Hydrogen Electrolysis Plants: Fundamentals, Modelling, and System Impact Studies

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From the Land Down Under!

Monash University

Monash Engineering rankings

#1

Engineering

Ranked #1 in Australia for engineering, Times Higher Education (THE) World University Rankings 2023.

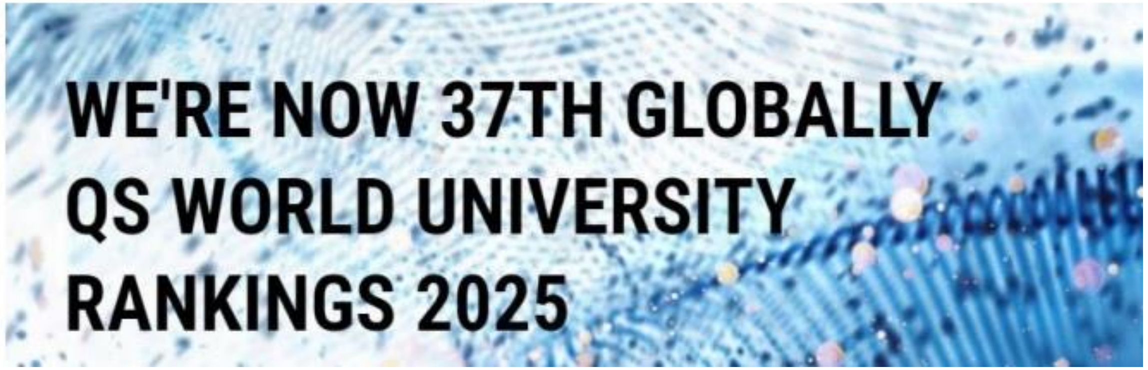
#39

Engineering and Technology

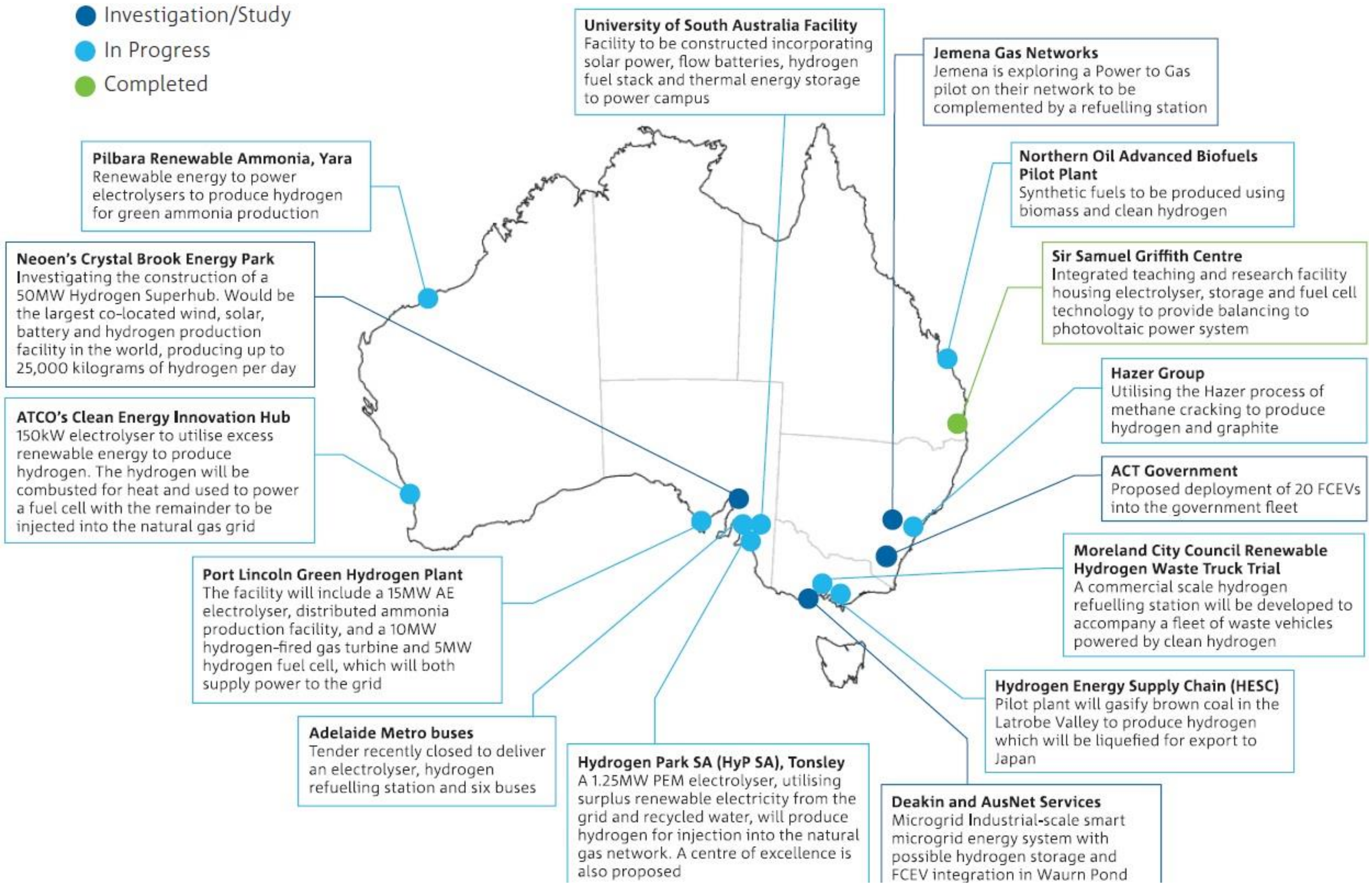
Ranked #39 in the world for engineering and technology, QS World University Rankings by Subject 2022.

Go8 Members

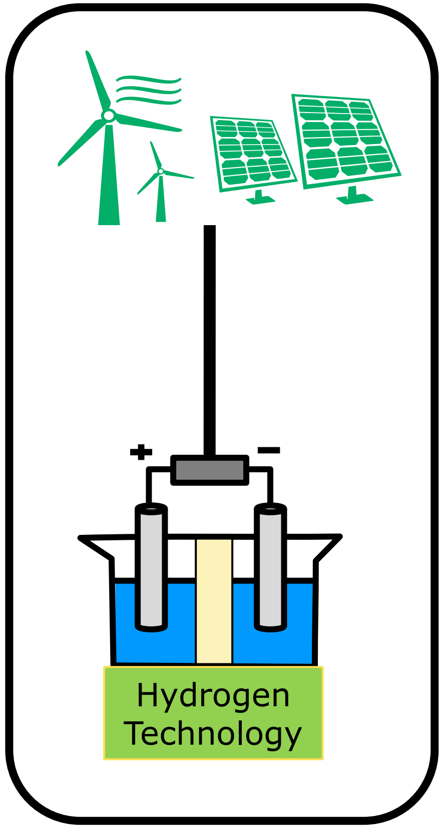
Monash University is a member of Australia's prestigious Group of Eight universities.



Hydrogen in Australia



From an Electrical Network Perspective!

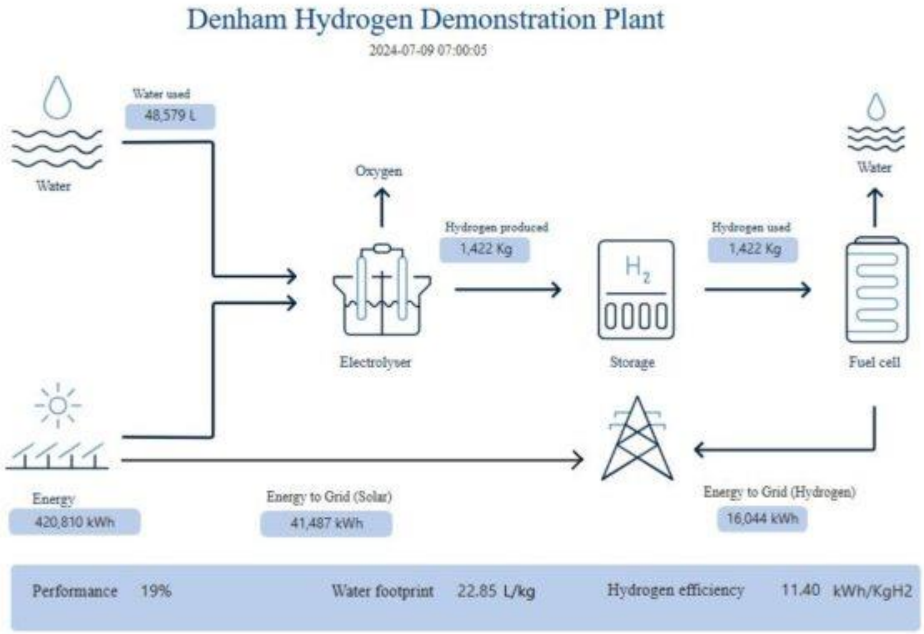


Off-grid (micro-grid)

Real-life Example: Denham Project in Western Australia

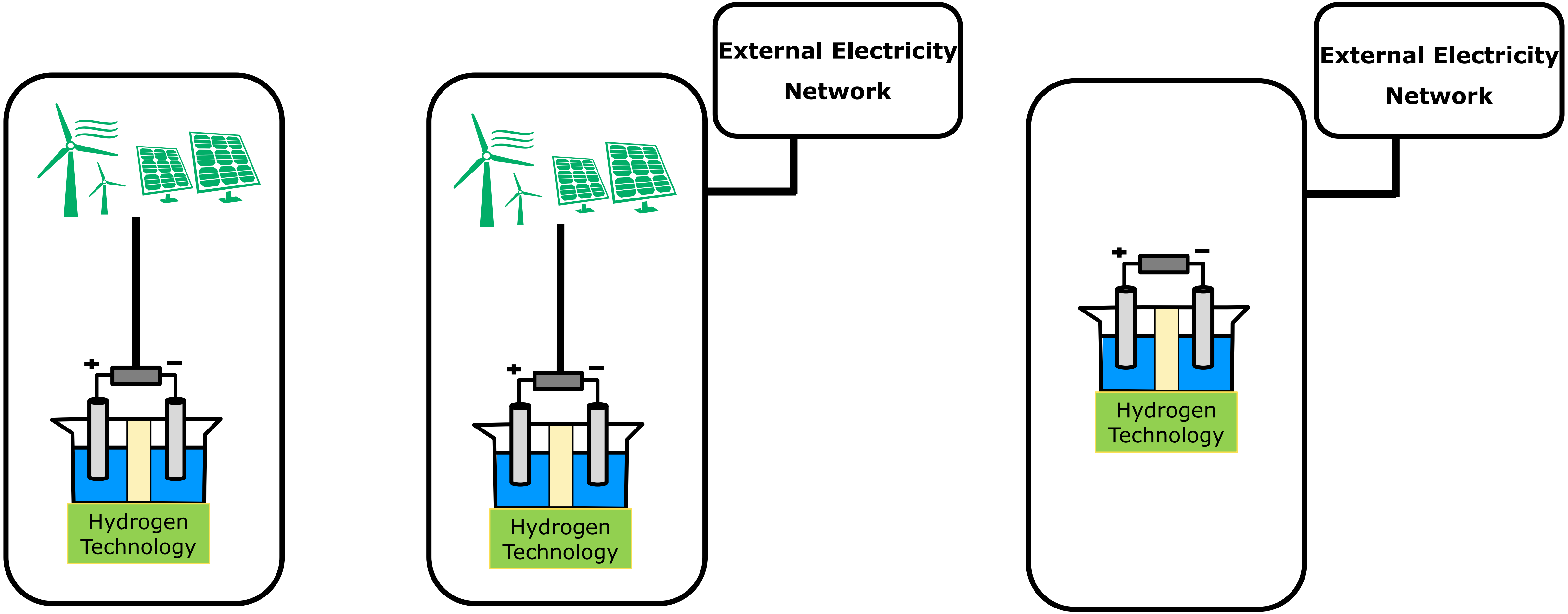
- 705 kW (DC capacity) solar farm
- 2x 174 kW of PEM electrolysers producing 5.4 kg H_2/h
- H_2 tank of 260 kg capacity under a 300-bar pressure
- 100 kW of fuel cell
- Aim: Enhance technology and commercial readiness for renewable hydrogen energy, fostering understanding of its application in microgrids

https://www.wa.gov.au/system/files/2024-06/denham_hydrogen_demonstration_project.pdf



https://www.pv-magazine.com/2024/07/09/horizon-power-unveils-solar-hydrogen-microgrid-in-western-australia/

From an Electrical Network Perspective!

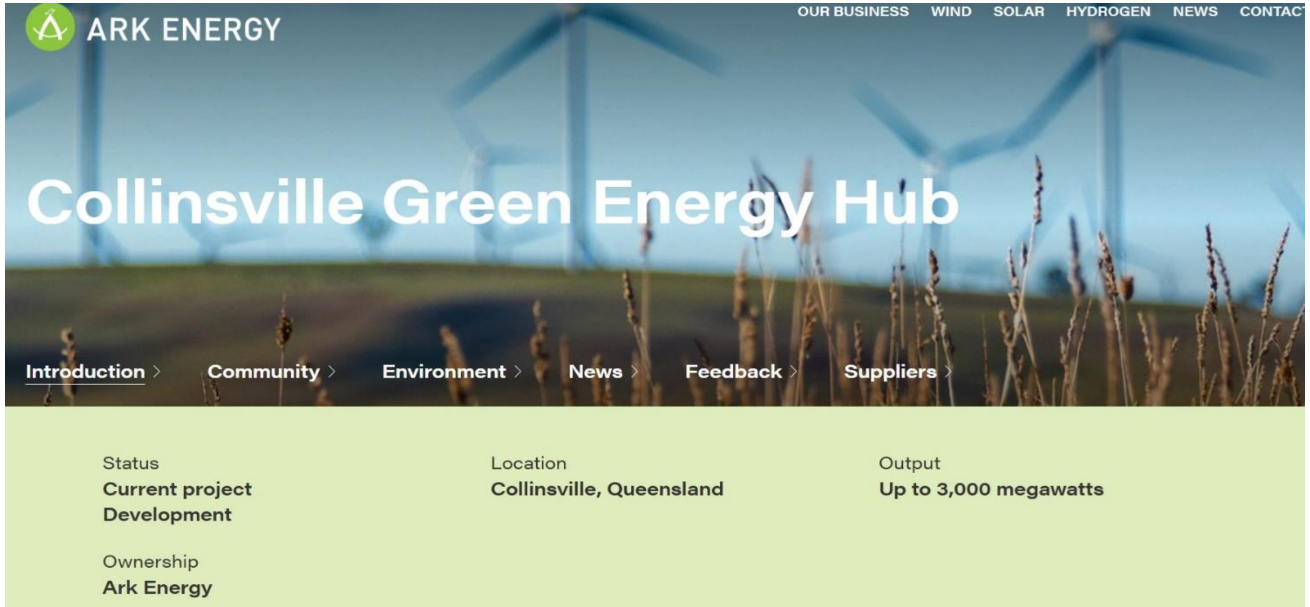


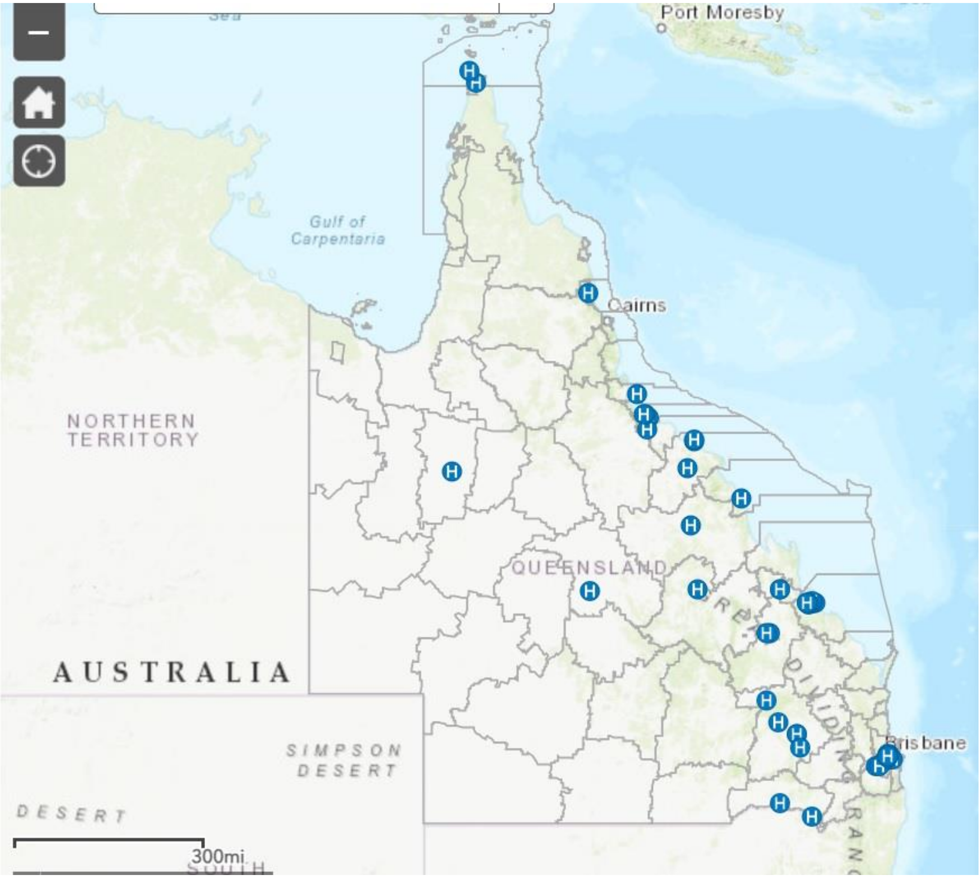
Off-grid (micro-grid) **Hybrid (e.g., grid-connected H_2 hub)** **Grid-connected electrolyser**

Real-life Example: Collinsville Green Hub in Queensland

- GW-scale electrolyser next to a GW-scale wind farm!

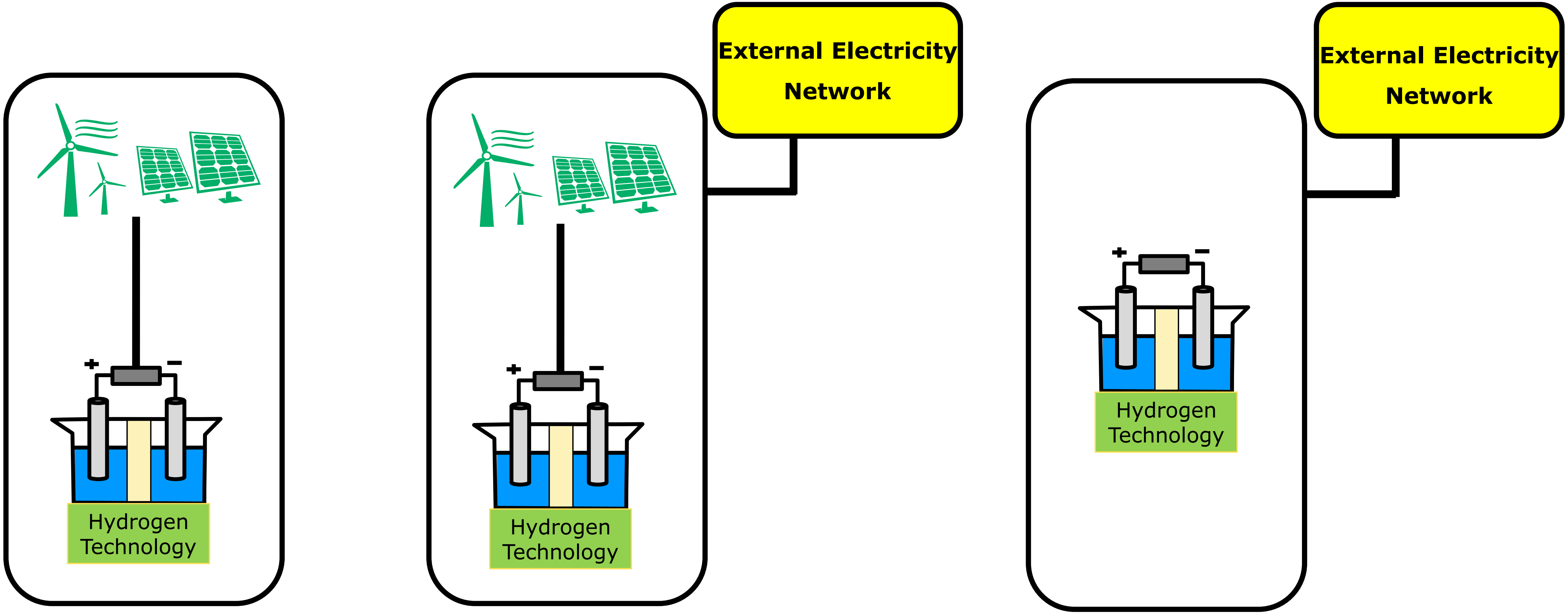
- In feasibility study stage!





https://arkenergy.com.au/wind/collinsville-green-energy-hub/

From an Electrical Network Perspective!

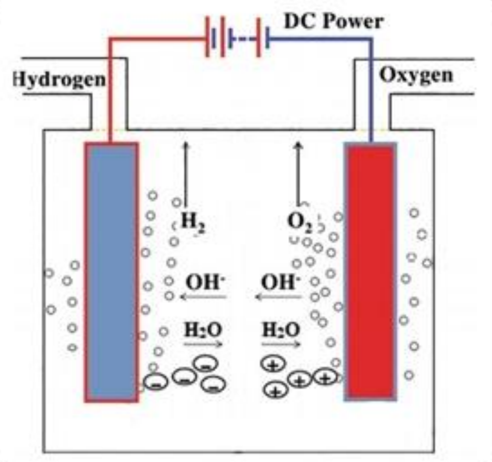


Off-grid (micro-grid) **Hybrid (e.g., grid-connected H_2 hub)** **Grid-connected electrolyser**

It is more than just Electrical Network Integration!

- ✓ Back-to-back converters
- ✓ DC-DC converters
- ✓ DC-AC converters

Electrolysis stack



Downstream H_2 storage/process ⟷ H_2 ⟷ Electrolysis stack ⟷ *DC power* ⟷ **Power-electronics interface** ⟷ *Power* ⟷ **External grid**

Wide range of applications!

- ✓ Large-scale
- ✓ Small-scale

- ✓ Proton Exchange Membrane (PEM)
- ✓ Alkaline
- ✓ Solid Oxide

- ✓ AC bulk power system (transmission, renewable-rich, low-inertia)
- ✓ DC/AC micro-grids, distribution networks
- ✓ DC-link in renewables (PV, wind)

System-Level Issues with Large-Scale Electrolyser Integration

(Large Load Integration)

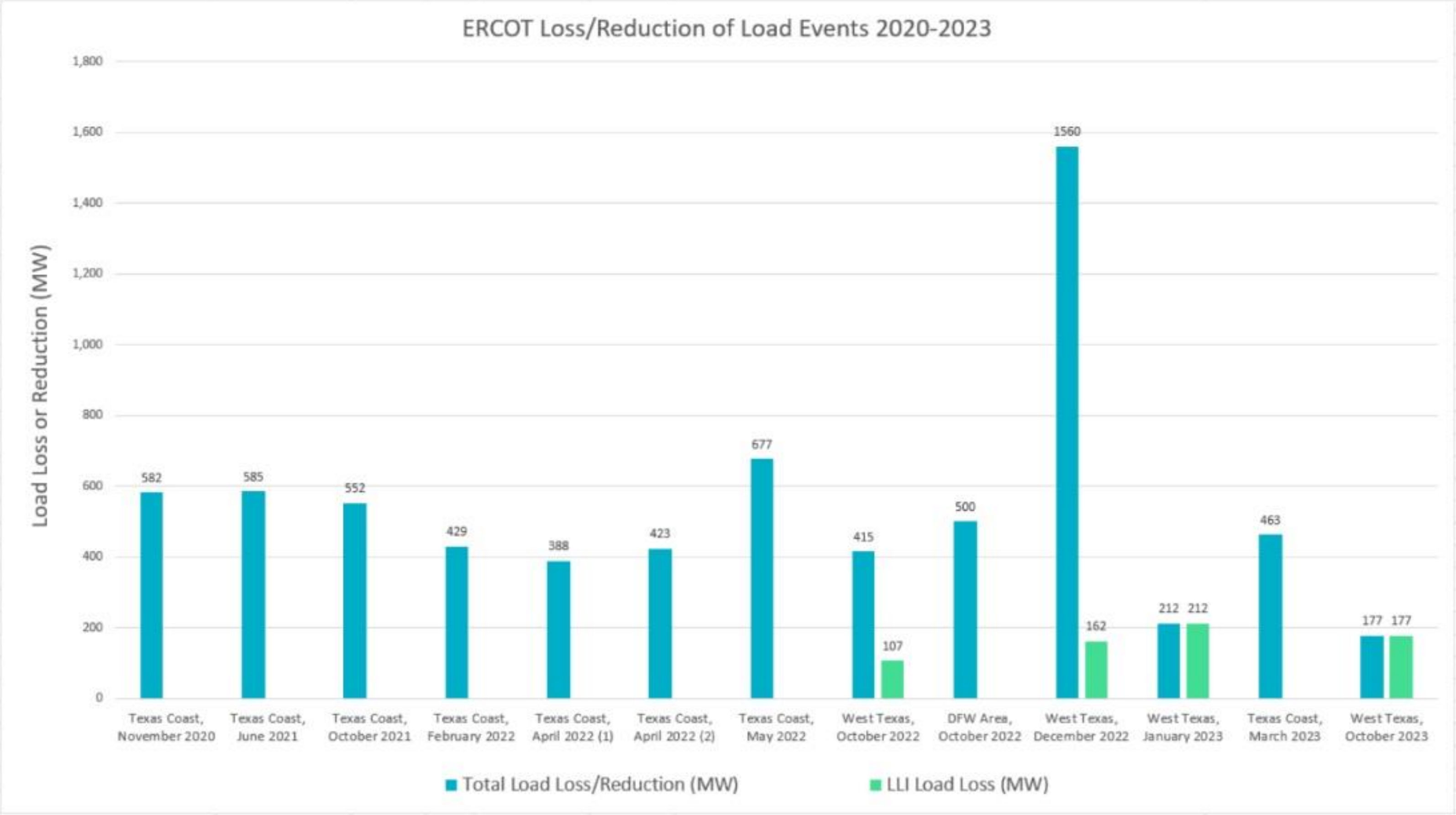
AEMO Stability Project

Conceptual Review of Stability for Power System Operation Under High IBR Futures

Principal Investigators: Prof. David Hill, Assoc Prof. Behrooz Bahrani, Dr. Mehdi Ghazavi Dozein

Large Load Tripping and System Disconnections (1/3)

Large load tripping events in ERCOT



Issues with System Interconnection of Electrolysers (2/3)

Grid-code requirements?!!!

AEMC

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

National Electricity Rules
Version 216

Status Information

This is the latest electronically available version of the National Electricity Rules as at 5 September 2024.

NATIONAL ELECTRICITY RULES
VERSION 216

CHAPTER 5
NETWORK CONNECTION ACCESS, PLANNING AND EXPANSION

5. Network Connection Access, Planning and Expansion

Do we have grid-code requirements for large-scale electrolysers?

Issues with System Interconnection of Electrolysers (3/3)

Modelling Requirements?!!!

Steady State Studies

System strength evaluations

Congestion studies

Fault current evaluation

Low flow/Thermal loading

Voltage control analysis

Reactive power capability

Contingency analysis

PV/QV analysis

Dynamic Studies

PSSE/PSCAD benchmarking

OEM model tuning and troubleshooting

NEM compliance testing

Event investigation studies

Rid-through operation studies

System-wide dynamic studies

Power Quality Studies

According to TNSP/DNSP/AEMO/NER (S5.2.5) requirements for grid connection evaluations:

Harmonics and Filter Design

Audio Frequency Injection

Flicker

Voltage Unbalance

Registration and Testing Package Studies

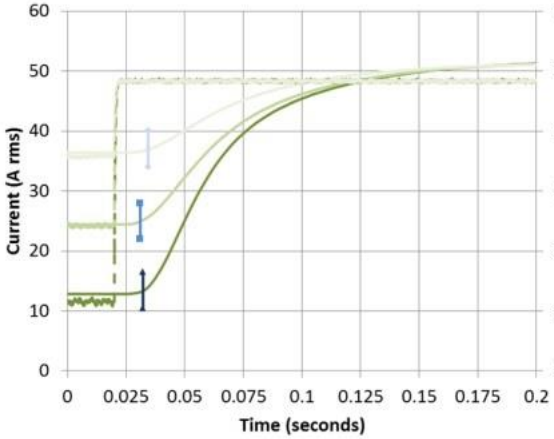
R1 package – including power system and detailed design

Hold point test simulations and troubleshooting.

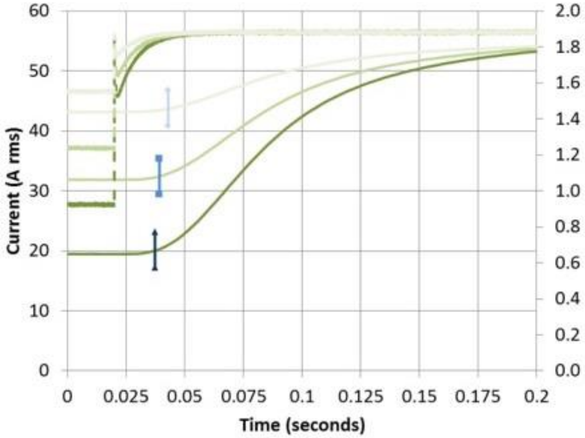
R2 – Validation and GPS Compliance Testing

Do have modelling framework available for grid connection studies of electrolysers?

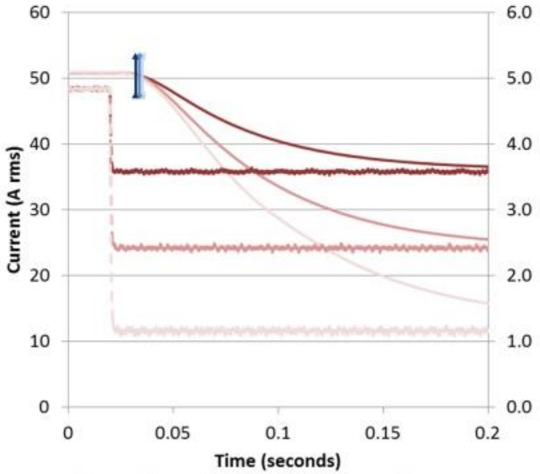
Electrolyser Modelling is NOT just about Inverter Modelling!



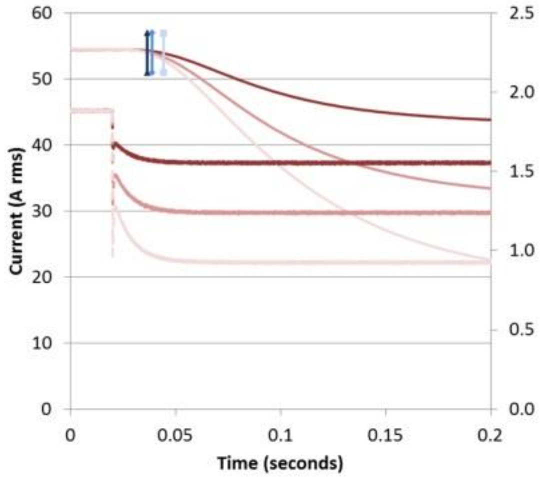
Ramp-up tests for PEM electrolyzer



Ramp-up tests for alkaline electrolyzer



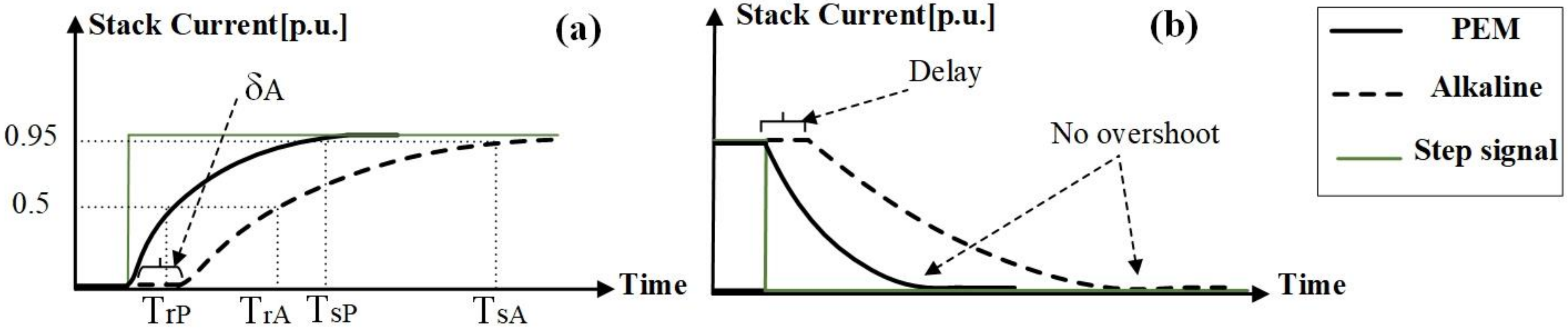
Ramp-down tests for PEM electrolyzer



Ramp-down tests for alkaline electrolyzer

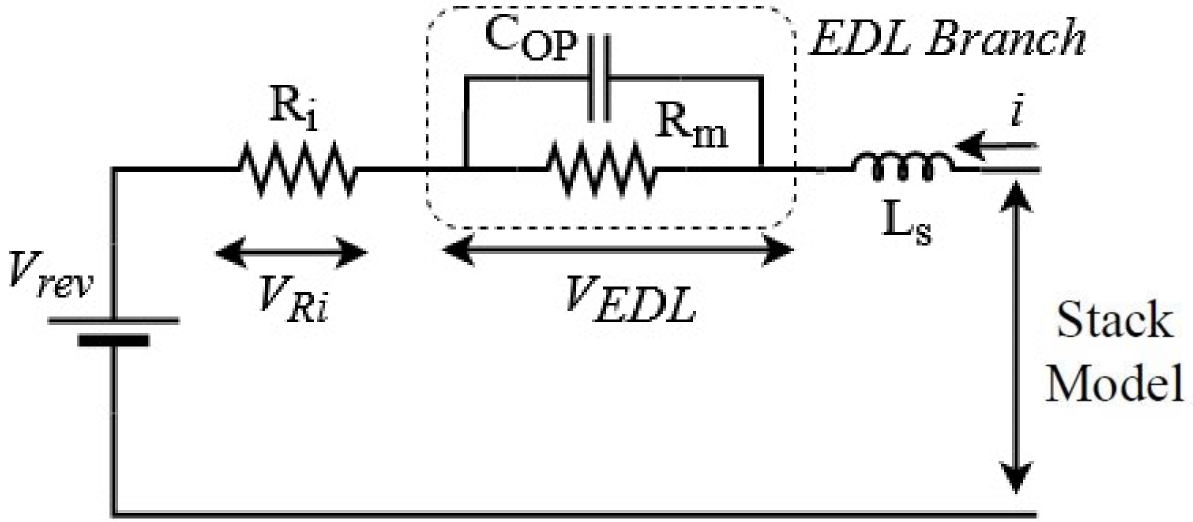
NREL, “ Novel Electrolyzer Applications: Providing More Than Just Hydrogen,” 2014.

Stack physical characteristics matter!

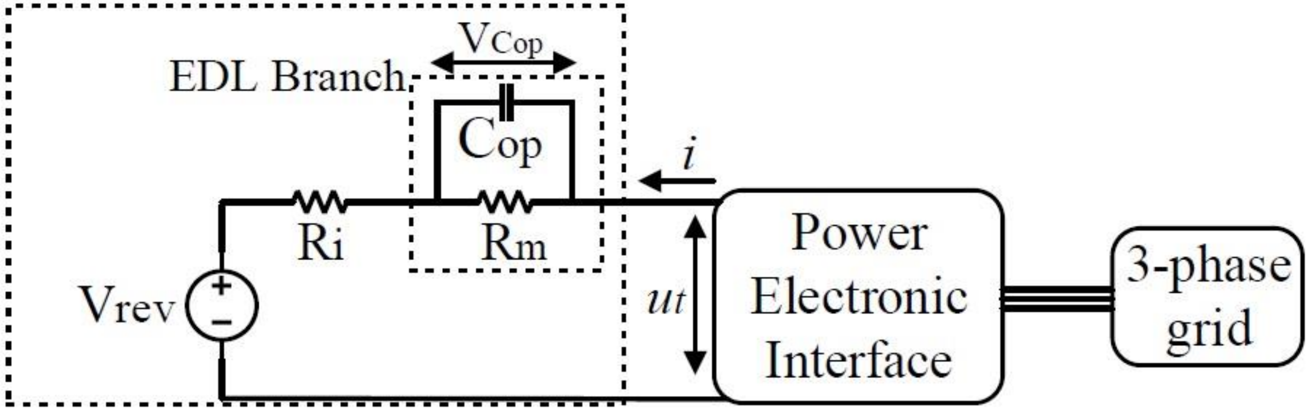


M. Ghazavi Dozein, A. M. De Corato, and P. Mancarella, “Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers," *IEEE Transactions on Power Systems,* 2022.

Electrolysis Stack Modelling
(Electrical Sub-Model)



Unified stack dynamic model



Example: PEM electrolyser circuit representation

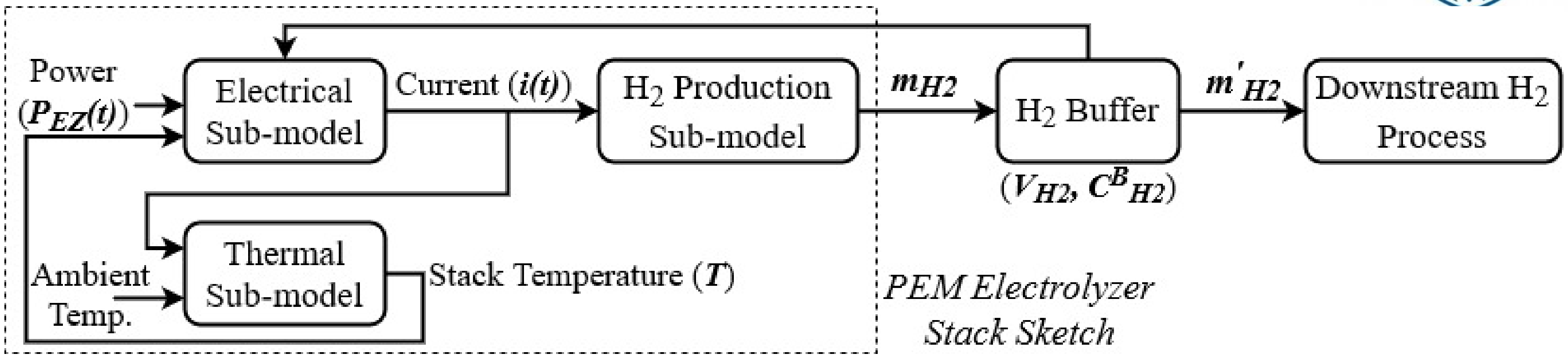
M. Ghazavi Dozein, A. M. De Corato, and P. Mancarella, "Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers," *IEEE Transactions on Power Systems,* 2022.

M. Ghazavi Dozein, A. Jalali and P. Mancarella, "Fast Frequency Response From Utility-Scale Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2021.

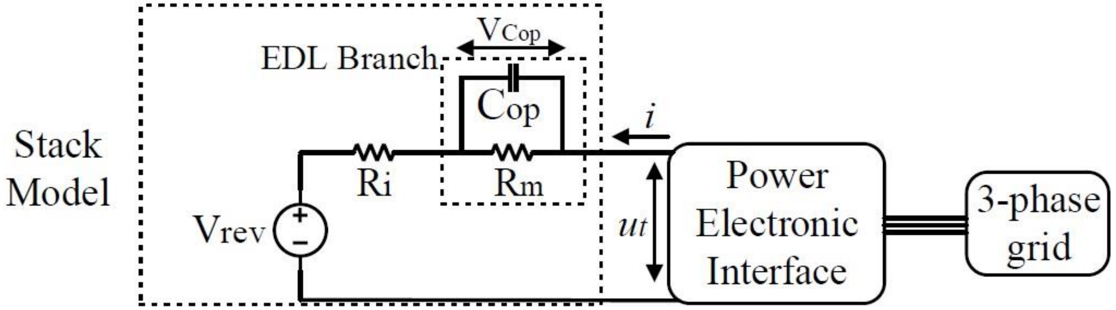
Electrolysis Stack Modelling
(H_2 Production and Thermal Sub-Models)

HE H_2 production sub-model

$$m_{H_2}(t) = \eta_F \frac{Ni(t)}{zF}$$



PEM Electrolyzer Stack Sketch



Thermal sub-model

$$\frac{T(s)}{P_{EZ}(s)} = \frac{N\,(1-\eta_e)}{C_{T_{HE}} \cdot s + (k_{cool} + k_{loss})}$$

1 $$V_{H_2}^{min} \le V_{H_2}(t) \le C_{H_2}^{B}$$

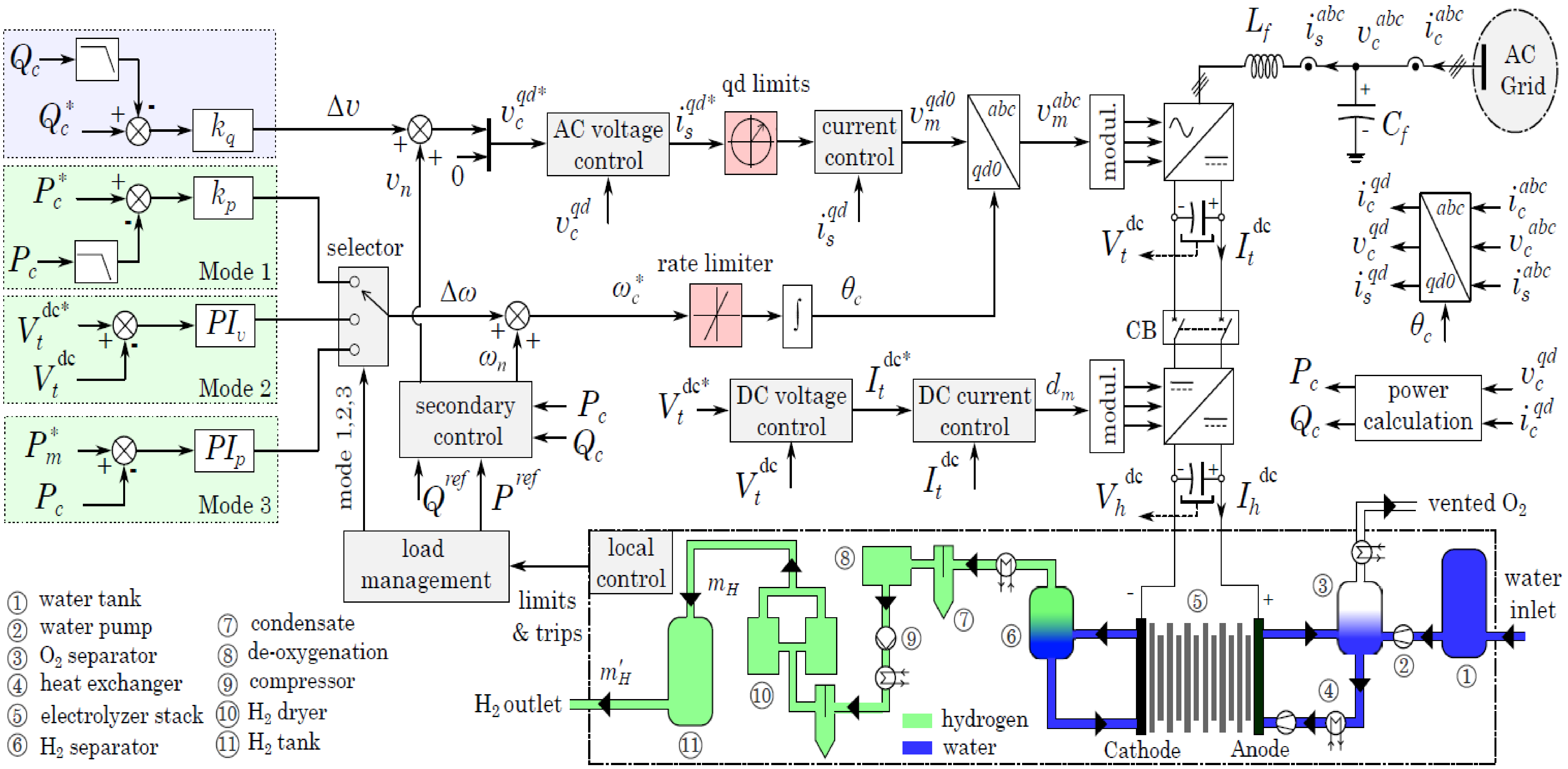
2 $$\frac{zF(V_{H_2}^{min} - V_{H_2}^{0} + m'_{H_2}(t_s - t_0))}{\eta_F N} \le \int_{t_0}^{t_s} i(t)dt \le \frac{zF(C_{H_2}^{B} - V_{H_2}^{0} - m'_{H_2}(t_s - t_0))}{\eta_F N}$$

Operational Constraints in H_2 Production

HE= Hydrogen Electrolyser

M. Ghazavi Dozein, A. Jalali and P. Mancarella, "Fast Frequency Response From Utility-Scale Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2021.

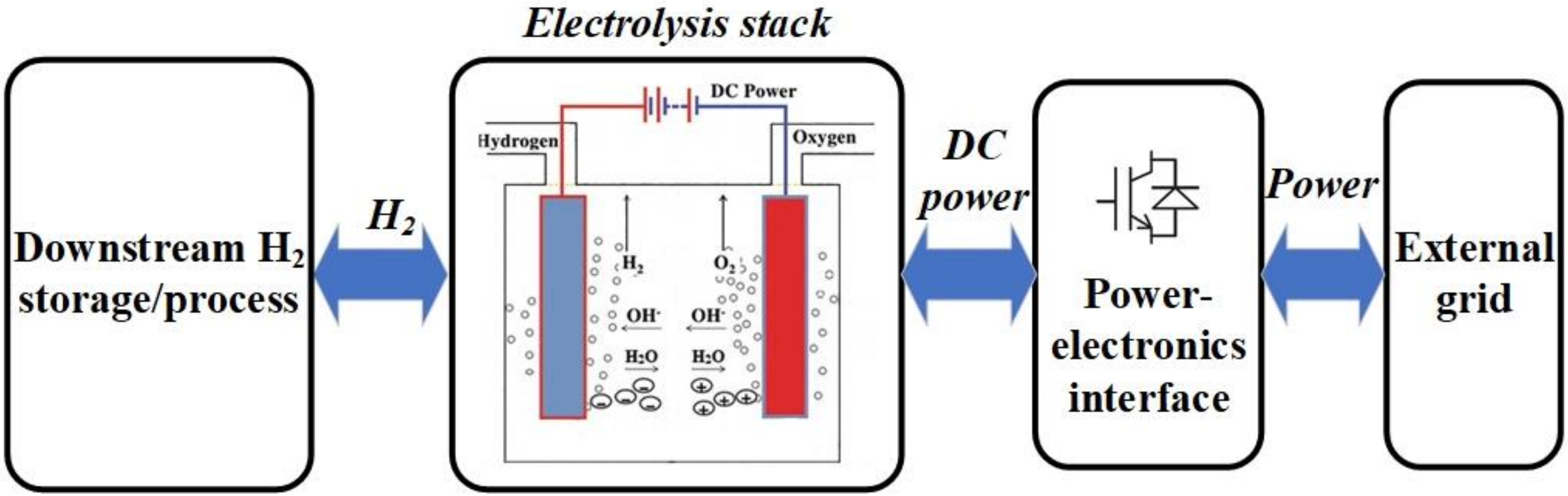
Electrolyser Power Electronics Interface Models
(Grid-following/forming- VSM)



System Support Services from Hydrogen Electrolysis Plants

Questions??!!!

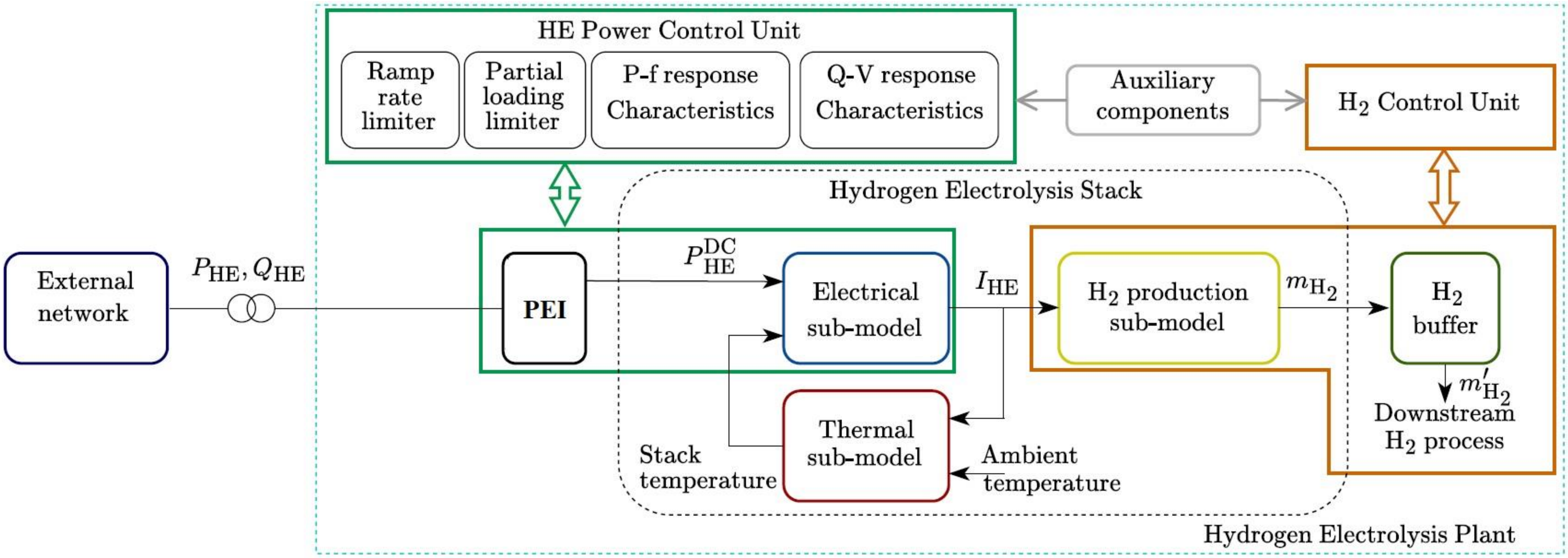
This is an inverter-based load! Can it provide more than just hydrogen???!!!



How should we assess electrolyser dynamic support capabilities and limitations, also their impacts on the grid!??!!

Overall Sketch of Hydrogen Electrolysis Plants

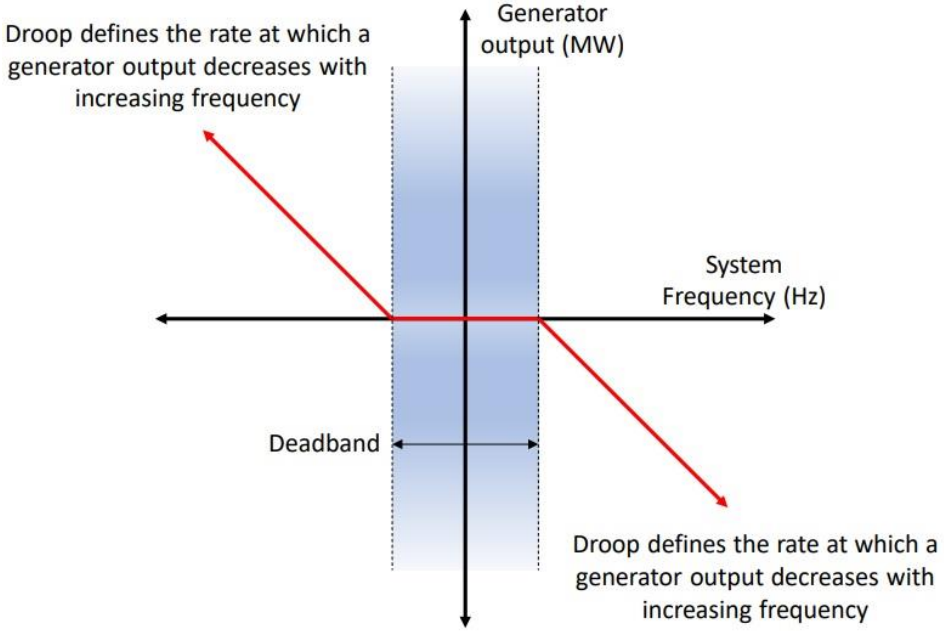
Response Characteristics and Limitations



S. Meetiyagoda, M. Ghazavi Dozein, B. Bahrani, "Distribution-Connected Electrolyzers with Partial Loading Limit and Power Response Characteristics," PowerTech, 2025.

Active Power- Frequency Characteristics

- For any generating/storage unit, there is a **frequency deadband** in their **droop characteristic**
- **Electrolysers can also employ the same characteristic!**
- **Stack ramp rate limiter** can be included here too!
- The technology should *not respond* to frequency deviations within their deadband range
  - Reduces stress on the technology
  - Results in smooth behaviour of generating/storage unit
  - Avoids possible oscillations in active power flow



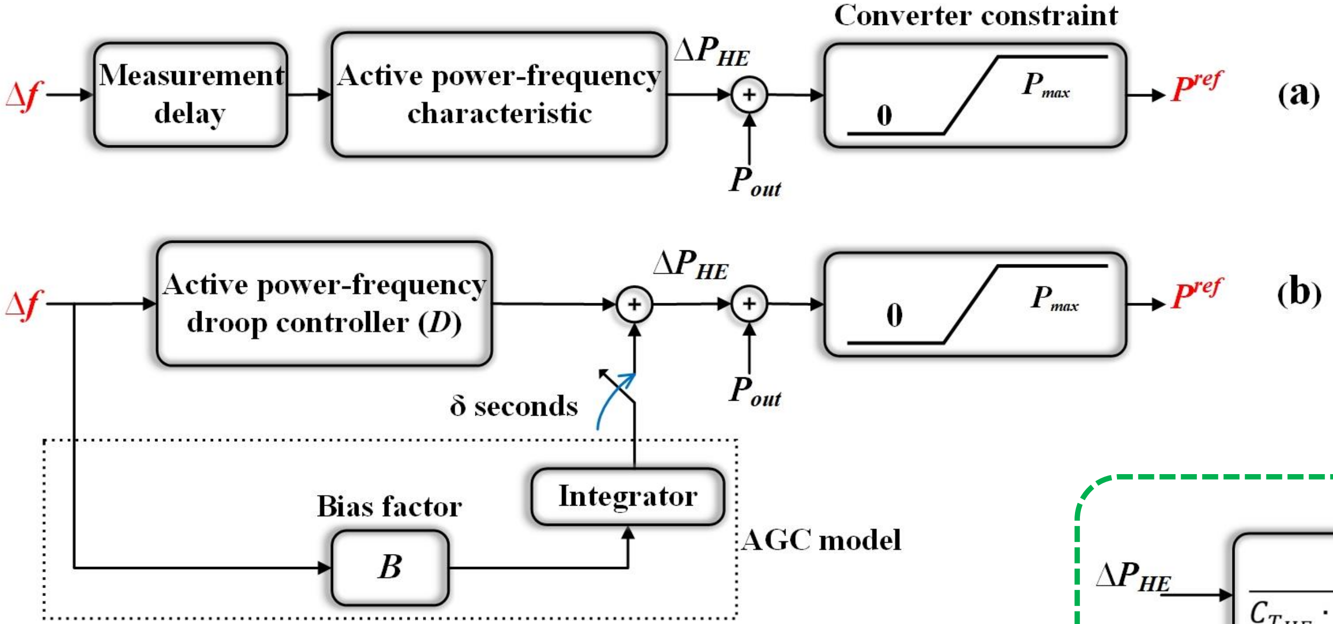
AEMC, "Enduring primary frequency response," 2021.

Active Power Reference Strategy (1/2)

(a) **Contingency** FCAS,

(b) **Contingency** and **Regulation** FCAS,

(c) FCAS for **long time durations** (**thermal** sub-model impacts)



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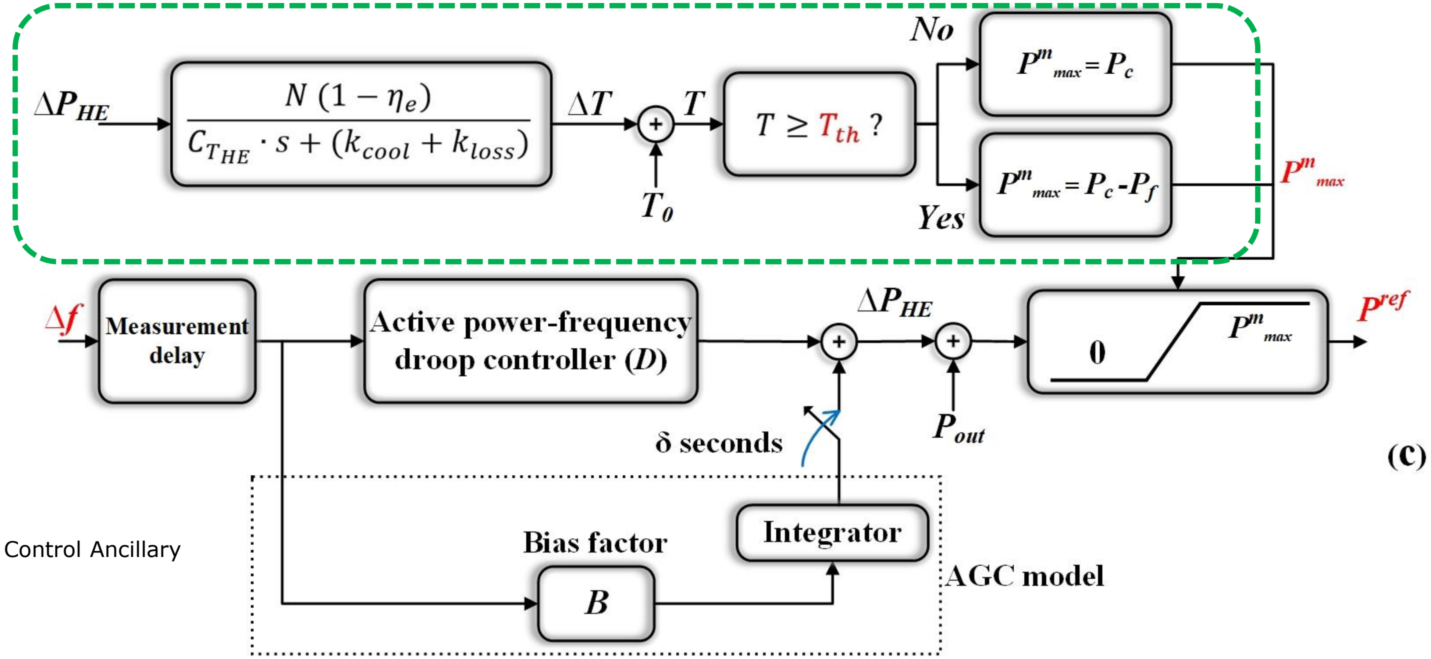
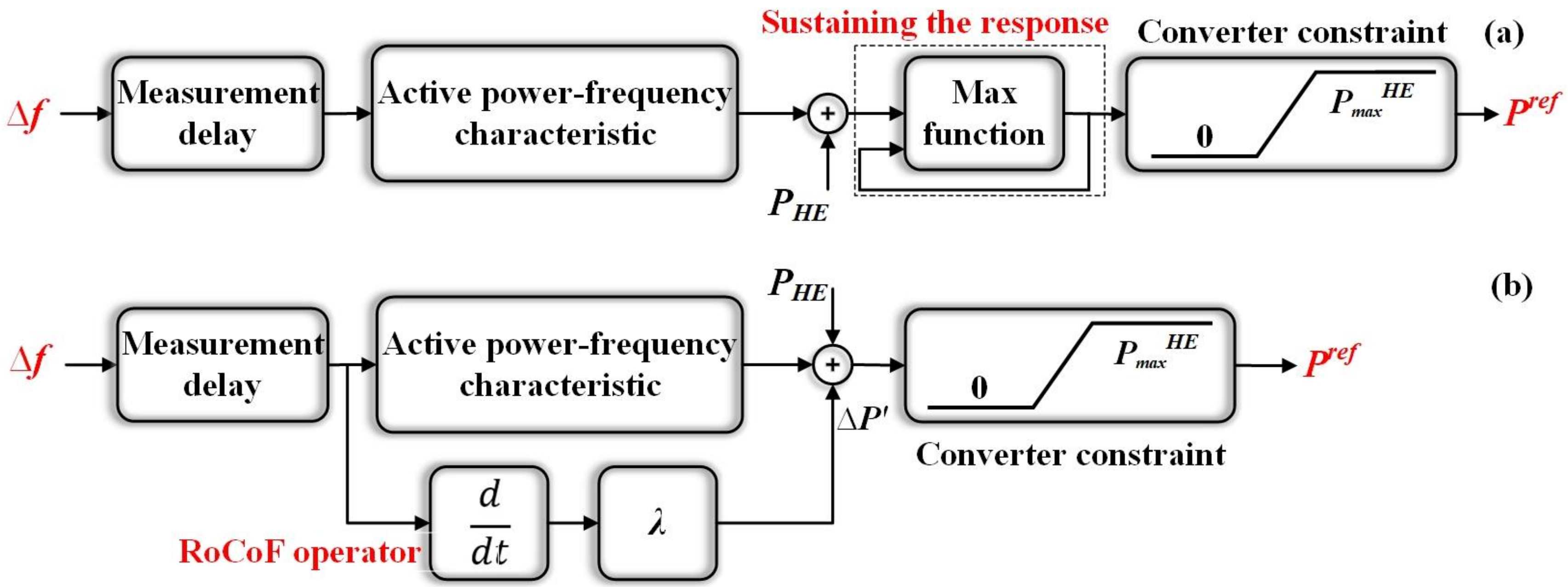


M. Ghazavi Dozein, A. M. De Corato, and P. Mancarella, "Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers," *IEEE Transactions on Power Systems,* 2022.

FCAS= Frequency Control Ancillary Services

Active Power Reference Strategy (2/2)

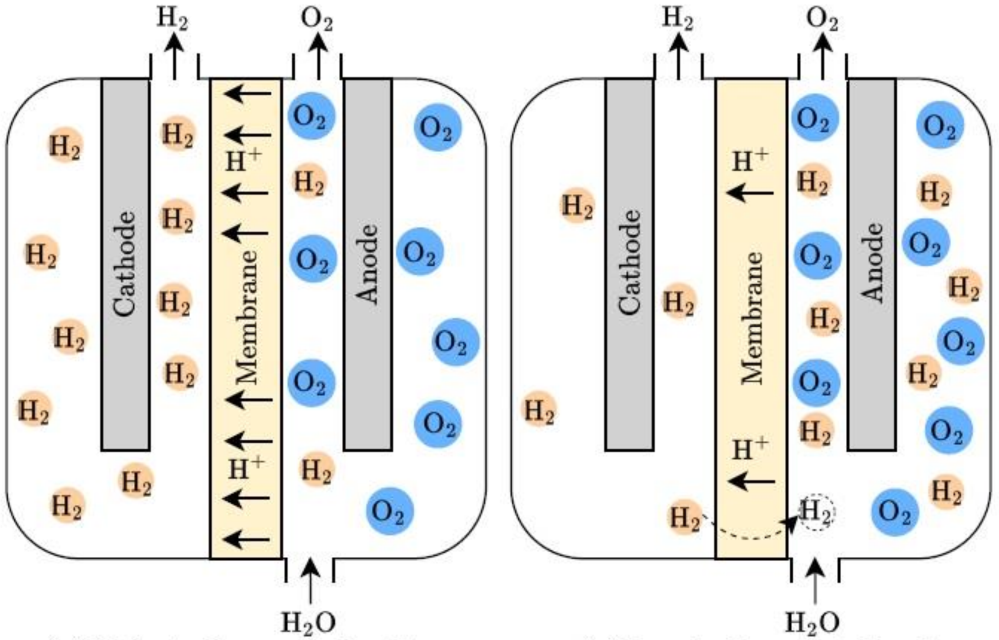
- **Sustained droop response** via the strategy presented in (a)
- **RoCoF-based response** via the strategy presented in (b)
- Both strategies can further be developed to account for **thermal** sub-model impacts



M. Ghazavi Dozein, A. Jalali and P. Mancarella, "Fast Frequency Response From Utility-Scale Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2021.

Stack Partial Loading Limiter

- There may be a **partial loading limit** on electrolysis stack technologies due to
  - ✓ Efficiency in hydrogen production
  - ✓ Safety concerns associated with the hazardous mixture of oxygen and hydrogen
  - ✓ Stack degradation



(a) High stack current densities (b) Low stack current densities

Is there any UPS in the H_2 project???!!!

PARTIAL LOADING LIMITS ON STACK TECHNOLOGIES BY DIFFERENT MANUFACTURERS

HE Manufacturer	Type	Partial loading limit (%)
Cummins (AEL)	HySTAT	40
NEL (AEL)	A	15
Cummins (PEM)	HyLYZER	5
NEL (PEM)	PSM	10

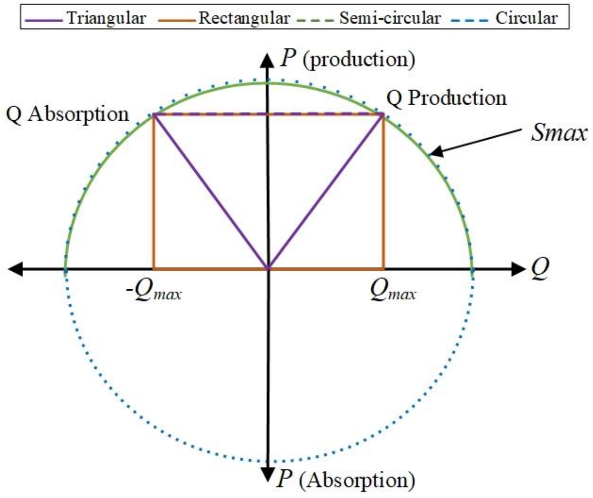
S. Meetiyagoda, M. Ghazavi Dozein, B. Bahrani, "Distribution-Connected Electrolyzers with Partial Loading Limit and Power Response Characteristics," PowerTech, 2025.

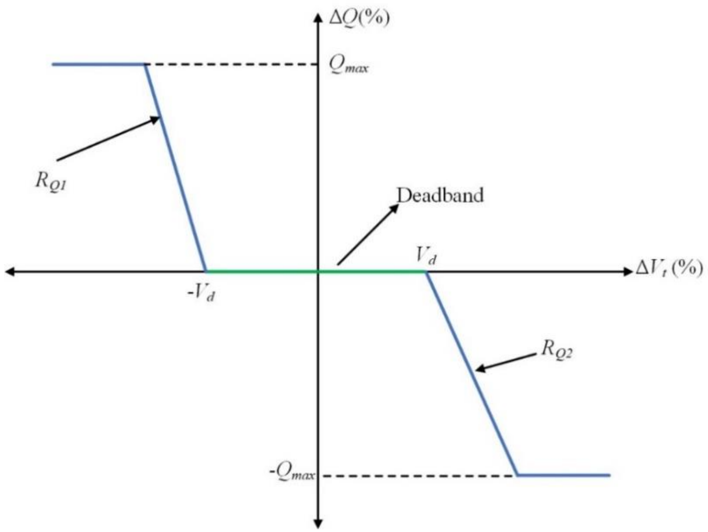
Reactive Power–Voltage Characteristics

- Two possible options for the reactive power characteristic:

- **Q mode:**
  - A reference reactive power value is given to the electrolyser
  - May come from an external controller (e.g., microgrid control system)
  - Power factor control

- **Droop mode:**
  - Changes in electrolysis plant reactive power as a response to voltage variations at the point of grid connection





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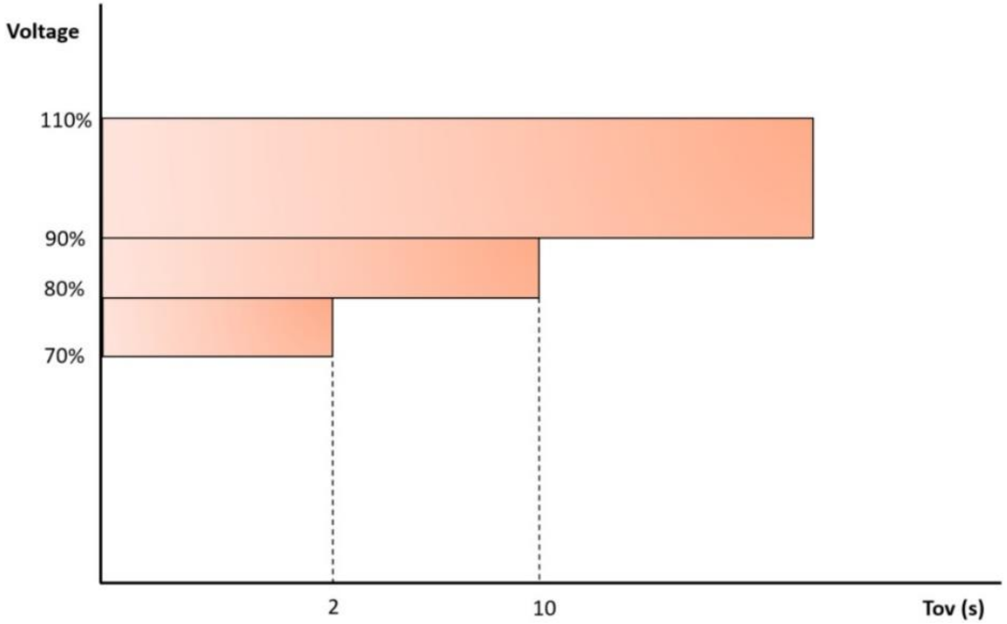
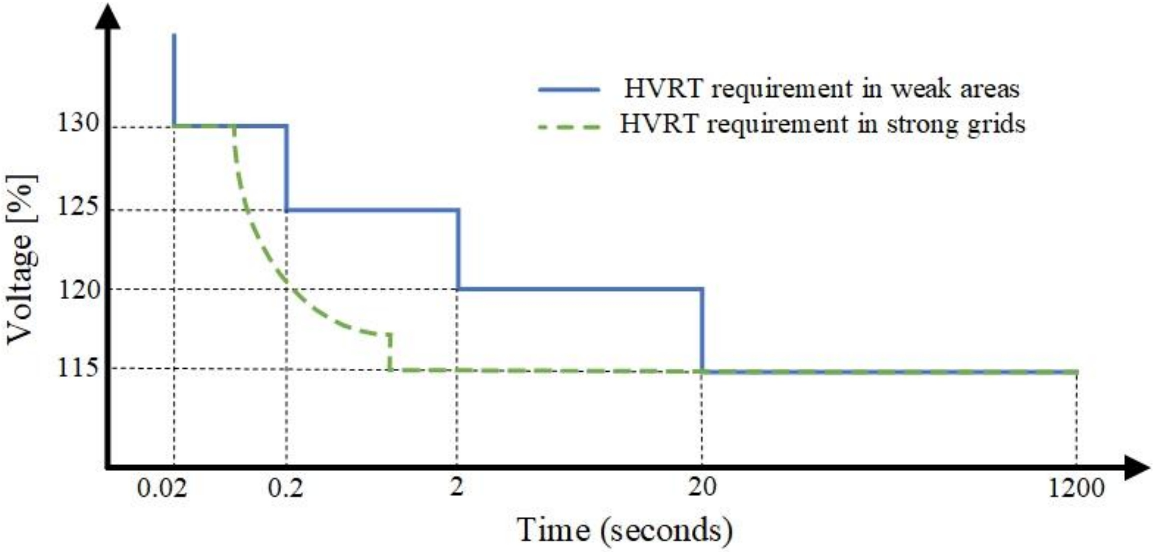
Fault Ride-through Characteristics- Reactive Power Support during the Fault!!!???!!





It is still under investigation how the electrolyser fault ride-through behaviour should be!!!!!

Simulation Case Studies

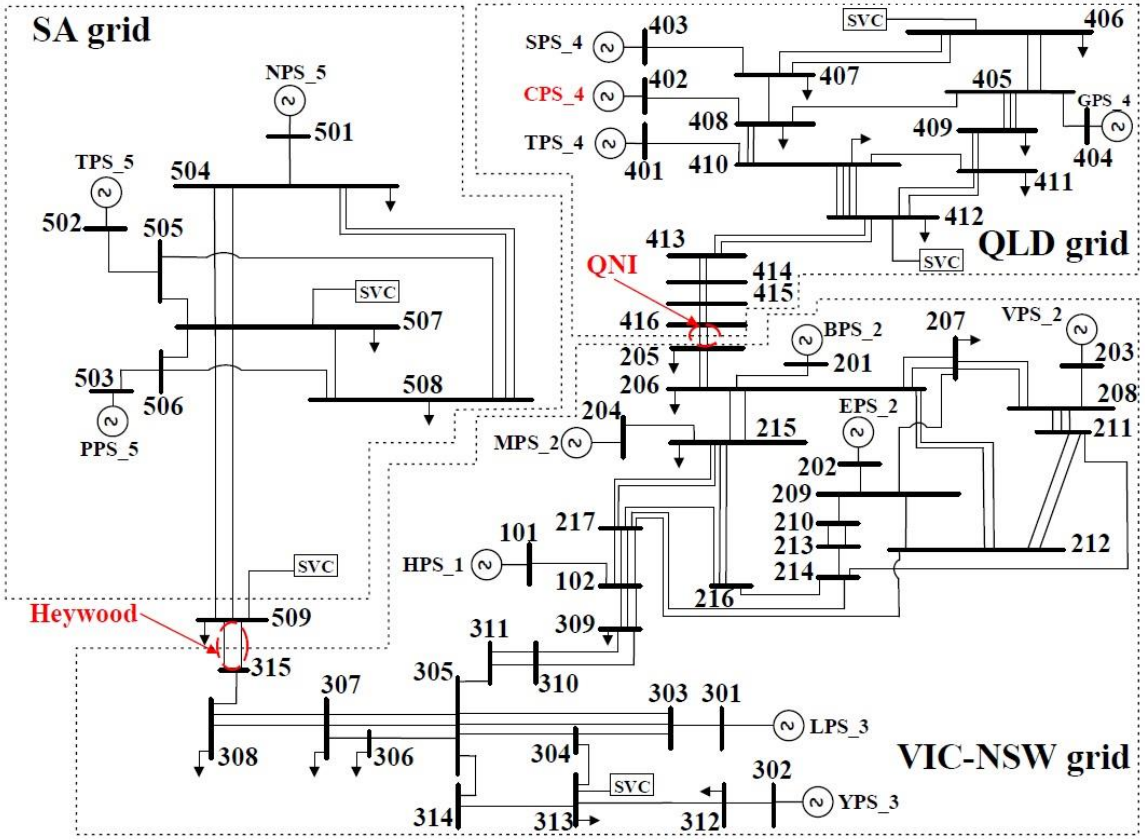
Case Studies (1/3):
Fast Frequency Response from Electrolysers

Electrolyser benefits to low-inertia systems

- Electrolyser's frequency support capability in the context of Australian 50% renewable energy target by 2030
- **Contingency**: the largest generating unit outage in Queensland with total capacity of 667 MW at t=40s

Generation and load data

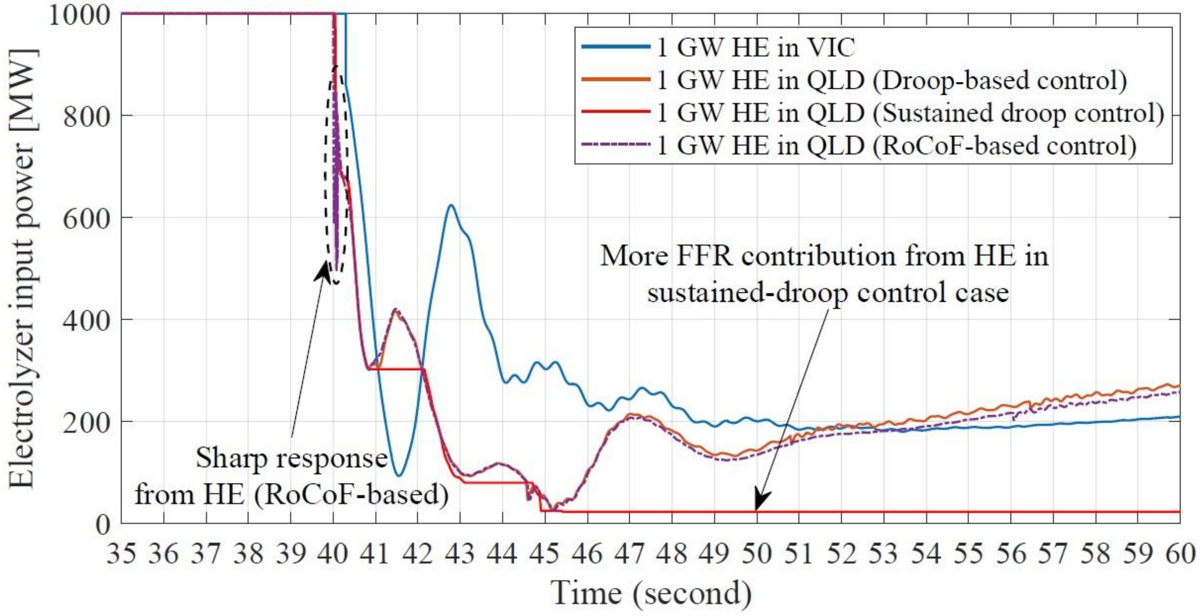
Case Study	*States*	*Synchronous Generation [GW]*	*Non-synchronous Generation [GW]*		*Load [GW]*
			PV	*Wind*	
Case-1	QLD	3.34	1.44	1.77	5.5
	VIC-NSW	11.4	5.58	5.36	17.6
	SA	1.12	0.48	1.07	2.3



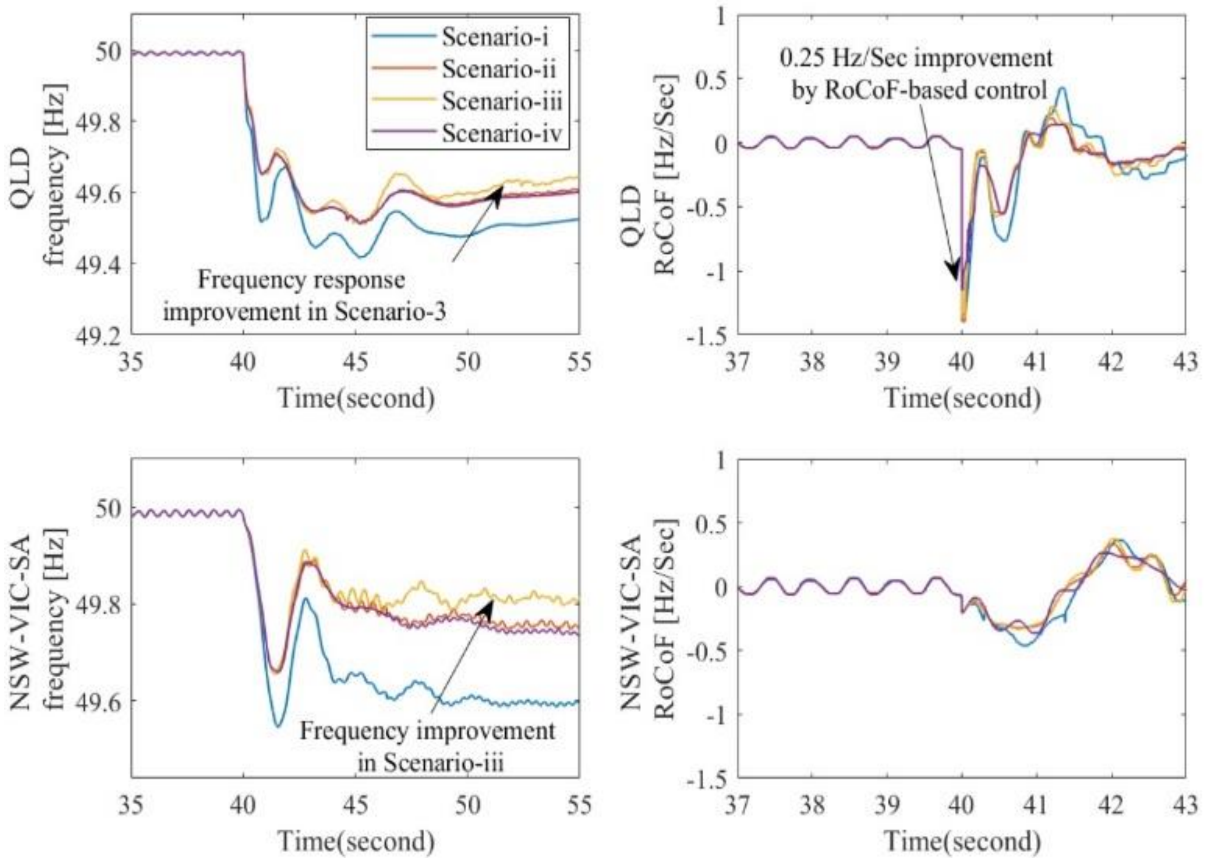
Modified 14-generator NEM grid with 50% renewable penetration

Case Studies (1/3):
Fast Frequency Response from PEM Electrolysers

- **Great FFR capability** in **PEM** electrolysers
- PEM electrolyser FFR capability depends on
  - **Grid location**
  - **Inverter control characteristics**



Fast frequency response from electrolysers

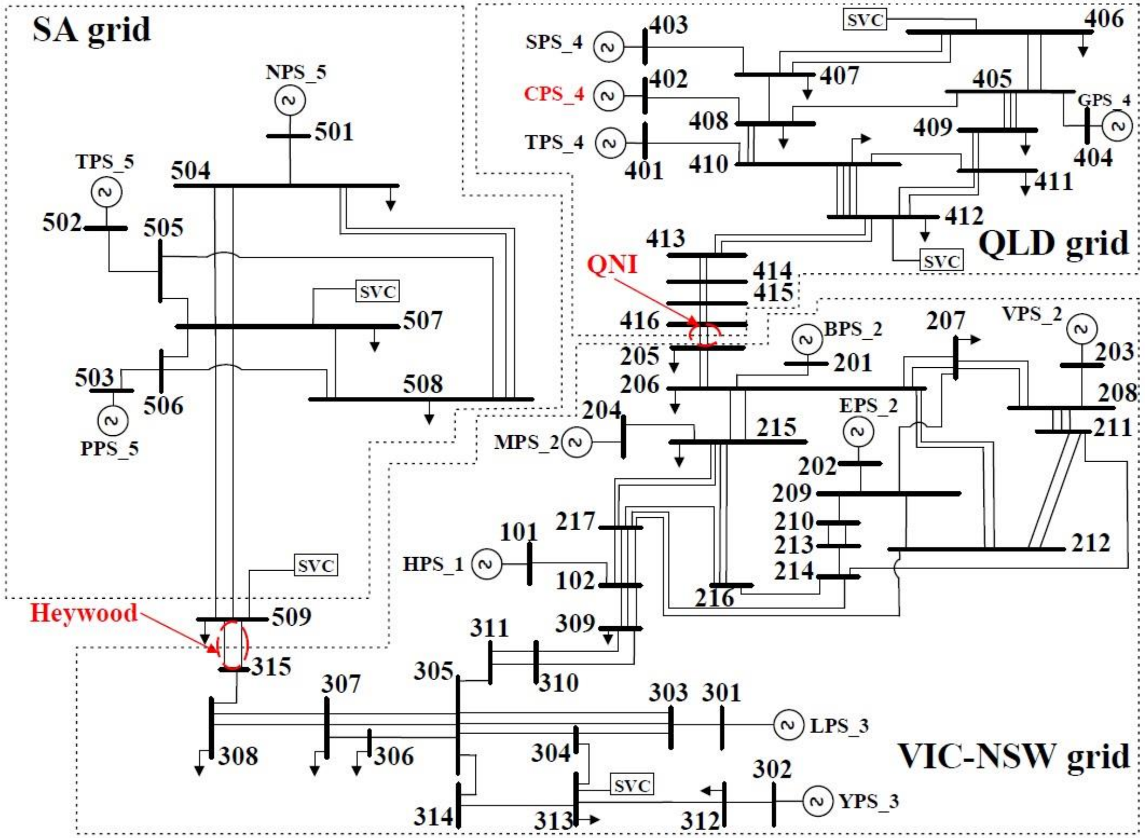


System dynamics in different scenarios

M. Ghazavi Dozein, A. Jalali and P. Mancarella, "Fast Frequency Response From Utility-Scale Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2021.

Case Studies (2/3): FFR Interaction with H_2 Operational/Converter Constraints

- **Contingency**: the Heywood trip at *t*=40s. Before the trip, 110 MW was being transferred from SA to VIC
- The following cases are studied:
  - ✓Case-1: System with **no electrolyser**
  - ✓Case-2: 1 GW electrolyser in SA, **no converter overloading capability**
  - ✓Case-3: 1 GW electrolyser in SA with **10% converter's overloading capability**
  - ✓Case-4: 1 GW electrolyser in SA grid, and **modelling of hydrogen buffer and downstream H_2 process**



Modified 14-generator NEM grid with 50% renewable penetration

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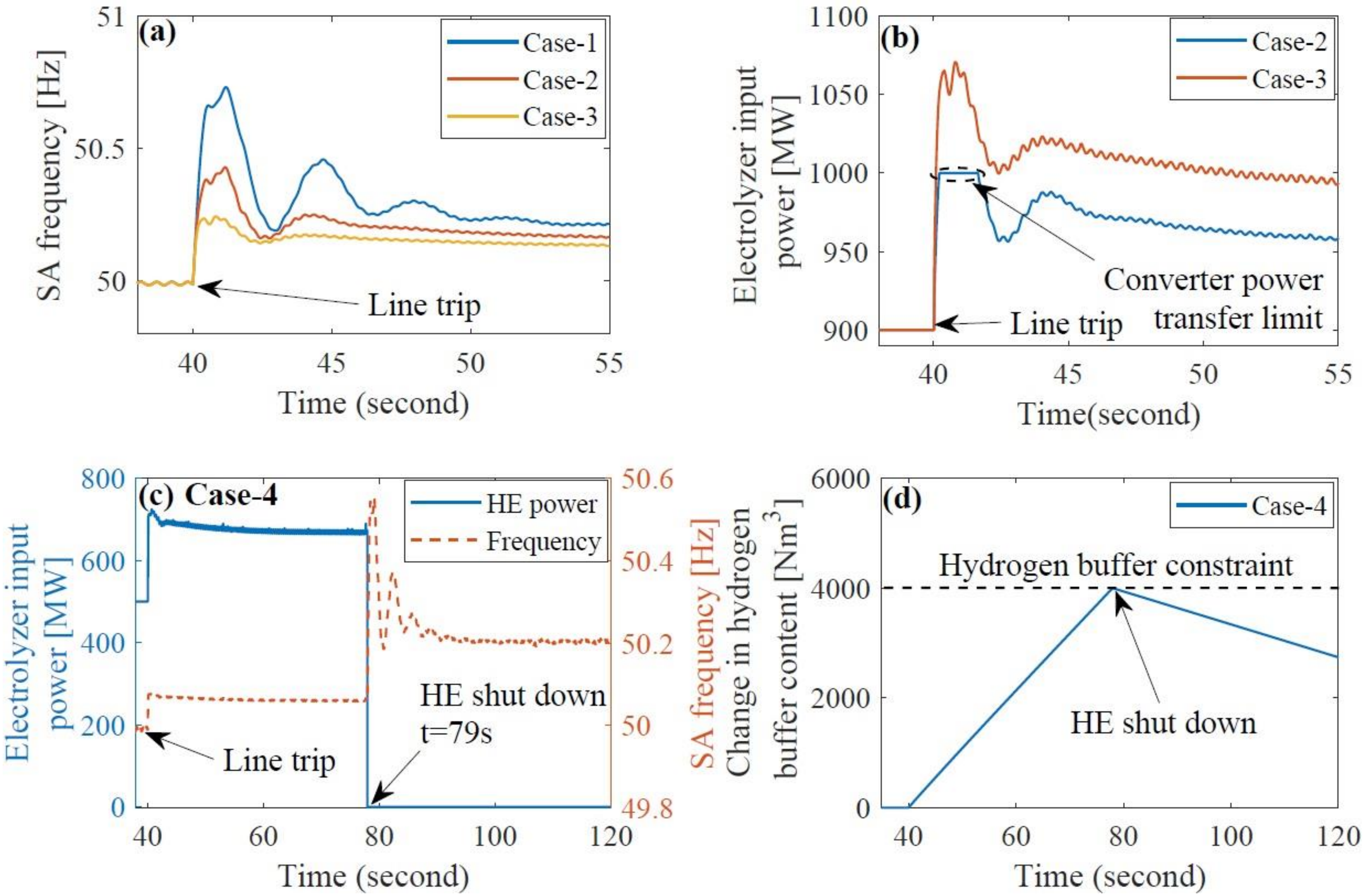
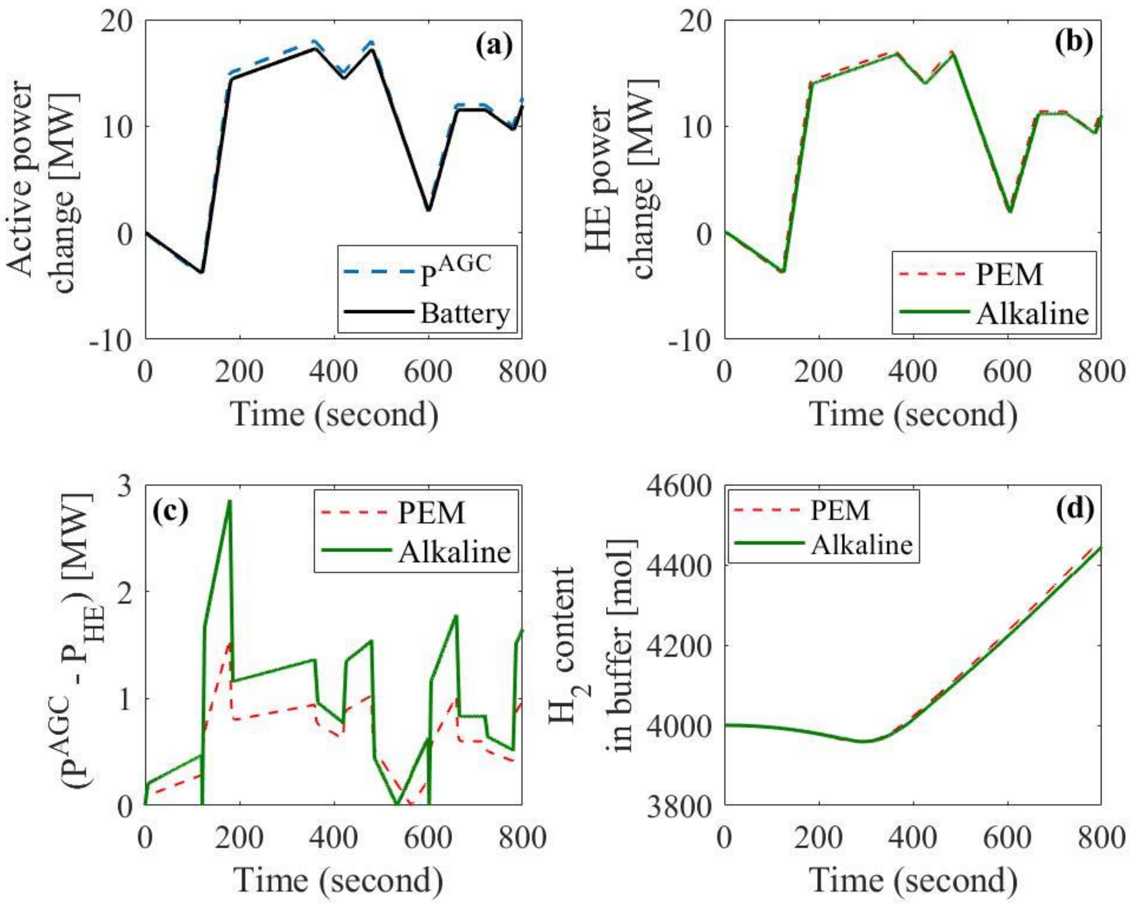
Case Studies (2/3): FFR Interaction with H_2 Operational/Converter Constraints



M. Ghazavi Dozein, A. Jalali and P. Mancarella, "Fast Frequency Response From Utility-Scale Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2021.

Case Studies (3/3): Regulation FCAS from Electrolysers



Take-Home Message:

Great potential in alkaline and PEM electrolysers for regulation FCAS

M. Ghazavi Dozein, A. M. De Corato, and P. Mancarella, "Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers," *IEEE Transactions on Power Systems,* 2022.

Concluding Remark!

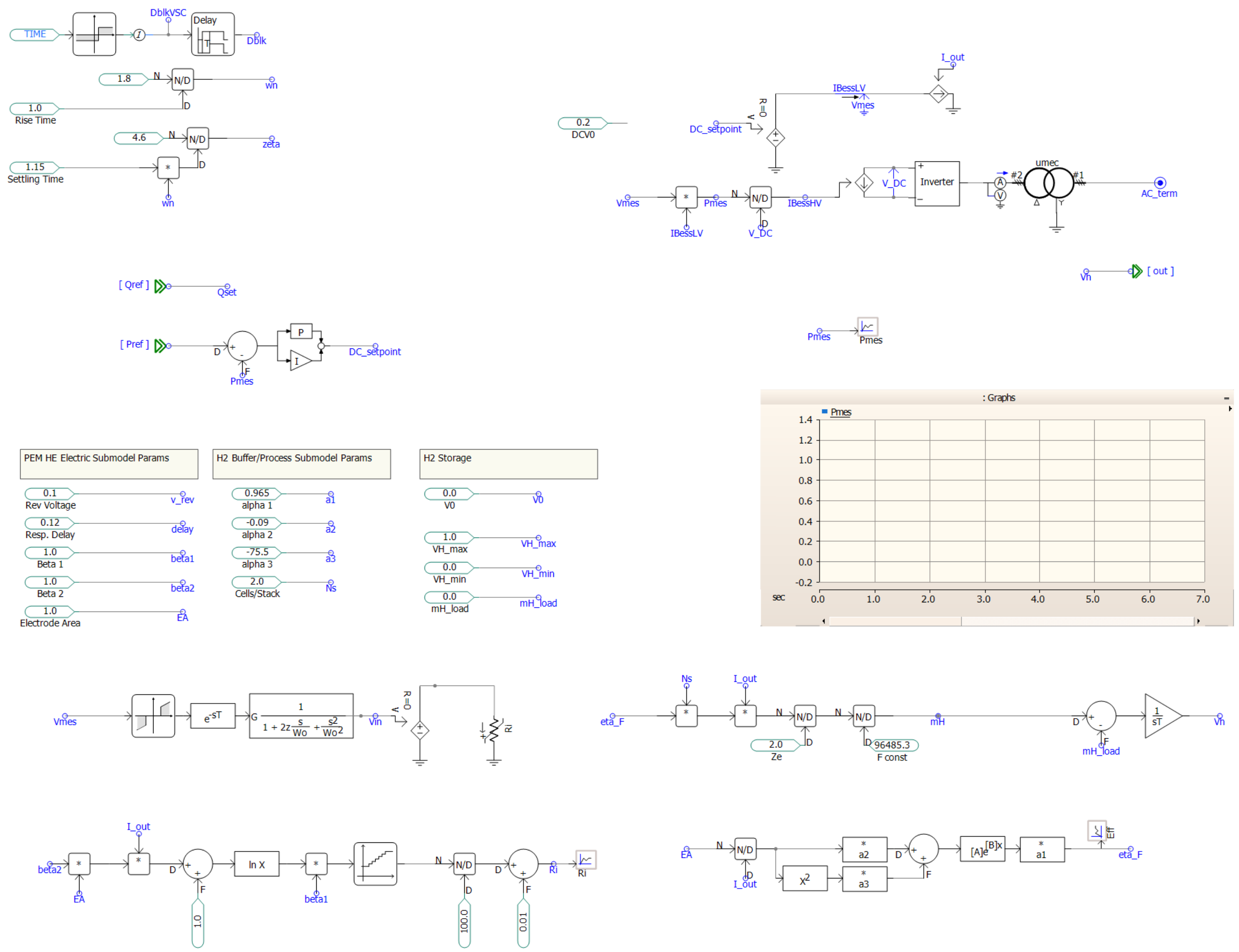
Electrolyser *vs* Battery

Technology	System Support Service			
	Virtual inertia response	Fast frequency response	Primary frequency response	Frequency regulation response
Grid-following Alkaline Electrolyzer				
Grid-following PEM electrolyzer				
VSM PEM electrolyzer				
Grid-following battery storage				
VSM battery storage				

The darker colour indicates a better performance in system dynamic support delivery

Some Ongoing Works….

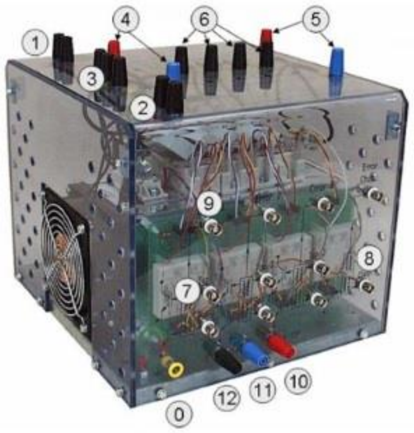
Electrolyser models in commercial software (PSCAD and PSSE)

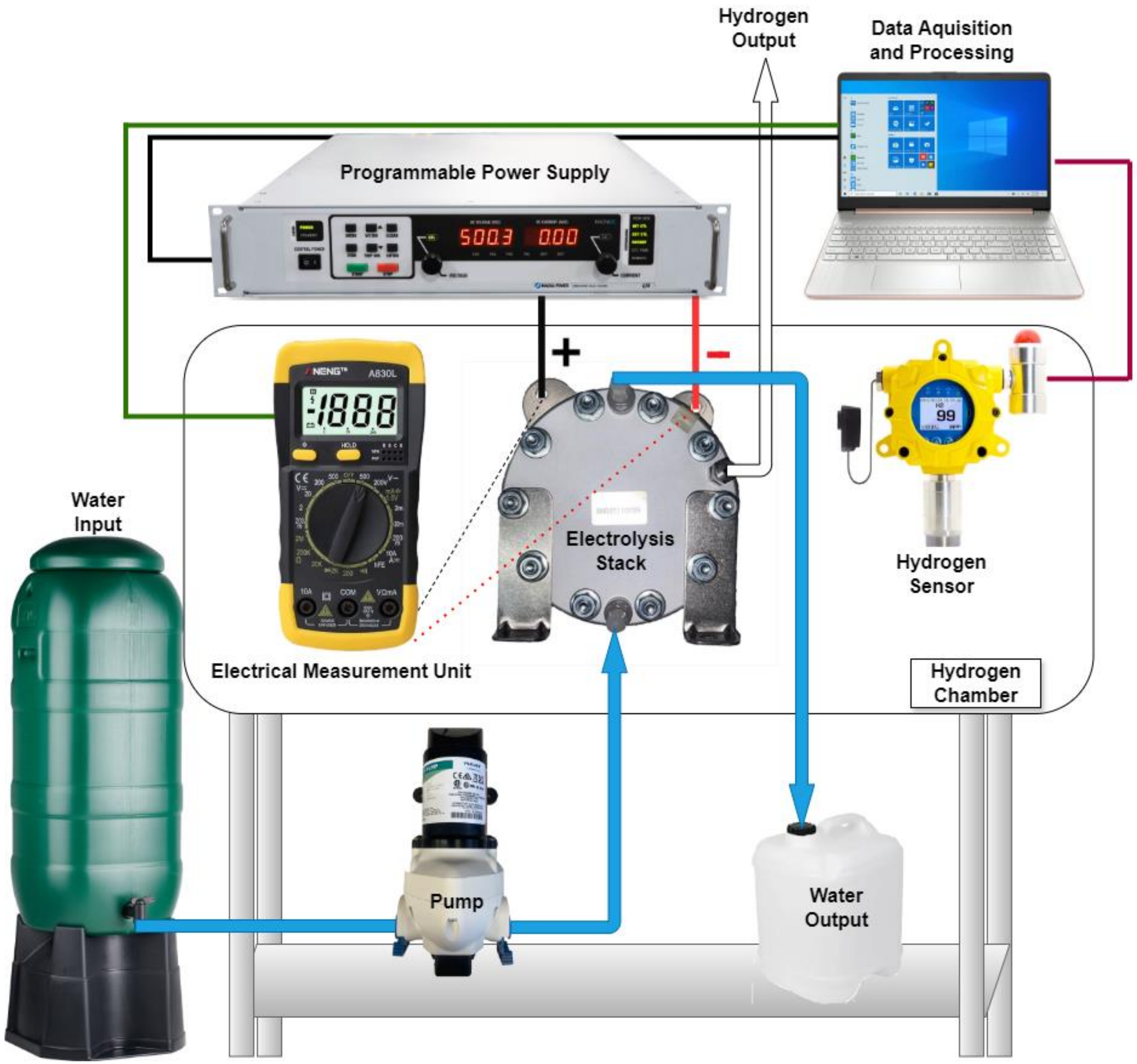


Some Ongoing Works….

Lab validation tests

H2-in-the-loop setup!





Upcoming Workshop

- **Electromentors Online Workshop on May 3 (EDT)**
- **5-hour workshop** on electrolysis plant fundamentals, modelling, and system case studies
- Includes **simulation exercises**
- Discount for students → Email to **info@electromentors.com**
- Link for the registration: https://www.electromentors.com/service-page/hydrogen-electrolysis-plants-april?referral=service_list_widget

World Class Training in Electrical and Computer Engineering

Acknowledgement

- **Industry partners**
- **Low-carbon Energy Team** at Monash University

Dr Mohammad Ramezani

Dr Amin Mahdizadeh

Mr Supun Meetiyagoda

Ms Ridma Wijethunga

Ms Amalie Bullen

Mr Oliver Kershaw

Mr Joshua Sutton

Mr James McAlister

Mr Morris Dumaresq

Dr Mehdi Ghazavi Dozein

Hydrogen Electrolysis Plants: Fundamentals, Modelling, and System Impact Studies

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