Offshore Energy Hubs - design and operation

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STRATEGIC GOAL

Designing a resilient, renewable-based energy system

CHALLENGE

A society fully powered by wind and other renewables requires a fundamental redesign of the energy system as we know it. Security and resilience must be more thoroughly addressed in a system characterised by electrification, massive renewables, efficient markets, and innovative digital technologies. Therefore, we will lead society's effort towards a future integrated, flexible, and resilient energy system based on renewables.

FOCUS AREAS

Local flexibility solutions	Cyber physical security	Large-scale Power-to-X
A converter-based power system	Massive offshore energy systems and hybrids	Data, AI and advanced computation

127 employees*	**27** senior scientific staff
104 research projects	**200+** project partners
>370 Journal articles 2022 - 2025	**1.83** CNCI 2021-25

Strong National and International Collaboration

Selected partners and networks

Academia: >100 partners

Industry and authorities: >100 partners

Networks:

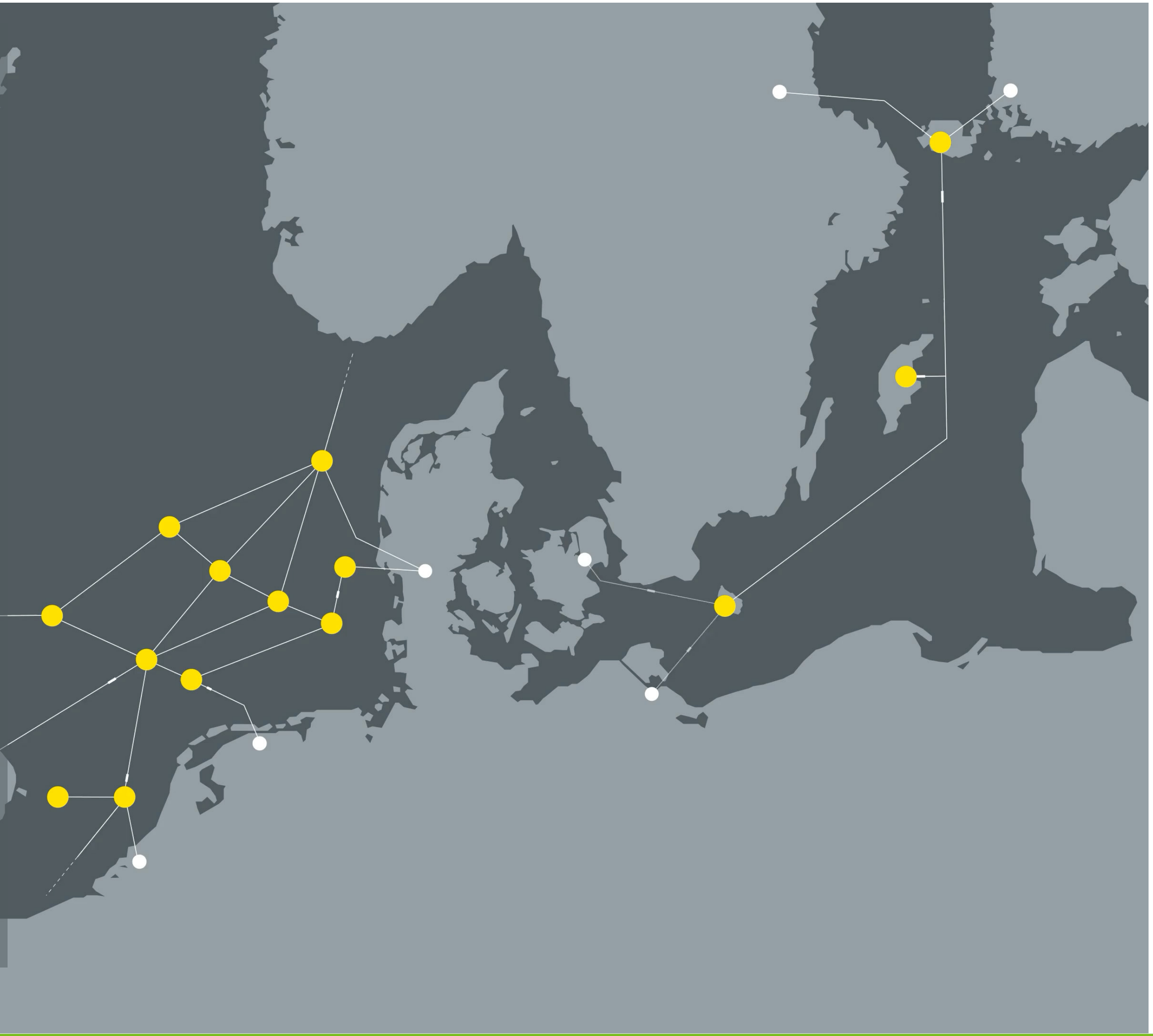
Energy Islands

Energy islands are **hubs** that efficiently collect energy from surrounding offshore wind power plants **far out at sea** (***offshore energy hubs***).

Large **DC power connections** are used to transport energy to surrounding countries or energy systems.

These connections facilitate the **energy exchange** between countries or energy systems.

The hubs may host production of **green fuels** through Power-to-X processes.

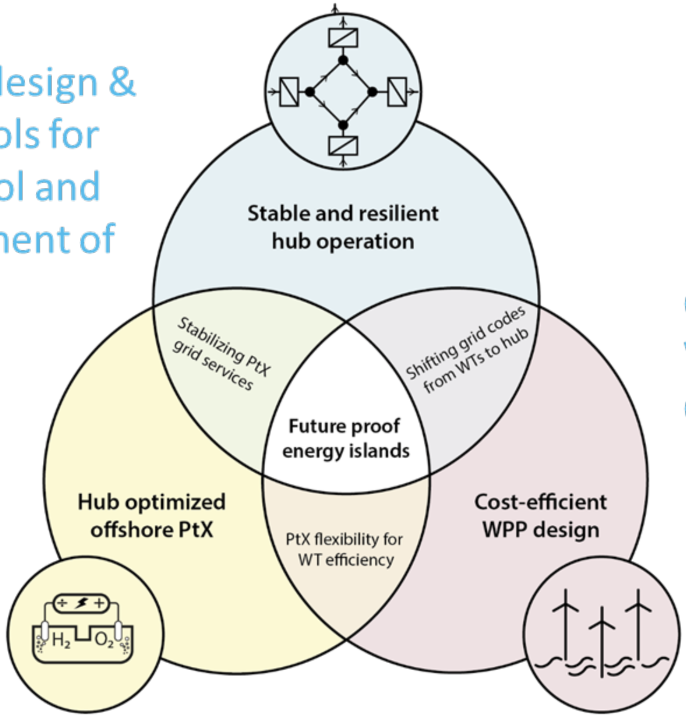


Offshore Energy Hubs project

Consortium and focus areas

Resilient hub design & Methods & tools for stability, control and fault management of OEH

OEH optimized electrolysers & cable solutions



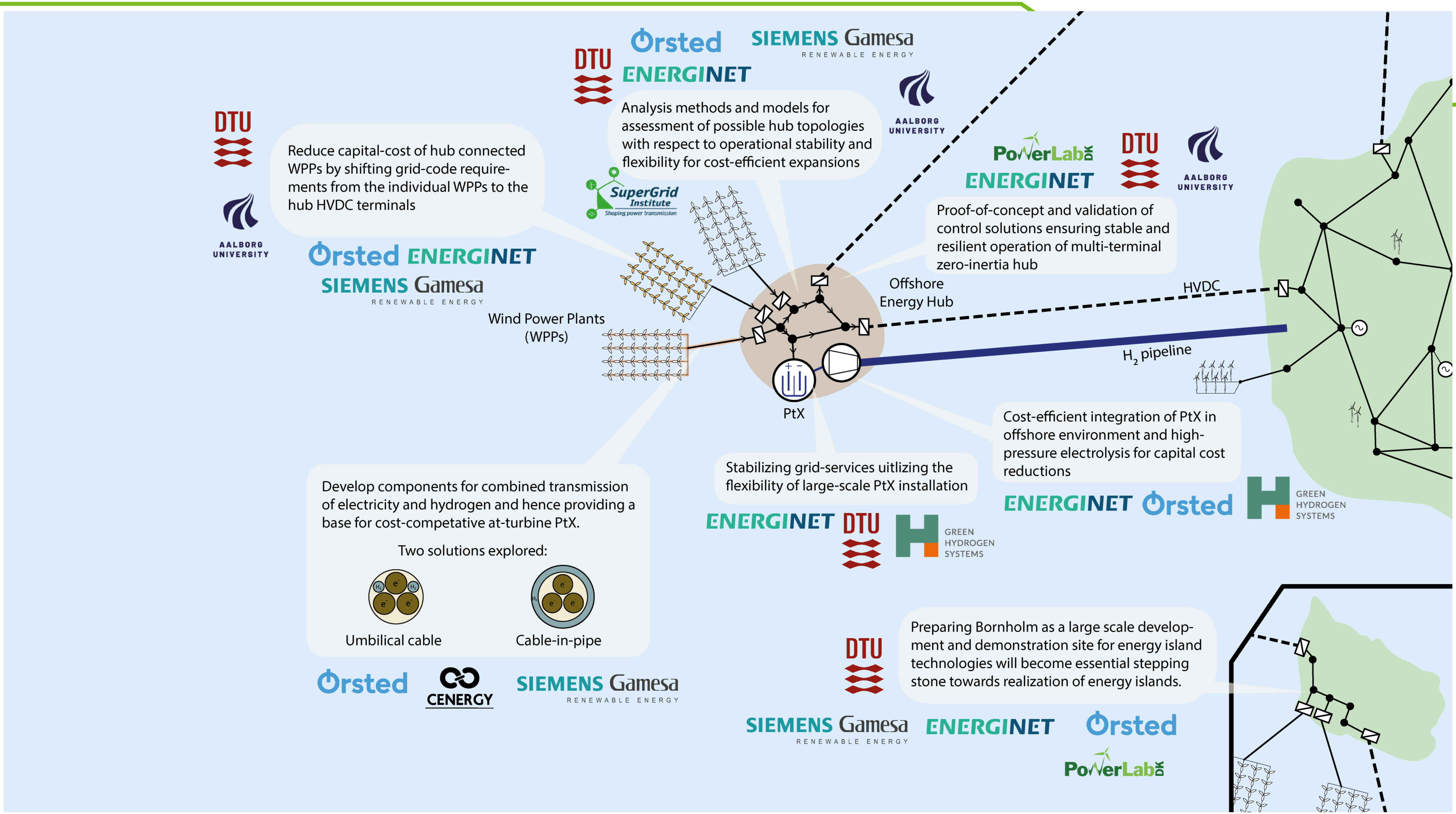
Optimized design of WPPs connected to OEH

Develop Bornholm as test center for energy hub technologies

DTU
AALBORG UNIVERSITET
Ørsted
SIEMENS Gamesa RENEWABLE ENERGY
CENERGY HOLDINGS
(Hellenic Cables)
GREEN HYDROGEN SYSTEMS
SuperGrid Institute Shaping power transmission
energy CLUSTER DENMARK

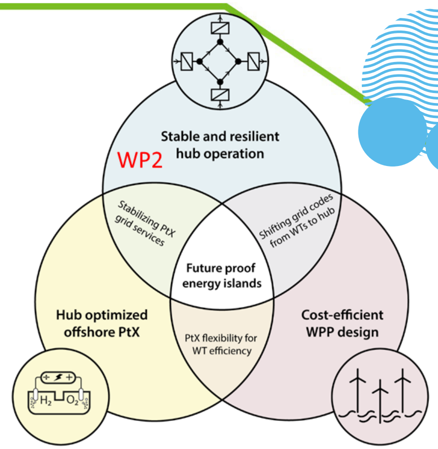
Strong synergies between the development areas
Framework to coordinate the development across the focus areas

https://offshoreenergyhubs.eu


Reduce capital-cost of hub connected WPPs by shifting grid-code requirements from the individual WPPs to the hub HVDC terminals
Analysis methods and models for assessment of possible hub topologies with respect to operational stability and flexibility for cost-efficient expansions
Proof-of-concept and validation of control solutions ensuring stable and resilient operation of multi-terminal zero-inertia hub
Wind Power Plants (WPPs)
Offshore Energy Hub
HVDC
H2 pipeline
PtX
Cost-efficient integration of PtX in offshore environment and high-pressure electrolysis for capital cost reductions
Stabilizing grid-services uitlizing the flexibility of large-scale PtX installation
Develop components for combined transmission of electricity and hydrogen and hence providing a base for cost-competative at-turbine PtX.
Two solutions explored:
Umbilical cable
Cable-in-pipe
Preparing Bornholm as a large scale development and demonstration site for energy island technologies will become essential stepping stone towards realization of energy islands.

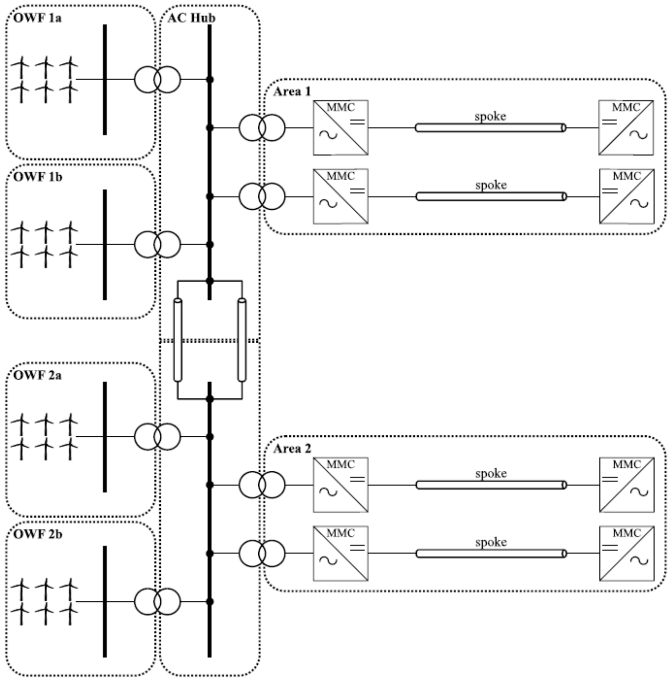
Small signal stability

Python-based tool



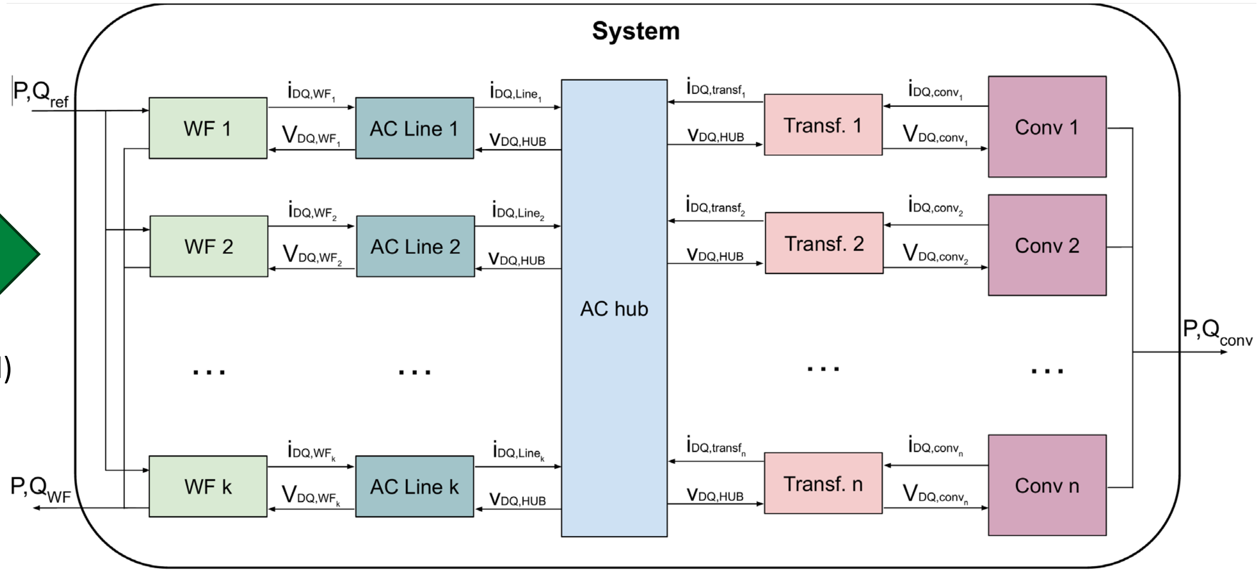
Based on input/output between the subsystems

- IOs in DQ frame
- Controls in local dq frame
- Linearized equations



SMOOTH

(**S**mall-Signal **M**odelling **o**f **O**ffshore Energy **H**ubs **T**ool)



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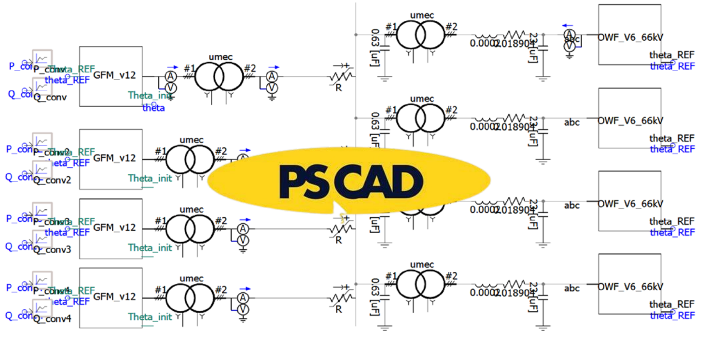
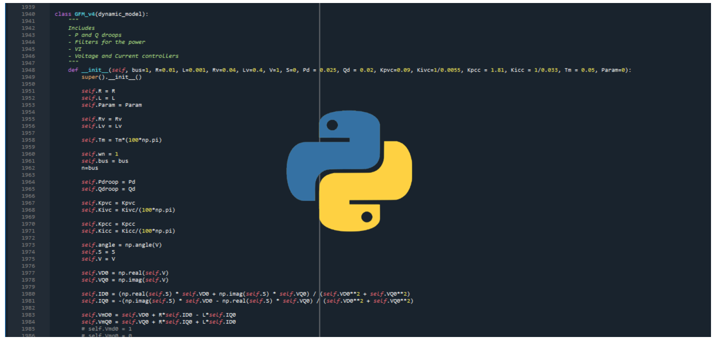
Source: Duvivier, A., et al, Small-Signal Modelling of Offshore Energy Hubs, PSCC 2026 (under review)

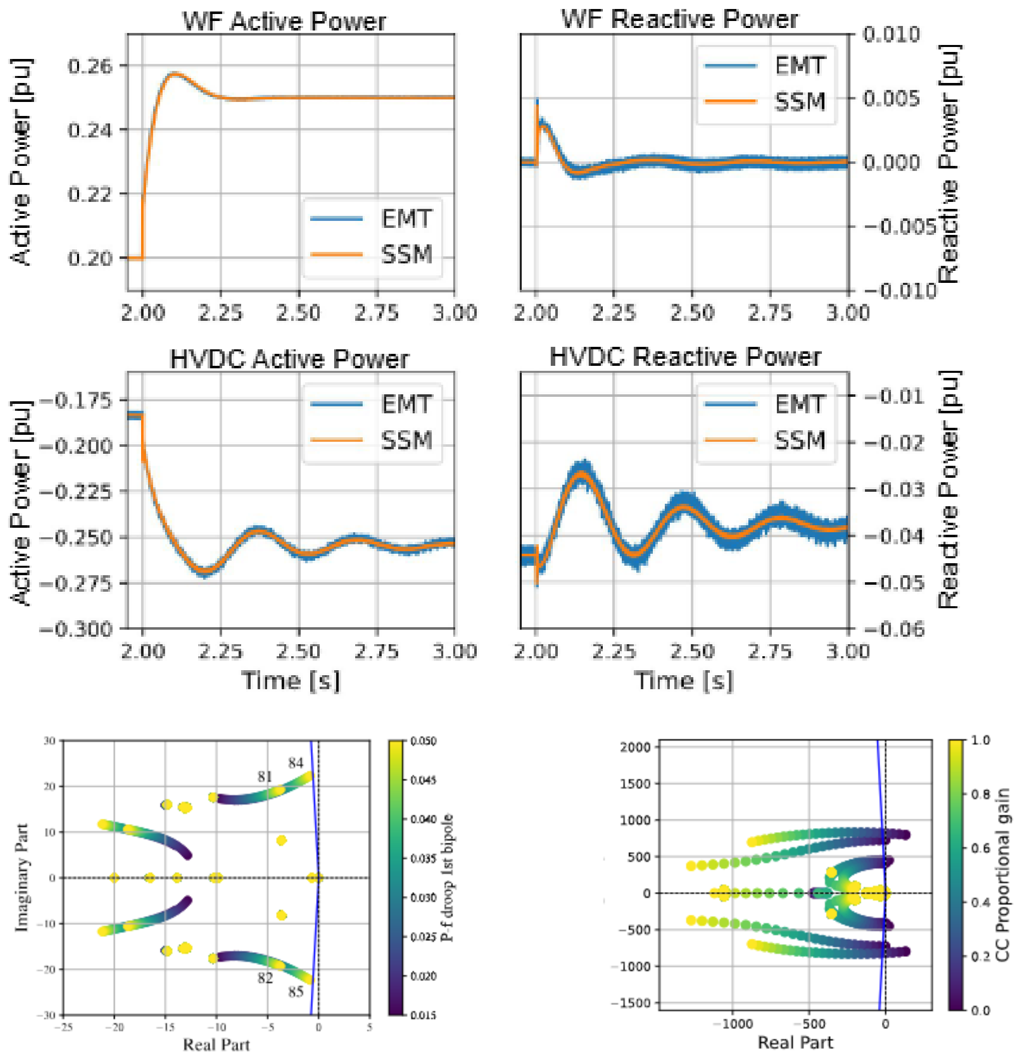
Small signal stability

Python-based tool

Model validation with power step scenario







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Source: Duvivier, A., et al, Small-Signal Modelling of Offshore Energy Hubs, PSCC 2026 (under review)

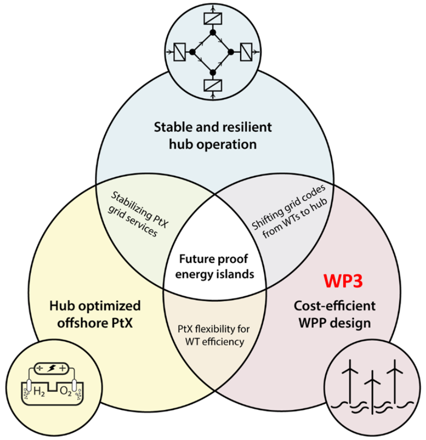
Grid codes for OWPP connected to OEH

Due to HVDC transmission system, OWPPs are **isolated** from the AC grid.

Opportunity: Develop cost-efficient solutions for OWPPs connected to OEH

Focus: GCR modifications for WPP design optimization

- Two types of identified challenges:
  - **Economical**
    - Voltage and Frequency operating range
    - Reactive power control
    - Fault ride through
    - Emergency power control
  - **Technical**
    - Grid-forming capability
    - Black-start and restoration services
    - Inertia provision
    - Fast frequency response



Source: Kamenica, M., et al. Offshore Wind Farms and Energy Hub Integration. In *Proceedings of 2025 CIGRE Symposium Trondheim*

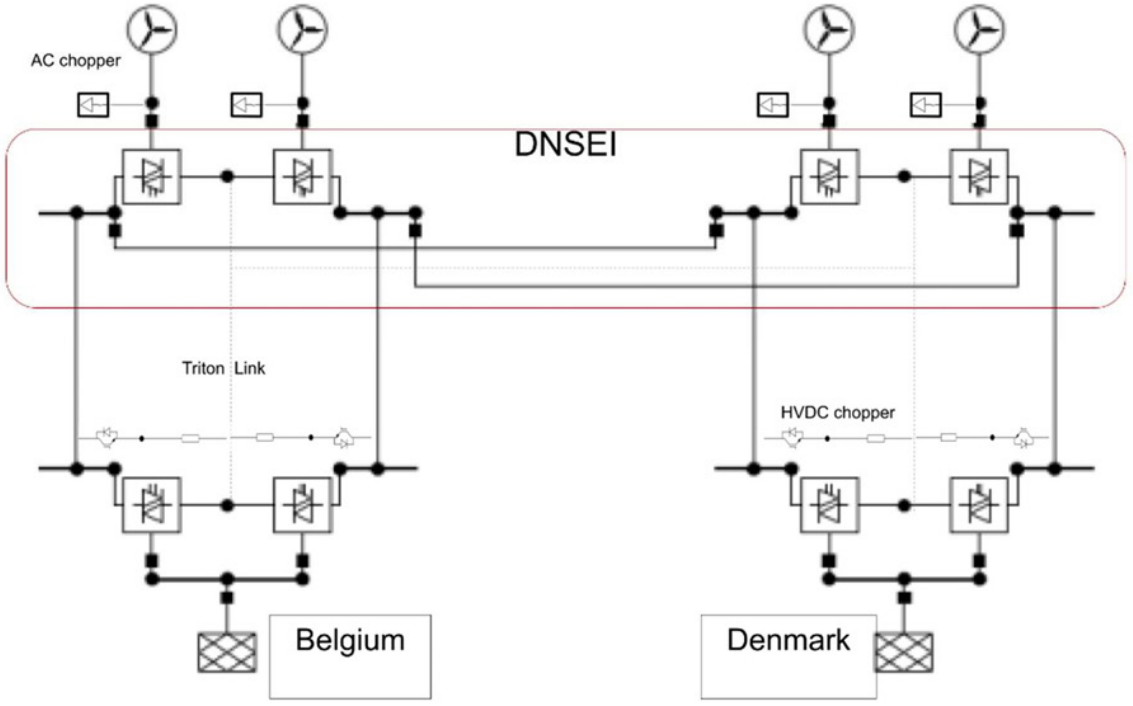
Energy dissipation strategies

Offshore energy hubs (or MT-HVDC)

In the event of a fault, power needs to be dissipated to keep WTs connected.

Options:

- Onshore HVDC choppers
- Offshore AC choppers
- WTs DC link choppers



Duvivier, A. J. F., et al., (2024). *Energy Dissipation Strategies for Offshore MT-HVDC Systems. In Proceedings of CIGRE Paris Session 2024*

Energy dissipation strategies

Results

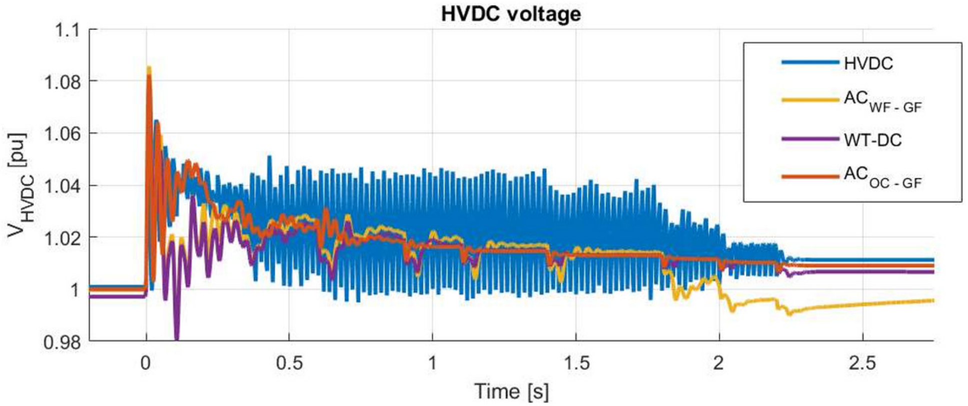


Figure 5. HVDC voltage magnitudes for an onshore AC 3P-G fault

	Energy [GJ]	Equivalent time at rated power [s]
HVDC	1.64	0.82
WF-GF	0.3	0.3
WT	0.4	0.4
OC-GF	0.45	0.45

Table 2: Energy dissipated for an onshore AC 3P-G fault

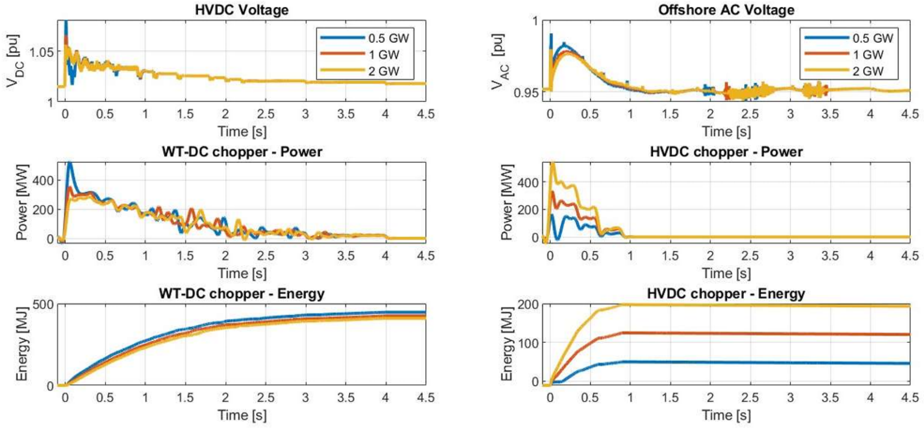


Figure 8: Impact of HVDC chopper power rating

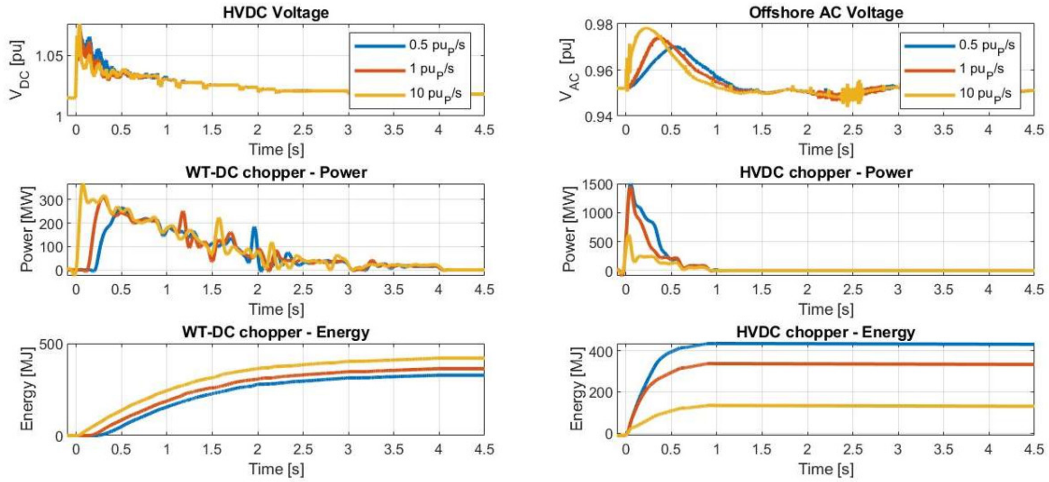
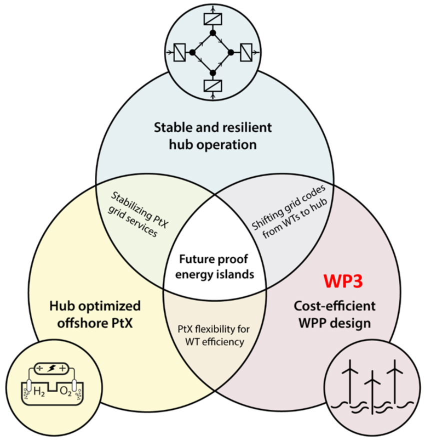


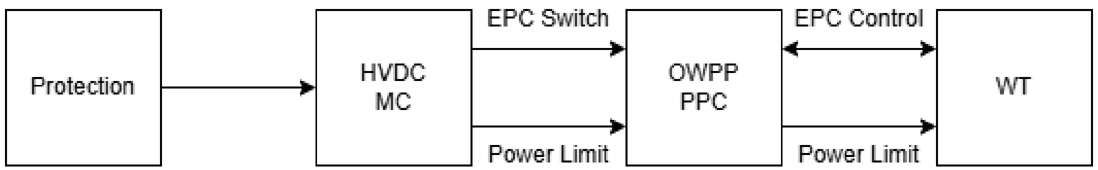
Figure 9: Impact of the rate of change in power of offshore converters

Duvivier, A. J. F., et al., (2024). Energy Dissipation Strategies for Offshore MT-HVDC Systems. In Proceedings of CIGRE Paris Session 2024

Emergency Power Control (EPC)



- Aims to protect OWPPs and enable active power dissipation
- Allows active power limit reduction from 100% to 0%
- Power output stays reduced while EPC signal is active
- Uses DC choppers to absorb excess energy



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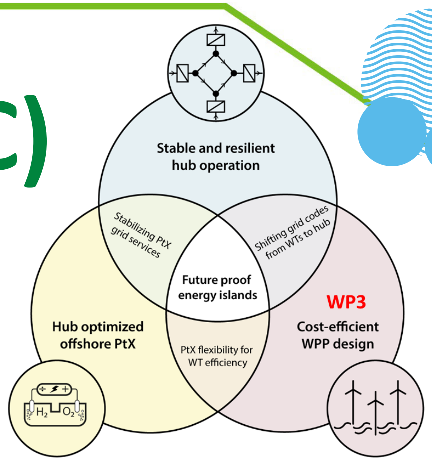
Emergency Power Control (EPC)



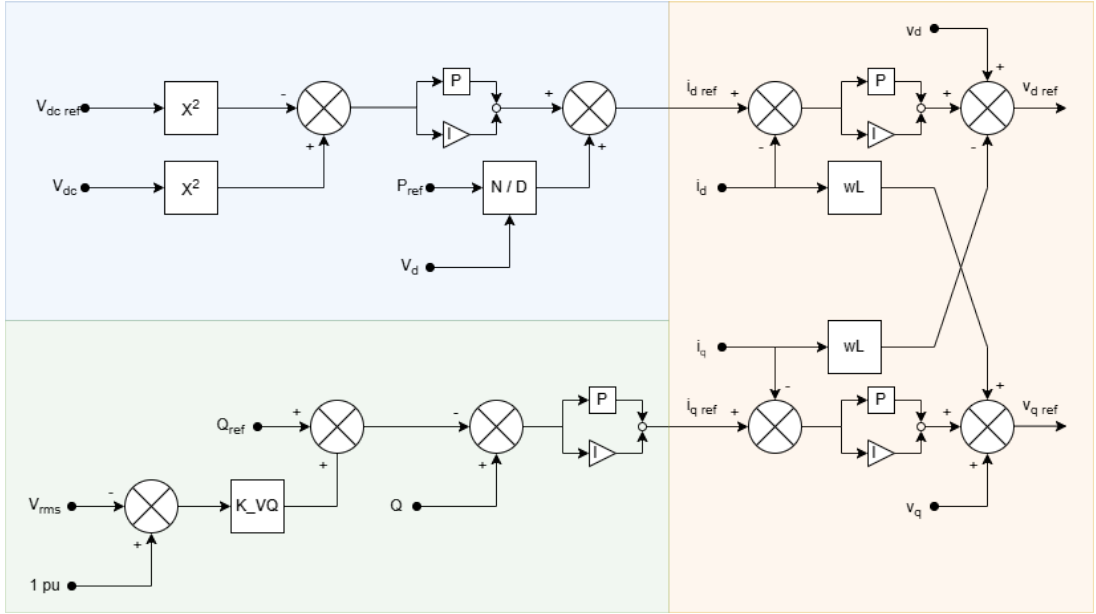
EPC control

EPC operates in two stages:

- FRT Operation
- Reduced Power Operation

After EPC activation:

- The control enters FRT mode, immediately forcing active power output (from grid side converter) to the new limit.
- The injected active power (from machine side converter) starts dropping towards the new limit, and once it reaches the new setpoint, the outer control resumes, and the turbine operates in reduced power mode.



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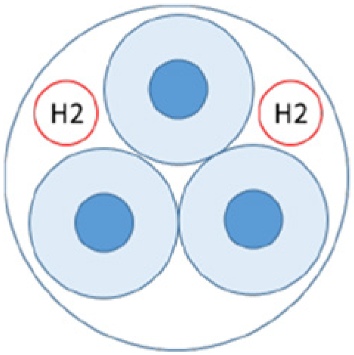
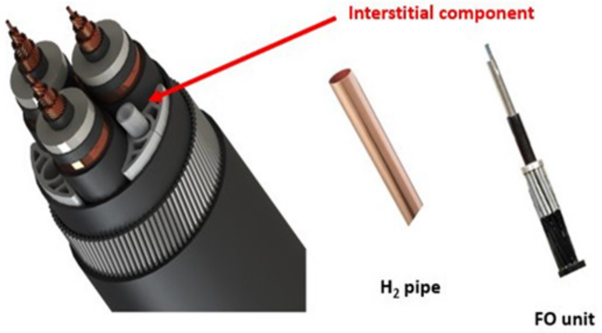
Umbilical cable

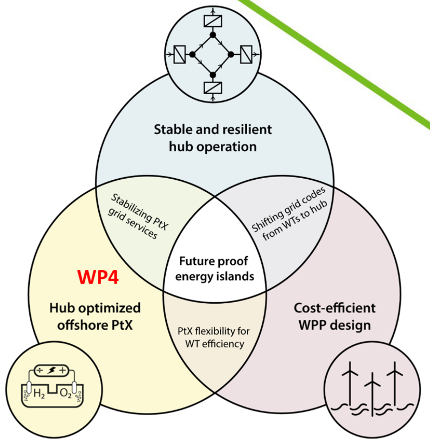
Hybrid transmission

Electric Power + Hydrogen Gas + FO

Static Submarine inter array cable







Concept:

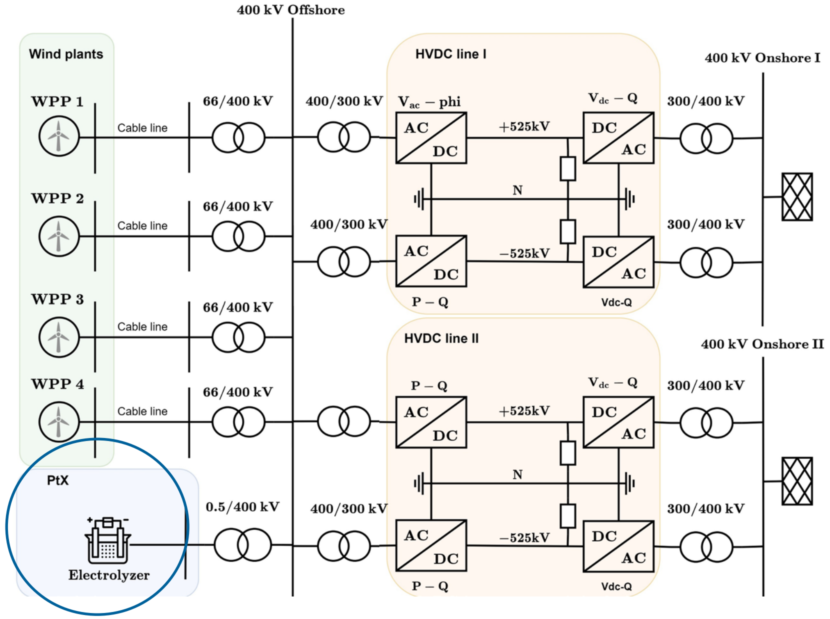
To integrate 1 up to 3 hydrogen gas pipes into the outer interstices of the laid-up cores of a 66kv inter array submarine cable.

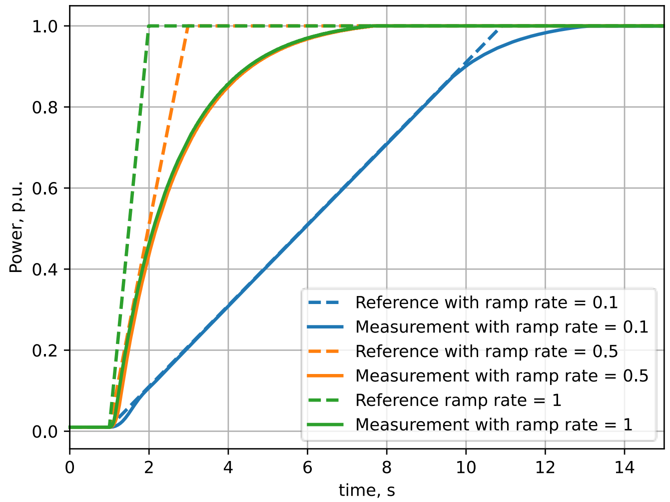
A two-stage approach:

- Design based on feasibility study
- Test according to relevant international standards

Electrolyzer on OEH

Ramp rate limitation





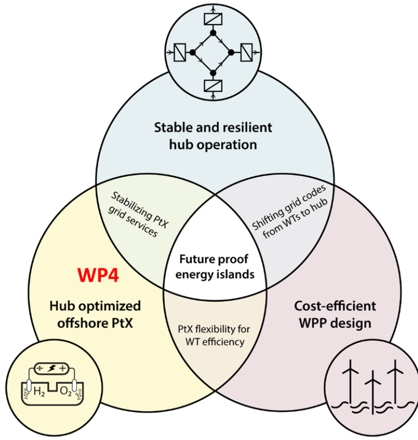


TABLE II: Electrolyzers' ramp rates comparison

Company	Technology	Plant capacity [MW]	Ramp rate [%/sec]
Nel [6]	ALK	2.2	0.2
Enapter [3]	AEM	1	1
Stiesdal [10]	ALK	3	1
Plug Power [8]	PEM	10	1 upwards, 4 downwards
Green Hydrogen Systems [11]	ALK	0.9	8
Nel [7]	PEM	10	10
Hystar [4]	PEM	5.9	100

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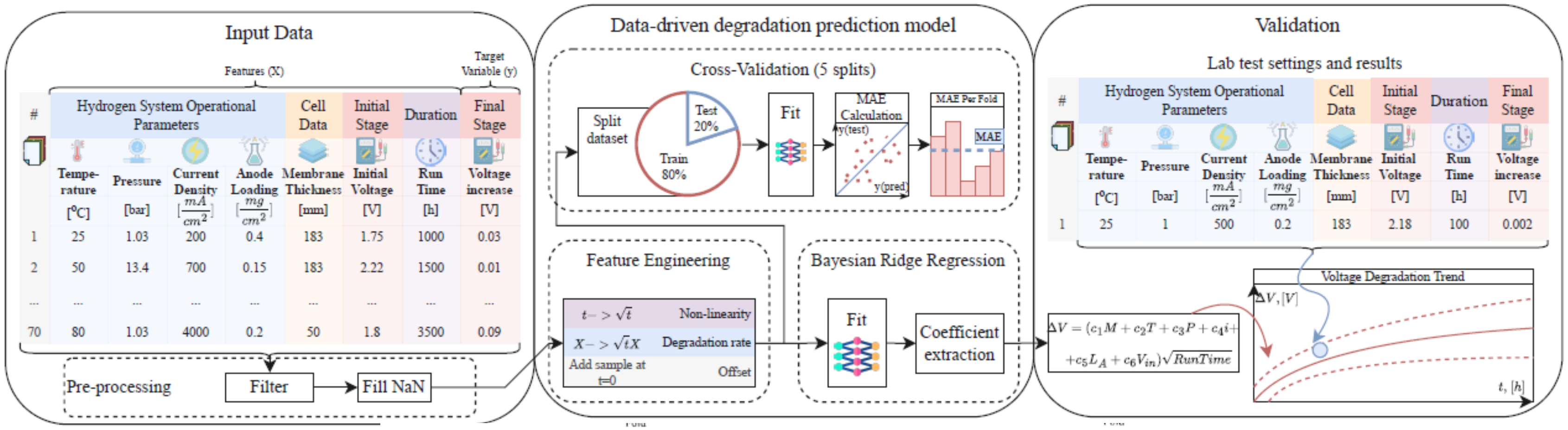
Taranin, N., et al., (Accepted/In press). On the Ramp-Rate Limitation of Electrolysis Plants: Modeling Fundamentals and System-Level Impact Analysis. *IEEE Transactions on Sustainable Energy*. https://doi.org/10.1109/TSTE.2025.3611711

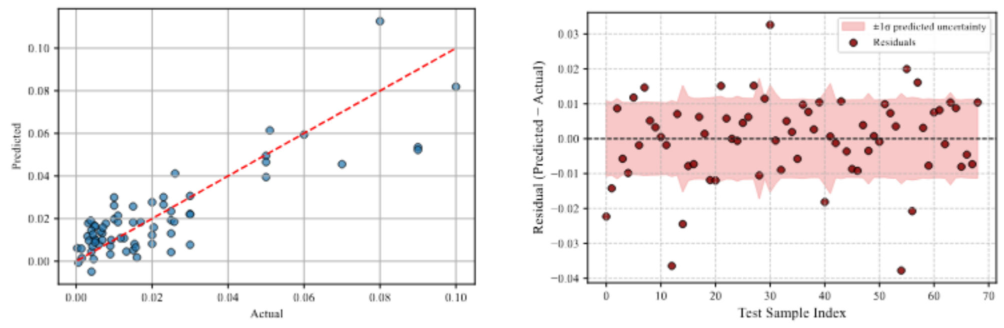
Electrolyzer on OEH

Data-driven degradation prediction model



(a) MAE across folds

(b) R^2 across folds



(c) Actual vs Predicted target variable

(d) Residuals of test samples

Fig. 6: Performance assessment results

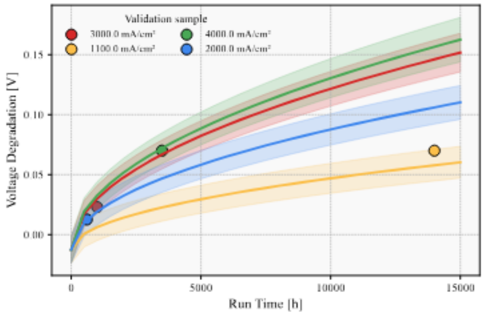
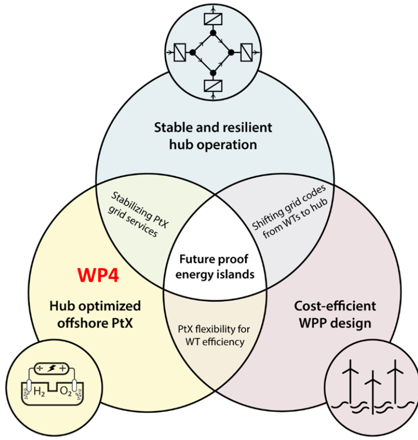


Fig. 7: Validation of the model based on the test samples from the dataset with $s_0 = 0$



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Taranin, N., et al. (in preparation). A Data-driven Model for Electrolysis Stack Degradation Estimation Under Different Power Consumption Profiles

Summary

- Offshore energy hubs control and operation quite challenging, tools for small signal stability are required

… also for large transients

- Opportunities for design optimization for OWPP connected to OEH

- Electrolyzers can provide balancing services, but better understanding/modeling of ramp rates & degradation needed

Thank you!

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References/additional reading

- Duvivier, A., et al, Small-Signal Modelling of Offshore Energy Hubs, PSCC 2026 (under review)
- Kamenica, M., et al. Offshore Wind Farms and Energy Hub Integration. In *Proceedings of 2025 CIGRE Symposium Trondheim*
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- Müller, D., et al., (2024) *FEASIBILITY ASSESSMENT OF HUB TOPOLOGIES*
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- Taranin, N., et al., "Leveraging Electrolyzer Portfolio For Power Balancing In Offshore EnergyHubs," in Wind&Solar Integration Workshop, 2025, Berlin, Germany