# Integrated electricity-gas-hydrogen systems: Techno-economic modelling, challenges, and opportunities

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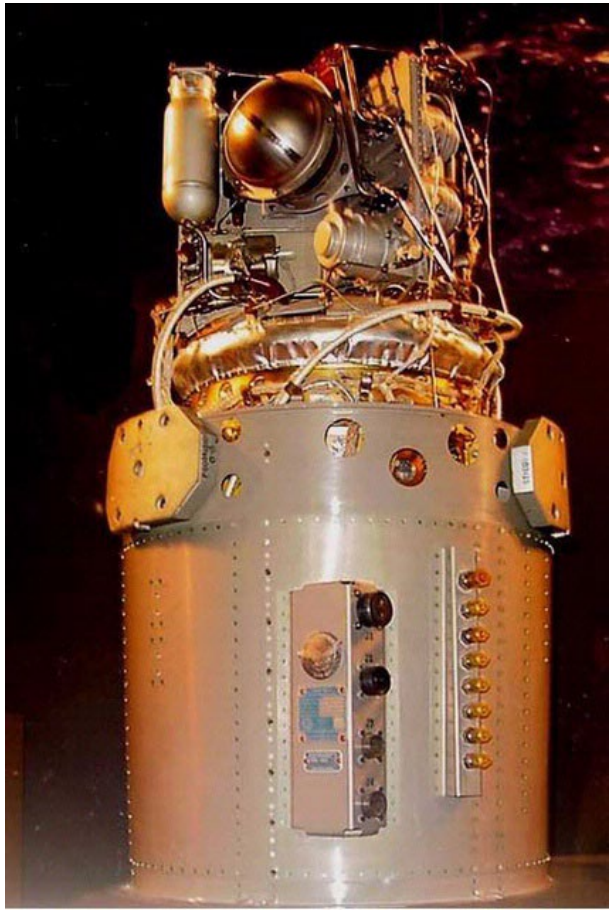
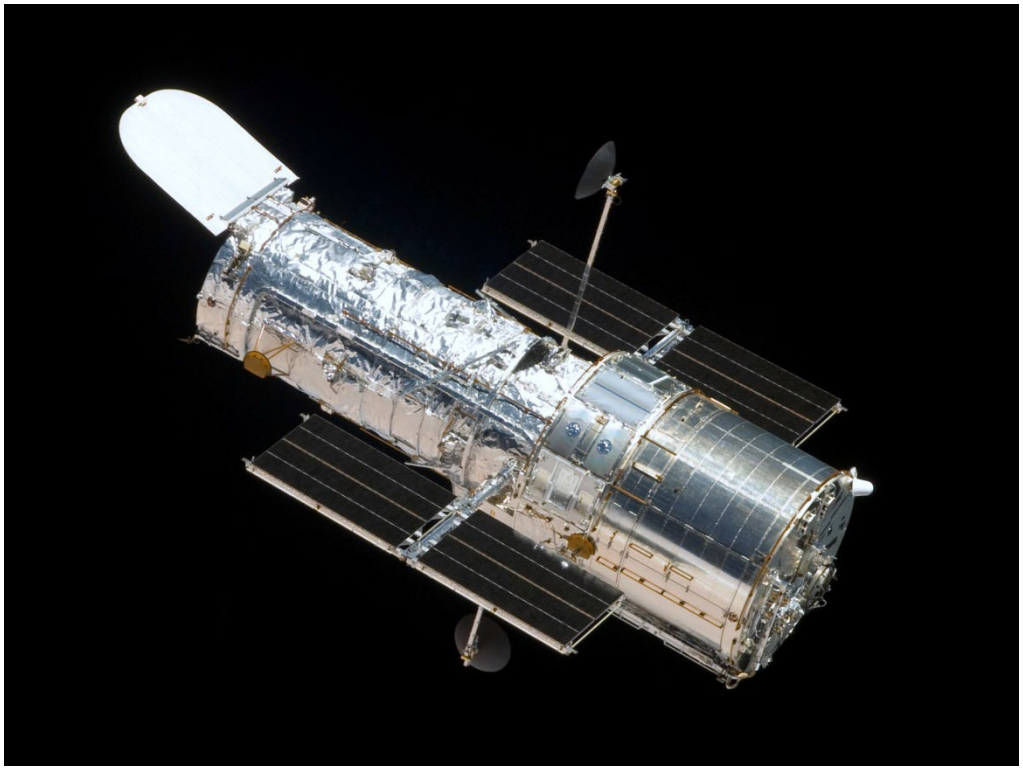
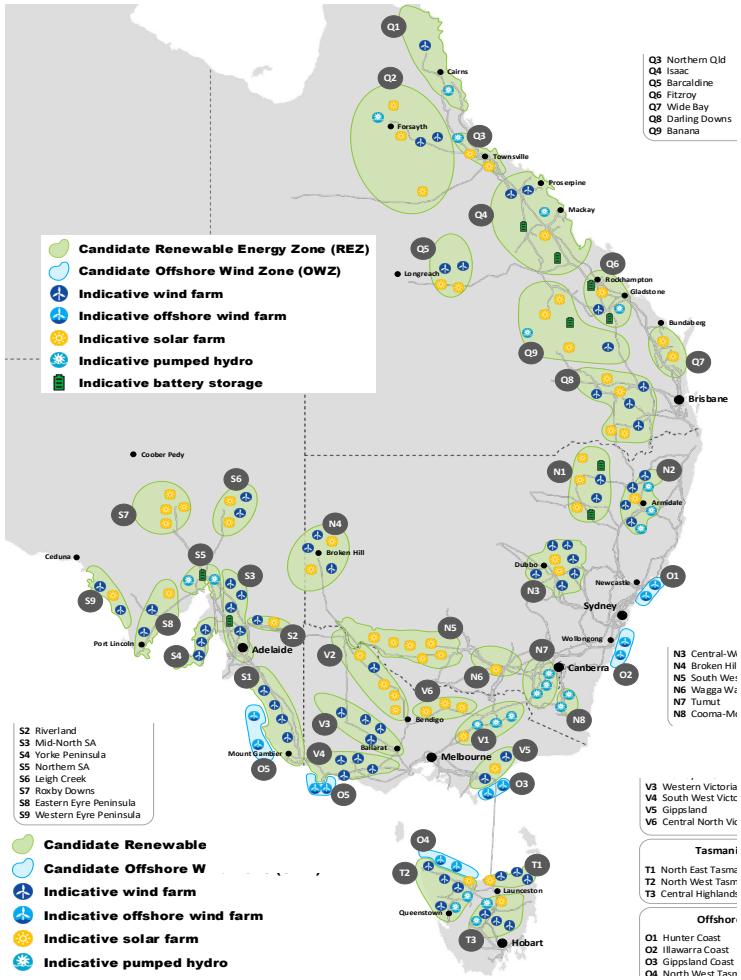
SOERC, Perth, 14th February 2024

# Back to the future!

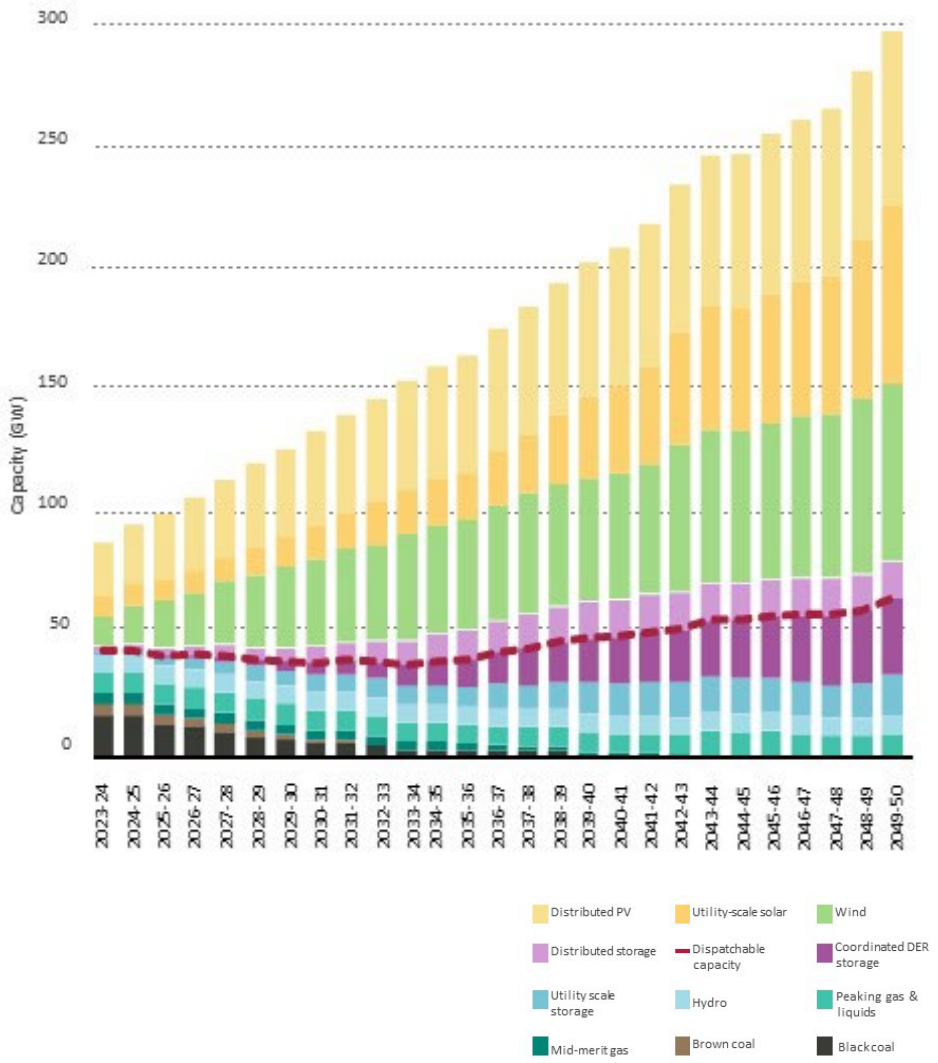




# Green electricity for all…

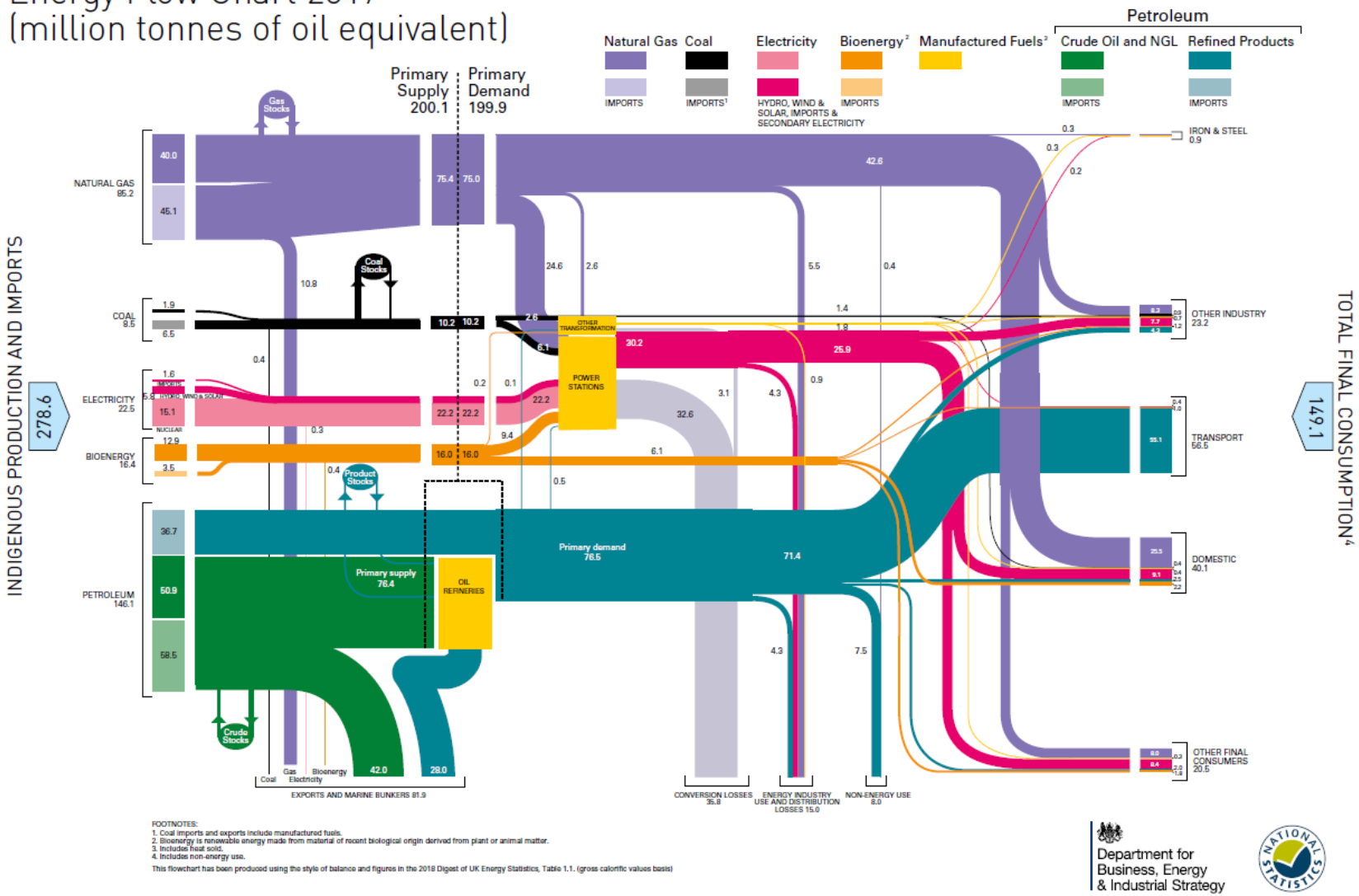



***Installed capacity in ISP 2022 "step change" scenario***

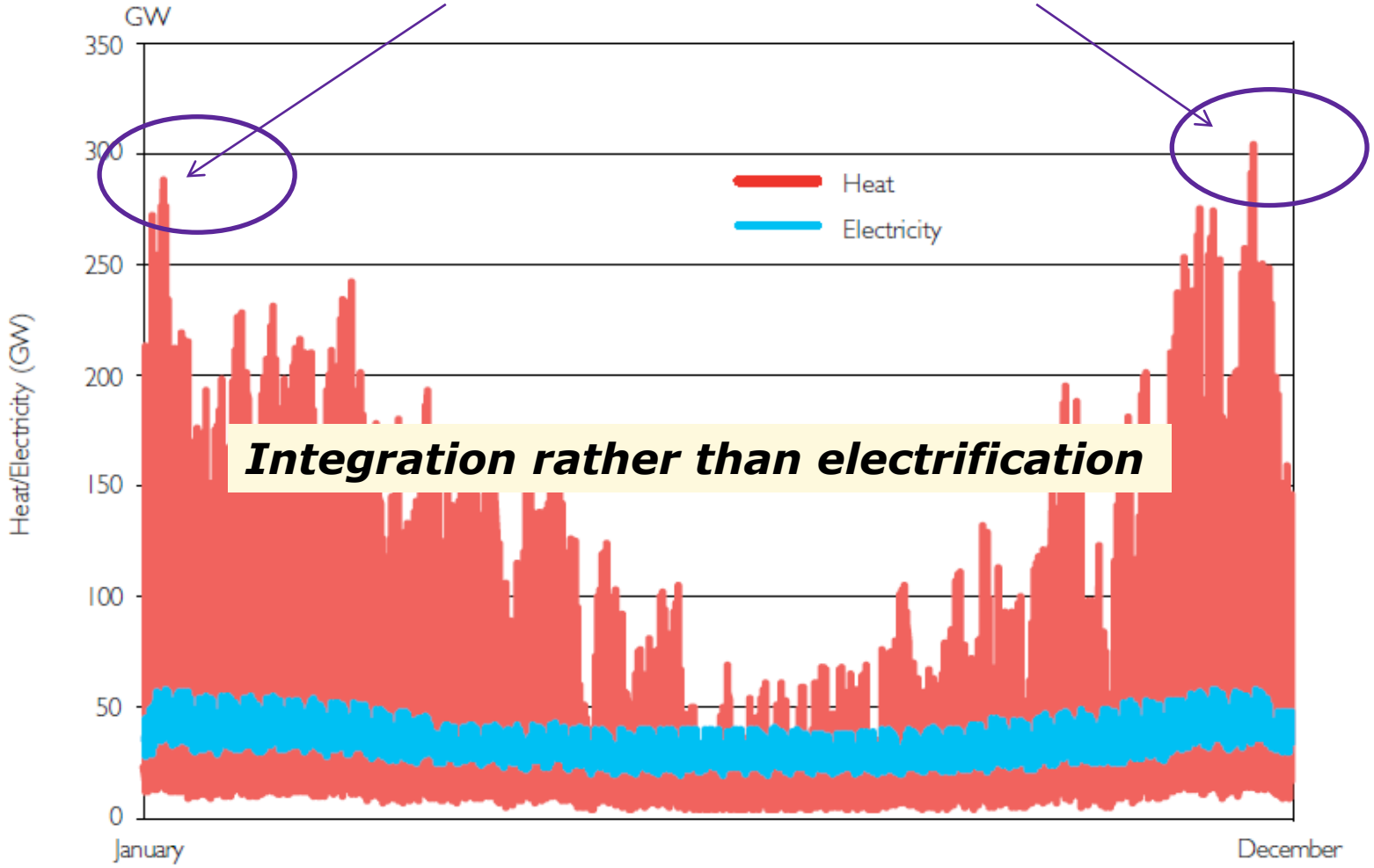



[5] AEMO - 2023 Electricity Statement of Opportunities; [6] AEMO - ISP 2022

# … but it's not only about electricity…

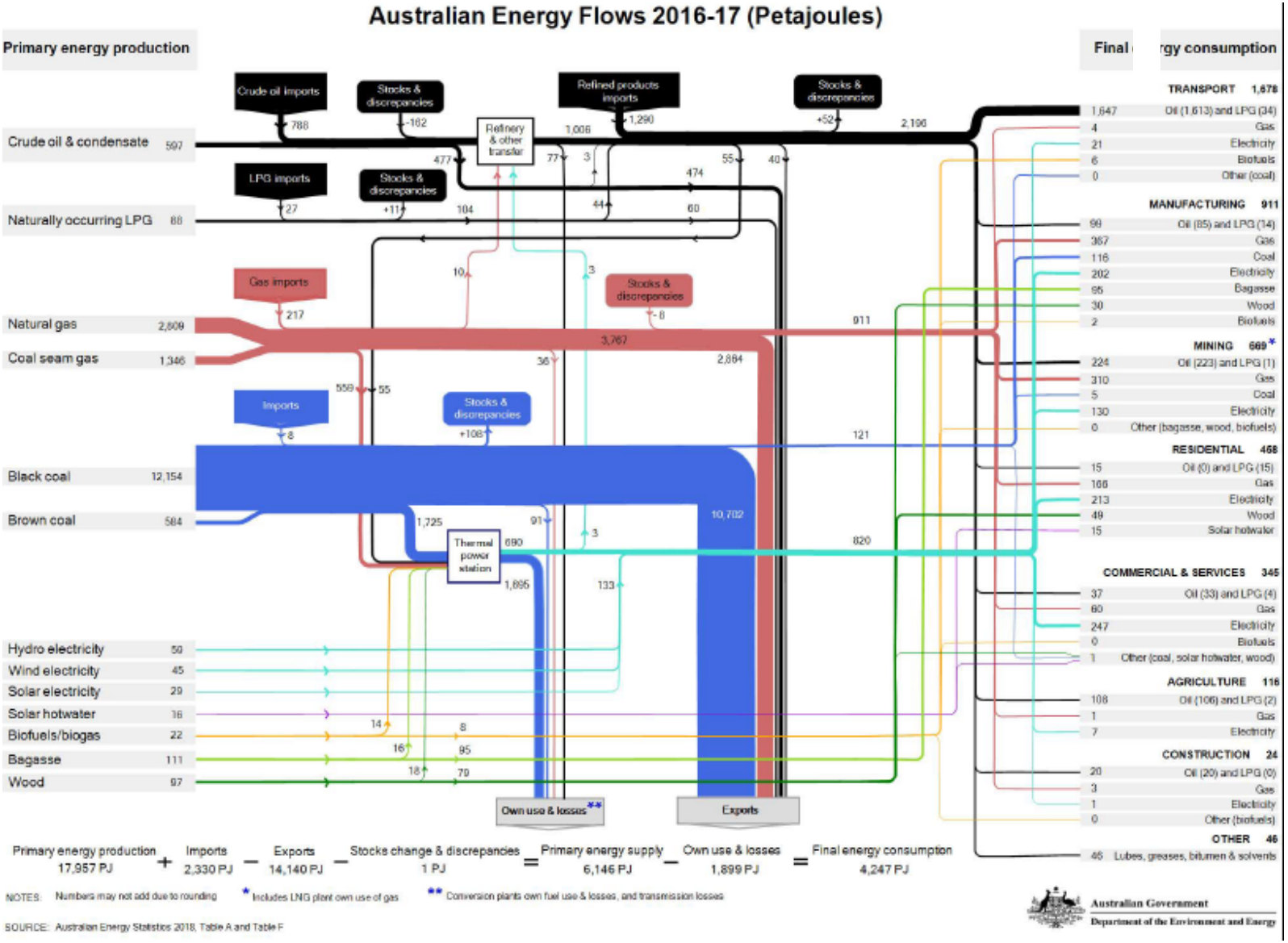


# Electrification by the numbers…



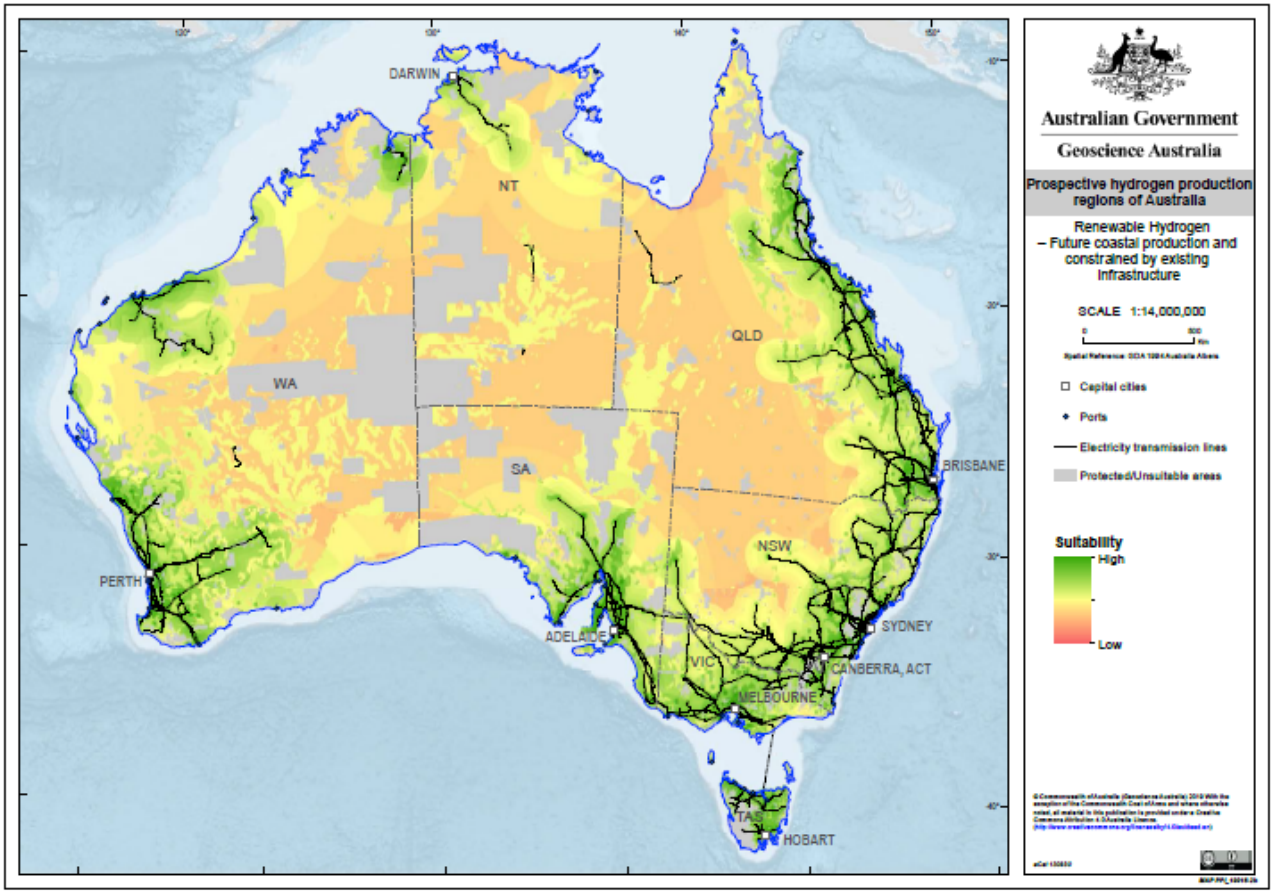

Source: Courtesy of Imperial College. For illustrative purposes only and based on actual half-hourly electricity demand from National Grid and an estimate of half hourly heat demand.

# An energy superpower: From "conventional" fuels…



# … to "future" fuels: Green hydrogen potential

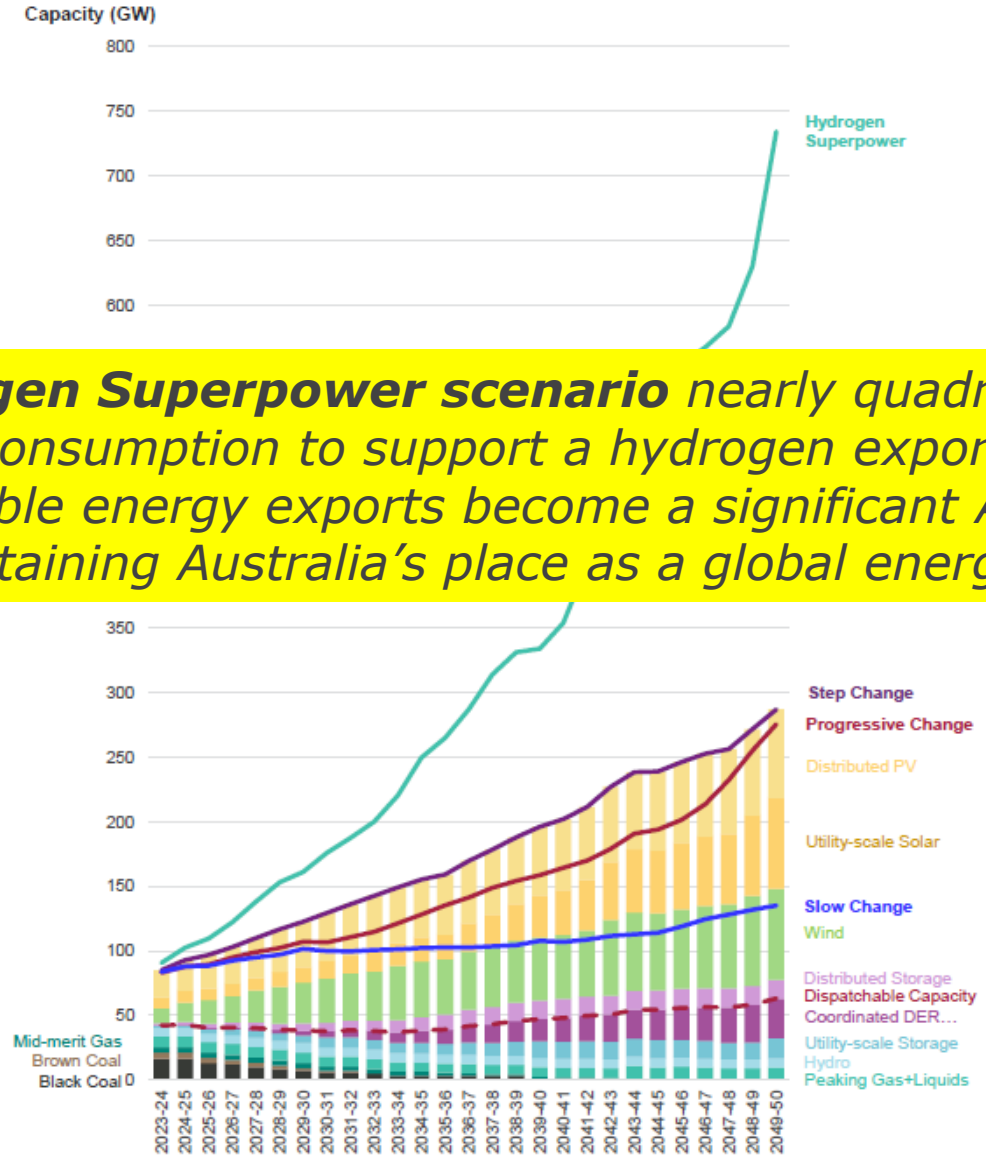
Potential with consideration for access to water, ports, pipeline easements, and electricity infrastructure




Source: COAG Energy Council, Australia's National Hydrogen Strategy, November 2019

# A clean "energy superpower"

Figure 11 Development opportunities to 2050 in *Step Change*, and compared to total capacity required in *Progressive Change* and *Hydrogen Superpower*



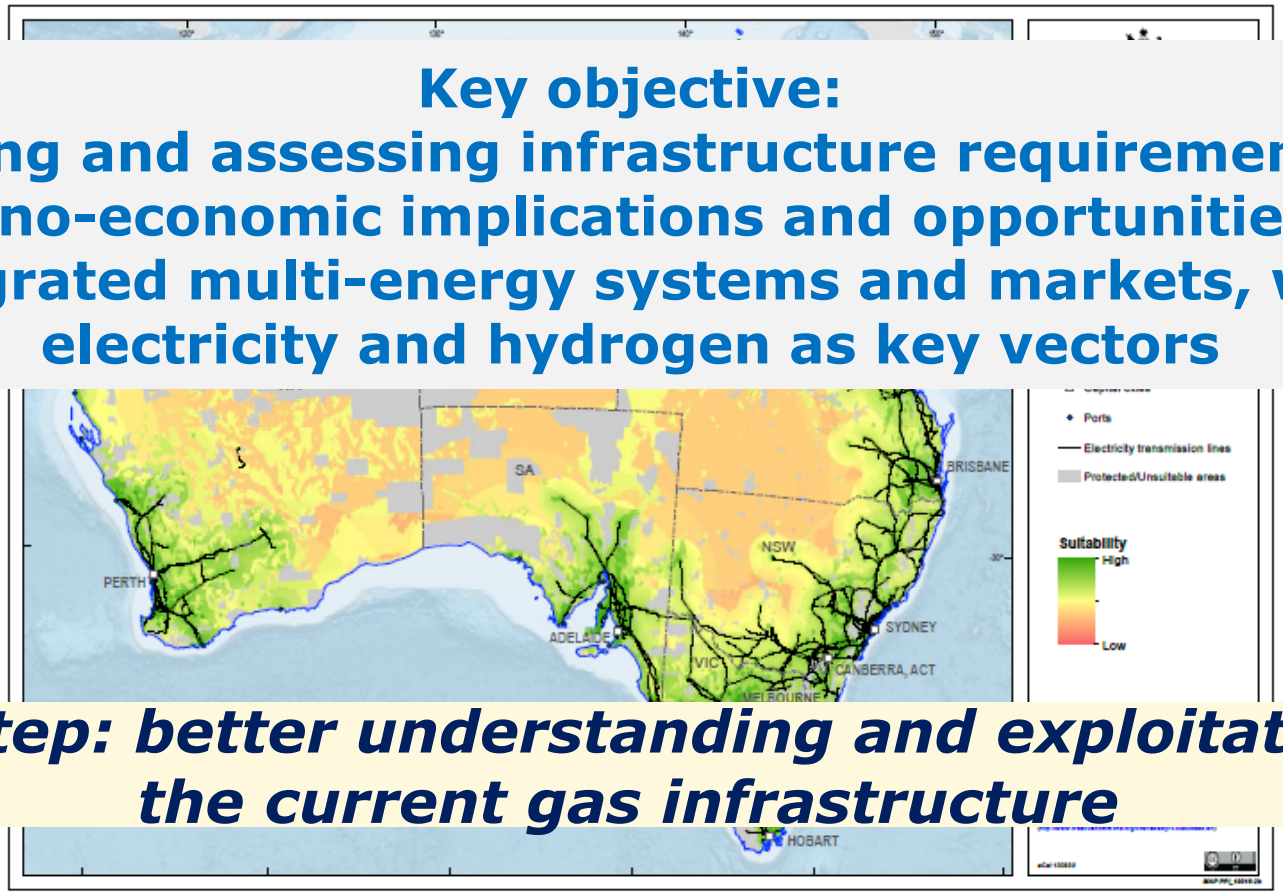

***"Hydrogen Superpower scenario** nearly quadruples NEM energy consumption to support a hydrogen export industry: renewable energy exports become a significant Australian export, retaining Australia's place as a global energy resource"*

Source: AEMO ISP 2022

# Exploiting the green hydrogen potential of Australia

Potential with consideration for access to water, ports, pipeline easements, and electricity infrastructure

**Key objective:**
**Modelling and assessing infrastructure requirements and techno-economic implications and opportunities of integrated multi-energy systems and markets, with electricity and hydrogen as key vectors**



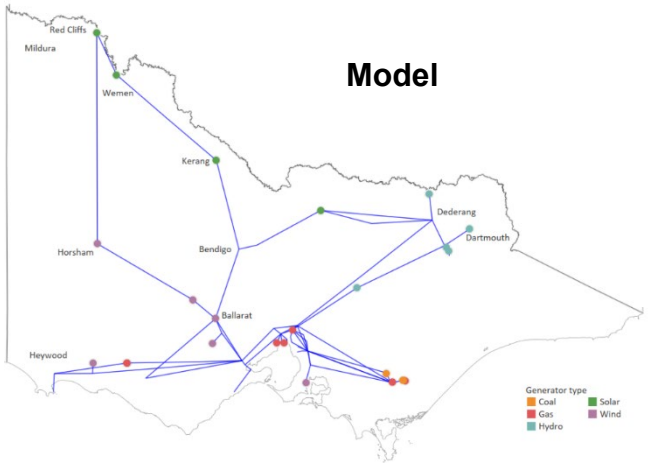

***First step: better understanding and exploitation of the current gas infrastructure***

Source: COAG Energy Council, Australia's National Hydrogen Strategy, November 2019

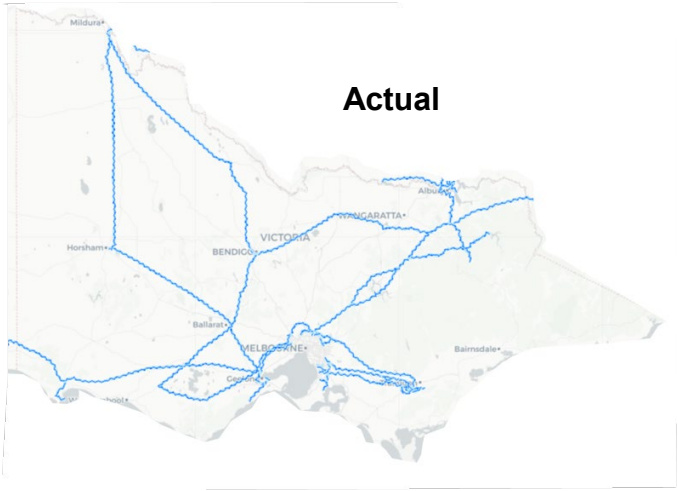
# Victoria's electricity and gas integrated network modelling

**Electricity**

**Model**

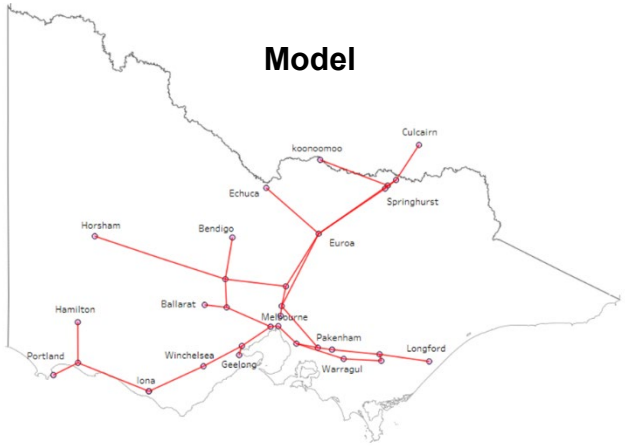



**Actual**

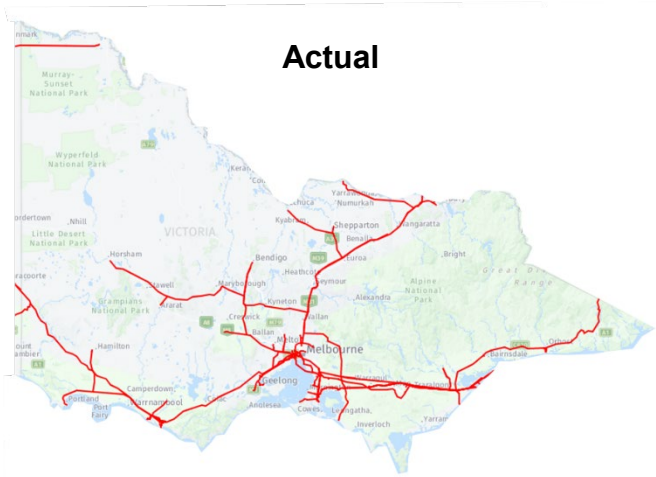



**Gas**

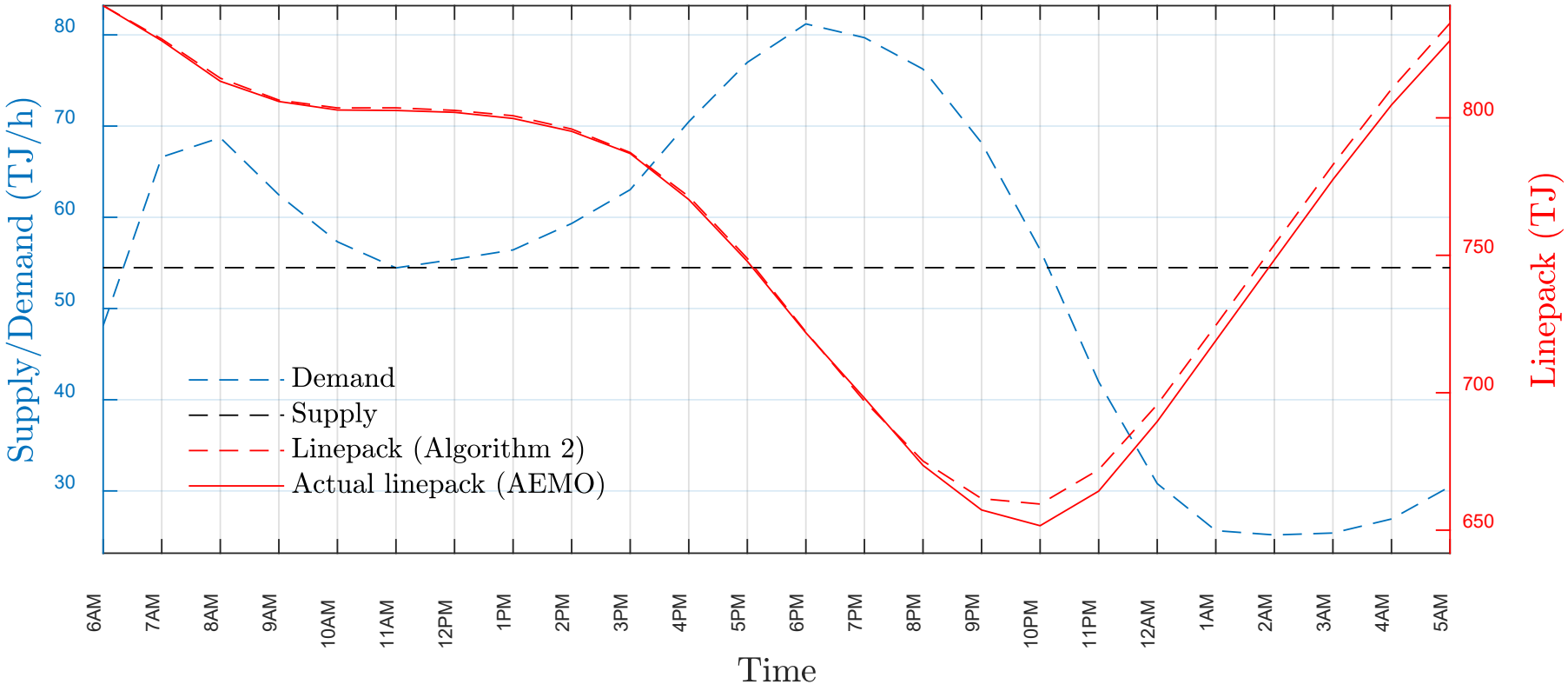
**Model**




**Actual**



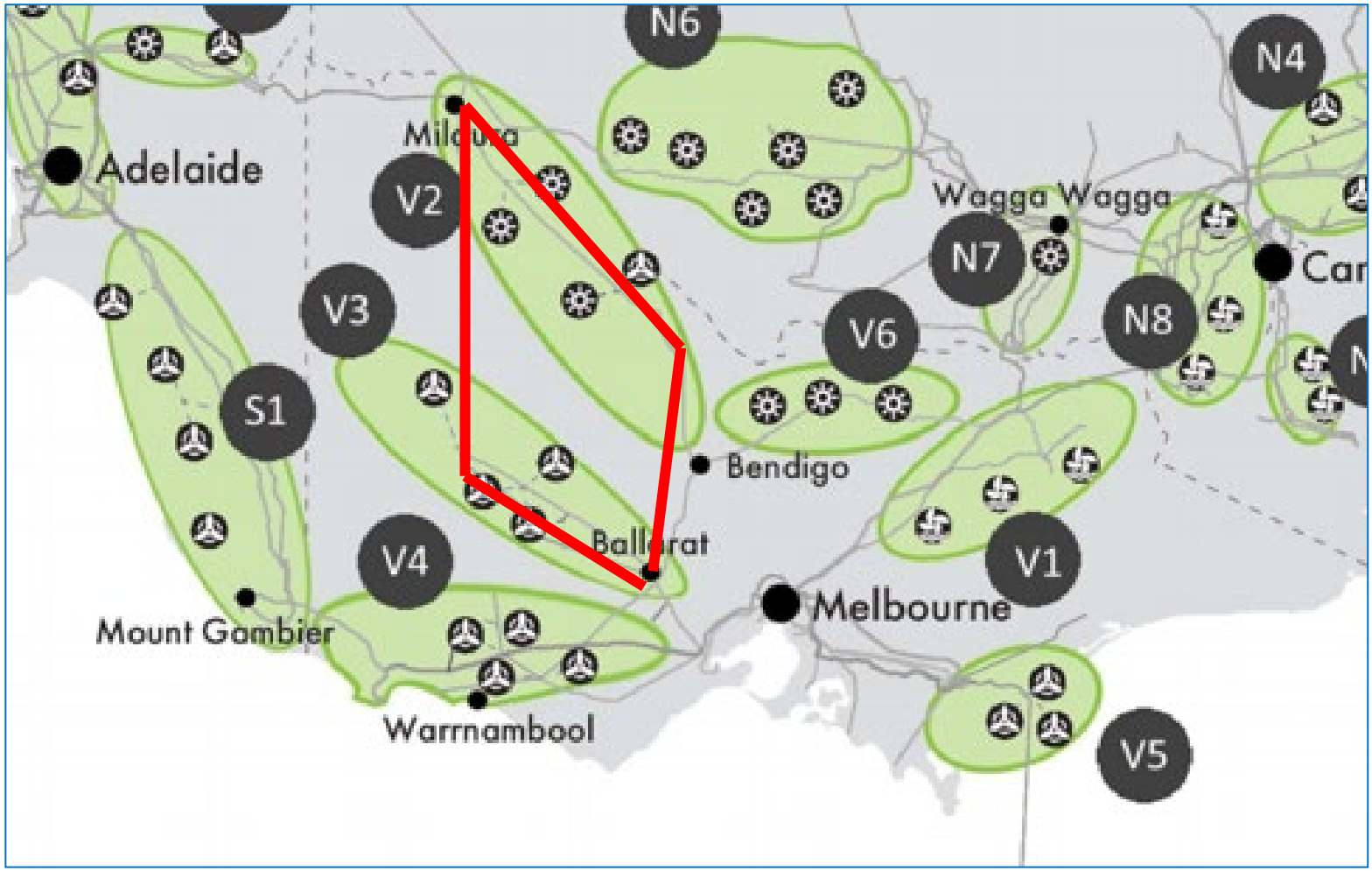
# Linepack modelling validation




***The fastest algorithm in the world, converging to feasible solutions***

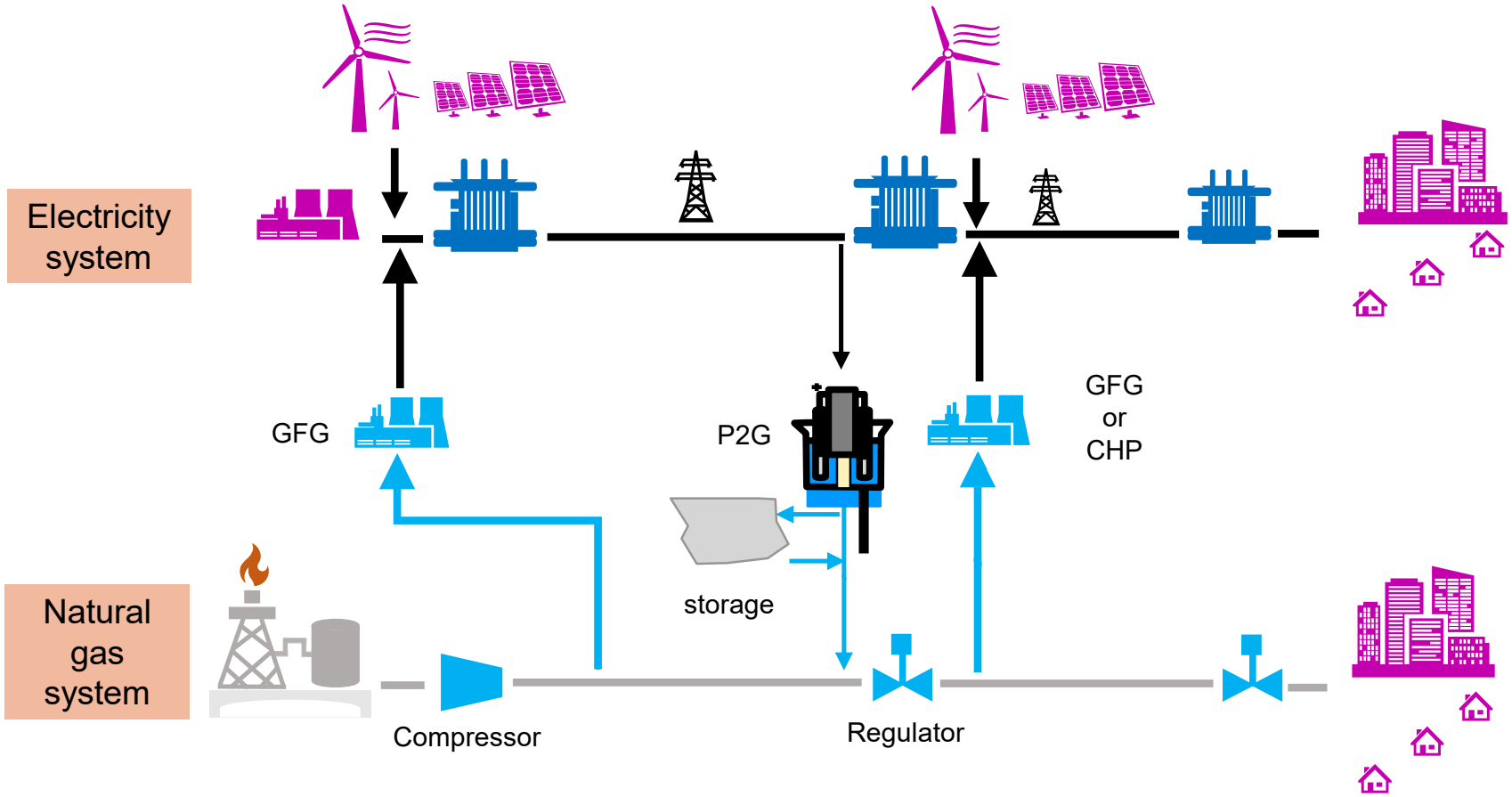
S. Mhanna, I. Saedi, and P. Mancarella, "Iterative LP-based Methods for the Multiperiod Optimal Electricity and Gas Flow Problem," IEEE Trans. Power Syst., 2021.

# The "rombus of regret"




Source: AEMO ISP 2020 and Environment Victoria

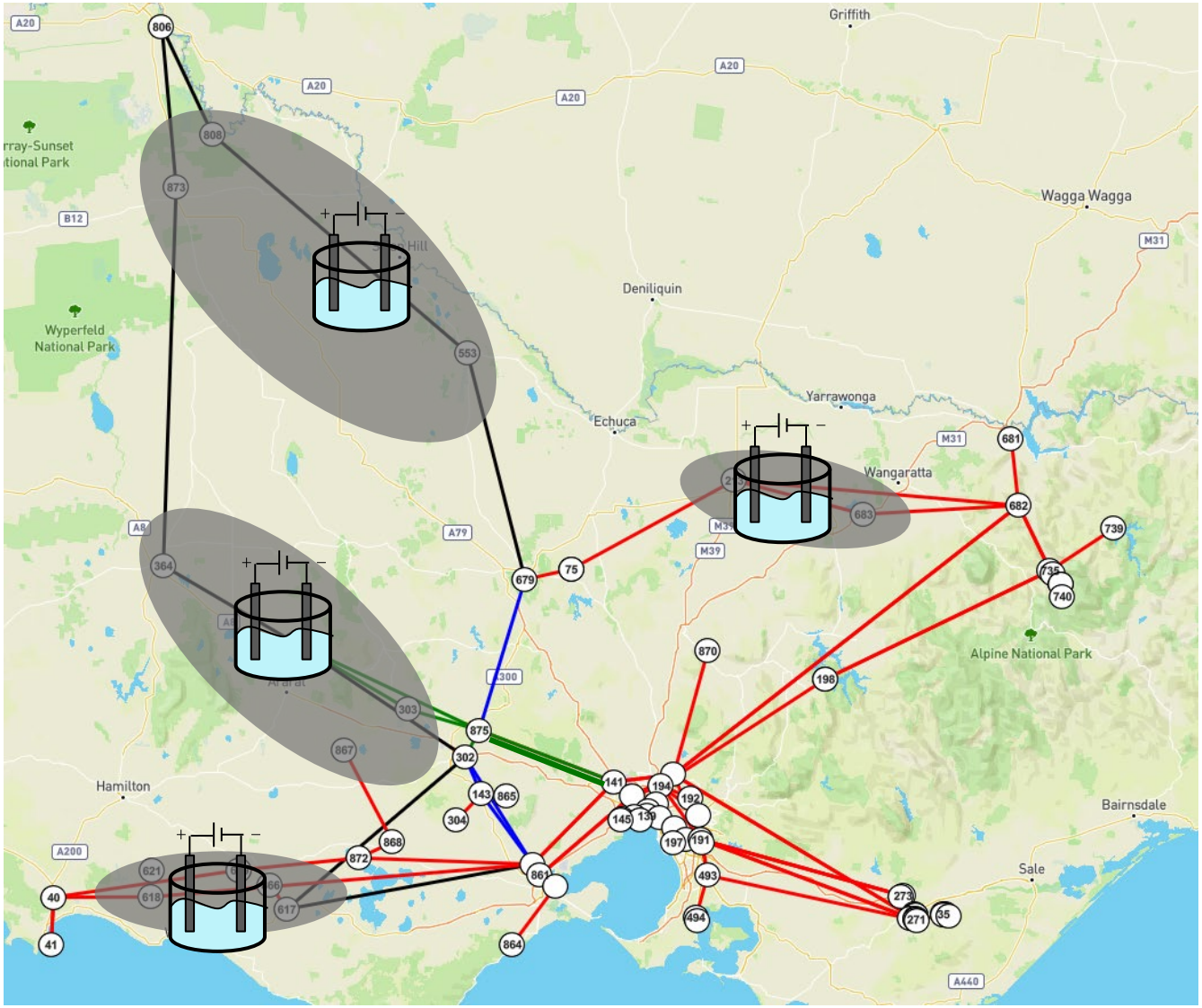
# Power-to-Gas (P2G): energy vector arbitrage and storage opportunity



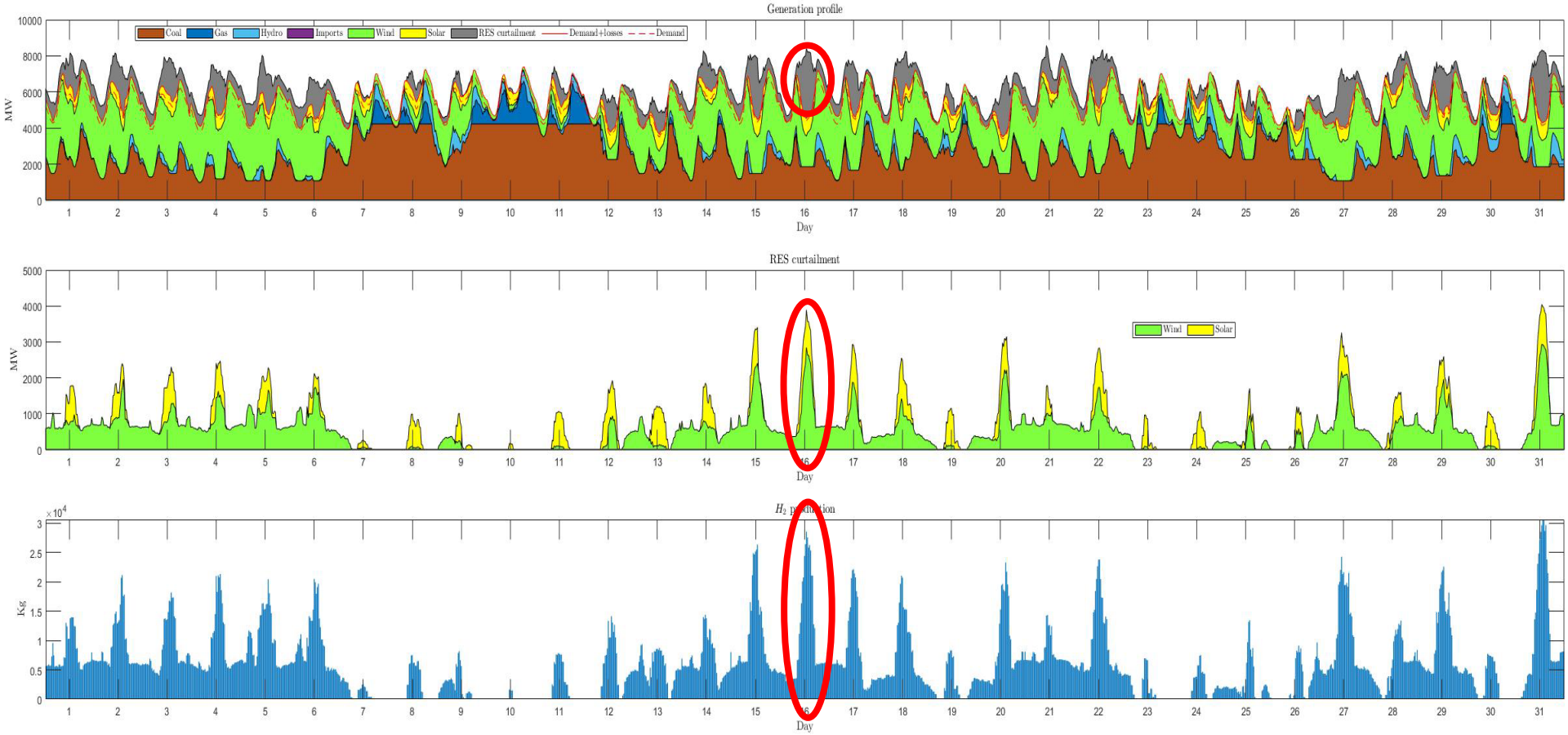

**GFG**: Gas-fired generators. **CHP**: Combined heat-and-power. **P2G:** Power to gas

S. Clegg and P. Mancarella, "Storing renewables in the gas network: modelling of power-to-gas (P2G) seasonal storage flexibility in low carbon power systems", *IET Generation, Transmission and Distribution*, vol. 10, Issue 3, 18 February 2016, p. 566 – 575.
S. Clegg and P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks", *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1234 - 1244, October 2015.

# P2G in the rombus of regret and green H2 injection from renewable energy zones



# H2 production:
# July 2025 (Scenario: Central)

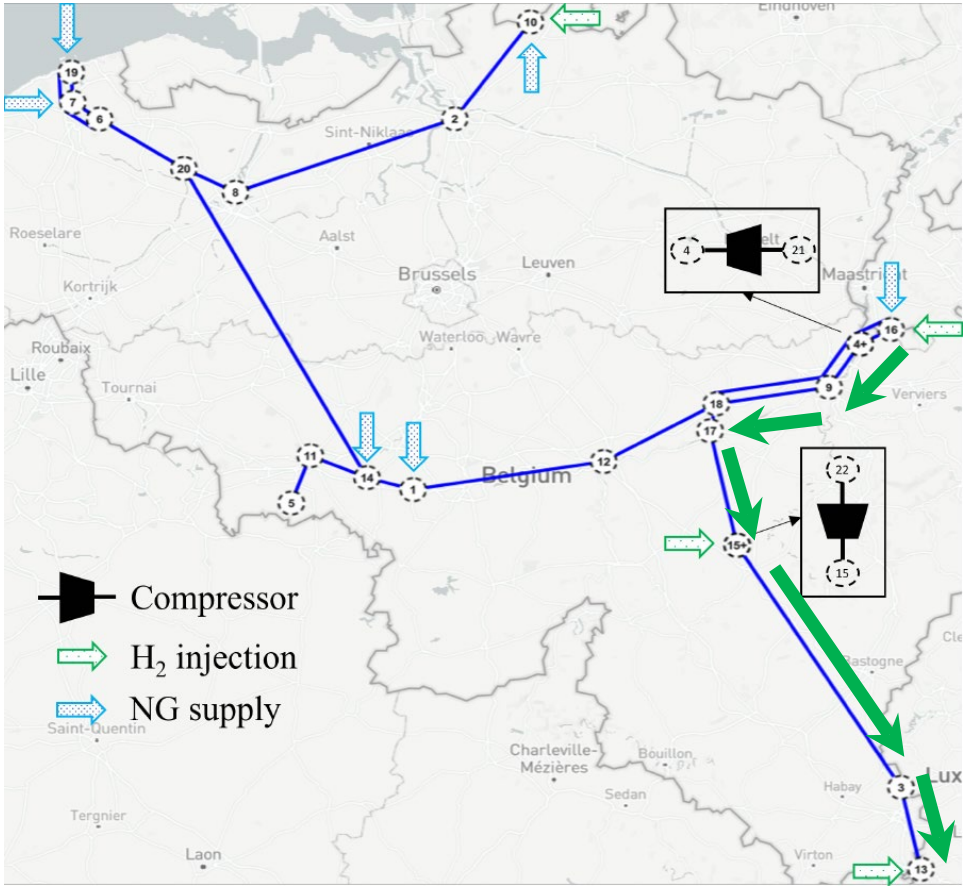


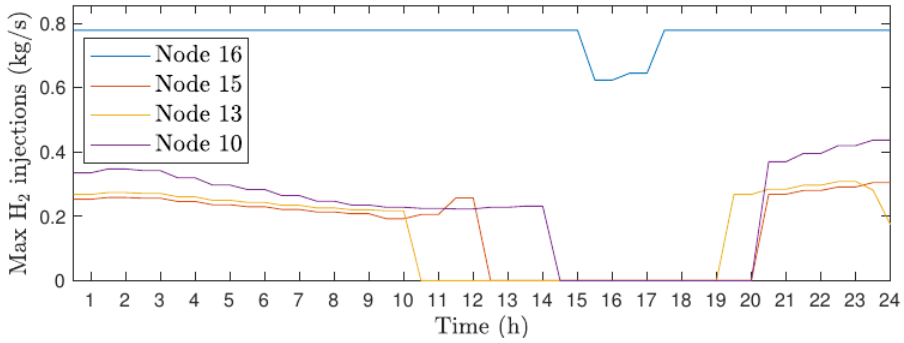

**But not all of this hydrogen can be used for network injection!**

I. Saedi, *et al.*, "Integrated Electricity and Gas System Modelling with Hydrogen Injections and Gas Composition Tracking", *Applied Energy*, 2021

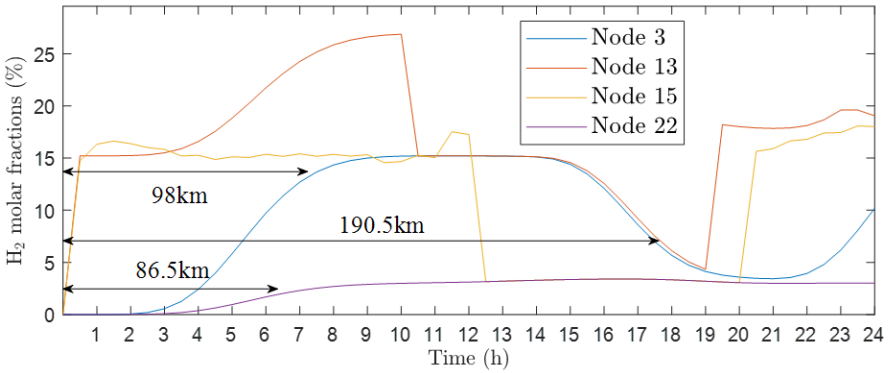
# $H_2$ concentration tracking

Belgian network case: $H_2$ path: nodes 16 —› 18 —› 17 —› 3 —› 13



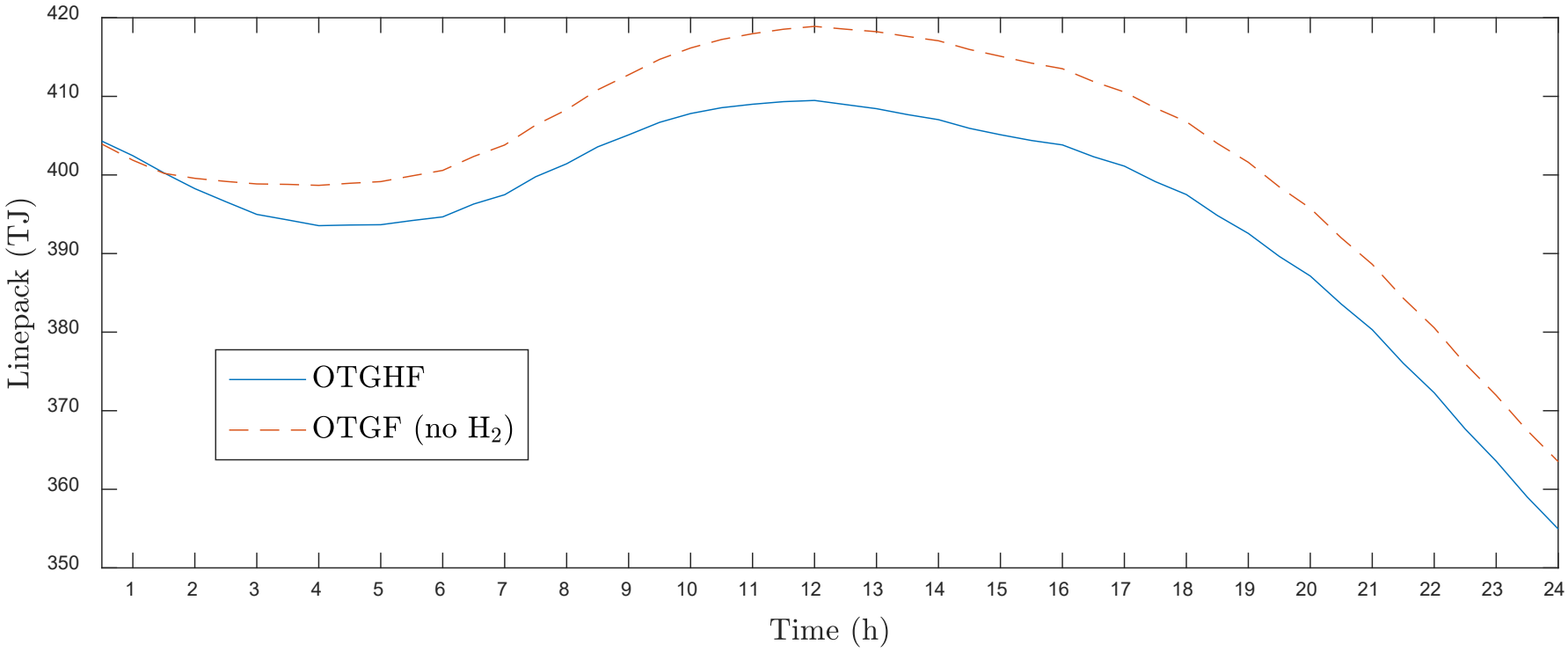

Profile of maximum $H_2$ injection rates from P2G




$H_2$ molar fractions (%)

S. Mhanna, I. Saedi, P. Mancarella, and Z. Zhang, "Coordinated operation of electricity and gas-hydrogen systems with transient gas flow and hydrogen concentration tracking ," Electr. Power Syst. Res., 2022.

# Effect of $H_2$ blending on the linepack

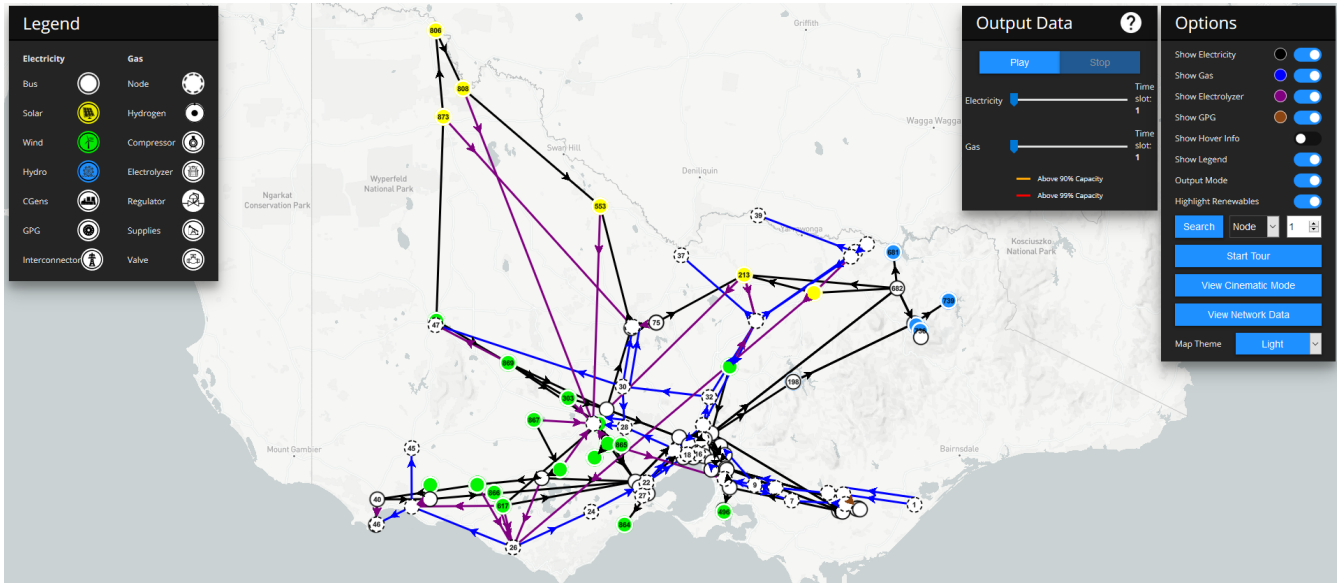


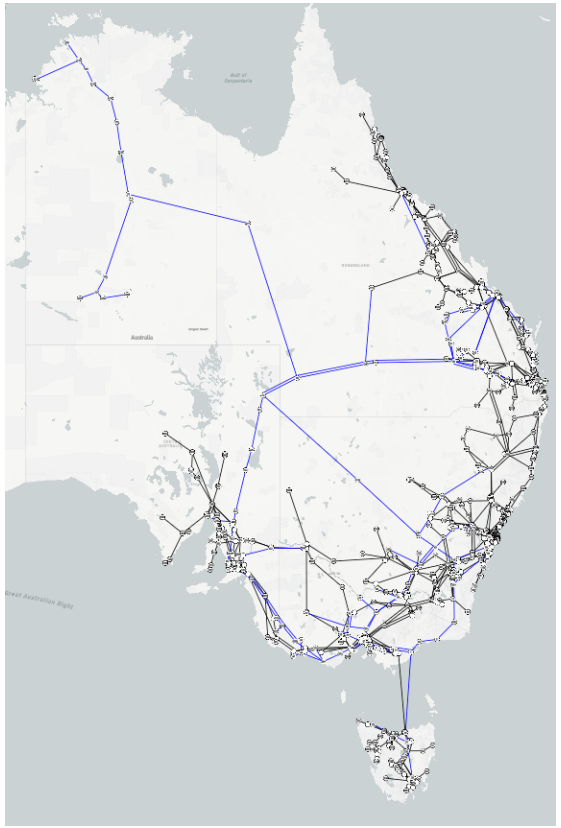

OTGHF: Optimal transient NG-$H_2$ flow

OTGF: Optimal transient NG flow

S. Mhanna, I. Saedi, P. Mancarella, and Z. Zhang, "Coordinated operation of electricity and gas-hydrogen systems with transient gas flow and hydrogen concentration tracking ," Electr. Power Syst. Res., 2022.
S. Clegg and P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems," in IEEE Transactions on Sustainable Energy, vol. 7, no. 2, pp. 718-731, April 2016.

# Integrated Electricity-Gas-Hydrogen system modelling tool



*Gas transient dynamics and quality tracking and constraints*


S. Mhanna, *et al.*, "Coordinated operation of electricity and gas-hydrogen systems with transient gas flow and hydrogen concentration tracking ," Electr. Power Syst. Res., 2022.

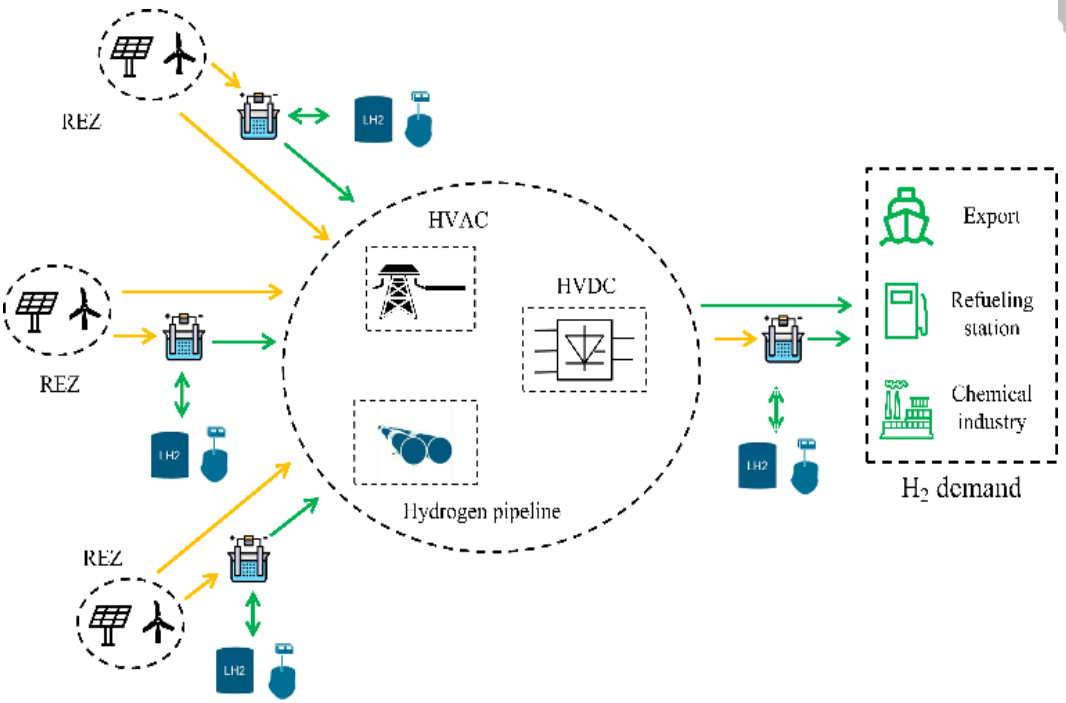
I. Saedi, *et al.*, "Integrated Electricity and Gas System Modelling with Hydrogen Injections and Gas Composition Tracking", *Applied Energy*, 2021

S. Mhanna, *et al.*, "Iterative LP-based Methods for the Multiperiod Optimal Electricity and Gas Flow Problem", *IEEE Trans. on Power Systems*, 2021

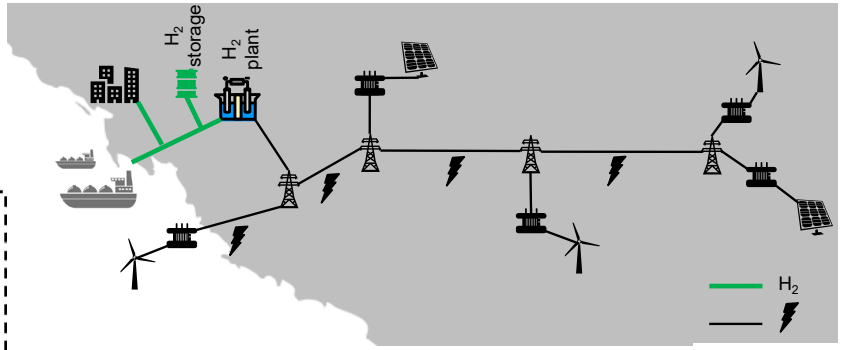
# Planning co-optimization of electricity and hydrogen infrastructures

## Key infrastructure research question:

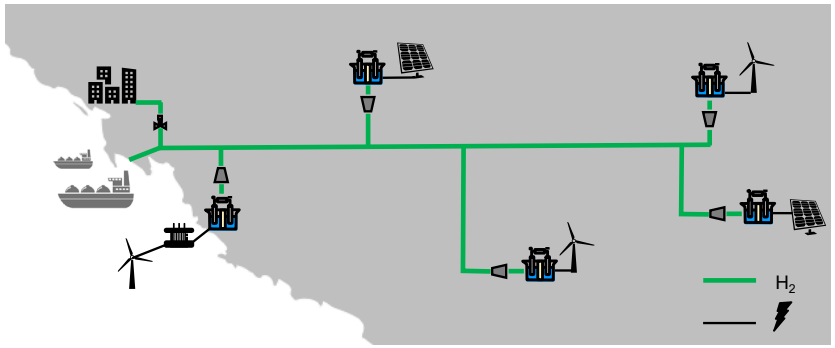
## *Do we move electrons or molecules?*




Centralised $H_2$ production…

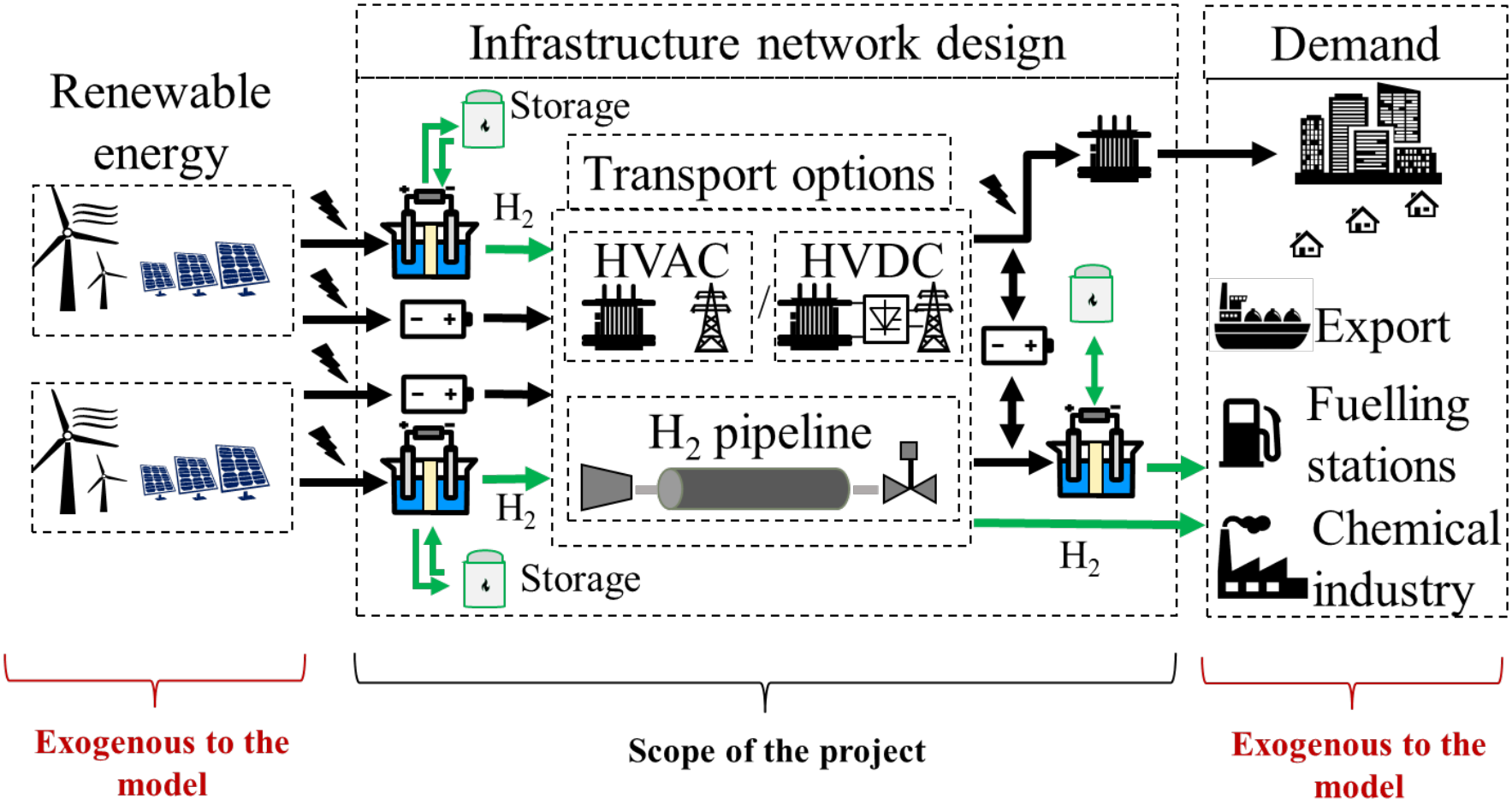



… or distributed?




S. Mhanna, I. Saedi, G. Liu, P. Mancarella, "Towards Optimal Integrated Planning of Electricity and Hydrogen Infrastructure for Large-Scale Renewable Energy Transport", in *Proceedings of the 11th Bulk Power Systems Dynamics and Control Symposium (IREP 2022)*, July 25-30, 2022, Banff, Canada

# Planning co-optimization of electricity and hydrogen infrastructures



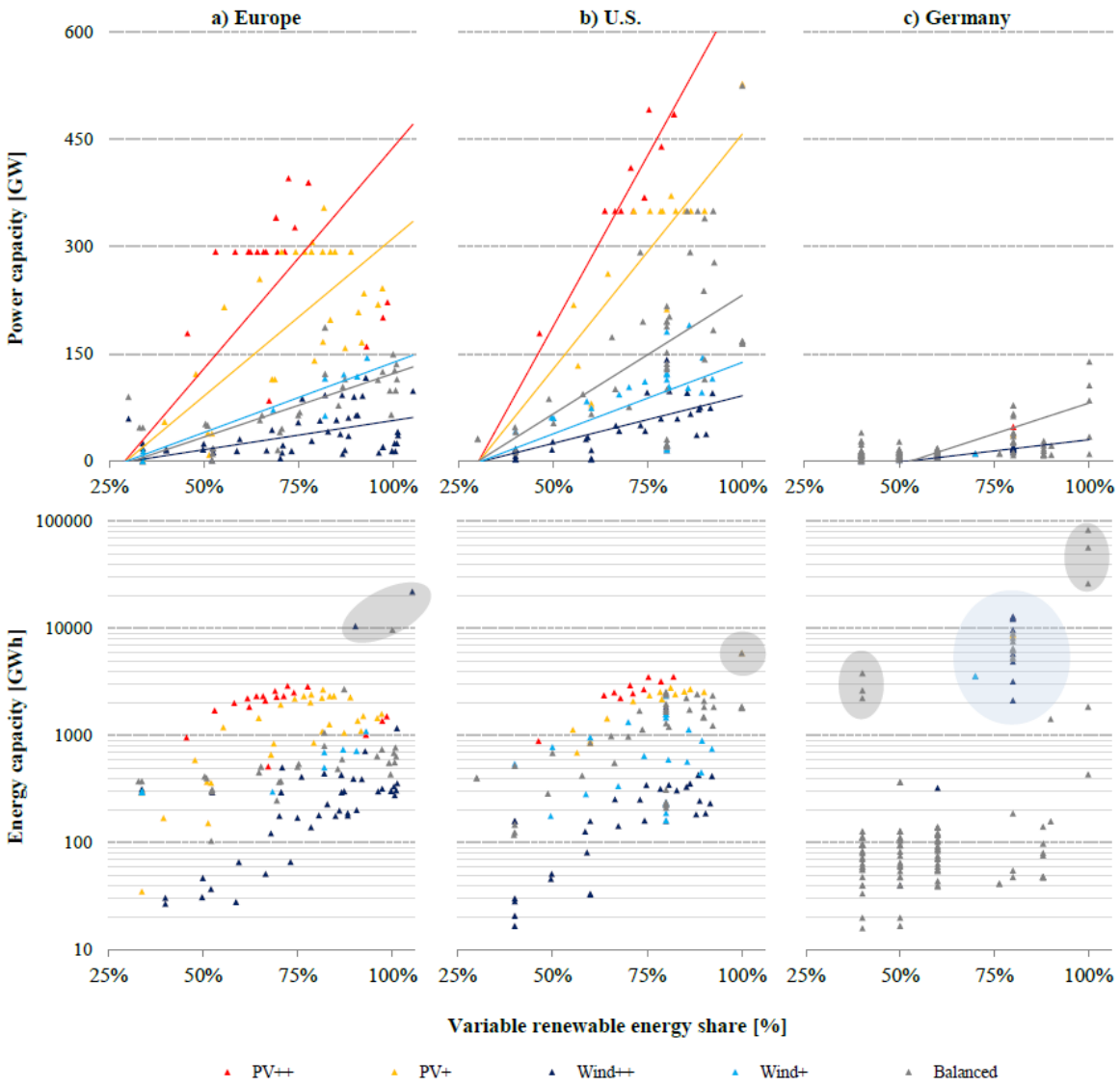

Courtesy of Future Fuels CRC

# How much and what storage do we need?

GW

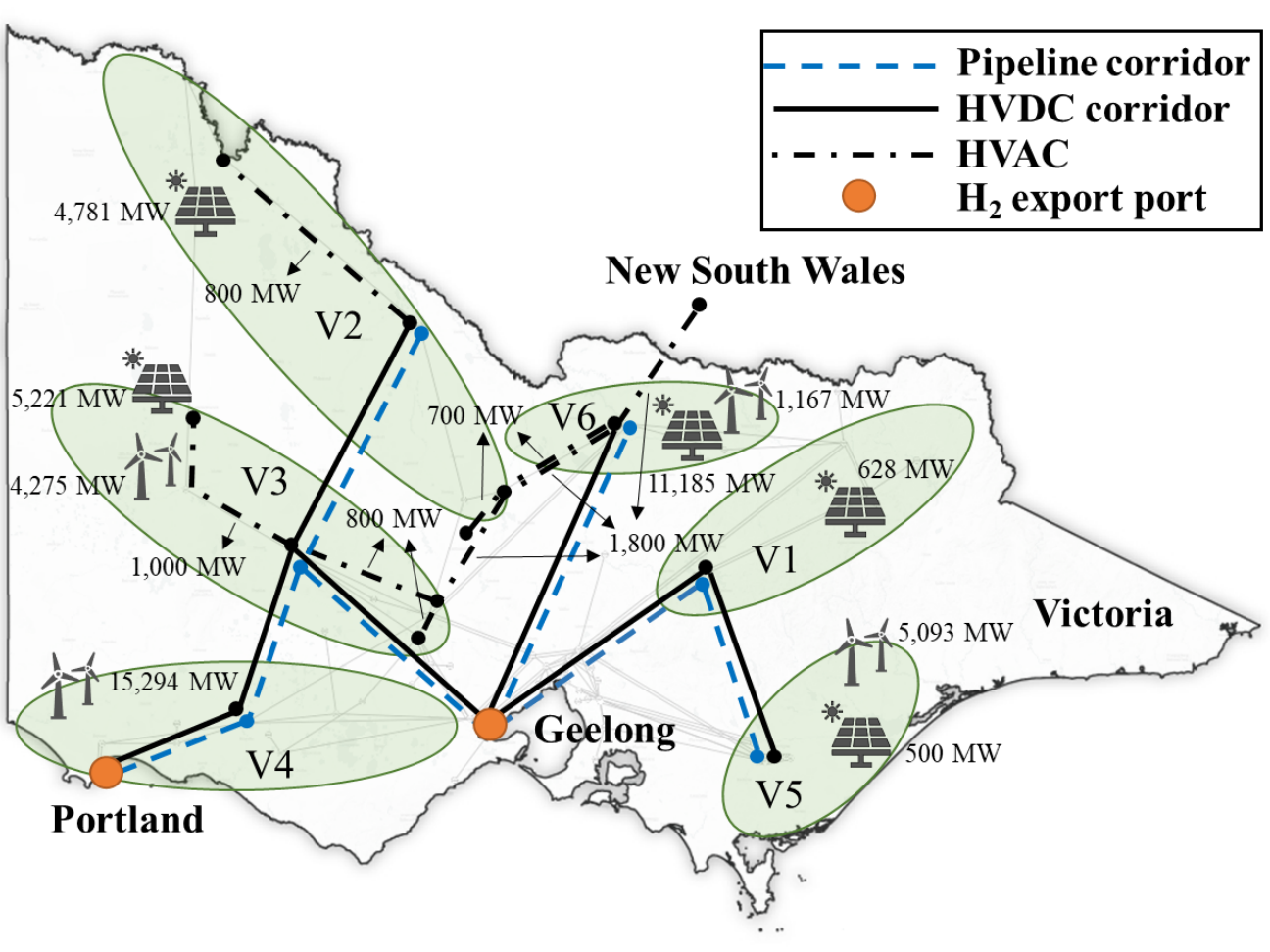
*Renewables penetration*

GWh



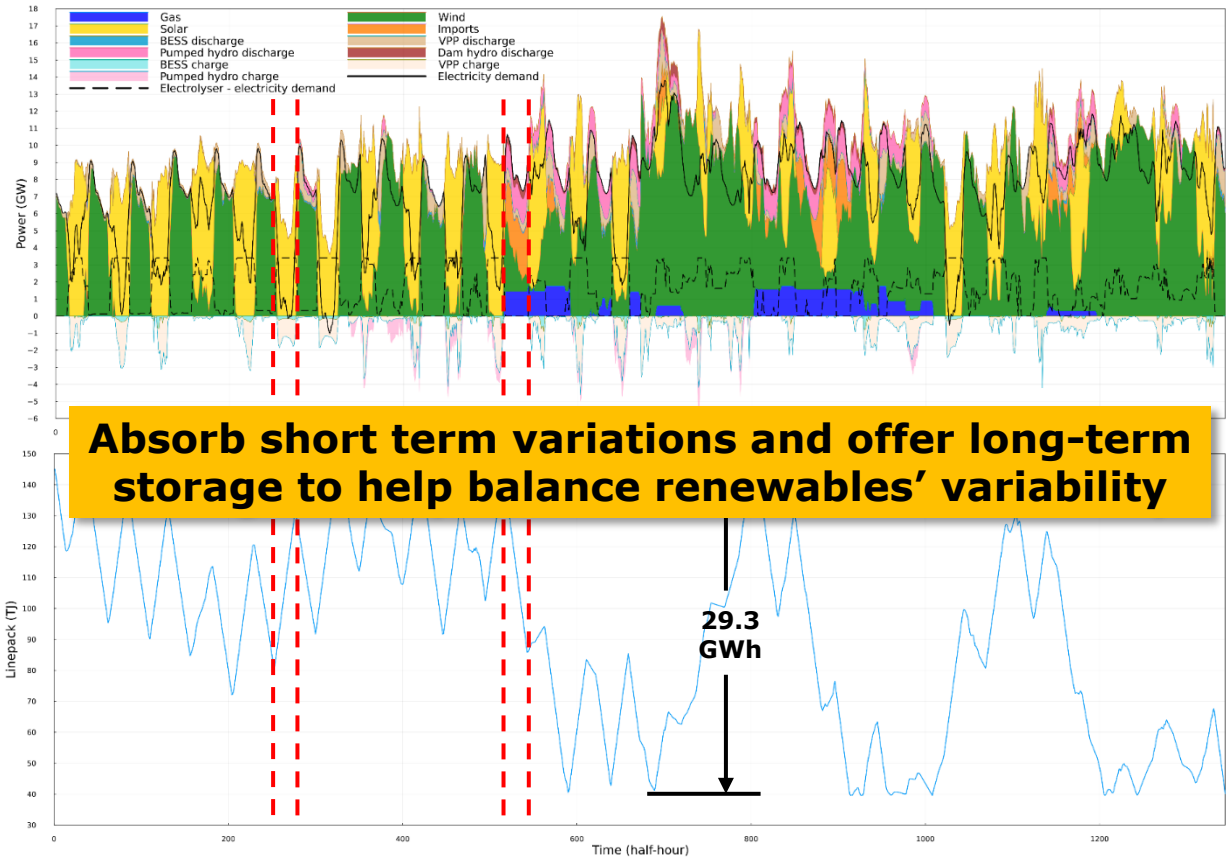

F. Cebulla, *et al.*, "How much electrical energy storage do we need?", *Journal of Cleaner Production*, Volume 181, 20 April 2018, 449-459

# Green energy, electrolyser, storage and infrastructure integrated planning




**HVAC**: High-voltage alternating current. **HVDC**: High-voltage direct current. **REZ**: Renewable energy zone.

# Example:
# A Victorian case study

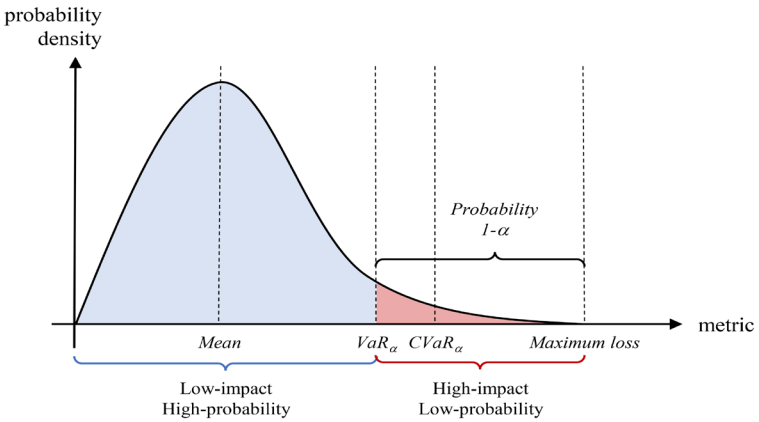


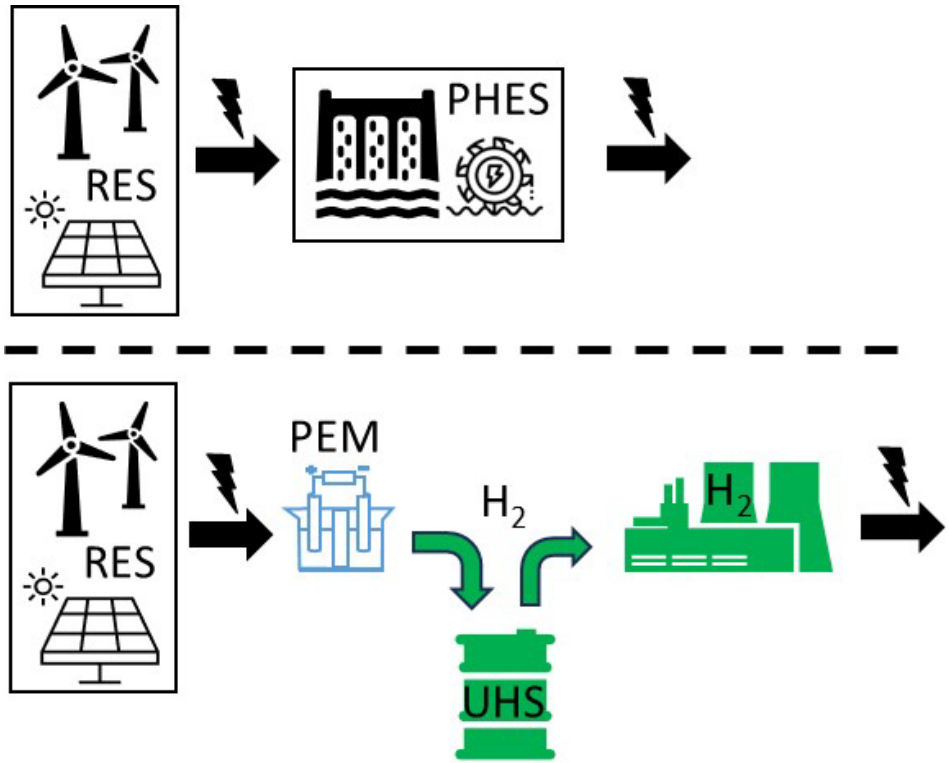

**Absorb short term variations and offer long-term storage to help balance renewables' variability**

**RES**: Renewable energy sources.

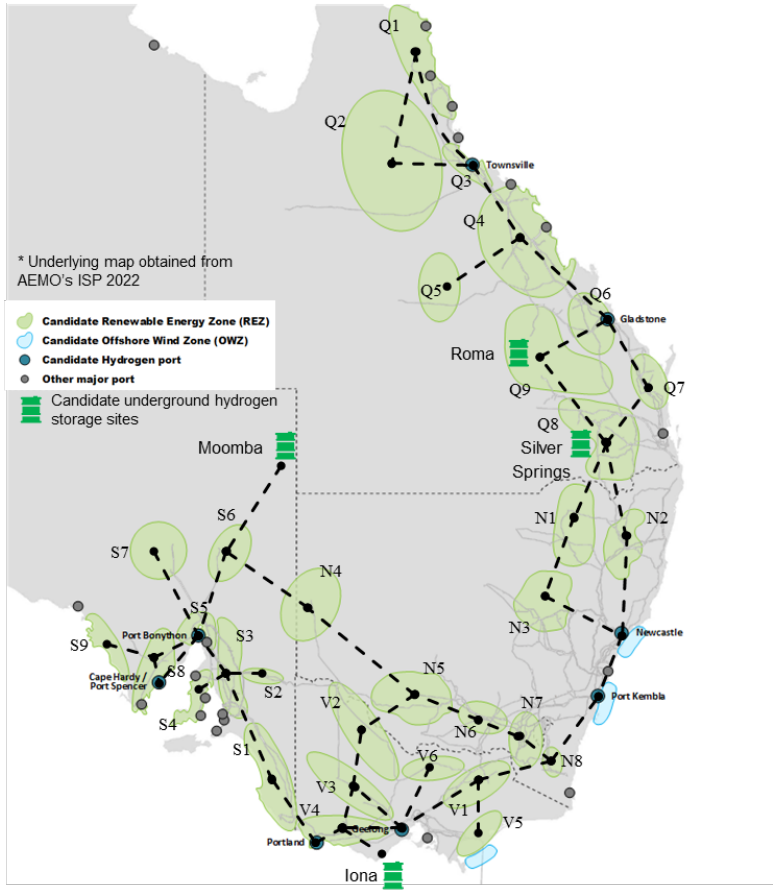
- **Surplus variable renewable energy (VRE)** → **$H_2$** → stored in the **pipeline**
- The **stored $H_2$** → **later supply** to export ports during times of high demand → **reduce reliance** on electricity imports
- **Linepack** plays an important role in managing the **variability** of RES due to the **storage capabilities** of the pipeline
- **More renewable energy** could potentially be built and alternative storage options cost avoided

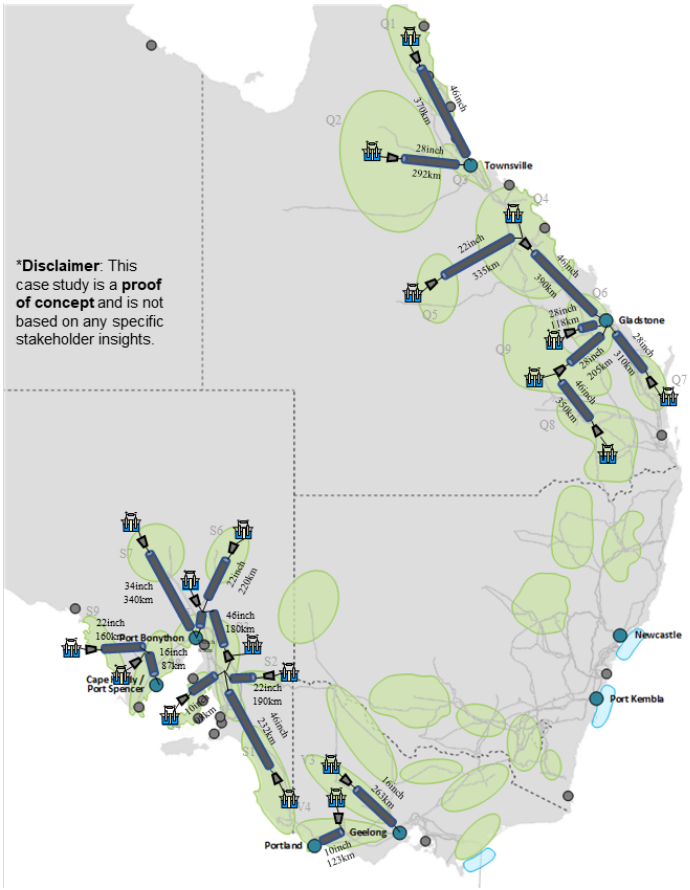
# Planning for the black swan



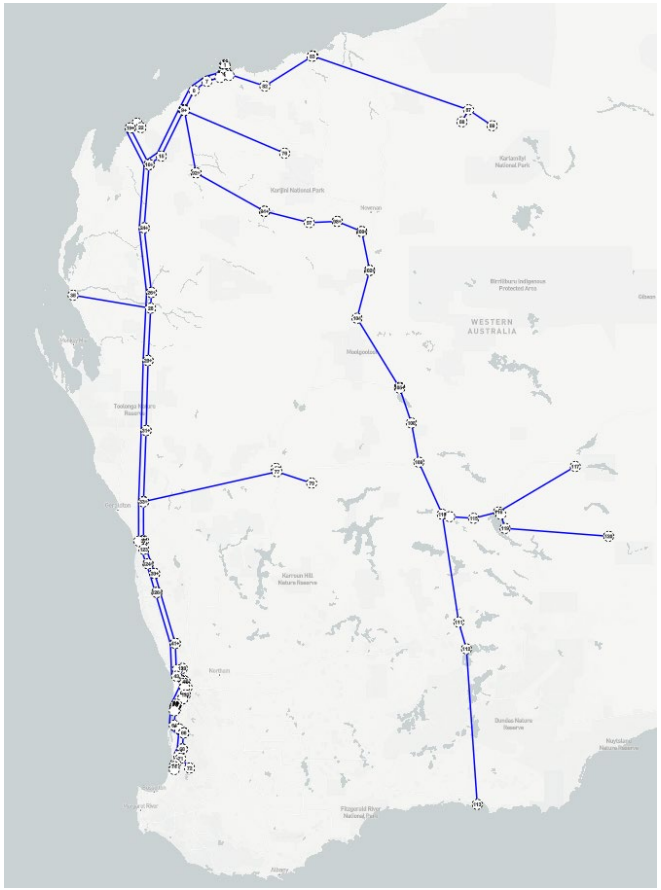
# Towards whole-system planning

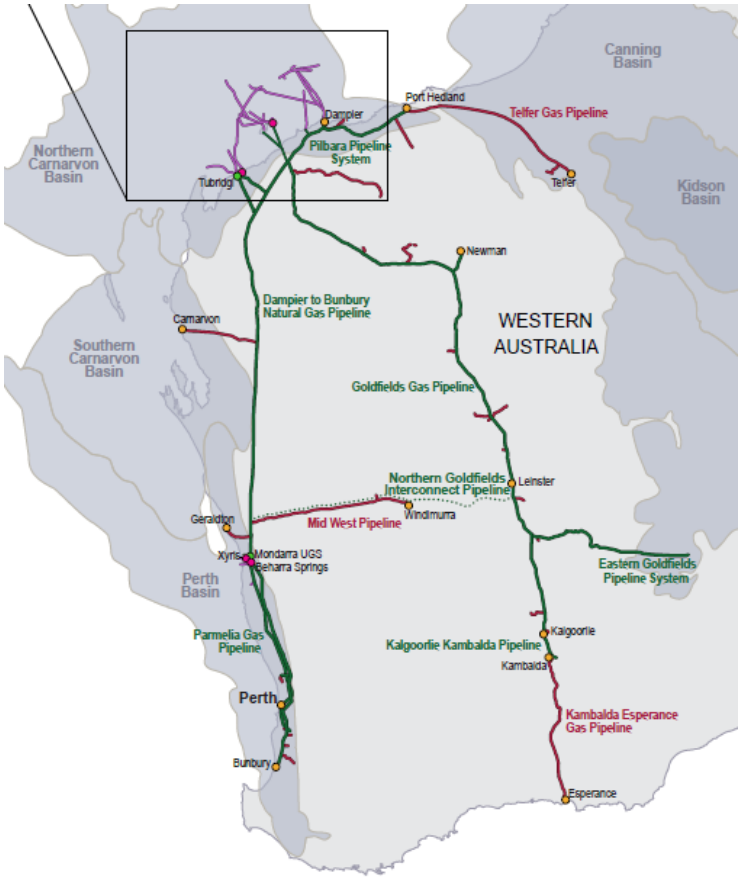


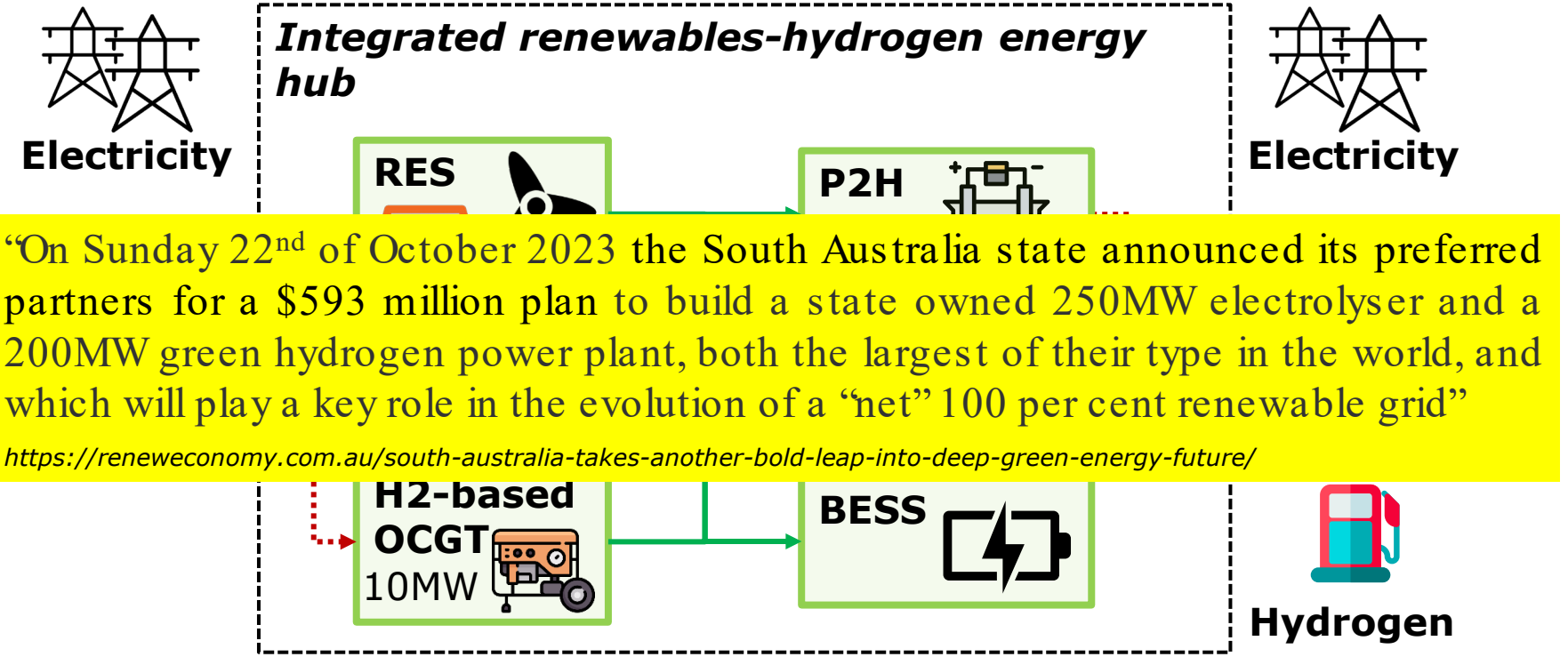

Courtesy of Future Fuels CRC

# And just in case you thought we are forgetting WA…





# Operation of the future grid: Renewables-storage hybrid plants

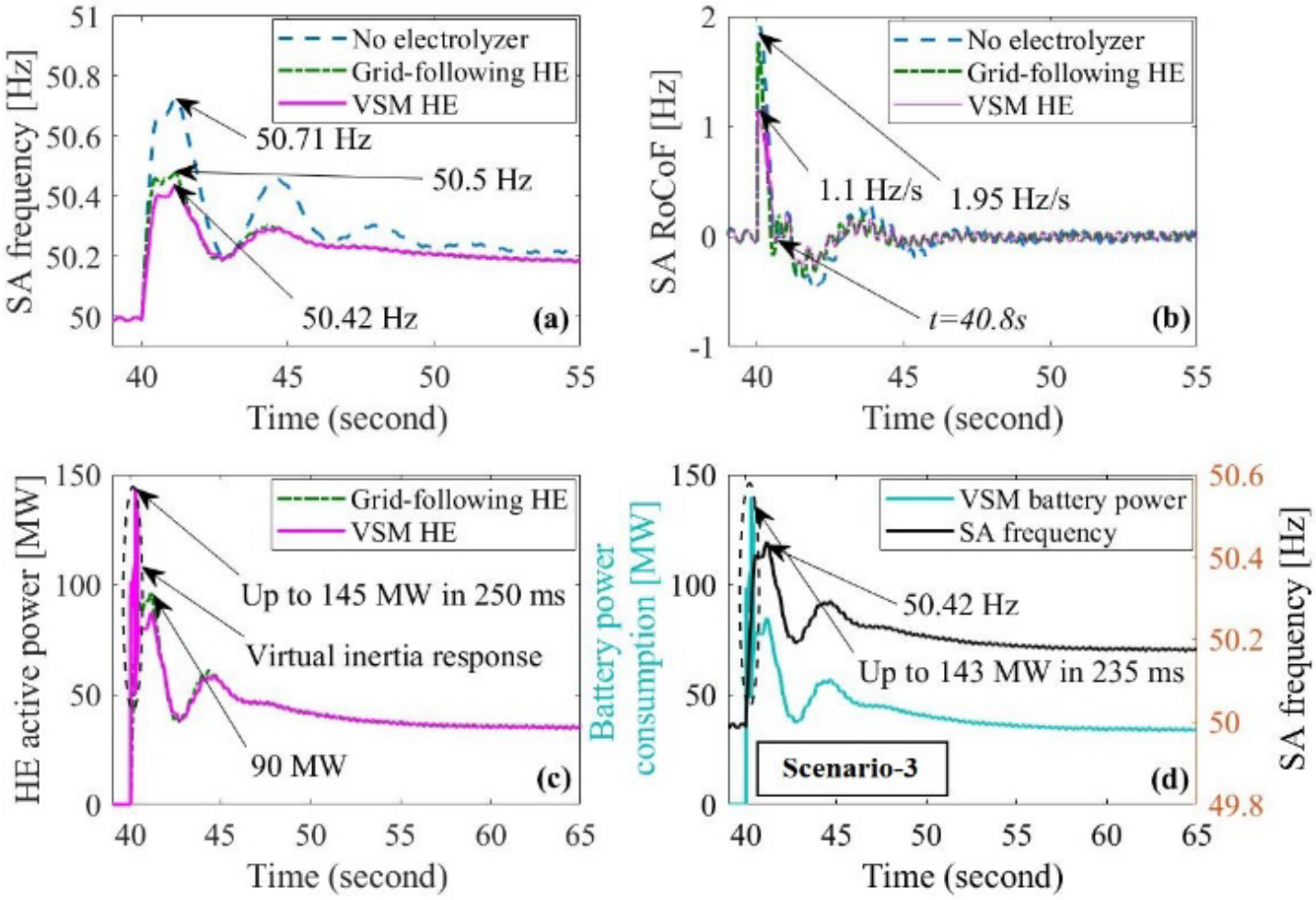



"On Sunday 22nd of October 2023 the South Australia state announced its preferred partners for a $593 million plan to build a state owned 250MW electrolyser and a 200MW green hydrogen power plant, both the largest of their type in the world, and which will play a key role in the evolution of a "net" 100 per cent renewable grid"

*https://reneweconomy.com.au/south-australia-takes-another-bold-leap-into-deep-green-energy-future/*

J. Naughton *et al.*, "Optimization of Multi-Energy Virtual Power Plants for Providing Multiple Market and Local Network Services", *Electric Power System Research*, 2020

# Not only batteries…



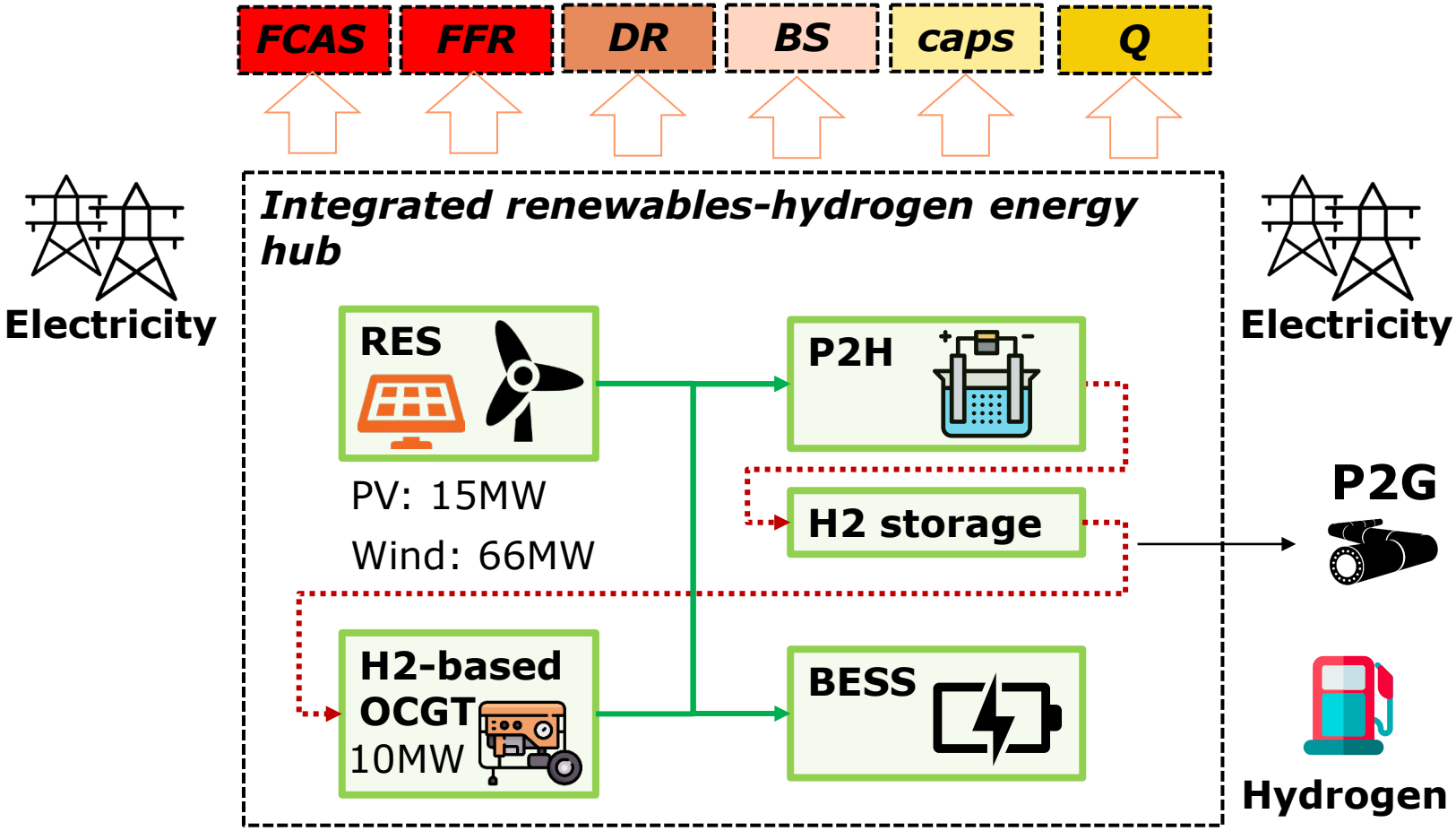


M. Ghazavi Dozein *et al.*, "**Virtual Inertia Response** and Frequency Control Ancillary Services from Hydrogen Electrolyzers", *IEEE Tran. on Pow. Syst*, 2022

M. Ghazavi, *et al.*, "**Fast frequency response** from utility scale hydrogen electrolysers", *IEEE Trans. Sustainable Energy*, 2021

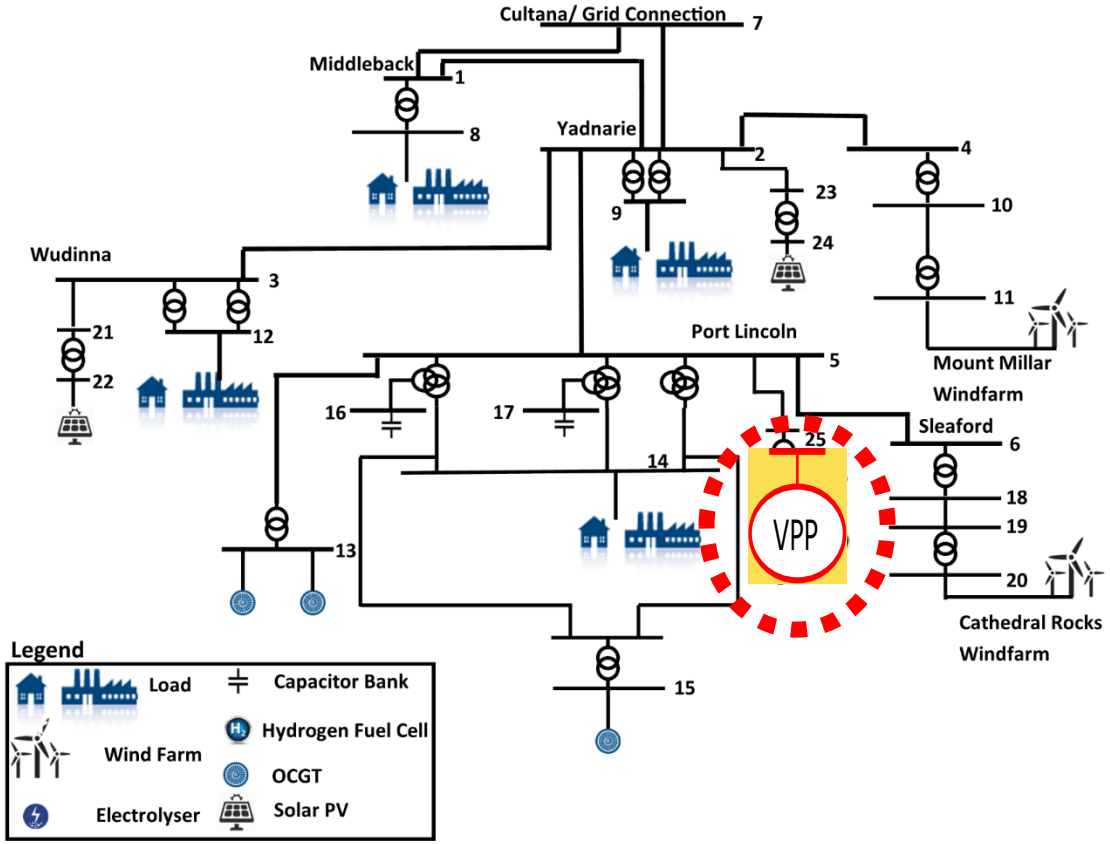
S. D. Tavakoli et al., "**Grid-Forming Services** From Hydrogen Electrolyzers", *IEEE Transactions on Sustainable Energy*, 2023

# Operation of the future grid: Renewables-storage hybrid plants




J. Naughton *et al.*, "Optimization of Multi-Energy Virtual Power Plants for Providing Multiple Market and Local Network Services", *Electric Power System Research*, 2020

# Hybrid VPP case study example




***Markets/Services***

*Wholesale Energy, FFR, FCAS, Hydrogen Export Contract, Local Voltage Support, Reactive Power Support to Grid*


J. Naughton, S. Riaz, M. Cantoni, X.P. Zhang and P. Mancarella, "Comprehensive Optimization-Based Techno-Economic Assessment of Hybrid Renewable Electricity-Hydrogen Virtual Power Plants," in *Journal of Modern Power Systems and Clean Energy,* 2022

J. Naughton, H. Wang, S.Riaz, M. Cantoni and P. Mancarella, "Optimization of multi-energy virtual power plants for providing multiple market and local network services." Electric Power Systems Research vol. 189: 106775, 2022

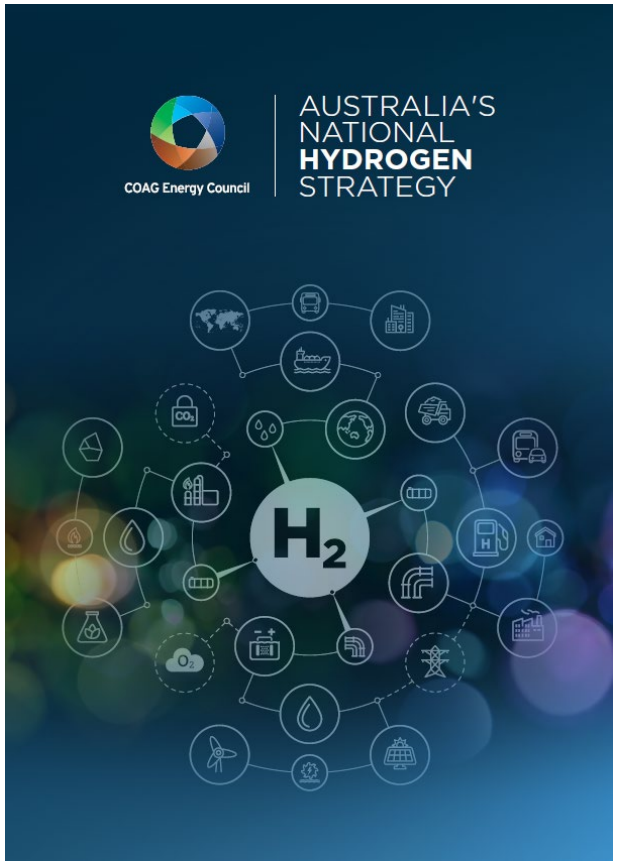
# Some interesting considerations

- Huge **multi-energy flexibility** potential
- Ability and opportunity to **arbitrage across energy vectors** and markets
- Effective **multi-commodity price risk hedge**
- Multiple markets/services and **value-stacking** co-optimization unlock additional revenue and additional hydrogen production
- Participating in multiple markets **reduces the net cost of hydrogen** production

# Concluding remarks

- **Increasing complexity but also opportunities** from integrated energy systems and markets
- **Renewables-based hybrid electricity-$H_2$ systems** have the opportunity to deploy **high flexibility**, provide **multi-commodity services**, participate in **multiple markets**, and **risk-hedge** against price volatility and uncertainty and network constraints
- Future **integrated electricity-H2 systems/markets** need to develop in a **coordinated way** and can highly benefit from each other
- It will be important to understand the potential use of existing **gas infrastructure** and **integrated infrastructure developments**
- *Ongoing research is being supported by the **Future Fuels CRC,** which I gratefully acknowledge*

# Back to the future!




*"Water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.*

*Someday the coal-rooms of steamers and the tenders of locomotives will, instead of coal, be stored with these two condensed gases, which will burn in the furnaces with enormous calorific power."*

*Jules Verne, "The Mysterious Island",1874*

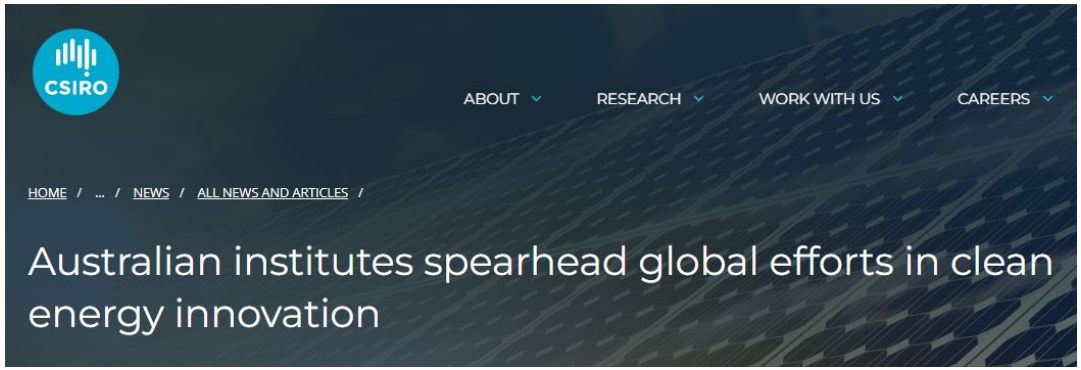
Source: COAG Energy Council, *Australia's National Hydrogen Strategy*, November 2019

# New US-UK-Australia NSF Global Centre in Climate Change and Clean Energy

## *Electric Power Innovation for a Carbon-free Society (EPICS)*

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

# Thank you!

# Any Questions?

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# Integrated electricity-gas-hydrogen systems: Techno-economic modelling, challenges, and opportunities

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SOERC, Perth, 14th February 2024