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Control of Multi-Stack PEM Water Electrolyzer Systems: From Optimal Operation to Control Design

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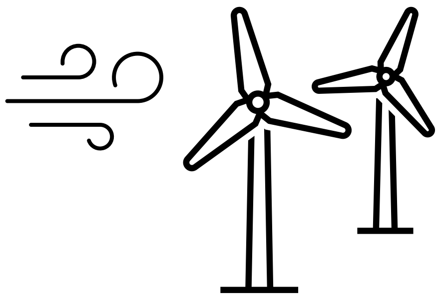
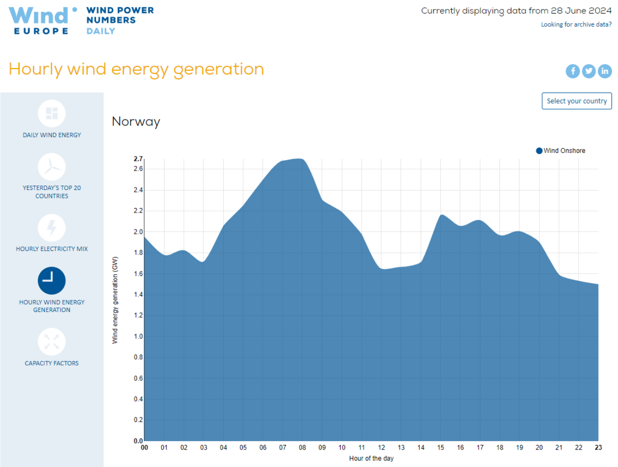
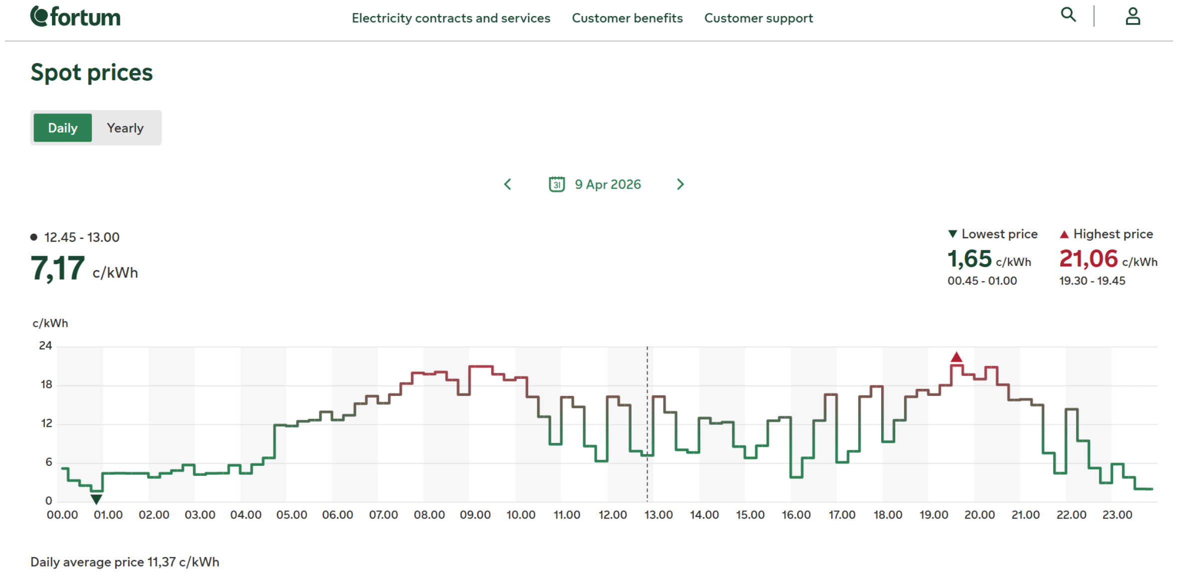
PEM Electrolyzers Face a Dynamic Environment

- Hydrogen to store and transport green energy
- Fluctuating energy output from renewable sources such as wind and solar
- Volatile Energy prices
- Hydrogen demand from downstream consumers







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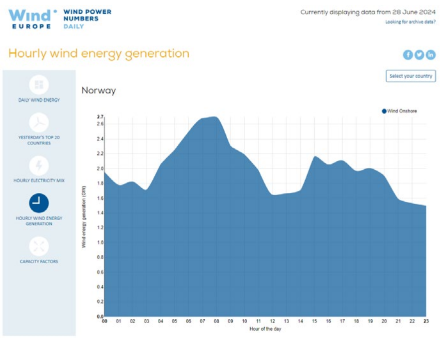
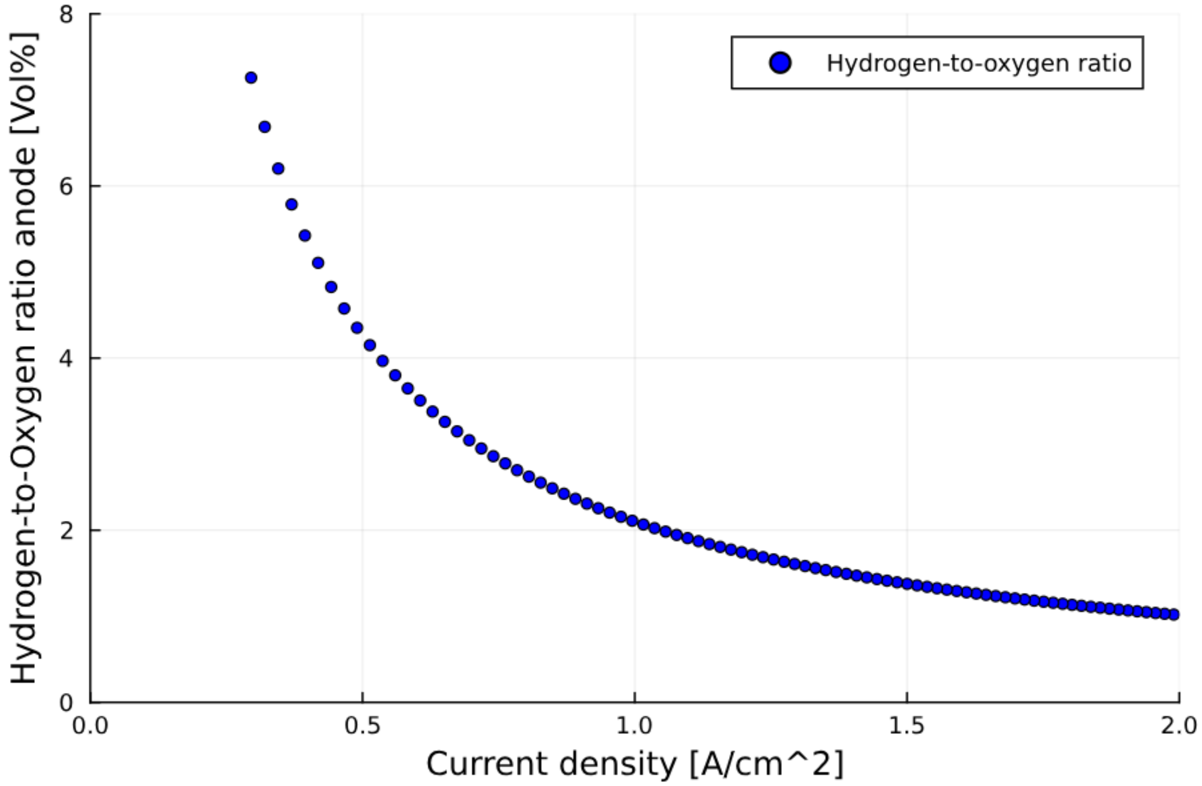
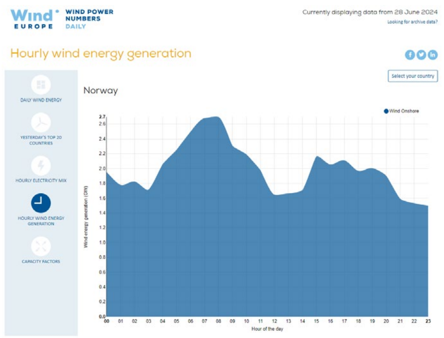
Fluctuations and Safety

- The Hydrogen-to-Oxygen ratio (HTO) is closely related to the power input
  - At low power, we have lower current density
  - At low current densities, we have high HTO





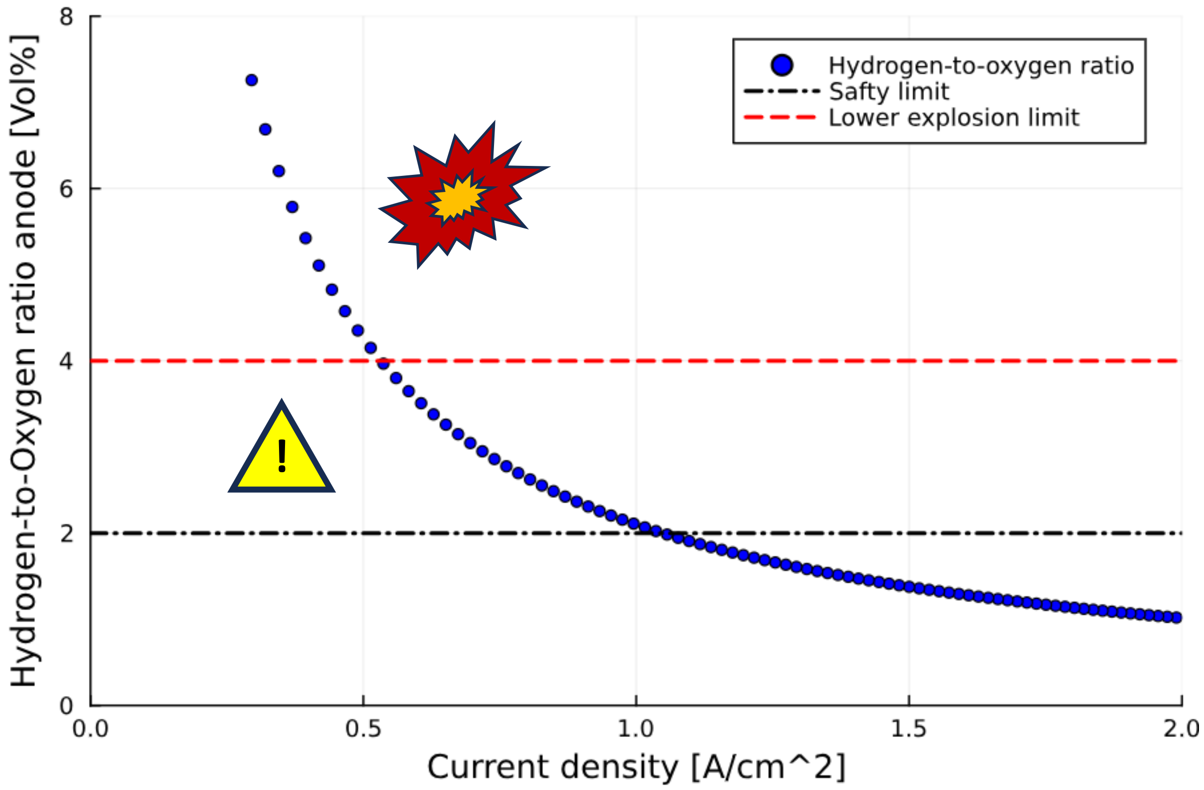
Fluctuations and Safety



- Major safety risk:
  - H_2/O_2 mixtures are flammable
  - Safety limit:

    2 vol%
  - Lower explosion limit:

    4 vol%



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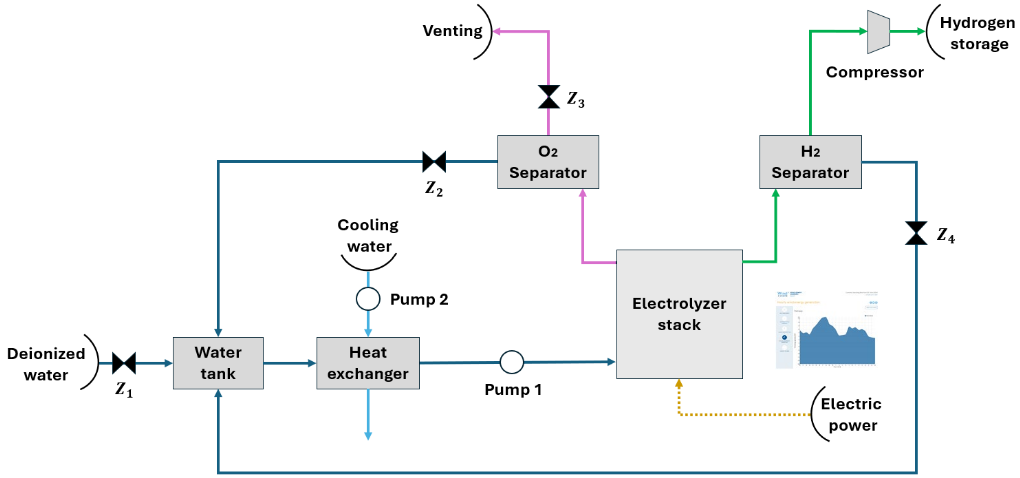
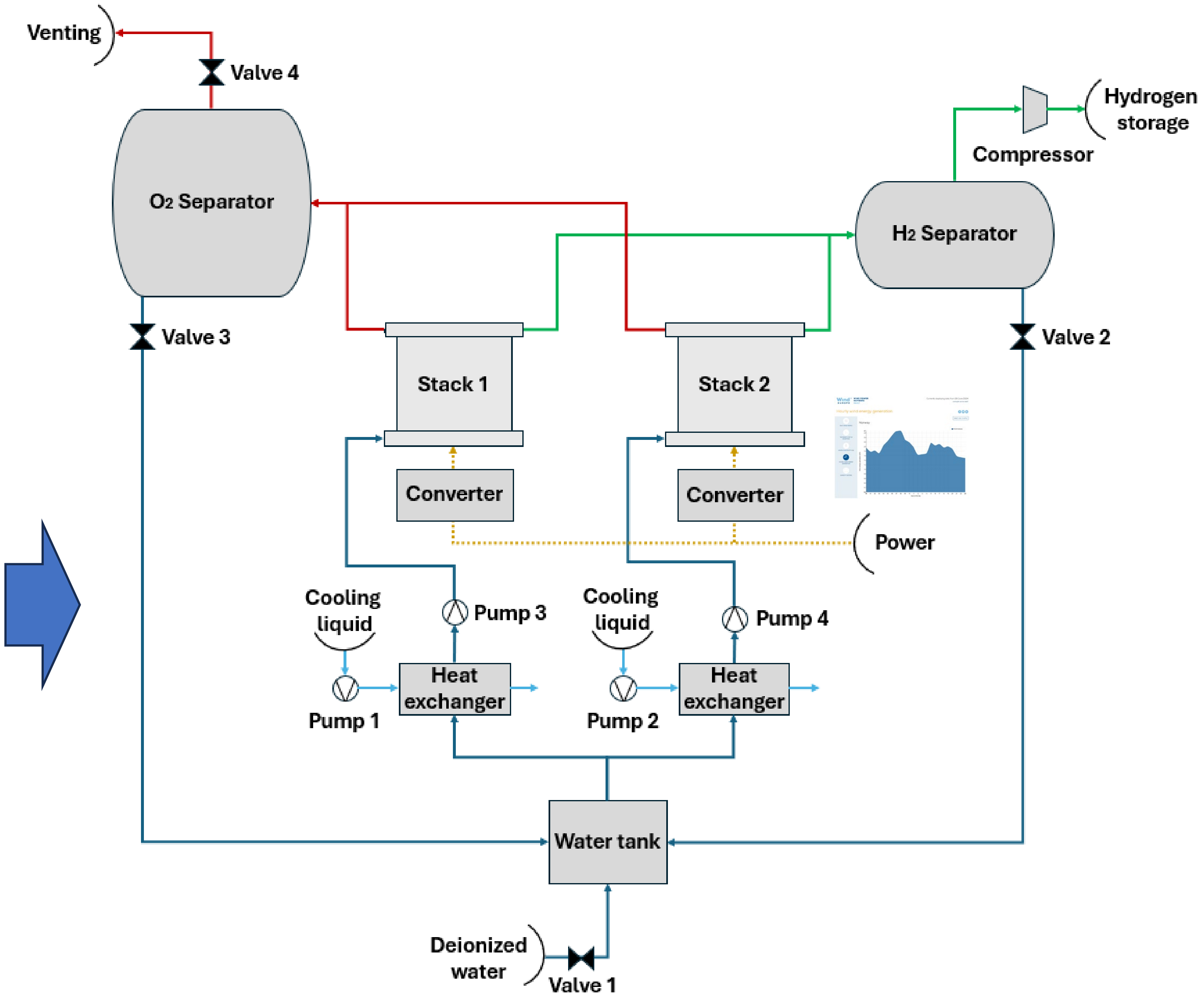
Two-Stack System Description

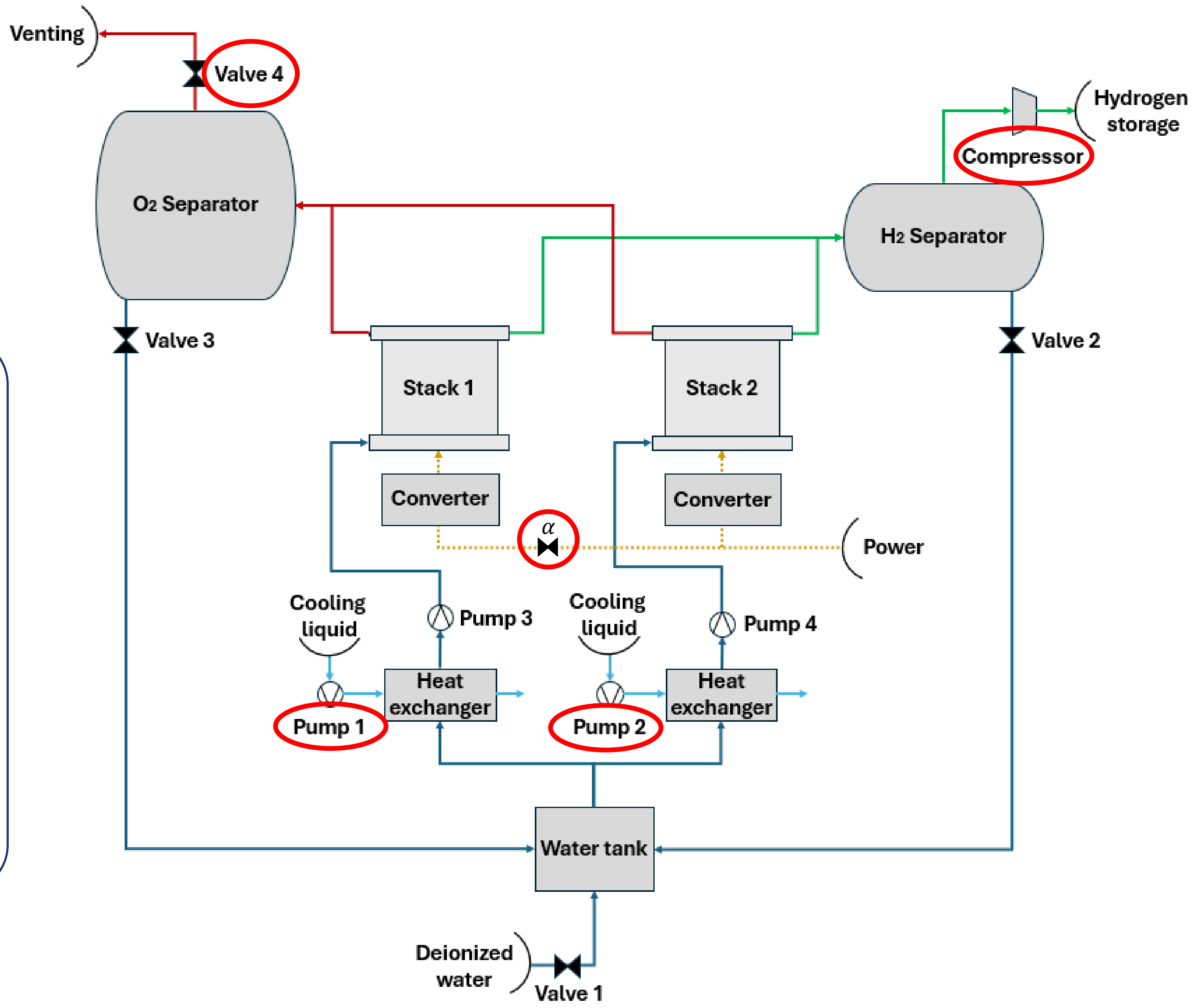




Available Actuators

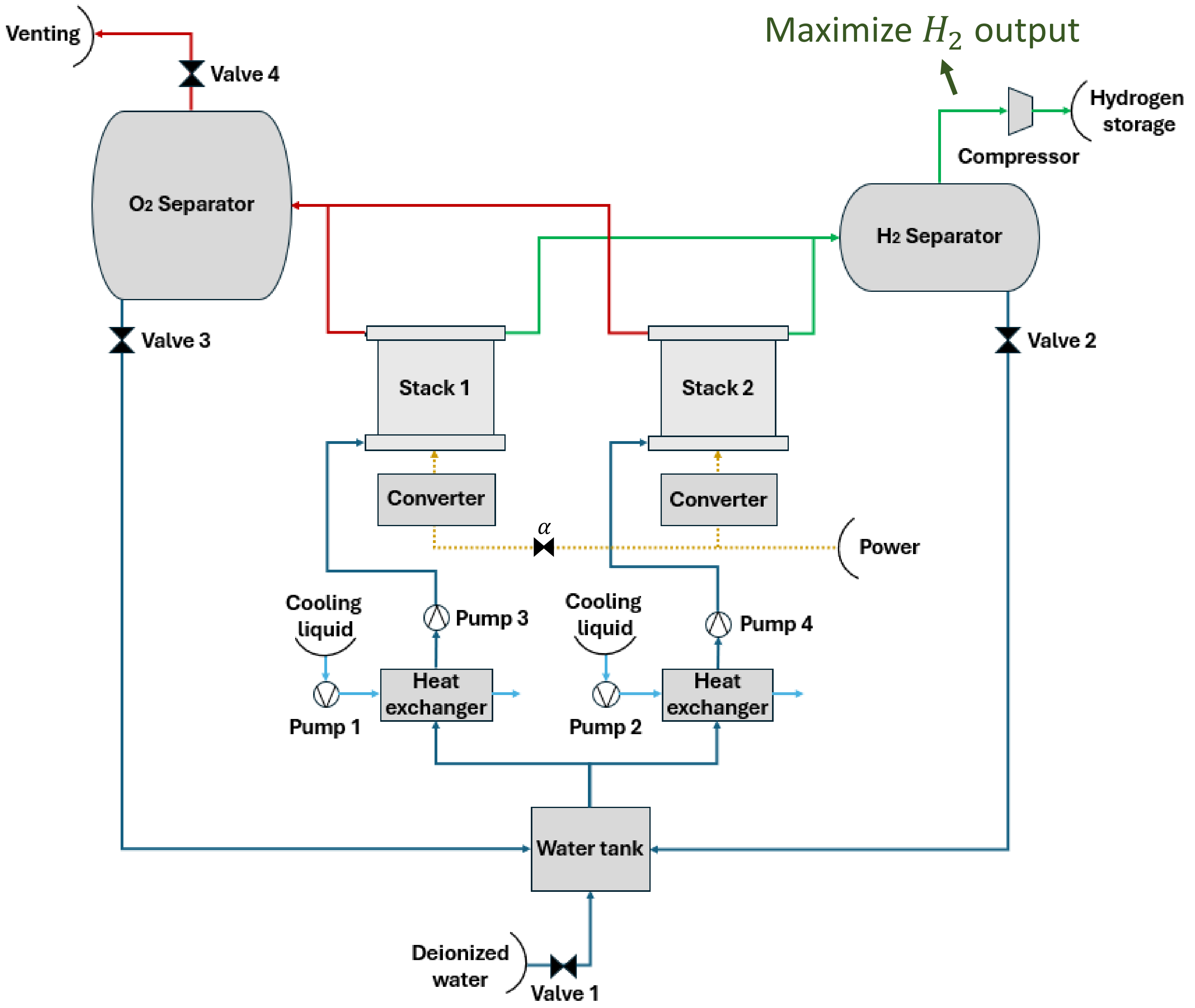
5 available actuators after level control:

- Oxygen purge
- Hydrogen flow rate
- Power allocation between the stacks
- Cooling liquid flow rates



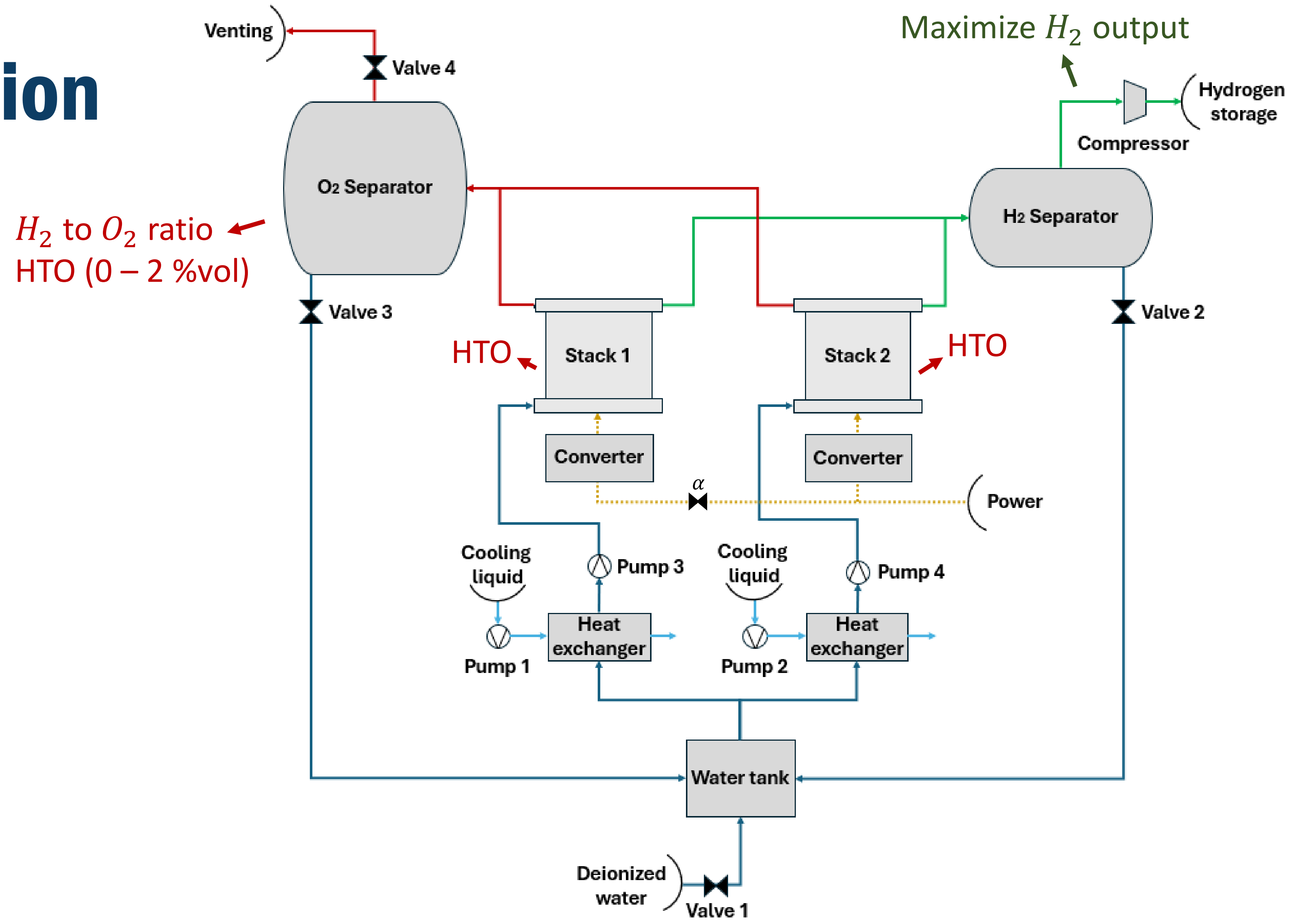
Optimization

- Objective



Optimization

- Objective
- Constraints



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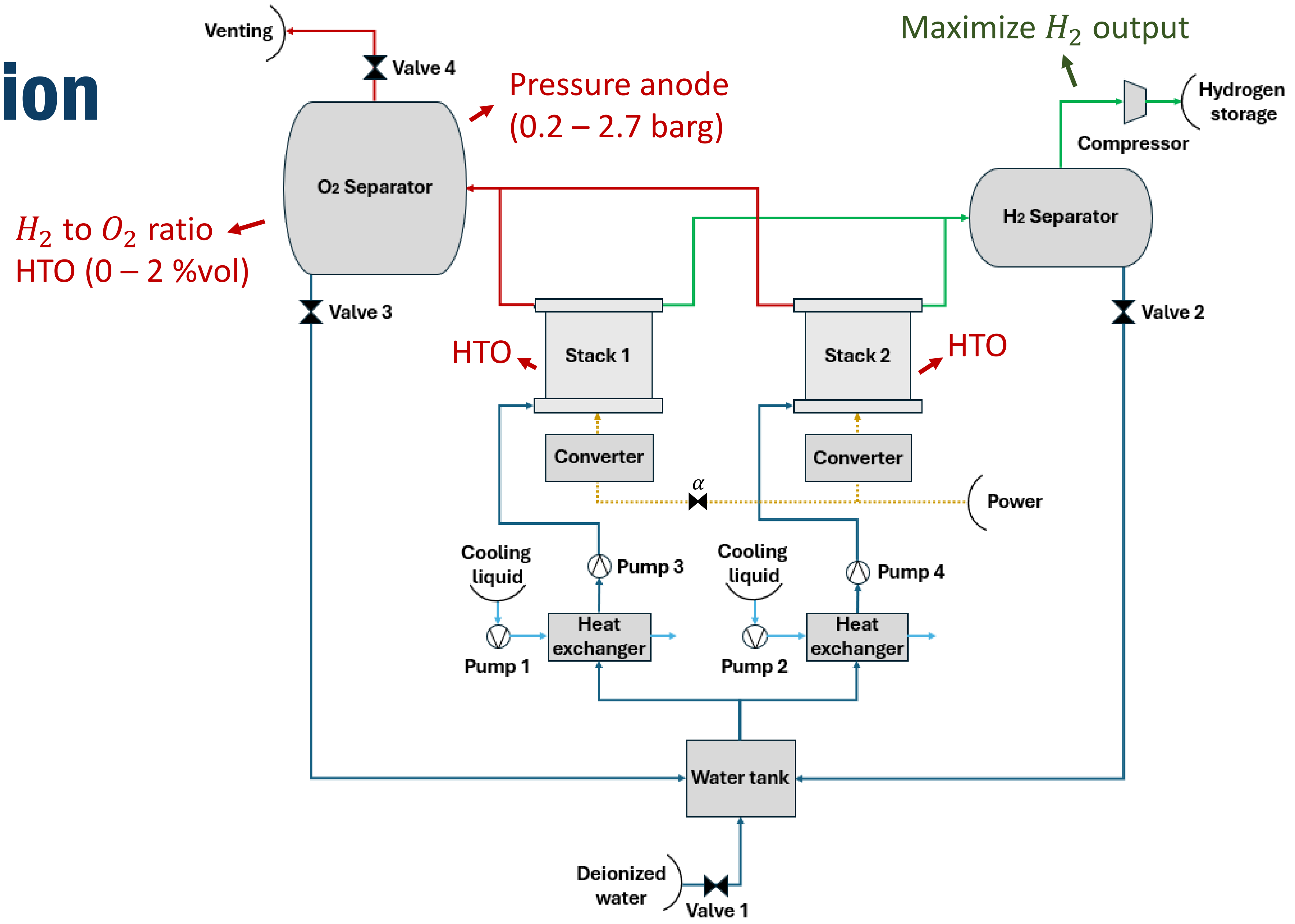

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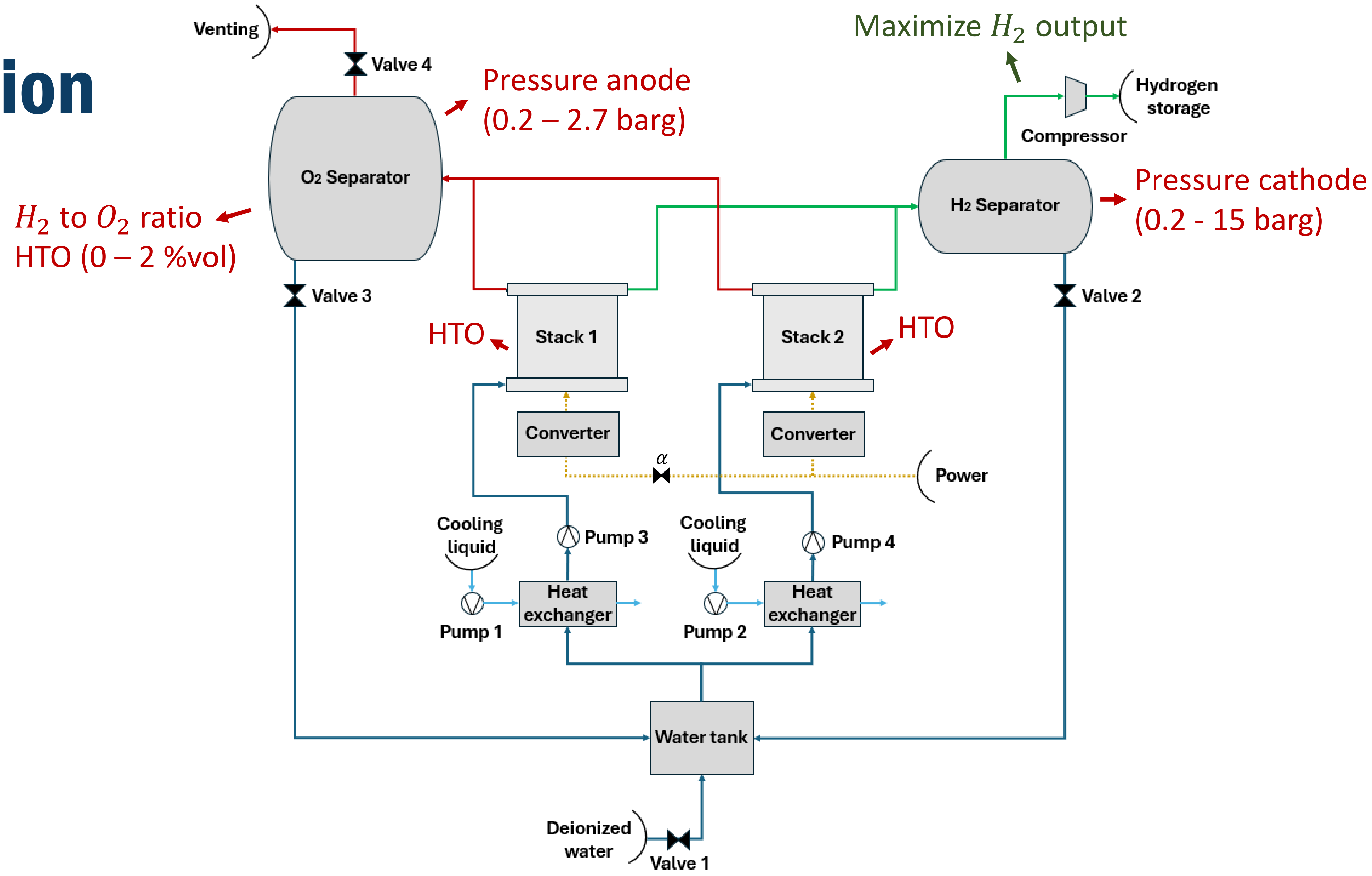

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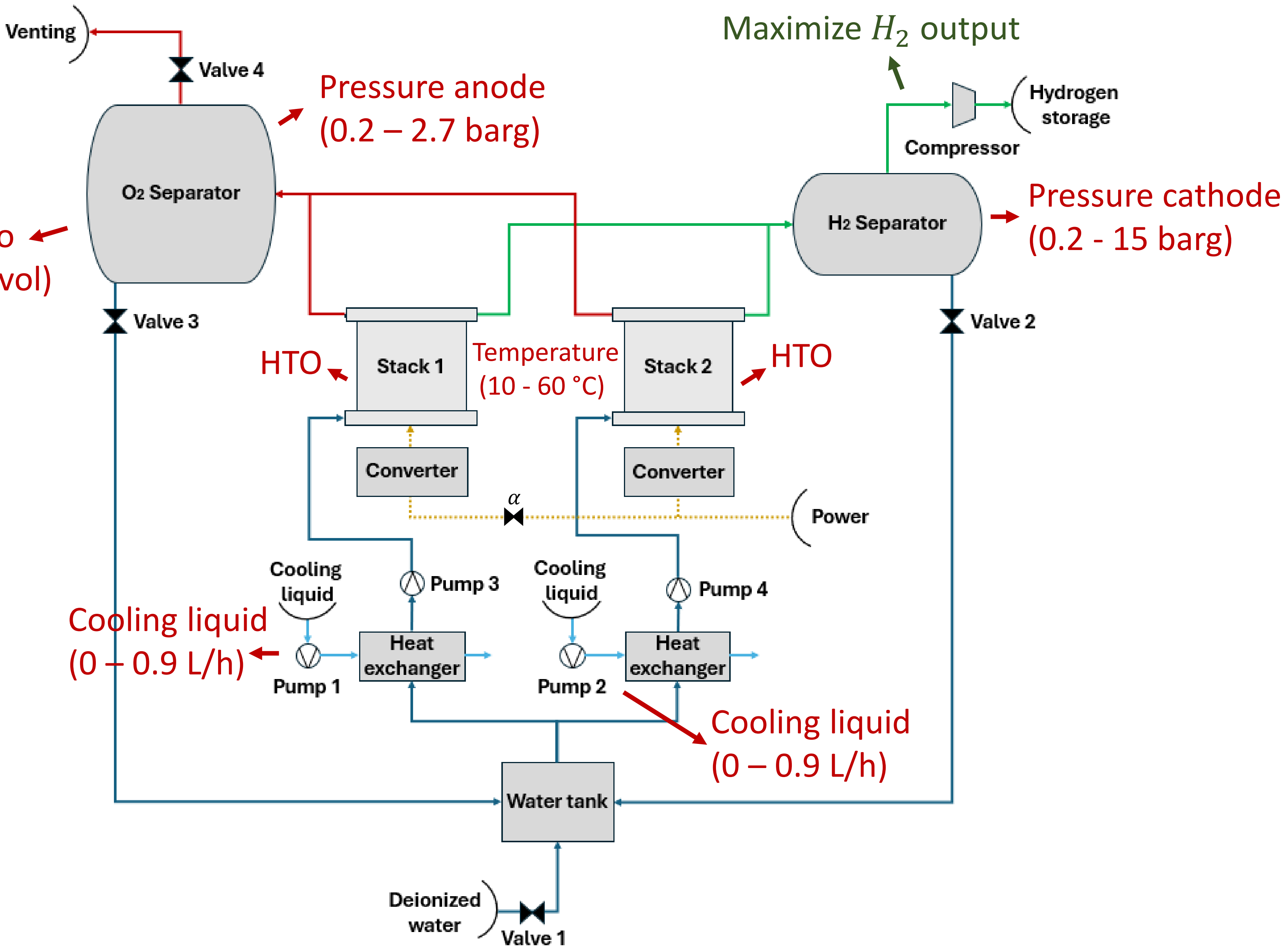

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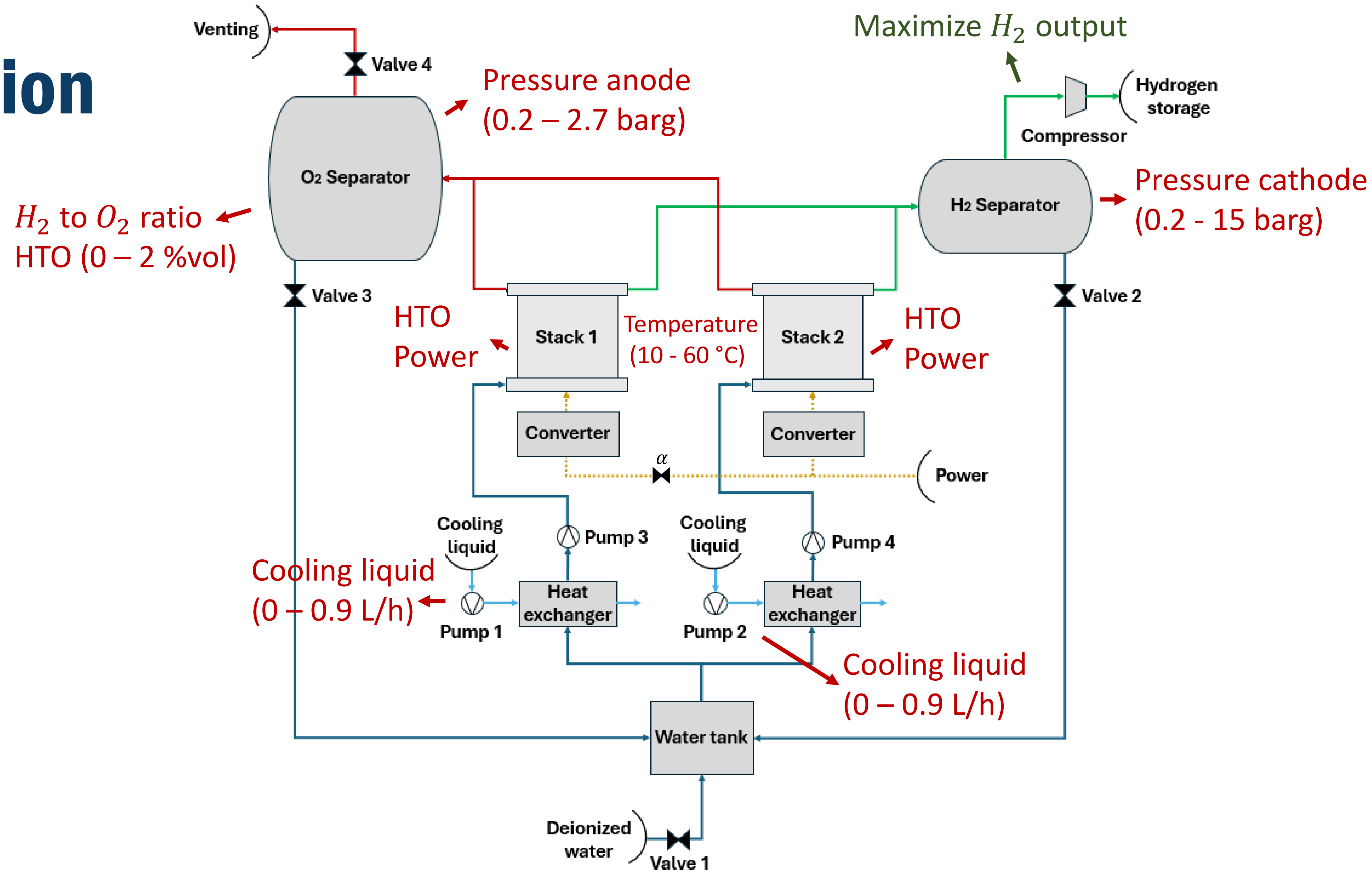
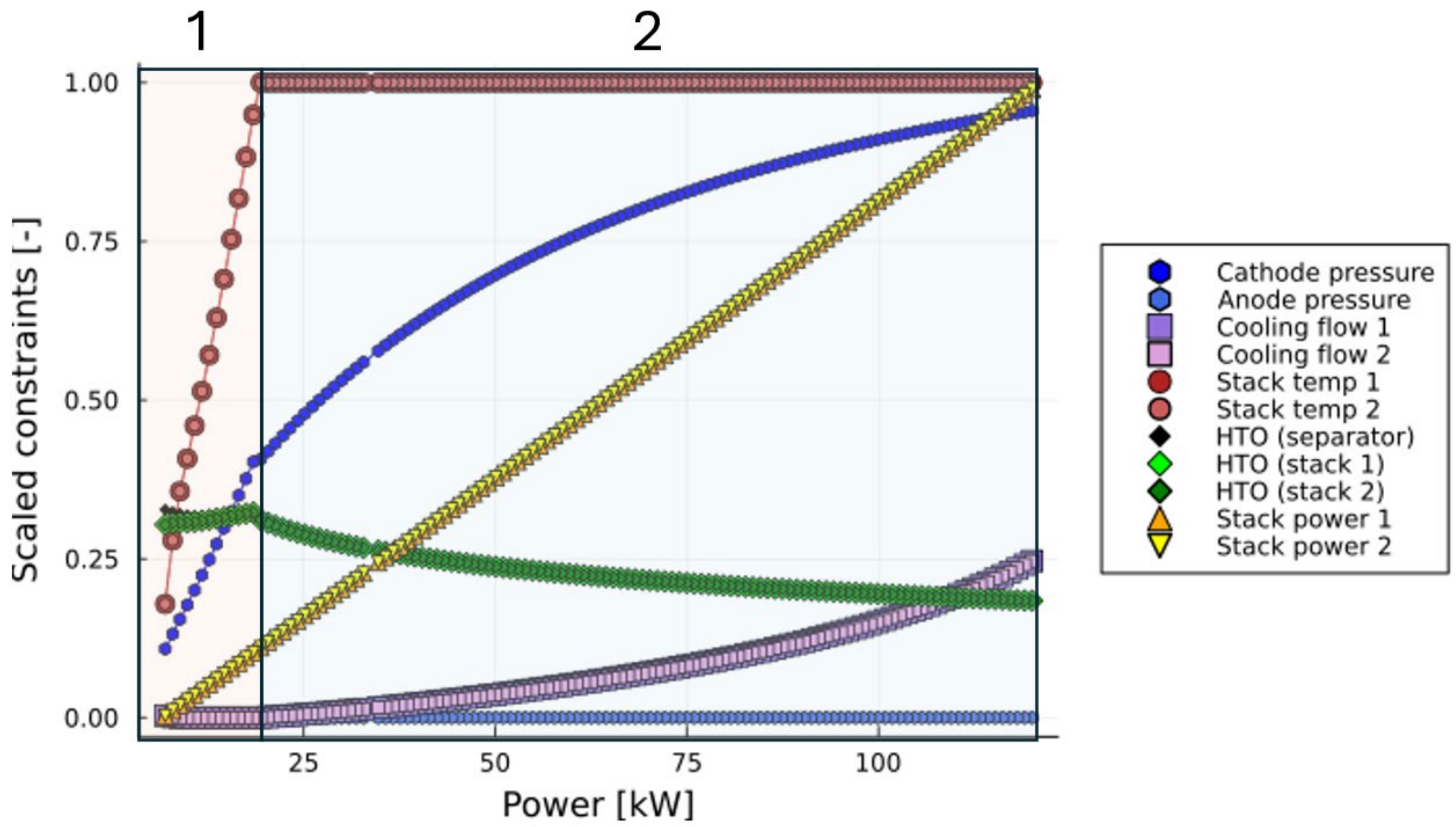


Optimal Operating Regime – Identical Stacks



Main takeaways

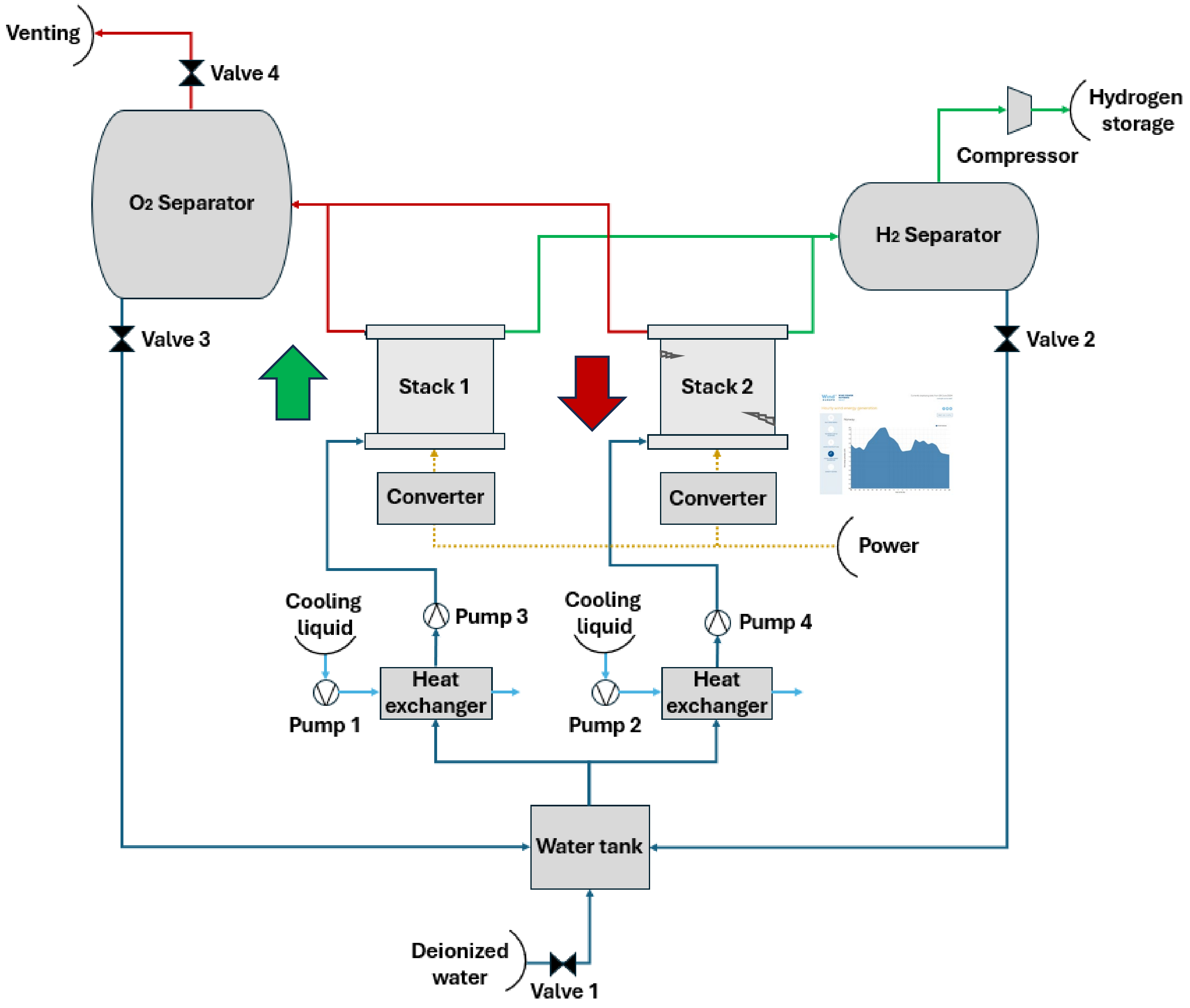
- 2 active constraint regions
- Divides power equally between stacks
- Closely resembles a single-stack system

Two-Stack System Description

Non-identical stacks

- Stack 1 – 100%
- Stack 2 – 75%

Degradation and stack difference are represented through reduced Faraday efficiency



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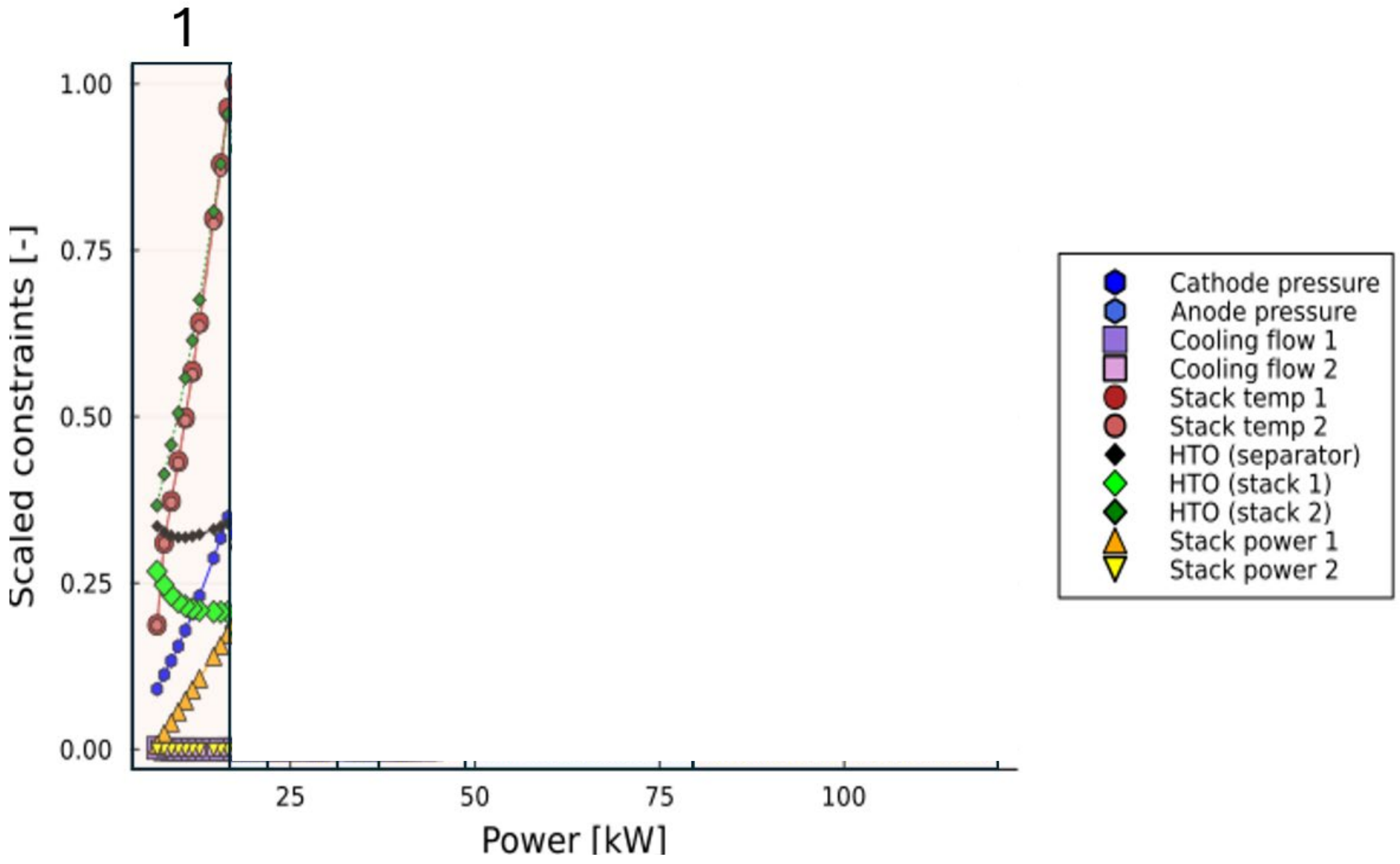
Optimal Operating Regime – Non-Identical Stacks (75%)



Observations

- 7 active constraint regions
- Preferentially loads Stack 1 (most efficient stack)
- HTO constraint active for Stack 2 (least efficient stack)
- Uses both power and pressure gradient to maintain HTO

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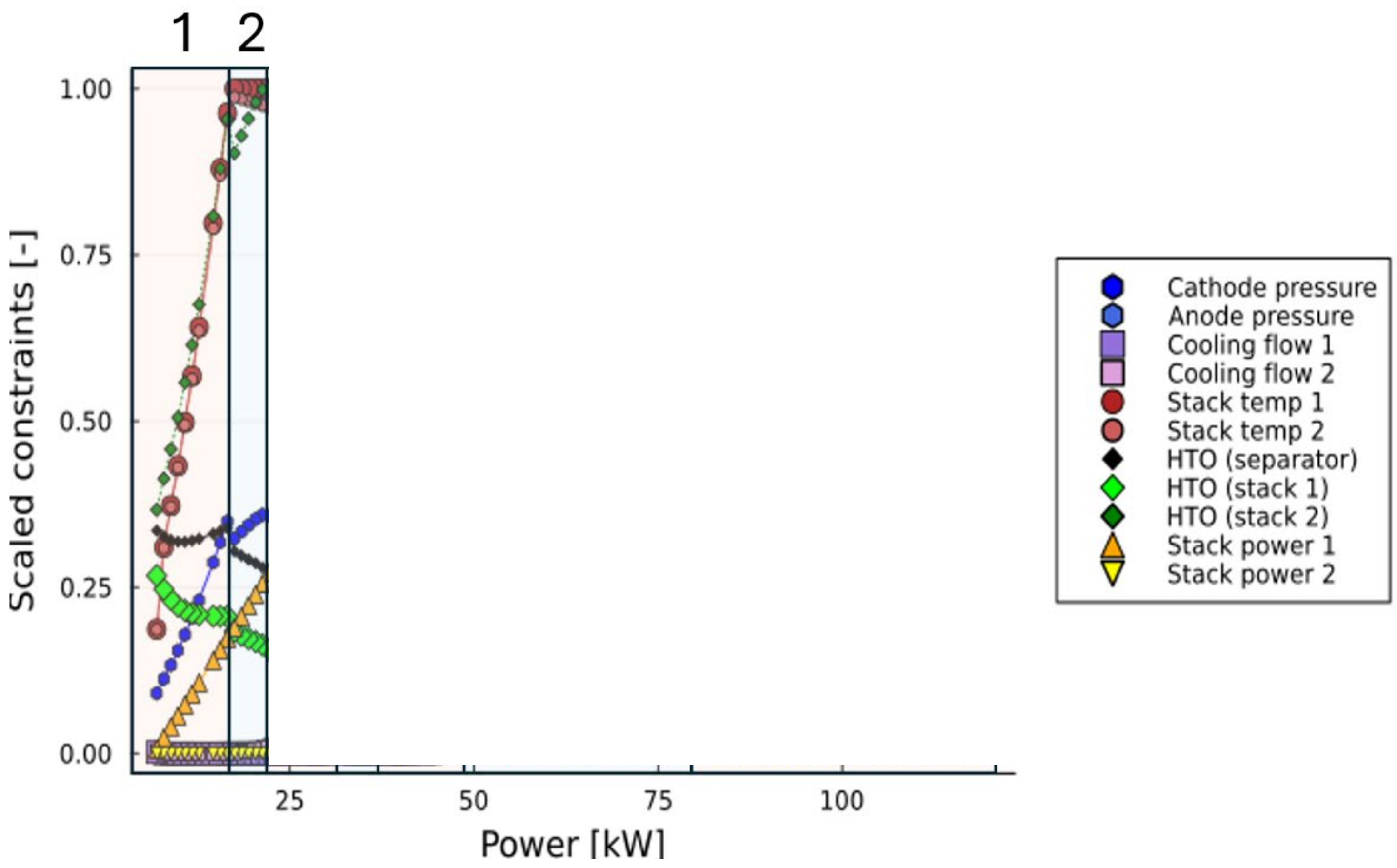

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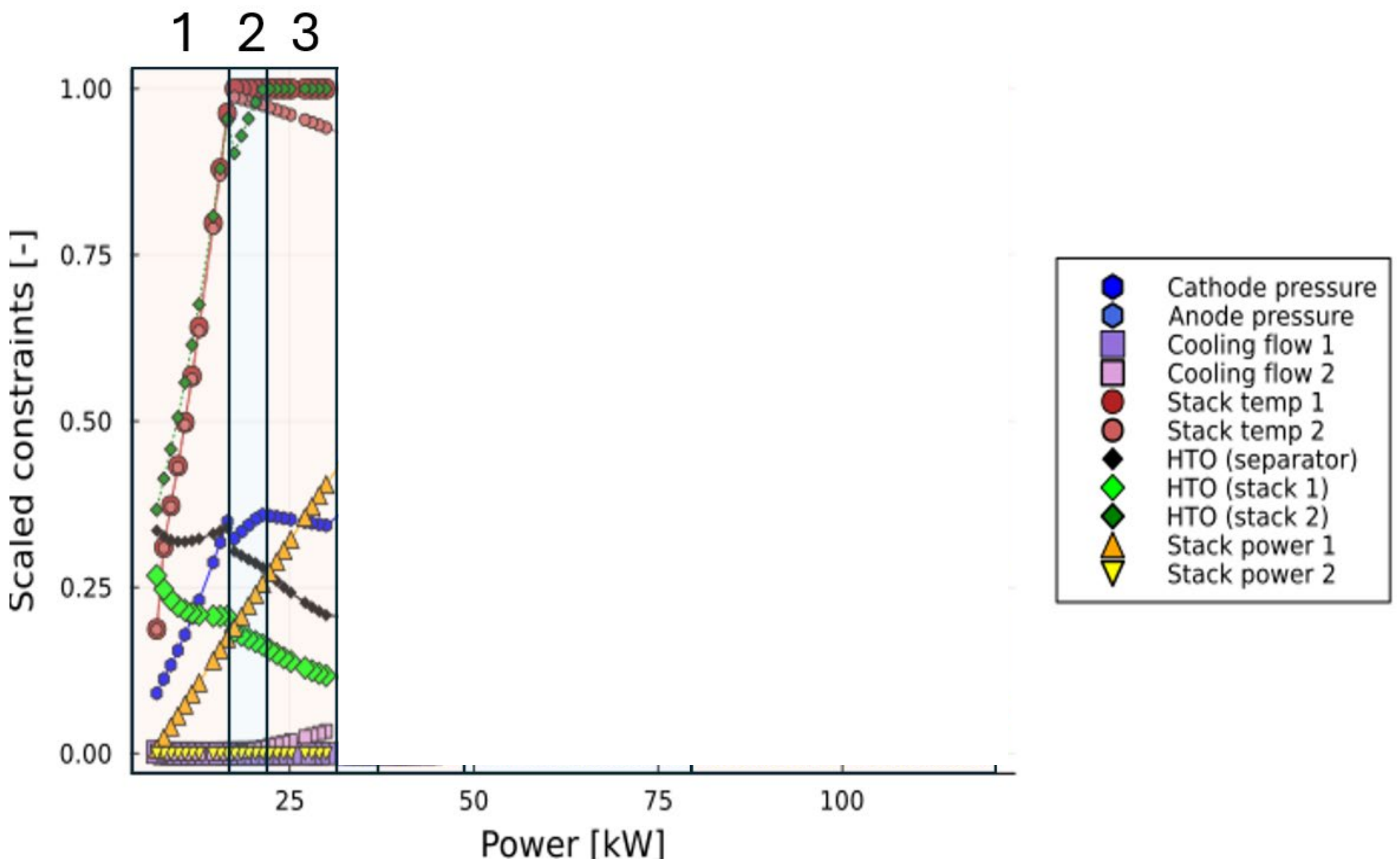

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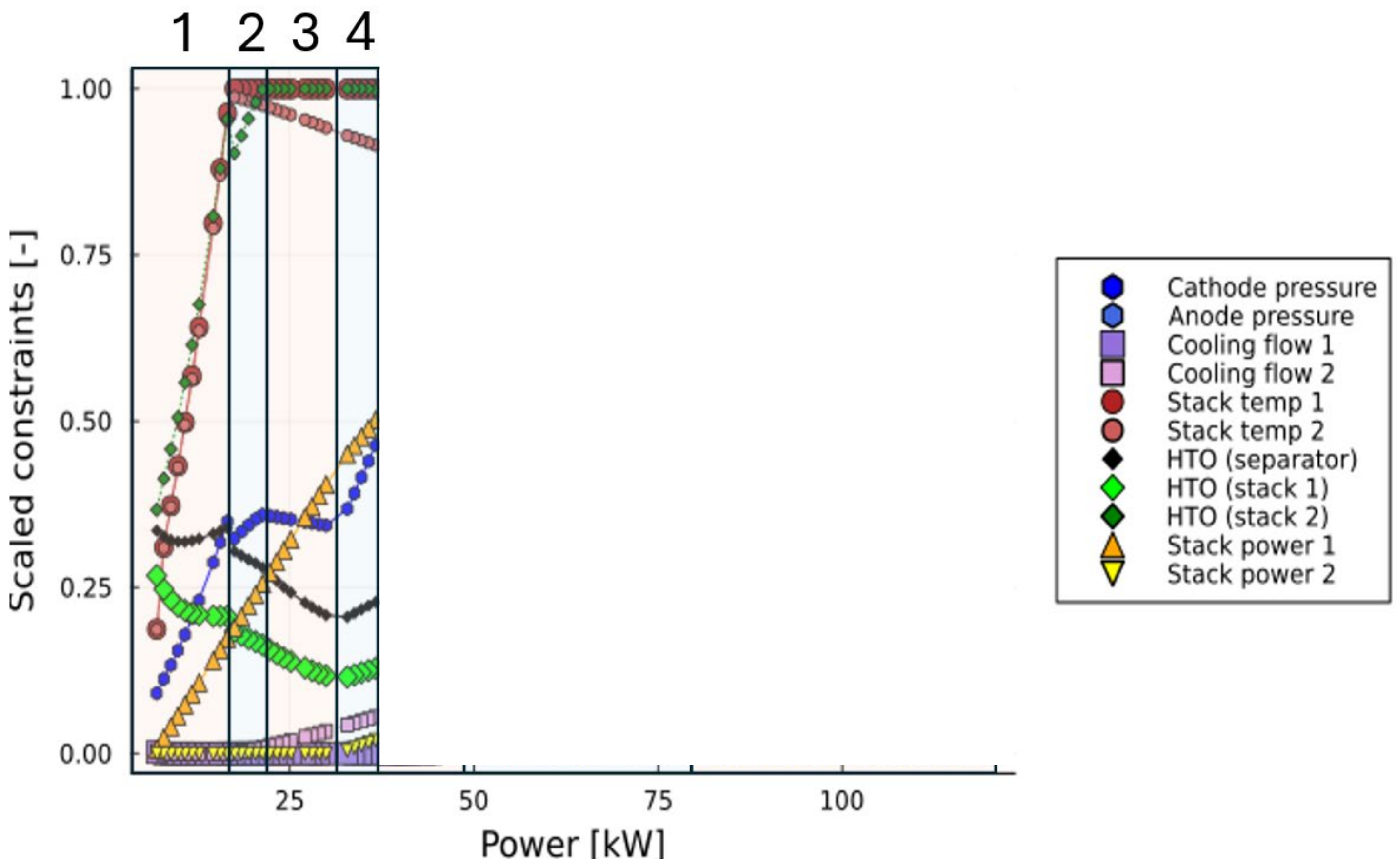

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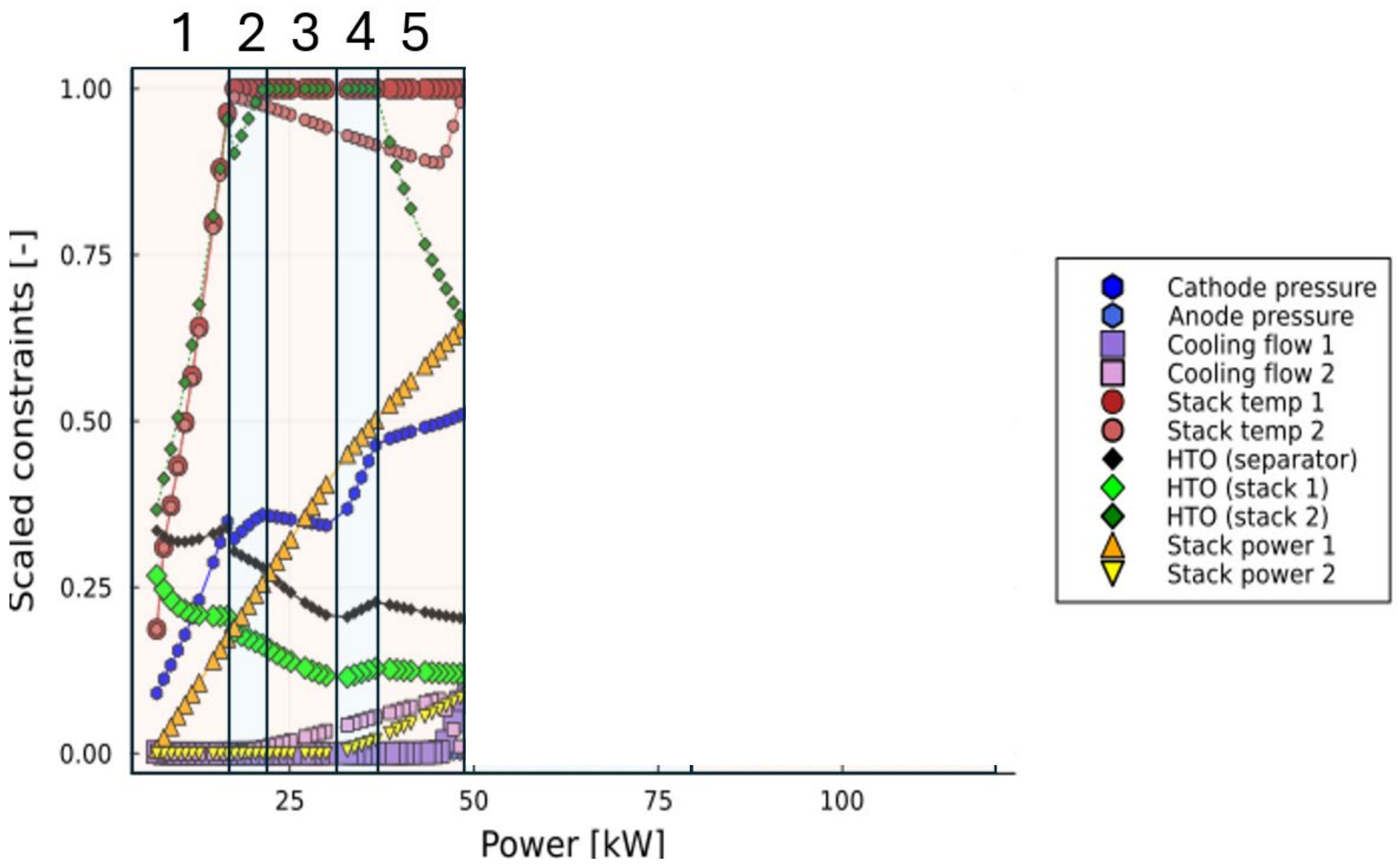

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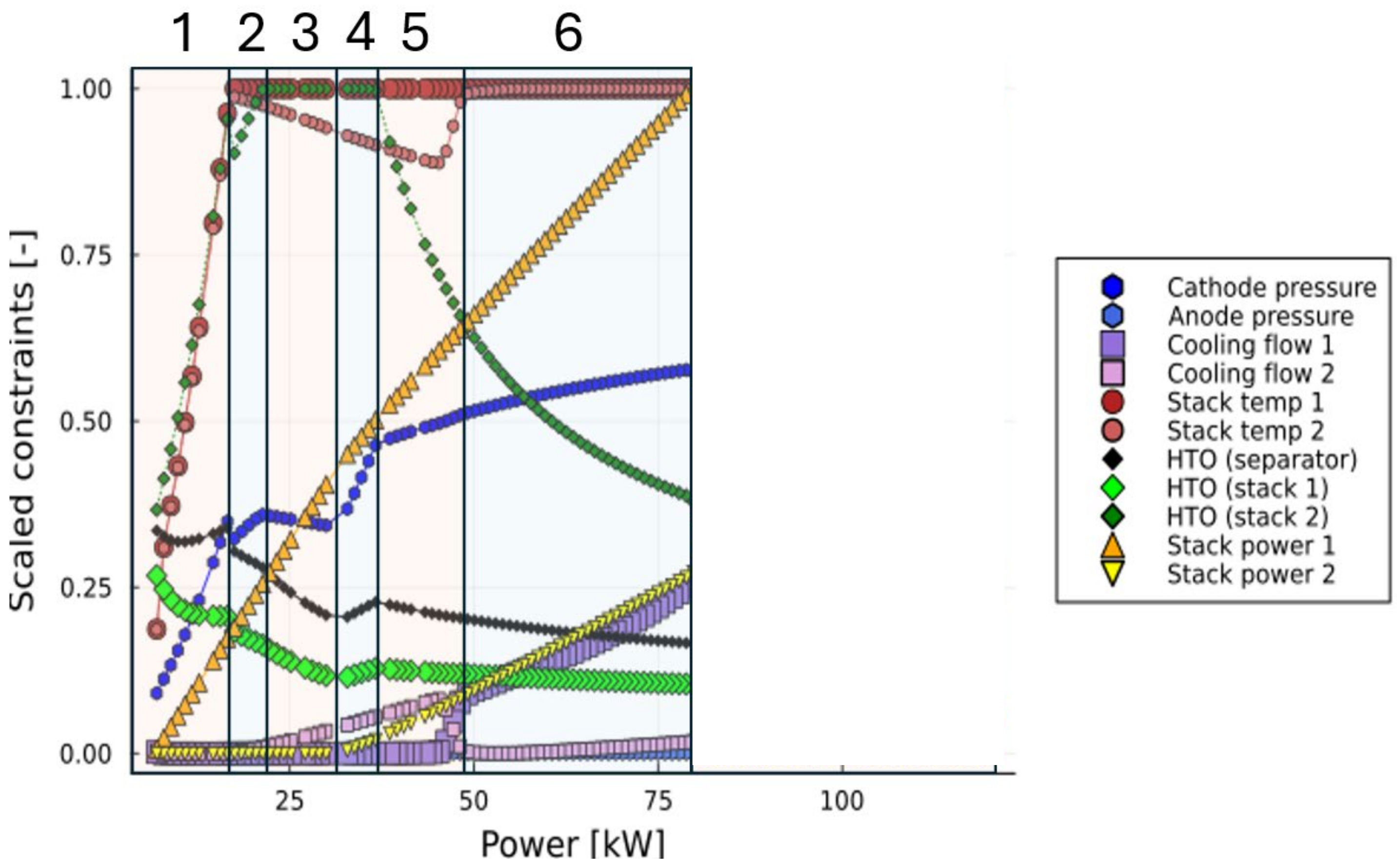

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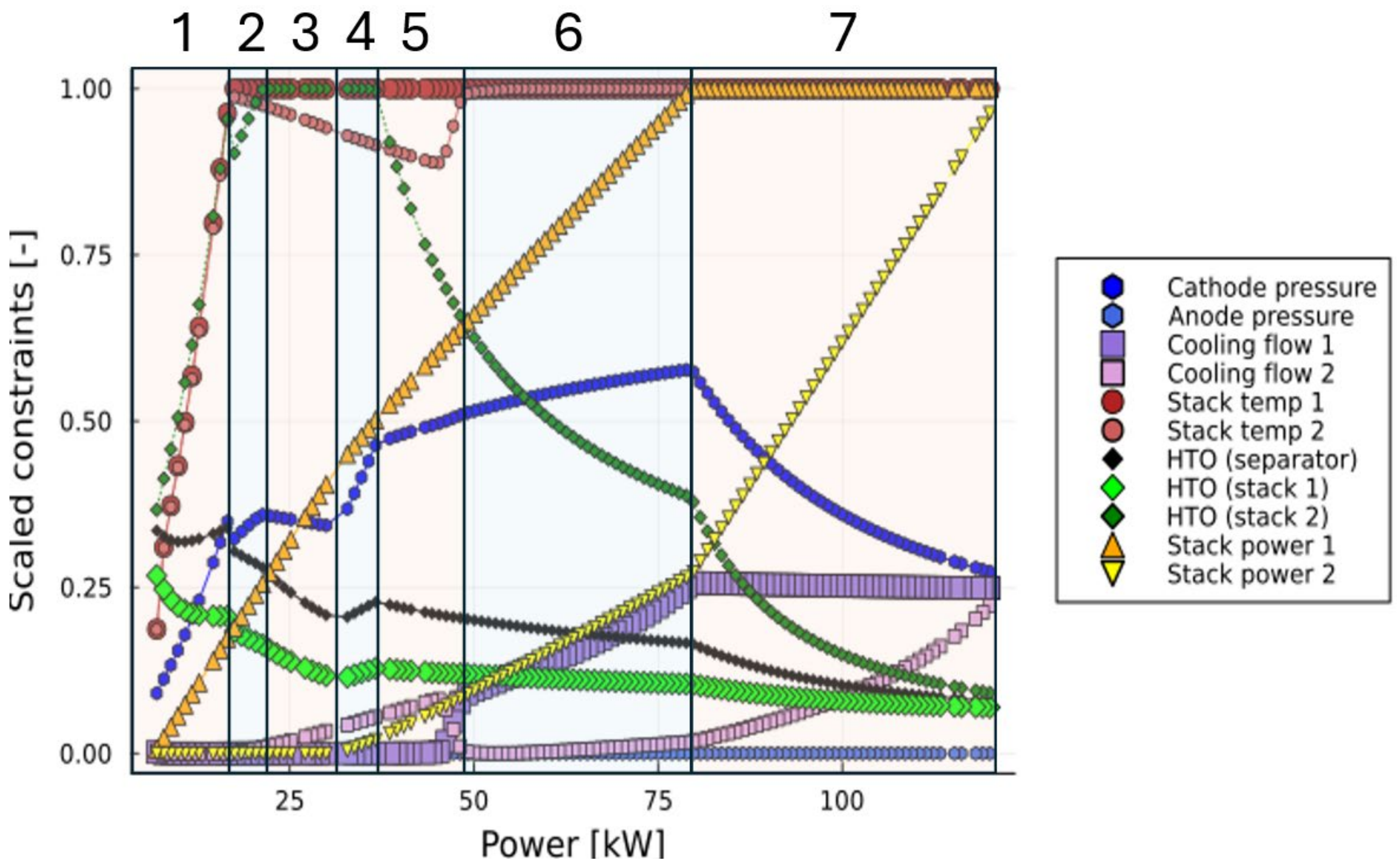

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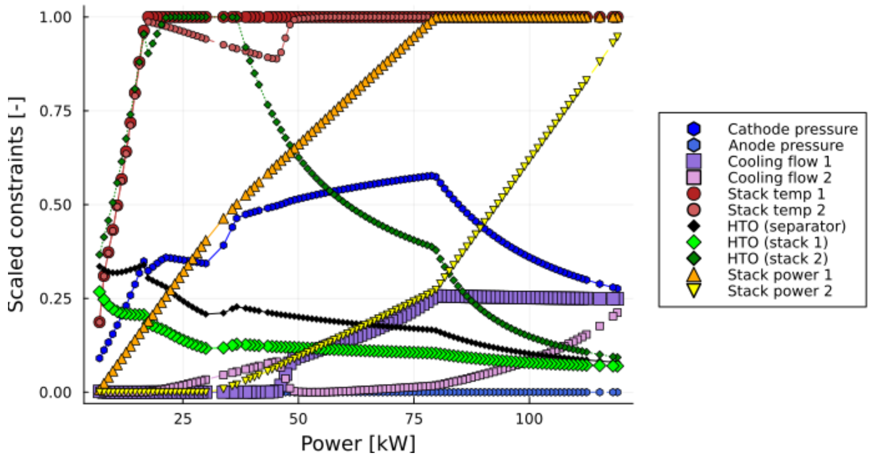
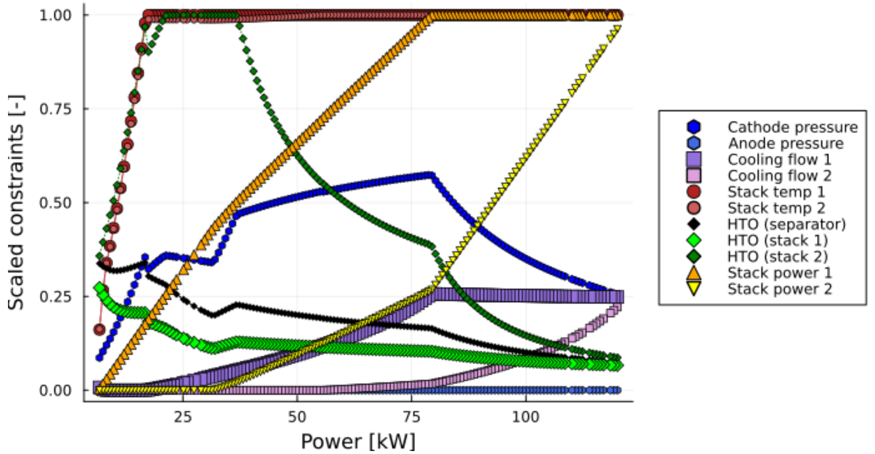
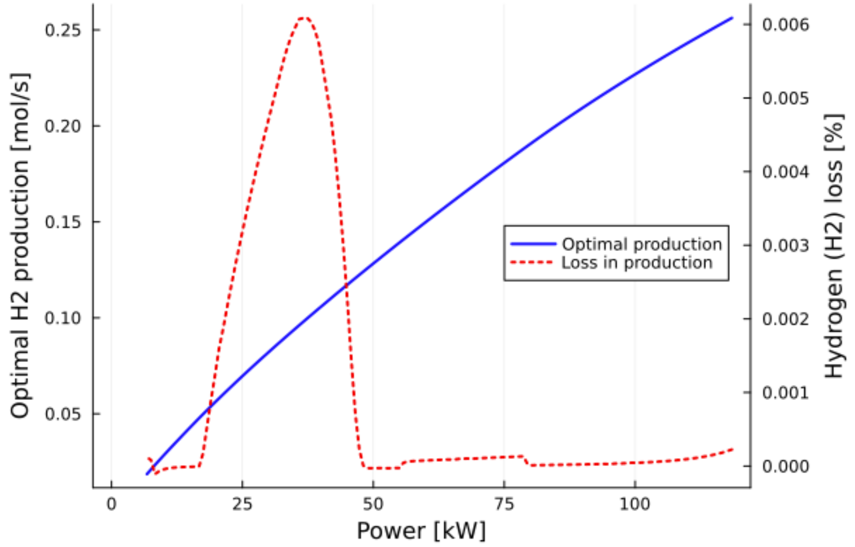
Simplification – Increase Stack 2 Temperature



Objective: max $H_2 - F_{cool,2}$





Observations

- Maximizing Stack 2 temperature gives a negligible loss in hydrogen production
- Stack 2 temperature becomes an active constraint, simplifying our system

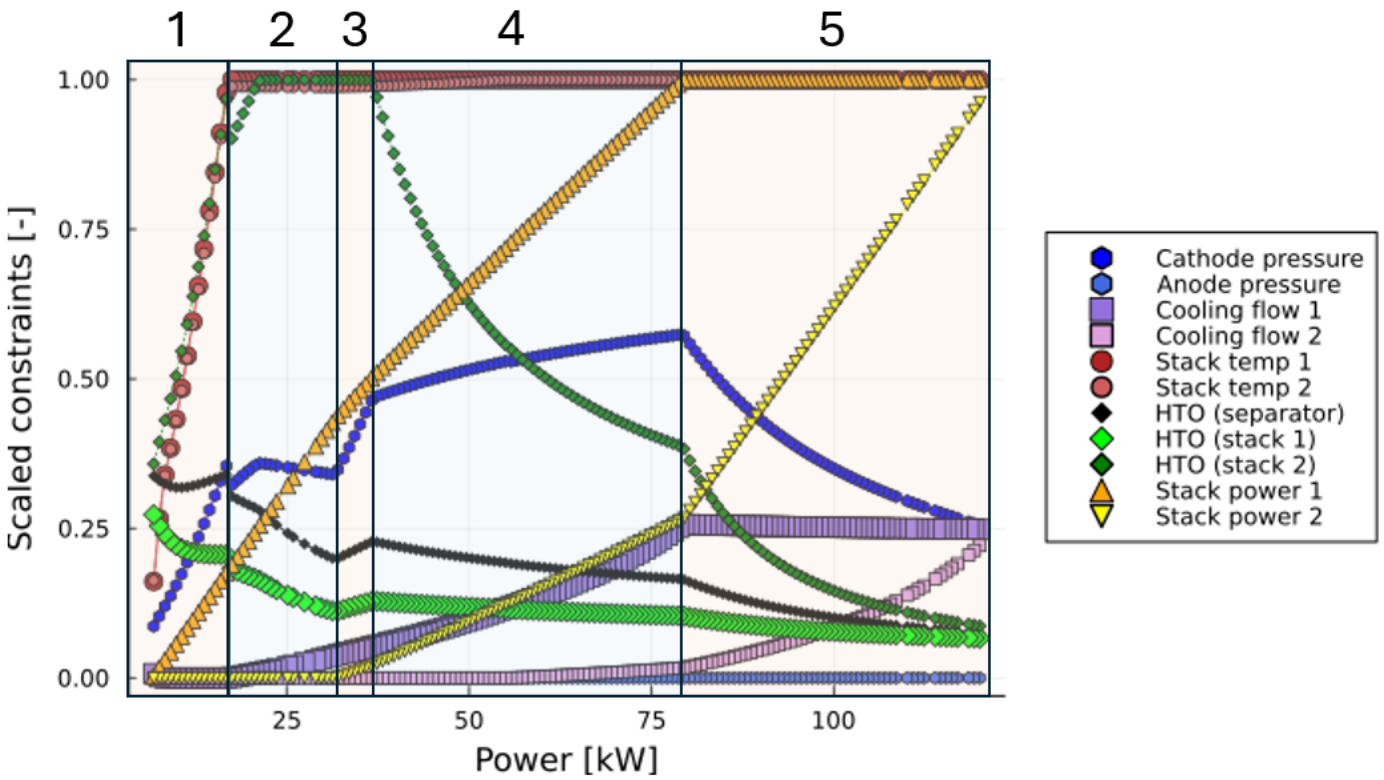
Control Design

5 Available actuators

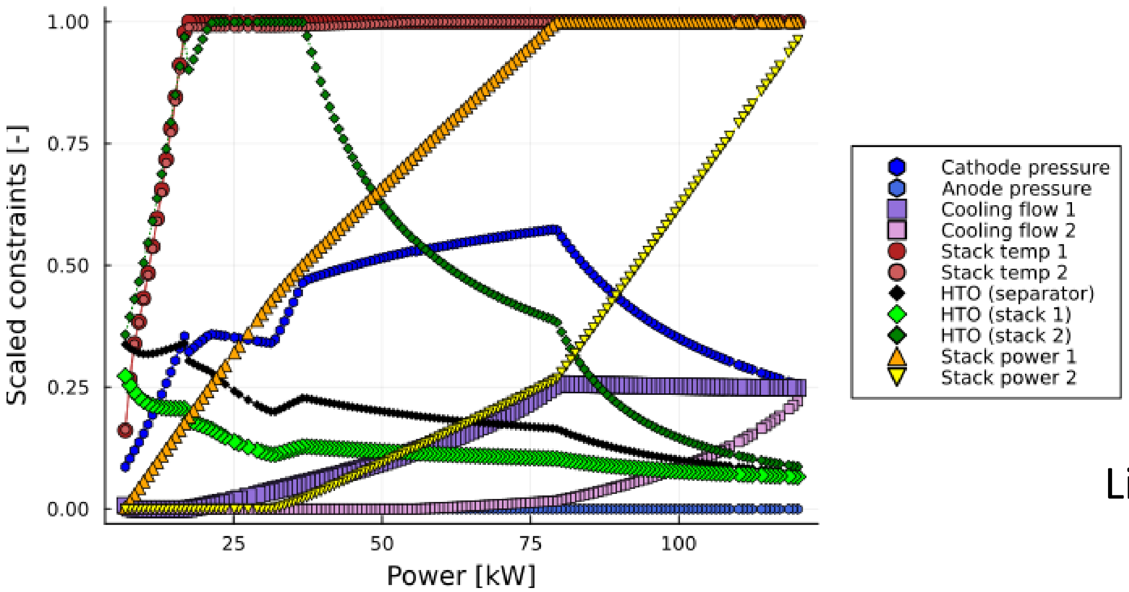
≥ 3 Active constraints (all regions)

- Anode pressure
- Stack 1 temperature/cooling
- Stack 2 temperature/cooling

=> 2 DoFs after active constraints

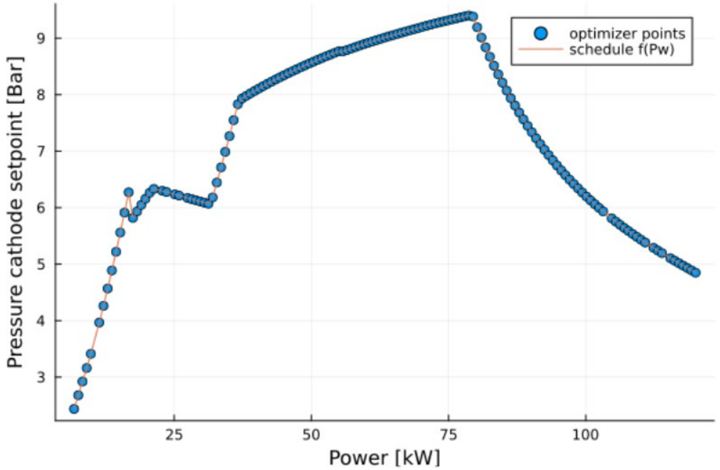


Optimal Reference Values – HTO Constrained

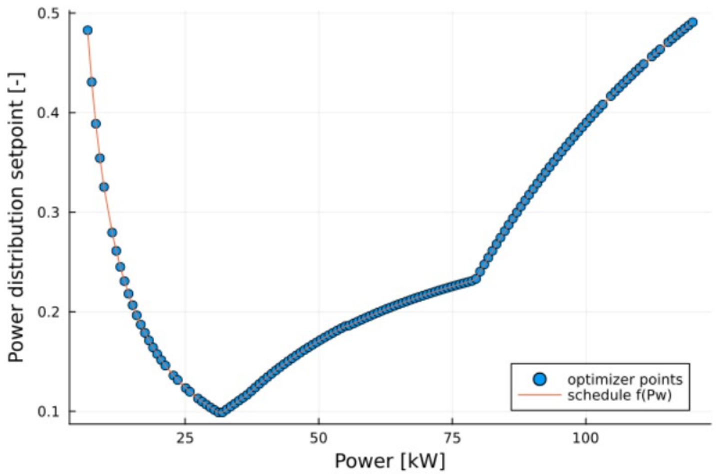


Linear interpolation

Optimal cathode pressure



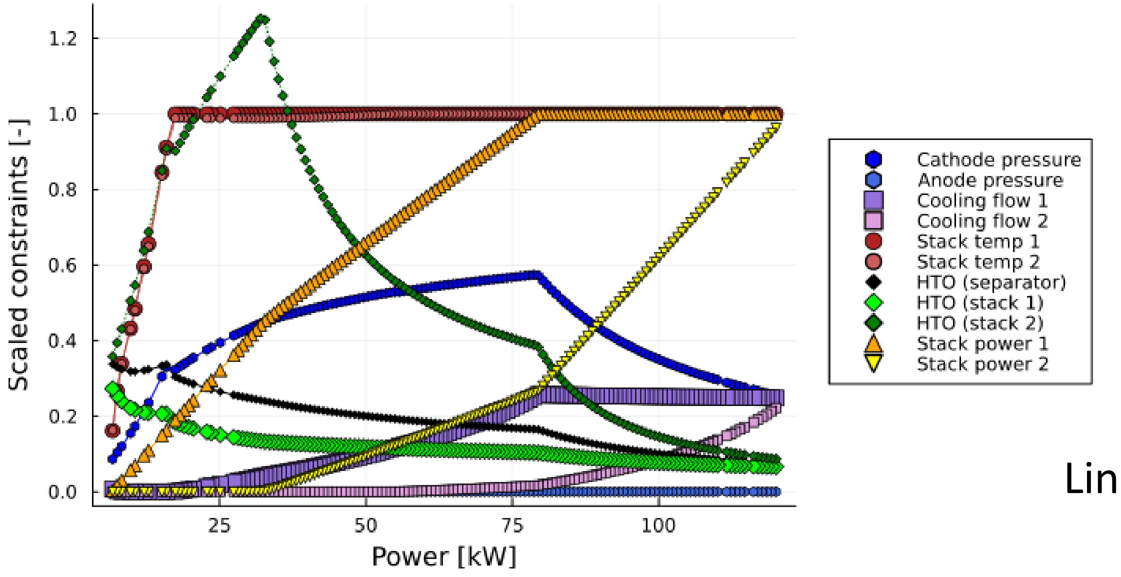
Optimal power distribution



Remarks

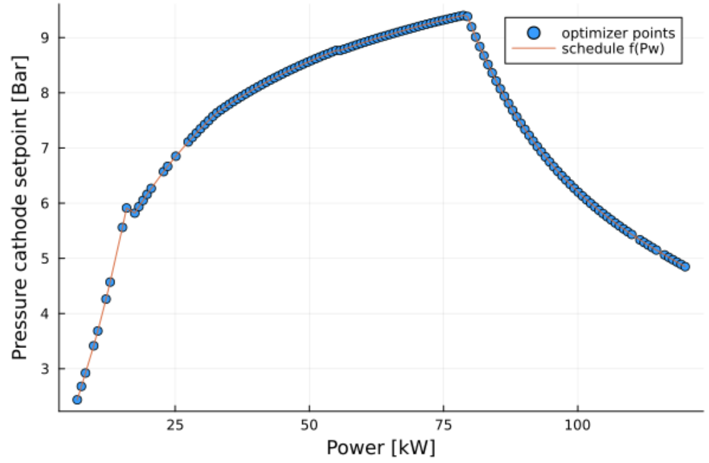
- The pressure and power distribution determine the HTO
- What if we have a model mismatch?

Optimal Reference Values – No HTO Constraint

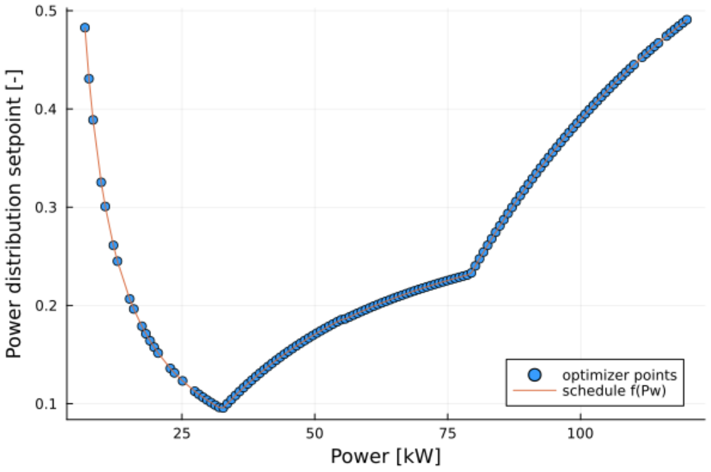


Linear interpolation

Optimal cathode pressure



Optimal power distribution



Observations

- The optimal operating regime is very similar; however, we may use higher cathode pressures at lower power

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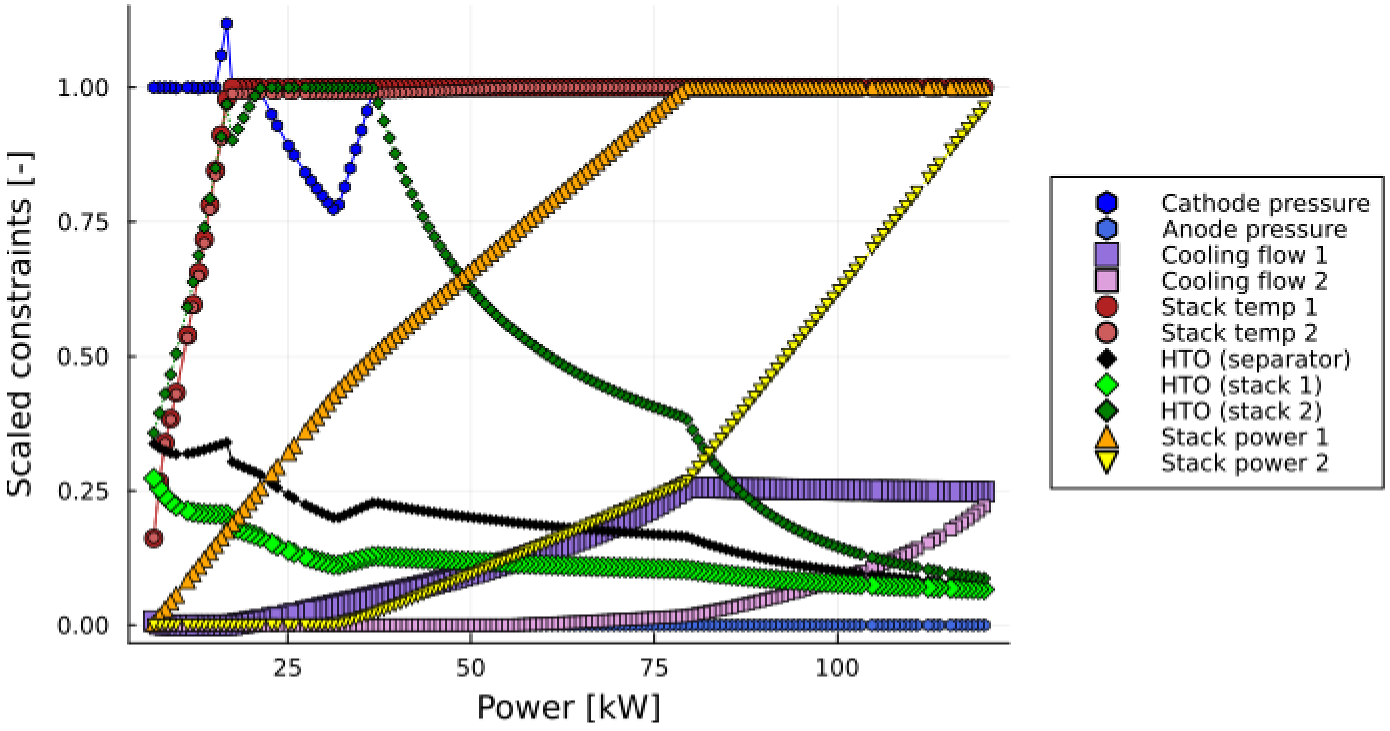
Cathode pressure-HTO Relationship



Observations

- We have a small section where the unconstrained optimum cathode pressure reference is smaller than the constrained one
- The cathode pressure and the HTO of Stack 2 swap between being active constraints (can be facilitated using selectors)

Remarks

- We use the cathode reference value as its scaled upper constraint

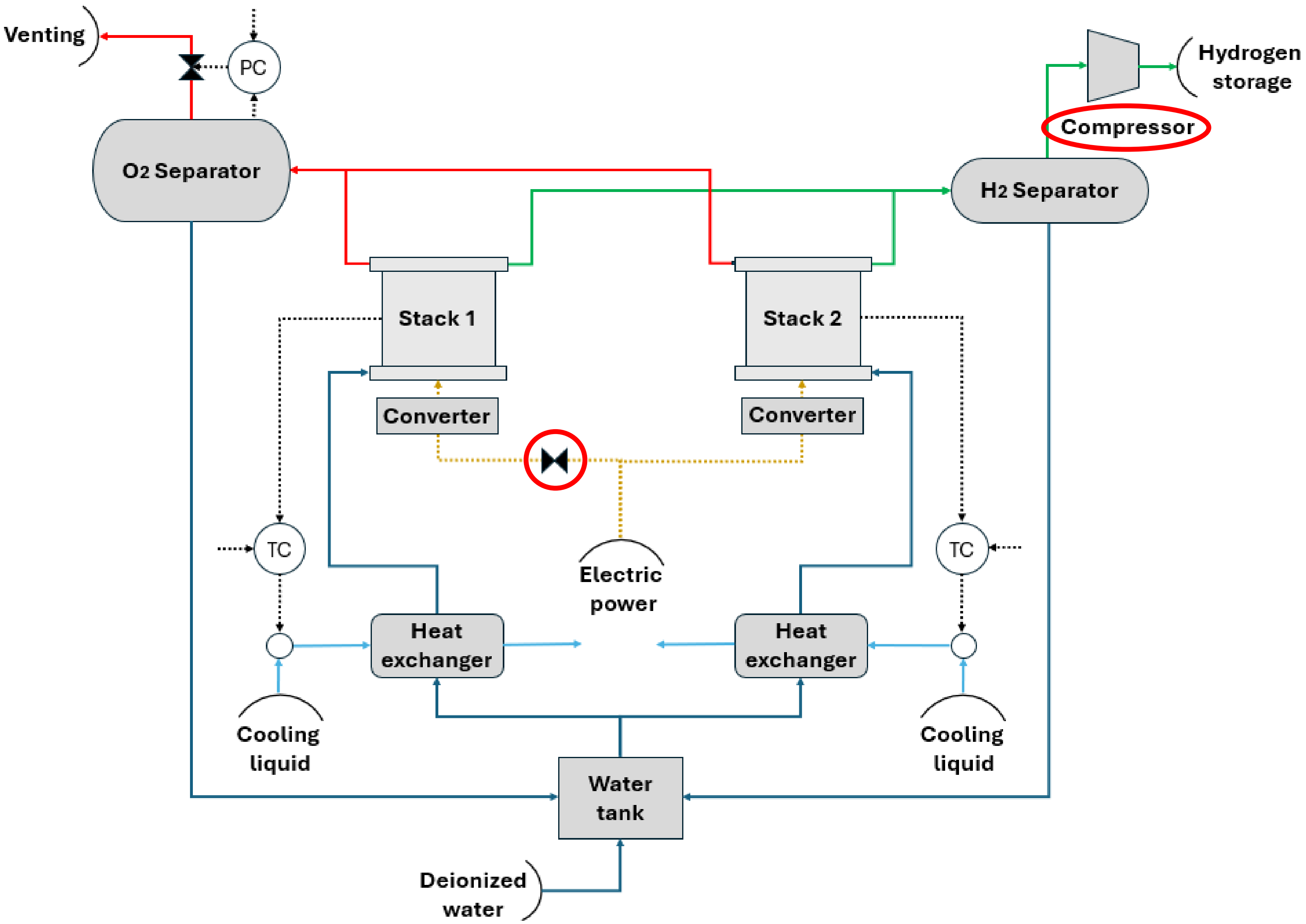
Control Active Constraints

Active Constraints

- Oxygen pressure
- Temperature Stack 1
- Temperature Stack 2

Remaining DoFs

- Power distributor
- Hydrogen compressor



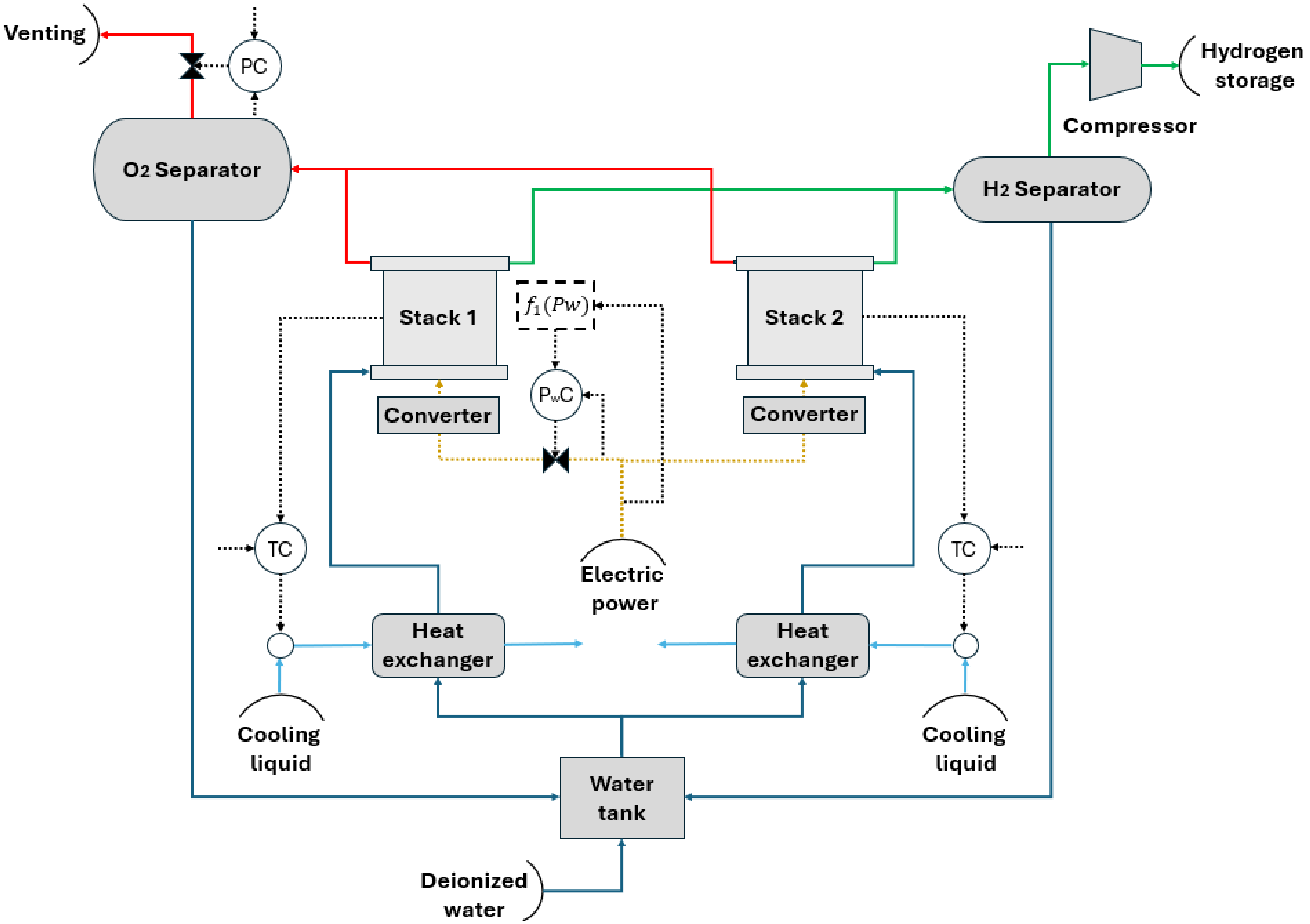
Setpoint Scheduling

Active Constraints

- Oxygen pressure
- Temperature Stack 1
- Temperature Stack 2

Setpoint Scheduling

- Power distributor (f1)



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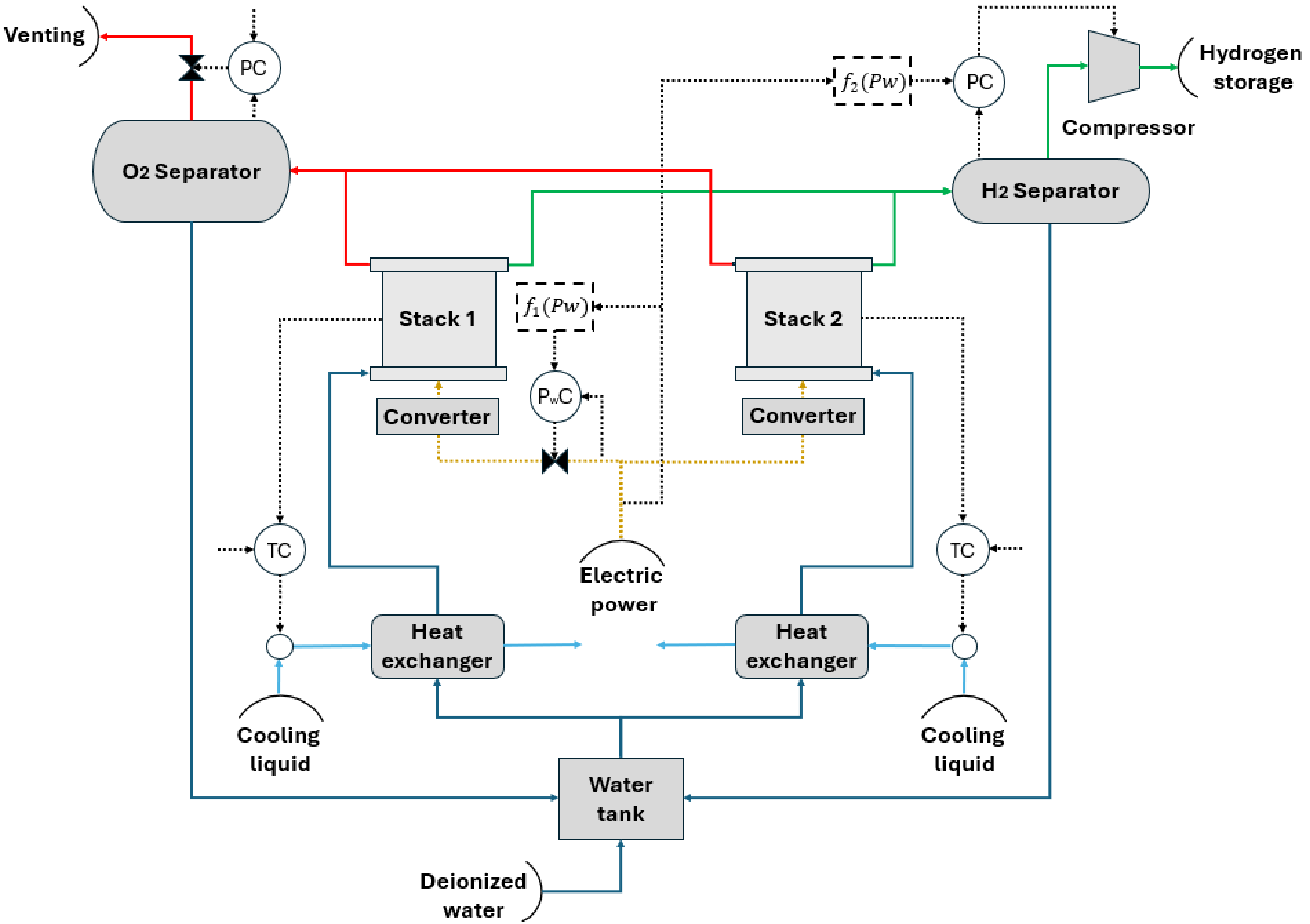
Setpoint Scheduling

Active Constraints

- Oxygen pressure
- Temperature Stack 1
- Temperature Stack 2

Setpoint Scheduling

- Power distributor (f1)
- Hydrogen pressure (f2)



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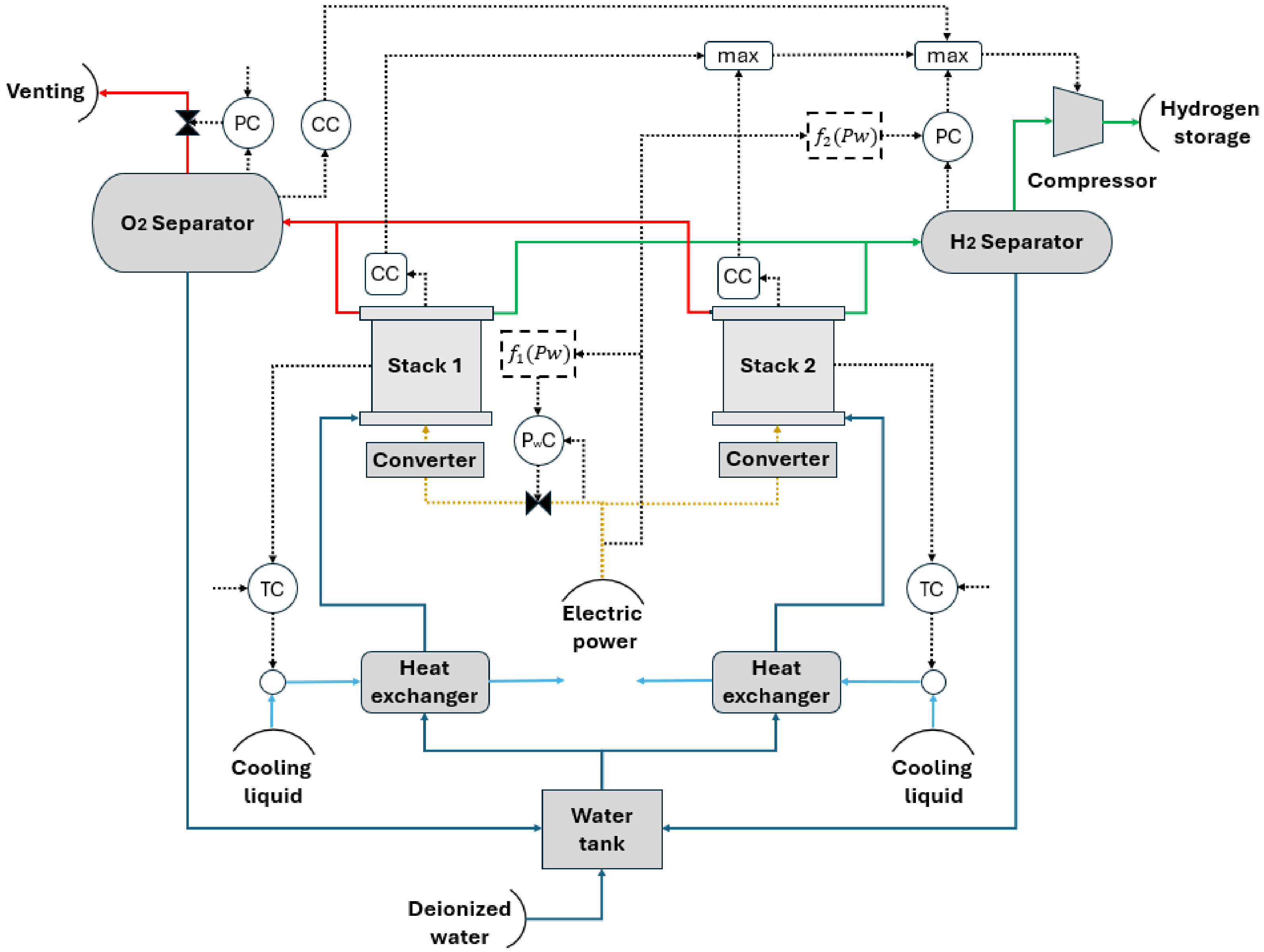
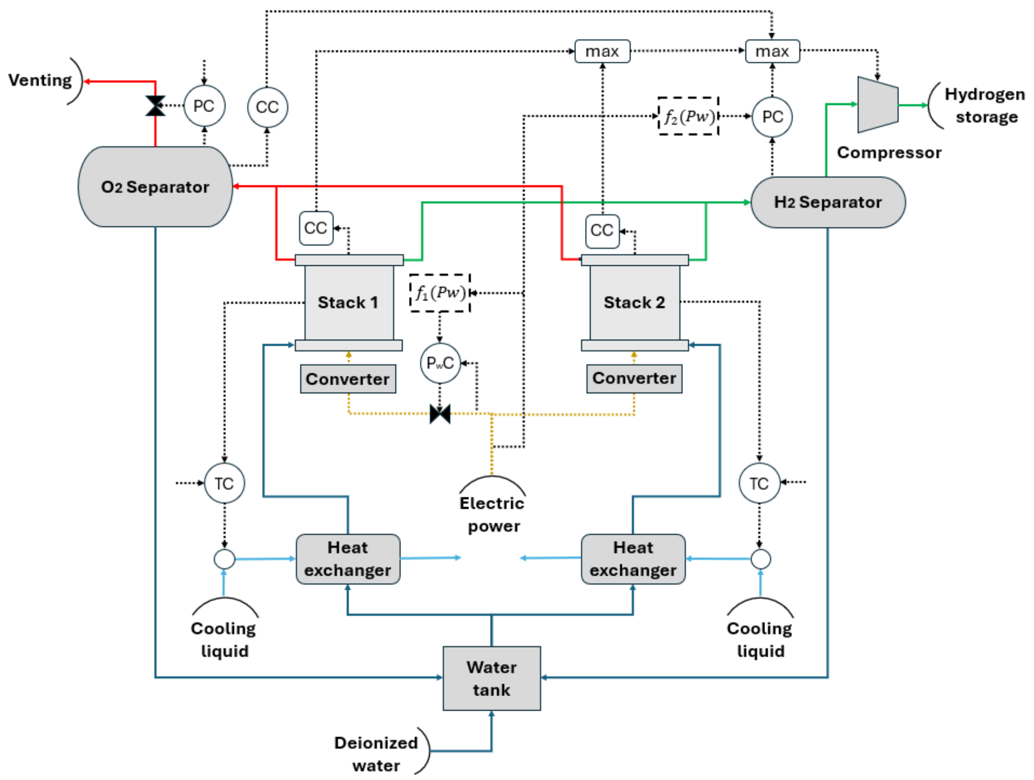
Selectors for Safety

Remarks

- Selectors added to guard for safety concerns from model mismatch
- HTO and pressure constraints can be met by increasing compression work
- HTO in stacks must be estimated
- HTO in the separator may be measured



Conclusion and Future Work



In this work, we have

- Mapped the optimal operating regime of a two-stack PEM water electrolyzer system.
- Shown that performance differences between stacks fragment the operating space, increasing the number of active constraint regions.
- Showed that HTO constraints in degraded stacks may become a critical limiting factor for hydrogen pressure and power distribution.
- Proposed a simplified control structure for a multi-stack PEM system.

Next steps

- Test the proposed control structure in a dynamic system model.
- Develop state estimators to find the HTO content in the electrolyzer stacks.

Acknowledgements

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