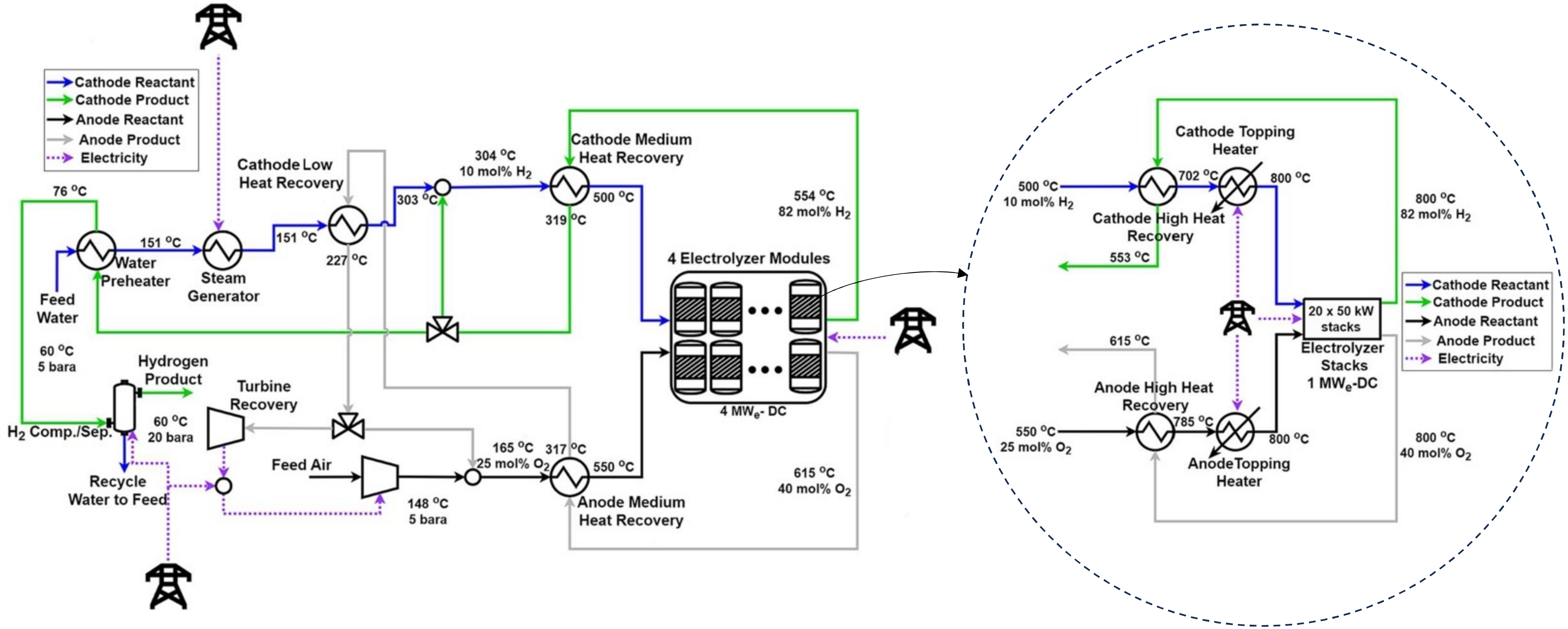
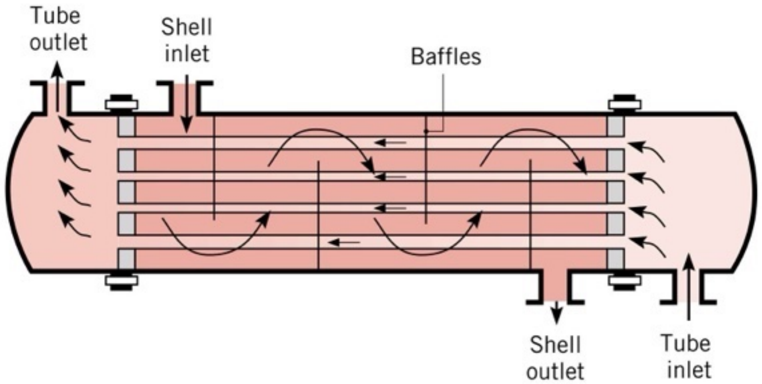
Electrolysis and Wind Turbine Modelling

SOEC Model



Cathode Reactant
Cathode Product
Anode Reactant
Anode Product
Electricity
Cathode Low Heat Recovery
Cathode Medium Heat Recovery
304 °C
10 mol% H_2
303 °C
500 °C
319 °C
554 °C
82 mol% H_2
76 °C
151 °C
151 °C
227 °C
Water Preheater
Steam Generator
Feed Water
4 Electrolyzer Modules
4 MW_e- DC
60 °C
5 bara
Hydrogen Product
Turbine Recovery
H_2 Comp./Sep.
60 °C
20 bara
Recycle Water to Feed
Feed Air
165 °C
25 mol% O_2
317 °C
550 °C
148 °C
5 bara
Anode Medium Heat Recovery
615 °C
40 mol% O_2
Cathode Topping Heater
500 °C
10 mol% H_2
702 °C
800 °C
800 °C
82 mol% H_2
Cathode High Heat Recovery
553 °C
20 x 50 kW stacks
Electrolyzer Stacks
1 MW_e-DC
615 °C
Anode High Heat Recovery
550 °C
25 mol% O_2
785 °C
800 °C
800 °C
40 mol% O_2
AnodeTopping Heater



$$\frac{\partial}{\partial t}\left[T_i(x)\right] = \frac{\dot{m}_i}{\rho_i A_i^H}\frac{\partial}{\partial x}\left[T_i(x)\right] - \frac{U^H P_{\text{tube}}}{\rho_i C_{p,i} A_i^H}\left[T_i(x) - T_{j\neq i}(x)\right]$$

$$\text{for } i, j \in \{\text{tube, crossflow}\}$$

Each heat exchanger is discretised by the number of total crossflow passes and the total length of the tubes.

- T is temperature, x is the length down the tubes,
- $\dot{m}$ is mass flow rate, ρ is density,
- A^H is the cross sectional area of flow,
- U^H is the overall heat transfer coefficient.
- P_{tube} is the total perimeter of all the tubes.

1

Heat Exchanger Modelling

- Ensures efficient heat transfer between process streams in the rSOC system
- Captures temperature dynamics that impact efficiency, durability, and response time
- Provides realistic boundary conditions for the full SOEC model and system simulations
- Key enabler for accurate prediction of hydrogen production and grid service performance

$$\frac{\partial}{\partial t}[T_i(x)] = \frac{\dot{m}_i}{\rho_i A_i^H}\frac{\partial}{\partial x}[T_i(x)] - \frac{U^H P_{\text{tube}}}{\rho_i C_{p,i} A_i^H}[T_i(x) - T_{\text{crossflow}}], \ i = \text{tube}$$

- The Steam Generator does not contain crossflow passes and is only sized by the length of the tubes which flow through the water.
- The electrical load required from resistive heating is calculated via the heat of vaporization for the Steam Generator.
- For topping heaters, the electrical load is calculated from the sensible heat to raise the fluid to its setpoint temperature.

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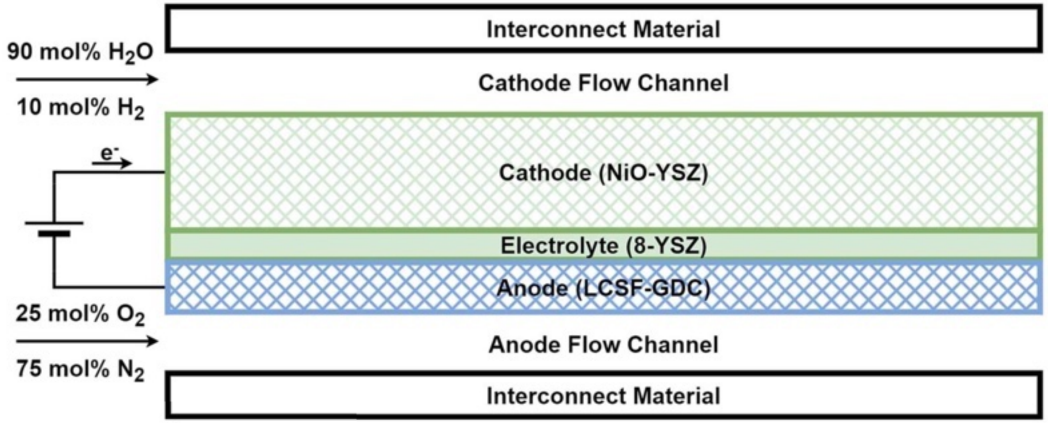
Steam Generator Modelling

- Produces high-temperature steam required for SOEC operation
- Electrical load determined by vaporization energy and sensible heating requirements
- Strongly affects system efficiency, start-up time, and operational flexibility
- Provides realistic thermal input conditions for accurate hydrogen production modelling



Mass balance equations:

$$\frac{\partial}{\partial t}[C_i(x)] = -u_{C/A}\frac{\partial}{\partial x}[C_i(x)] + \frac{1}{h_{C/A}}v_i R(x) \quad \text{for } i \in \{H_2, H_2O, O_2, N_2\}$$

- C_i is concentration, x is the length down the cell,
- $u_{C/A}$ is the fluid velocity, $h_{C/A}$ is the height of the flow channel,
- v is the stoichiometric coefficient of each reacting species

3

Stack Model

- Captures electrochemical reactions, mass flow, and heat transfer inside the cell stack
- Links gas composition, temperature, and current density to hydrogen production
- Models key physical limits (activation, ohmic, and concentration losses) that drive efficiency and degradation
- Provides the foundation for predicting stack performance under real operating conditions and grid service demand.

The four energy balances are separated for the cathode stream (C), the anode stream (A), the electric conducting structure (S), and the interconnecting material between each cell (I).

$$\frac{\partial}{\partial t}[T_i(x)] = -u_i \frac{\partial}{\partial x}[T_i(x)] + \frac{k_i}{\rho_i C_{p,i} h_i}[T_S(x) - T_i(x)] + \frac{k_i}{\rho_i C_{p,i} h_i}[T_I(x) - T_i(x)] \;\; \text{for } i \in \{\text{C}, \text{A}\}$$

$$\begin{aligned}\frac{\partial}{\partial t}[T_S(x)] = & \frac{\lambda_S}{\rho_S C_{p,S}} \frac{\partial^2}{\partial x^2}[T_S(x)] - \frac{k_C}{\rho_S C_{p,S} h_S}[T_S(x) - T_C(x)] \\ & - \frac{k_A}{\rho_S C_{p,S} h_S}[T_S(x) - T_A(x)] - \frac{2}{\rho_S C_{p,S} h_S}\left[\frac{\sigma\left[T_S^4(x) - T_I^4(x)\right]}{\frac{1}{\epsilon_S} + \frac{1}{\epsilon_I} - 1}\right] \\ & + \frac{1}{\rho_S C_{p,S} h_S}\left[-\Delta H^{rxn}(x) R(x) + j(x) U\right]\end{aligned}$$

$$\begin{aligned}\frac{\partial}{\partial t}[T_I(x)] = & \frac{\lambda_I}{\rho_I C_{p,I}} \frac{\partial^2}{\partial x^2}[T_I(x)] - \frac{k_C}{\rho_I C_{p,I} h_I}[T_I(x) - T_C(x)] \\ & - \frac{k_A}{\rho_I C_{p,I} h_I}[T_I(x) - T_A(x)] + \frac{2}{\rho_I C_{p,I} h_I}\left[\frac{\sigma\left[T_S^4(x) - T_I^4(x)\right]}{\frac{1}{\epsilon_S} + \frac{1}{\epsilon_I} - 1}\right]\end{aligned}$$

3

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For a cell discretised in the length direction with n discretisations, there are $5n$ unknown variables

$U(i), j^{\text{cathode}}(i), j^{\text{anode}}(i), \eta_{\text{act}}^{\text{cathode}}(i), \text{and } \eta_{\text{act}}^{\text{anode}}(i) \text{ for } i = [1:n]$, and there are $5n$ equations:

$$
\begin{aligned}
f(1:n) = &-U(i) + U^{\text{rev}}(i) + \eta_{\text{ohm}}(i) + \eta_{\text{conc}}^{\text{cathode}}(i) + \eta_{\text{conc}}^{\text{anode}}(i) + \eta_{\text{act}}^{\text{cathode}}(i) + \\
&+ \eta_{\text{act}}^{\text{anode}}(i) + \eta_{\text{contact}}(i) \text{ for } i = [1:n] \\
f(n+1:2n) = j^{\text{cathode}}(i) - j_0^{\text{cathode}}(i) &\left[\frac{C_{H_2}^{TPB}(i)}{C_{H_2}(i)} \exp\left(\frac{2F(1-\alpha)}{\mathbb{R}T_S(i)} \eta_{\text{act}}^{\text{cathode}}(i) \right) \right. \\
&\left. - \frac{C_{\mathrm{H_2O}}^{TPB}(i)}{C_{\mathrm{H_2O}}(i)} \exp\left(\frac{-2F\alpha}{\mathbb{R}T_S(i)} \eta_{\text{act}}^{\text{cathode}}(i) \right) \right] \text{ for } i = [1:n] \\
f(2n+1:3n) = j^{\text{anode}}(i) - j_0^{\text{anode}}(i) &\left[\exp\left(\frac{2F(1-\alpha)}{\mathbb{R}T_S(i)} \eta_{\text{act}}^{\text{anode}}(i) \right) \right. \\
&\left. - \frac{C_{O_2}^{TPB}(i)}{C_{O_2}(i)} \exp\left(\frac{-2F\alpha}{\mathbb{R}T_S(i)} \eta_{\text{act}}^{\text{anode}}(i) \right) \right] \text{ for } i = [1:n] \\
f(3n+1:4n) &= j^{\text{cathode}}(i) - j^{\text{anode}}(i) \text{ for } i = [1:n] \\
f(3n+1:5n-1) &= U(i) - U(i+1) \text{ for } i = [1:n-1] \\
f(5n) &= j^{\text{applied}} - \text{mean}\left[j^{\text{cathode}}(i:n) \right]
\end{aligned}
$$

3

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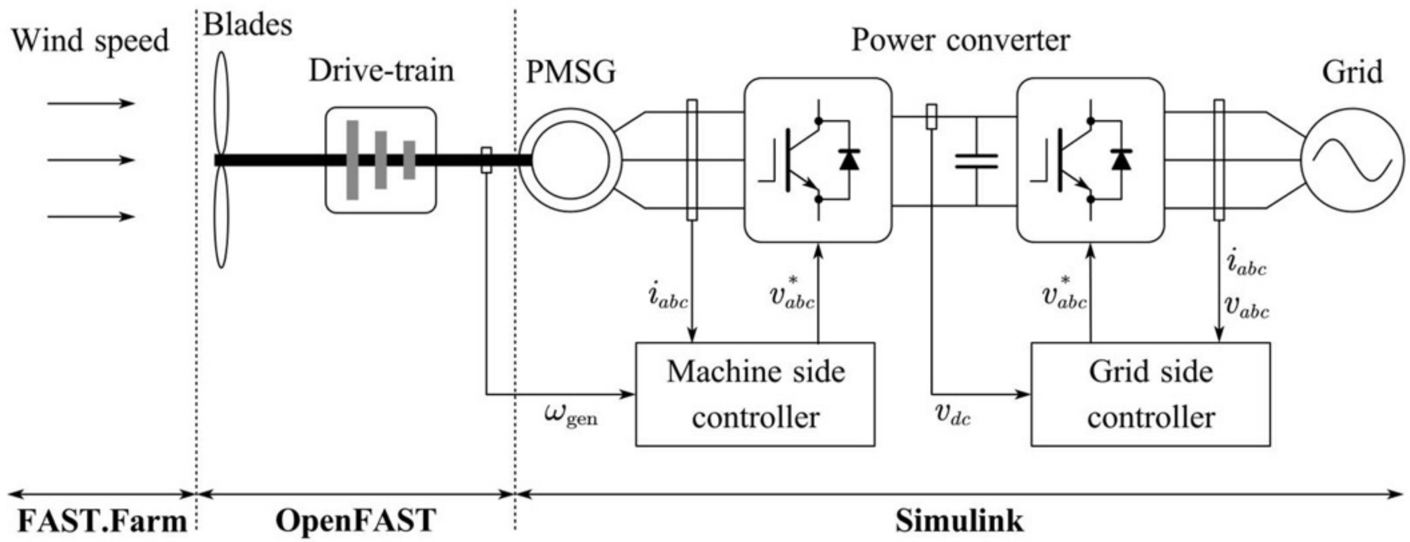

Simulation based on NREL OpenFAST and MATLAB/simulink

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Wind Turbine Model

- Simulated using NREL OpenFAST (aerodynamics & structural response) coupled with MATLAB/Simulink (generator, converter, grid control).
- Provides realistic power output under variable wind and grid conditions.
- Essential for assessing how wind farms interact with rSOCs to deliver frequency regulation and ancillary services.

Simulations

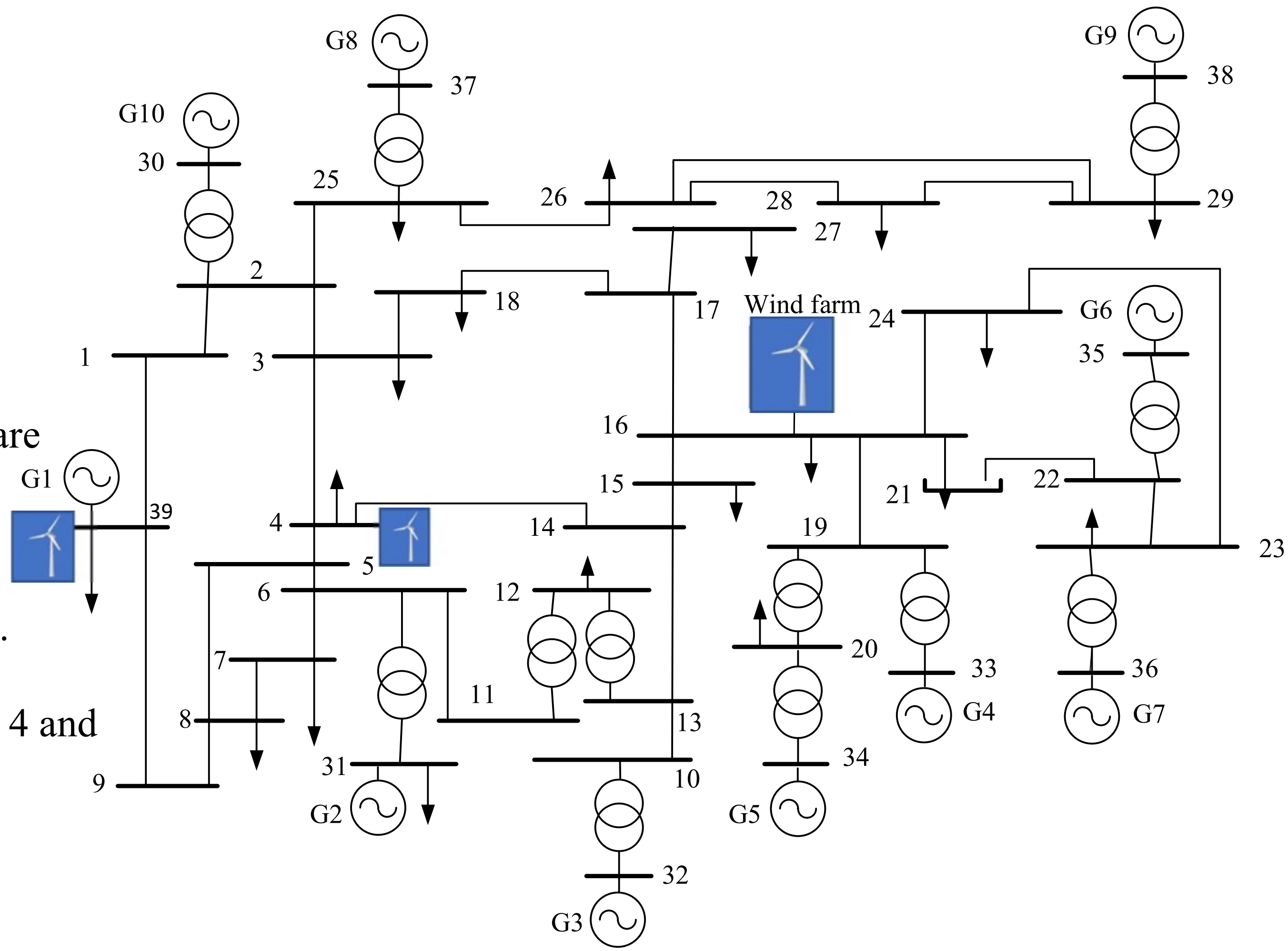
IEEE 39-bus test system,

- 39 buses
- 32 transmission lines
- 24 transformers
- 10 synchronous generators
- 3 OWFs
- 3 rSOCs
- Inertia of synchronous generators G1 and G9 are reduced
- Dynamic load change in the system
- rSOC model includes Nernst's equation,

activation loss, concentration loss and ohmic loss.

- The OWFs-rSOCs are located at different

geographical locations in the system (i.e., bus 16, 4 and 39)



Simulations

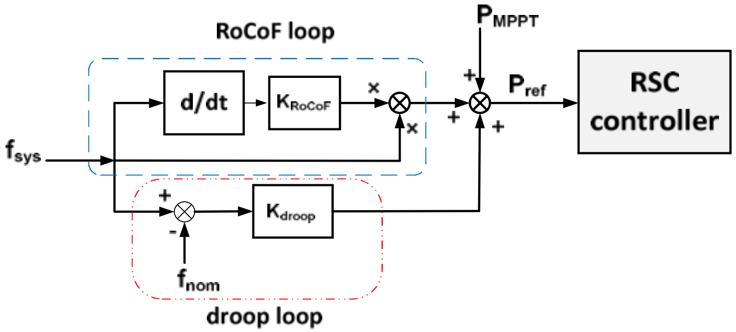
Dynamic regulation ancillary service:

- System: 3 OWFs (1 GW each) + 3 rSOCs (200 MW each), connected via HVAC to IEEE 39-bus grid.
- rSOC1 & rSOC2 in fuel cell mode (20% & 30% load).
- rSOC3 in electrolysis mode (50% load).OWFs: operate at maximum power point tracking (MPPT), then provide frequency support.

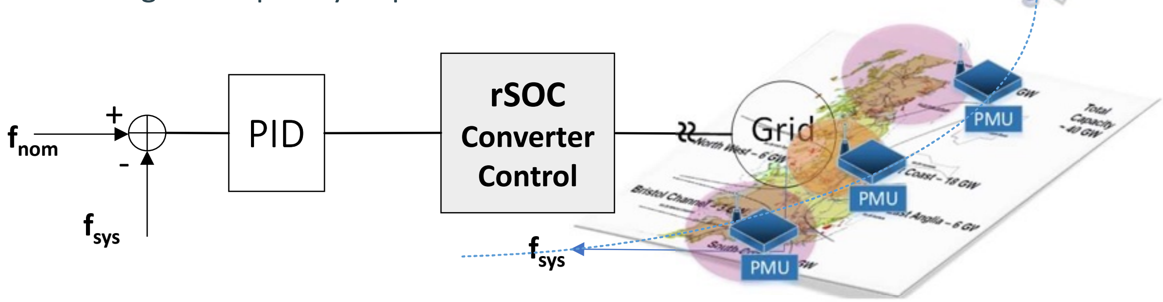
Outcome: joint OWF–rSOC response stabilises grid frequency under random, volatile load changes.

Location-independent: rSOCs can be placed onshore or offshore.

OWF:
Frequency-dependent Inertial Control (FDIC)

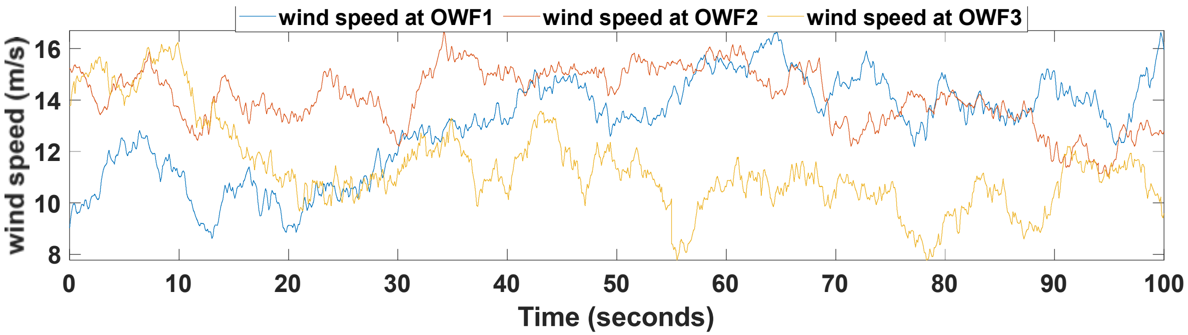


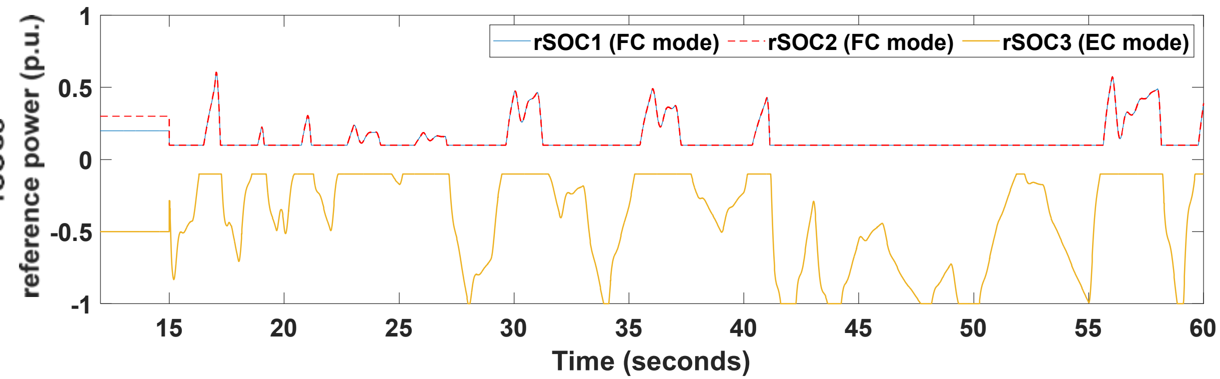
rSOC:
Fixed gain frequency-dependent control scheme

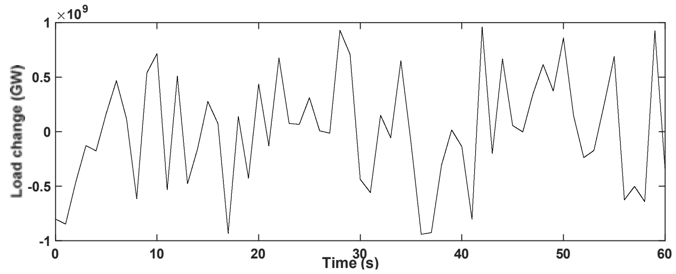


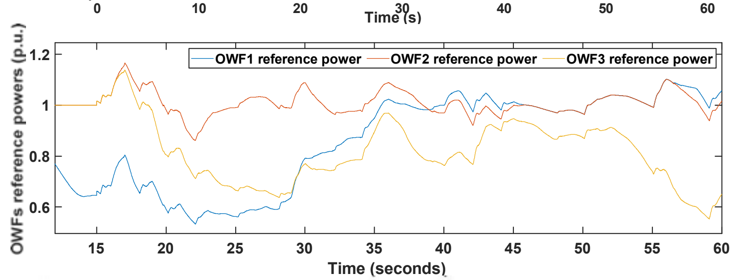
Simulation results

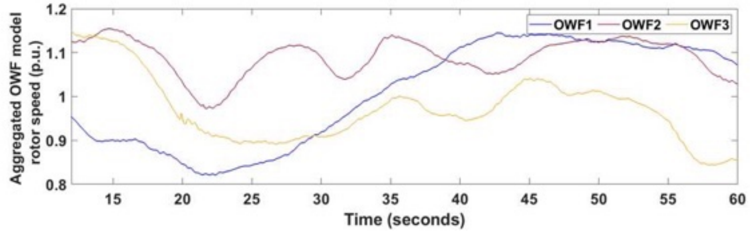
Case 1: OWFs & rSOCs provide dynamic frequency regulation service, variable wind speed, variable load pattern

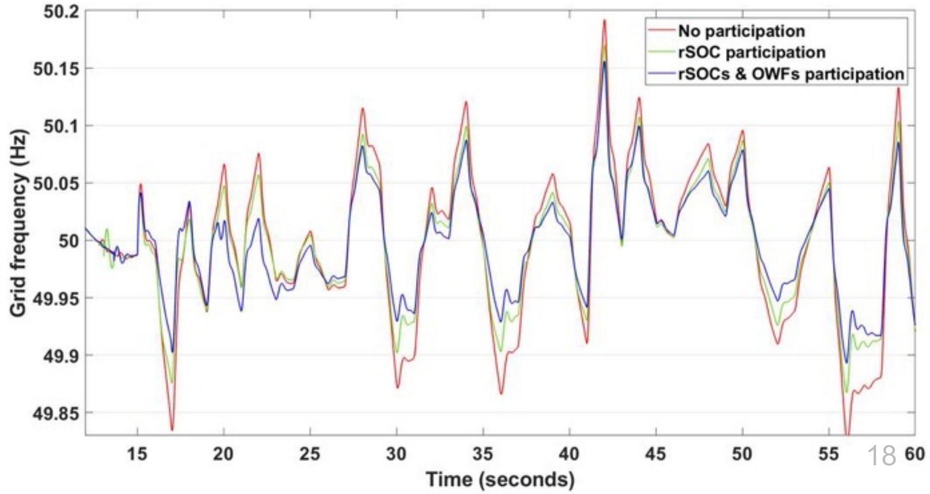




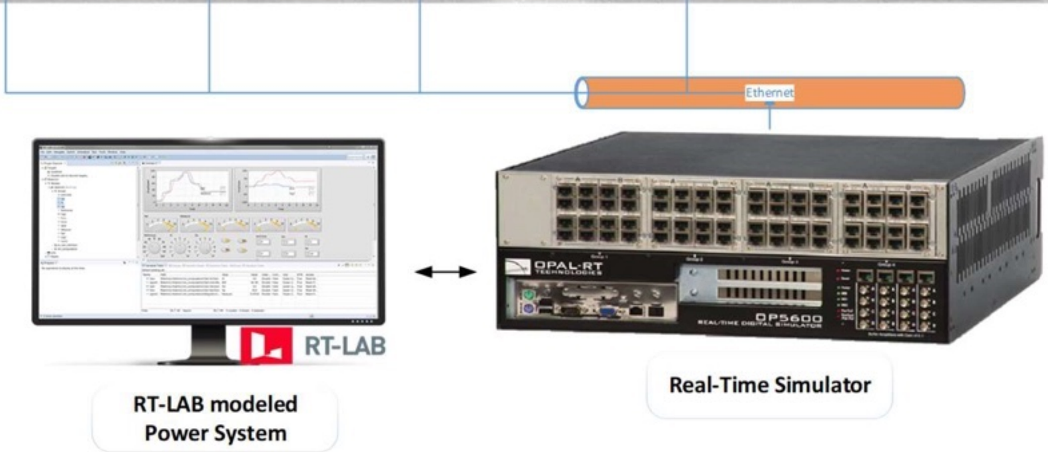








HIL test



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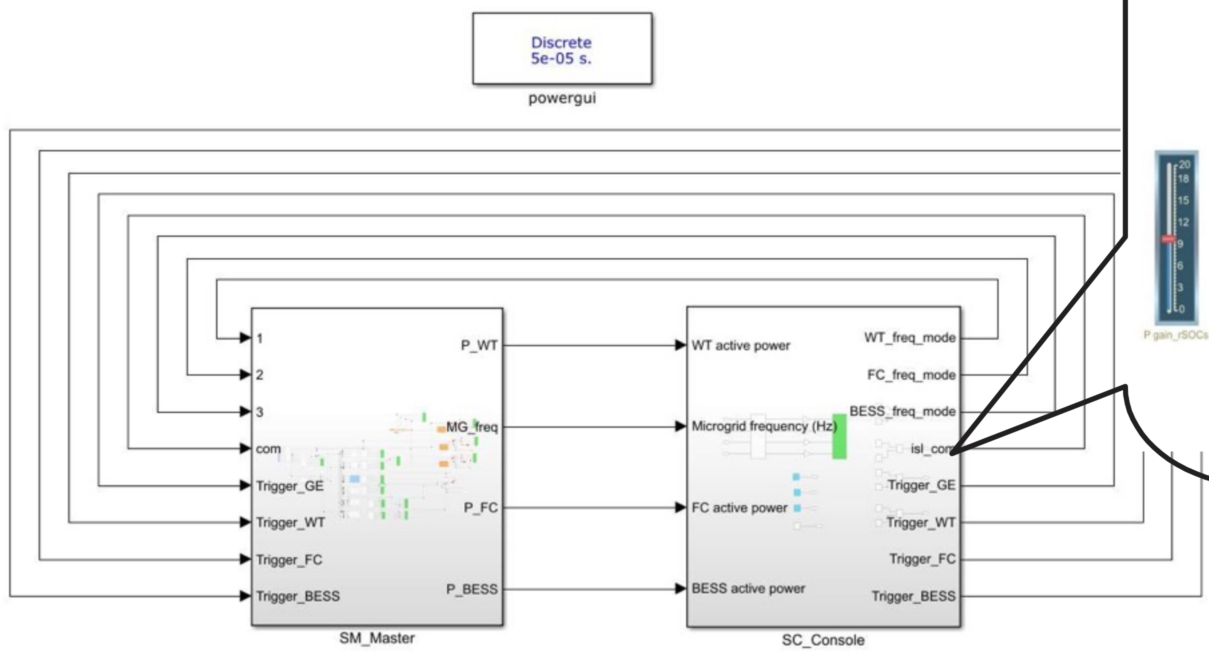
ICSE
Intelligent Control & Smart Energy

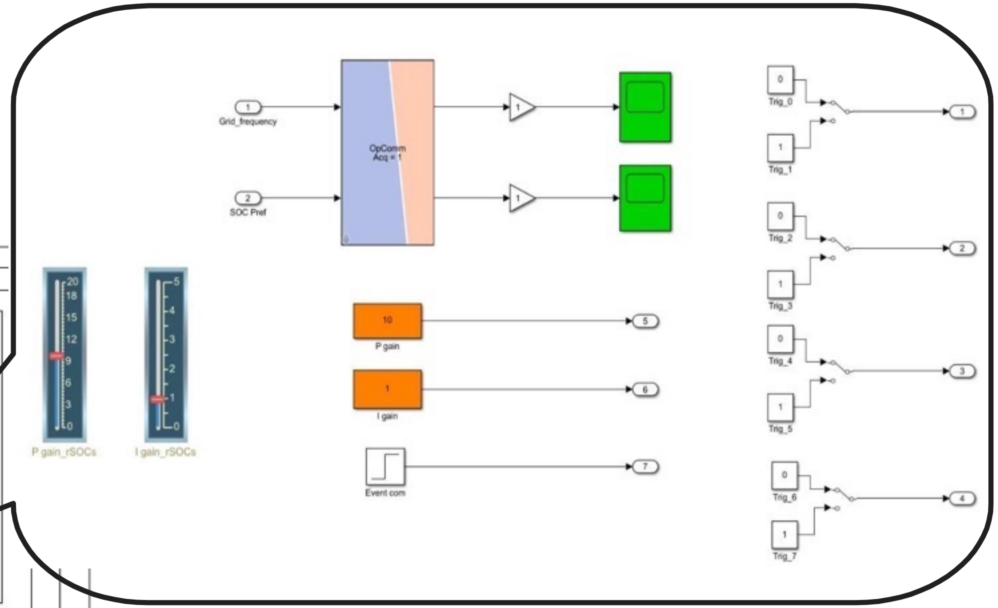
Offshore Renewable Energy Laboratory

Renewable Energy Integration & Smart Grid Laboratory

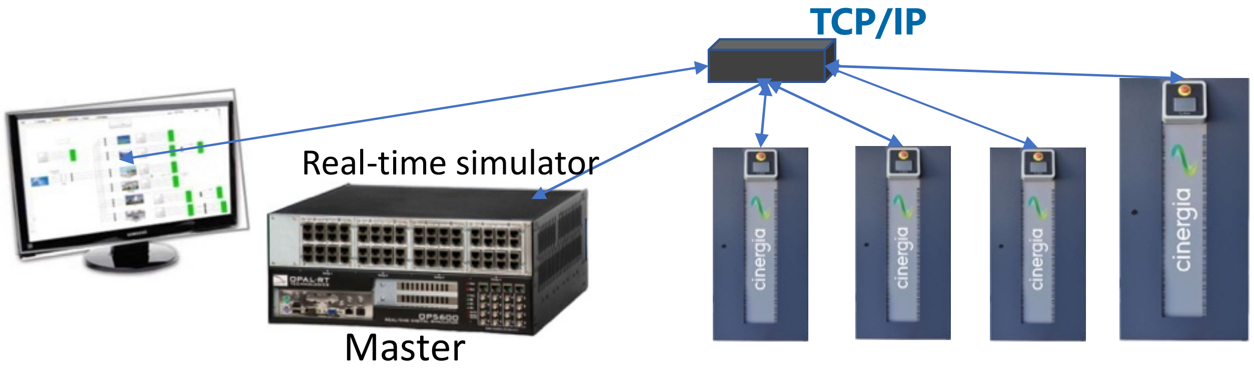
Autonomous Systems Laboratory

HIL test





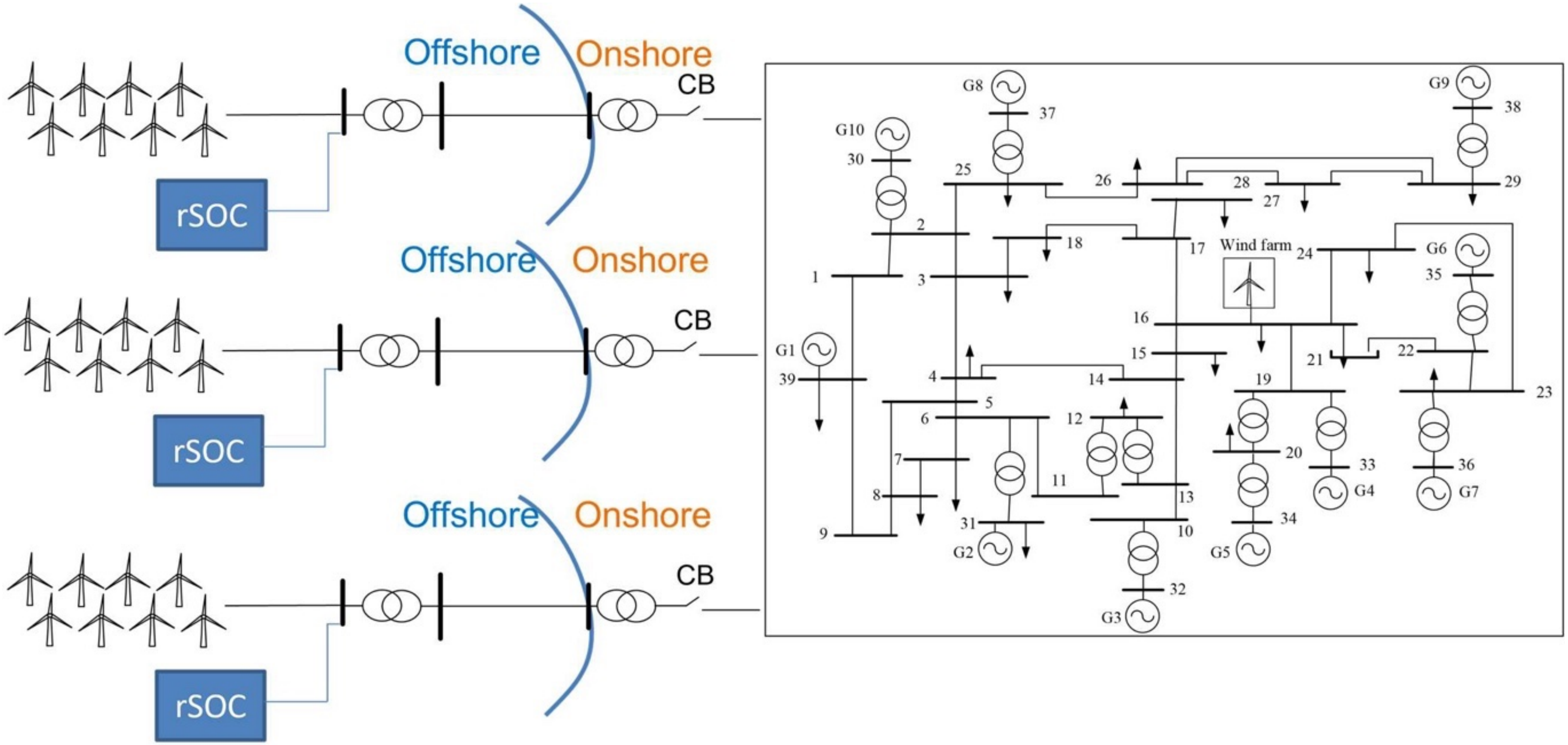
- Control of the rSOC control system on-the-fly in real-time
- Activation and de-activation of OWF-rSOCs in real-time



Slaves: replicating the output power of rSOCs and OWFs

HIL test

Connection of 3 OWFs (each 1GW) and 3 rSOCs (each 200MW) to the onshore power system (IEEE 39 bus system) via HVAC connection
rSOCs and OWFs participate in dynamic frequency regulation. The output of rSOCs and OWFs at the onshore node is replicated by electronic load emulator and grid is replicated by the Grid Emulator. The accumulated powers from the OWFs-rSOCs help regulate the grid frequency to be close to 50Hz.



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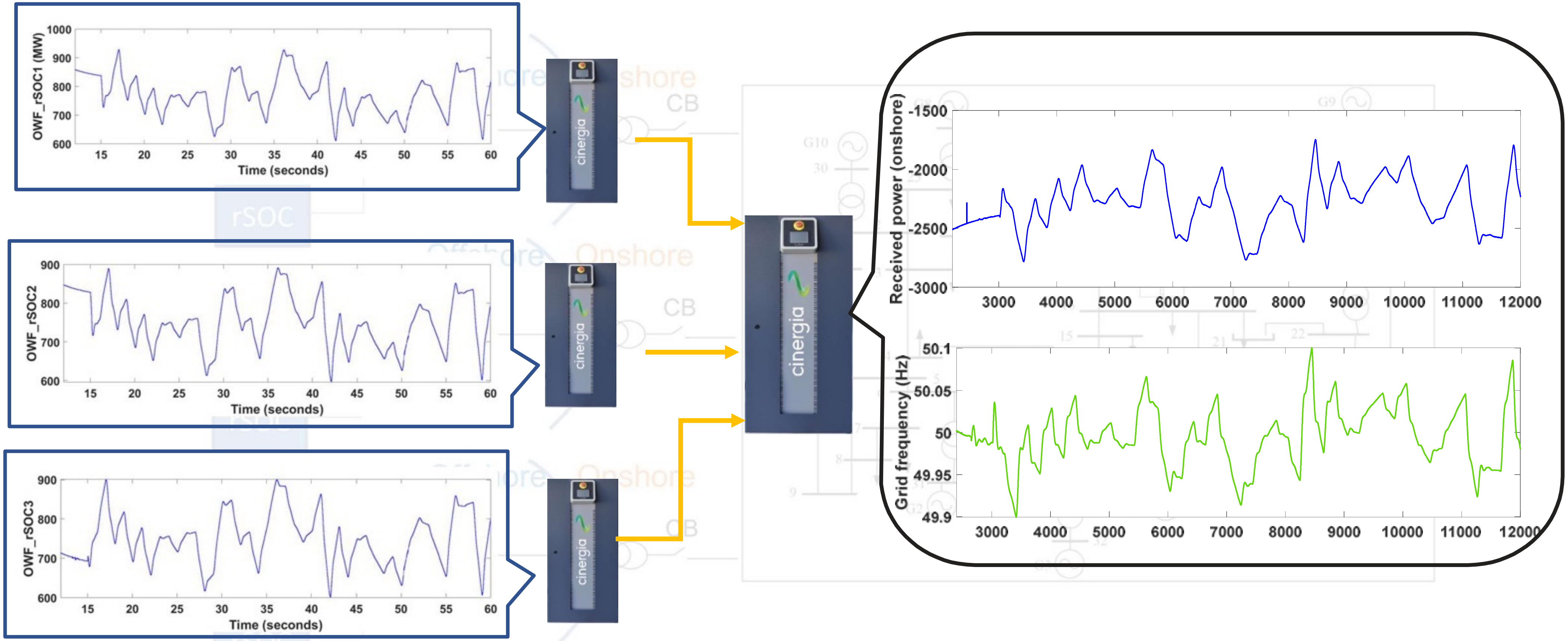

M. Kheshti, X. Zhao, "Analysis of Offshore Wind Farm and Reversible Solid Oxide Cell Integration for Grid Frequency Regulation" *Wind Energy Science Conference (WESC),* Glasgow, May 2023