Mhanna, and P. Mancarella, ***"Flexible planning of low-carbon power systems under deep uncertainty,"*** *CIGRE Science and Engineering*, vol. 31, 2023. https://cse.cigre.org/cse-n031/flexible-planning-of-low-carbon-power-systems-under-deep-uncertainty.html
- P. Apablaza, S. Püschel-Løvengreen, R. Moreno, S. Mhanna, and P. Mancarella, ***"Assessing the impact of DER on the expansion of low-carbon power systems under deep uncertainty,"*** *Electric Power Systems Research*, vol. 235, p. 110824, Oct. 2024, doi: 10.1016/j.epsr.2024.110824.
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- S. Püschel-Løvengreen, S. Mhanna, P. Apablaza, and P. Mancarella, ***"Assessing flexibility, risk, and resilience in low-carbon power system planning under deep uncertainty,"*** 2023. Available: https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Final-Reports/Topic-4-GPST-Stage-2.pdf
- P. Apablaza, C. Alcarruz, R. Chen, B. Moya, S. Mhanna, and P. Mancarella, ***"Energy infrastructure planning under deep uncertainty: Assessing impacts and benefits of energy system integration*** *- Prepared for CSIRO and Global PST Consortium,"* 2024. Available: https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Stage3-Final/Topic-4_Planning.pdf
- C. A. Olivos, R. Chen, P. Apablaza, B. Moya, S. Mhanna, and P. Mancarella, ***"Integrated energy system planning: Unlocking the value and flexibility from distribution networks and electricity-hydrogen energy hubs*** *- Prepared for CSIRO and Global PST Consortium,"* 2025. Available: https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Stage-4-Final/AR-PST-Stage-4-Topic-4-pdf.pdf

Thank you!
Any Questions?

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