AS PRESENTED IN THE FINH2 FINAL SEMINAR, 28 NOVEMBER 2024 (EXCEPT FOR SLIDES 2 TO 4)

Highlights of alkaline electrolyzer development – results of WP1

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WP1 tasks, targets, and results

Task 1: Energy and cost-efficient industrial scale alkaline water electrolyzer (AWE) system

On system level, how is the supplied energy spent in an industrial-scale AWE?

Target:

- Study and model industrial-scale (MW) AWE-based hydrogen plant in main component level.
- Highlight the most feasible opportunities to increase energy efficiency of hydrogen production.
- Verify the model with real plant data.

Results:

- Energy performance of 16-bar 3-MW and atmospheric 1-MW alkaline water electrolyzers revealed in various process conditions and loads.
    - Simulation model verified based on measurement data from corresponding real systems.
    - Conclusion: Stray currents are an important source of energy loss in industrial-scale AWE, especially challenging in pressurized systems.
- The electrolyzer plant simulation model was complemented with a compressor model to enable the analysis of the total specific energy consumption of electrolysis at various end-use or storage pressures.

Publications:

[1] *Sensitivity analysis of the process conditions affecting the shunt currents and the SEC in an industrial-scale alkaline water electrolyzer plant*
[2] *Influence of shunt currents in industrial-scale alkaline water electrolyzer plants*
[3] *Dynamic Mass- and Energy-Balance Simulation Model of an Industrial-Scale Atmospheric Alkaline Water Electrolyzer*

T1.1: Co-optimized component dimensioning and system control of industrial alkaline electrolysis process (M1-24)

The objective of the task is to model based optimization of the alkaline water electrolysis plant. The motivation is to provide detailed understanding of hydrogen production in all environments, and to highlight the most feasible opportunities to increase energy efficiency of hydrogen production. The main cost element in industrial-scale green hydrogen production is electricity being 60-75 % of the total cost. The component level process understanding is difficult without proper models, because all the data is not possible to measure from the individual processes. The research tasks are:

- Build up alkaline water electrolysis plant simulation model that includes component level models starting from AC power / raw water supply and ending to pure compressed hydrogen/oxygen
- Thermal, mass balance and electrical energy model
- Verification of models with real plant data, forming detailed analysis of the system operation and estimate potential to improve the whole process chain
- Documentation, e.g. as a form of scientific refereed publications.

WP1 tasks, targets, and results

LUT University

Task 2: Elevated-voltage and low-stray-current alkaline electrolyzer stack

Higher voltage → given H_2 output with decreased current → cheaper power electronics.

Target:

- To study methods that enable the design of an alkaline electrolyzer stack with elevated voltage level of >1000 V_{DC} (vs. typical ~300 V_{DC}) without increasing the stray currents of the stack.

Results:

- A lumped-parameter simulation model for the stack was developed to determine stray currents at different numbers of cells in the electrolyzer stack.
  - Conclusion: Dividing a higher-voltage (>1000 VDC vs. conventional <500 VDC) electrolyzer stack into substacks connected electrically in series is an effective way to reduce stray currents inside stacks.
  - **Publication:**
    - Journal article manuscript submitted: “Modeling and study of shunt currents in an industrial alkaline water electrolyzer with various number of cells in series” in the journal IET Renewable Power Generation.
- High-voltage stack prototyping
  - Single-cell, 10-cell, and 12-cell stacks were built and tested.
    - Stray currents inside and between series-connected 10- and 12-cell stacks were successfully measured.
  - System of 2x48 cells (200 V, 10 kW) was built and tested.
    - Notable amount of stray currents were measured between the stacks. The effect of the stack grounding options and dimensions of inter-stack piping on current efficiency were revealed.
    - **Publication:** journal article manuscript under preparation.

T1.2 Design and optimization of high-voltage, low stray current alkaline electrolyzer stack (M12-36)

The objective of the task is to study the design and optimization of up to 1000 Vdc alkaline water electrolysis stack. Currently, the stack voltage in commercial multi-MW stack varies around 300-500 Vdc. This relatively low system voltage results high currents, costly power electronics and high losses. The system voltage increase would be an obvious solution to this problem decreasing simultaneously both system losses and capital investment. However, the management of stray currents by stack design is the main challenge. The research tasks are:

- Electrical model for alkaline electrolyzer stack including model both for the electrolysis process and stray currents. This will be done by utilizing measurements and geometry obtained from the LUT reference design.
- High voltage stack structure minimizing stray currents, by utilizing different analysis tools. Also, the design for the manufacturing is considered.
- Implementation of fraction of the full-size stack (e.g. 10% of cells) and measurements to verify its operation, especially the percentage of stray currents.
- Documentation, e.g. as a form of scientific refereed publications.

WP1 tasks, targets, and results

LUT University

Task 3: Elevated-temperature alkaline electrolyzer cell

Higher operating temperature can improve the energy efficiency of alkaline electrolysis and increase the value of its surplus heat.

Target:

- To design and test an alkaline water electrolyzer (AWE) cell operating at 130 °C.
- To find a thermochemically stable polymeric material as a l gas separator facilitating AWE operation at 130 °C.

Results:

- Ex-situ testing in hot KOH at 130°C revealed that only PTFE and PPS can survive these conditions.
- A hydrophilic treatment was successfully developed for microporous PTFE membranes.
- The hydrophilic PTFE membrane and a PPS membrane removed from a commercial AWE stack were tested in an AWE cell at 60 °C. The developed PTFE membrane showed similar ionic resistance to the PPS membrane and improved gas separation properties.
- High temperature testing and research visit at DTU was postponed beyond the end of the project.

Publication:

- Manuscript under preparation.

T1.3 Design and verification of elevated temperature, zero-gap, alkaline electrolyzer cell (M6-36)

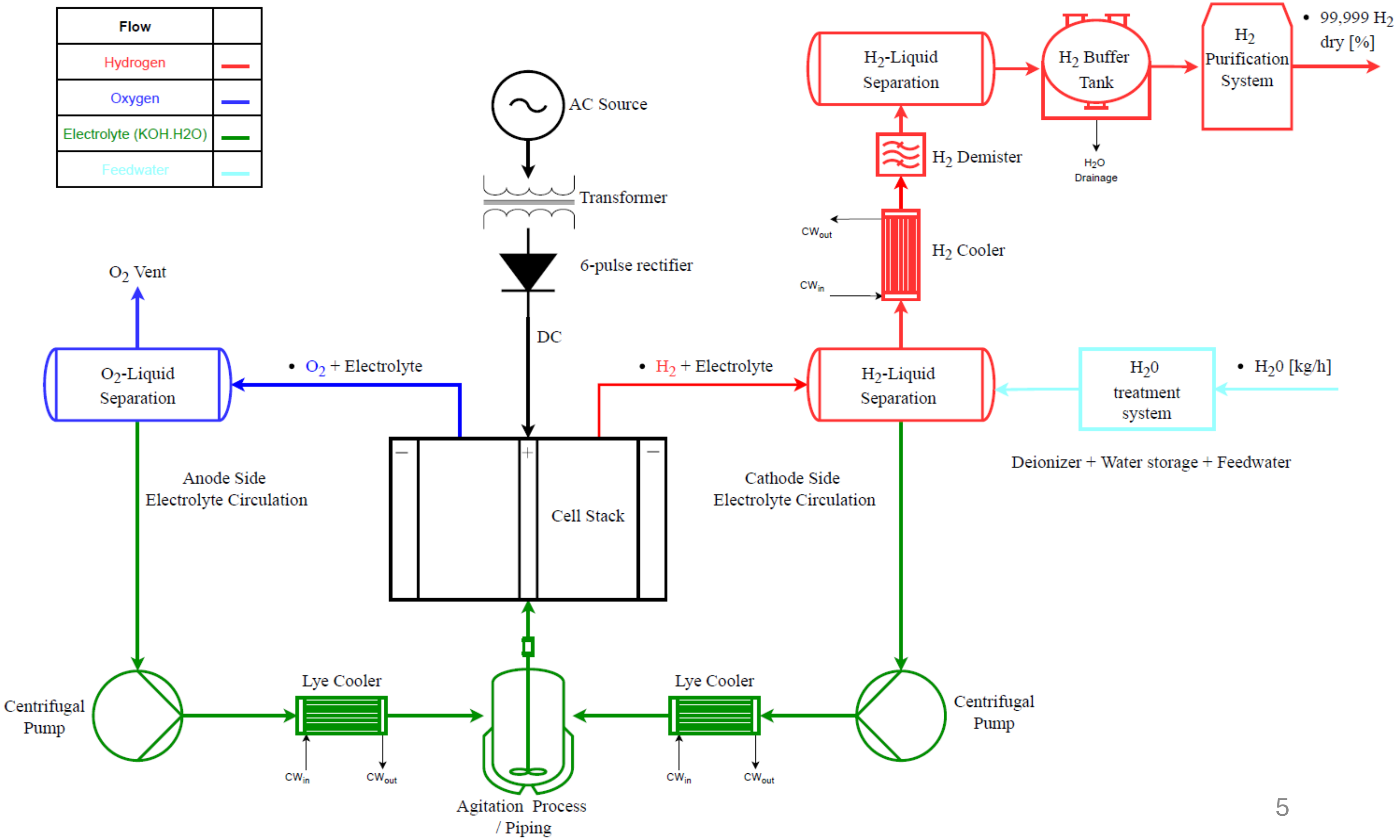
The objective of the task is to study the possibility to increase the operating temperature of alkaline water electrolyzer technology from current (70-90 °C) up to 150 °C. This would provide several benefits. Firstly, efficiency of the cell could improve to 85% (HHV). Secondly, the waste heat produced by electrolysis process would be directly suitable for industrial steam of district heating. The main problem is in durability of materials the most critical being the diaphragm. The research tasks are:

- Suitable materials for elevated temperature alkaline water electrolysis cell.
- Electrochemical model for cell and performance analysis of it compared to traditional alkaline water electrolysis cell
- Design and manufacturing of the proof-of-concept cell
- Elevated temperature alkaline water electrolysis cell measurements (efficiency and degradation)
- Documentation of the work as publications

Task 1: Energy and cost-efficient industrial scale alkaline water electrolyzer (AWE) system

Development of the LUT AWE plant model continued

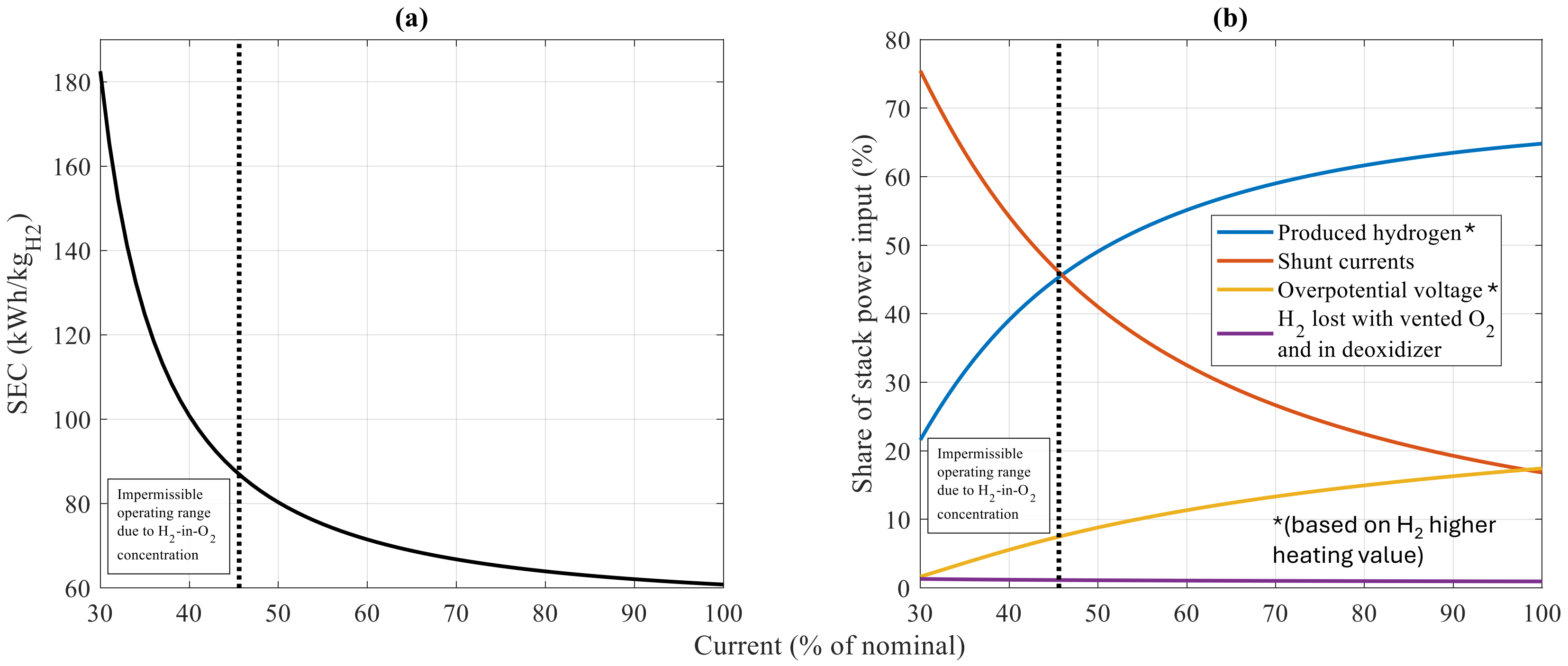
- Simulink/MATLAB
- Mass and energy balance of each plant unit operation
- Parameters fitted with measurement data from real industrial systems:
  - 3 MW, 16 bar
  - 1 MW, atmospheric



Task 1: Energy and cost-efficient industrial scale alkaline water electrolyzer (AWE) system

Results from modeling the 3-MW 16-bar system

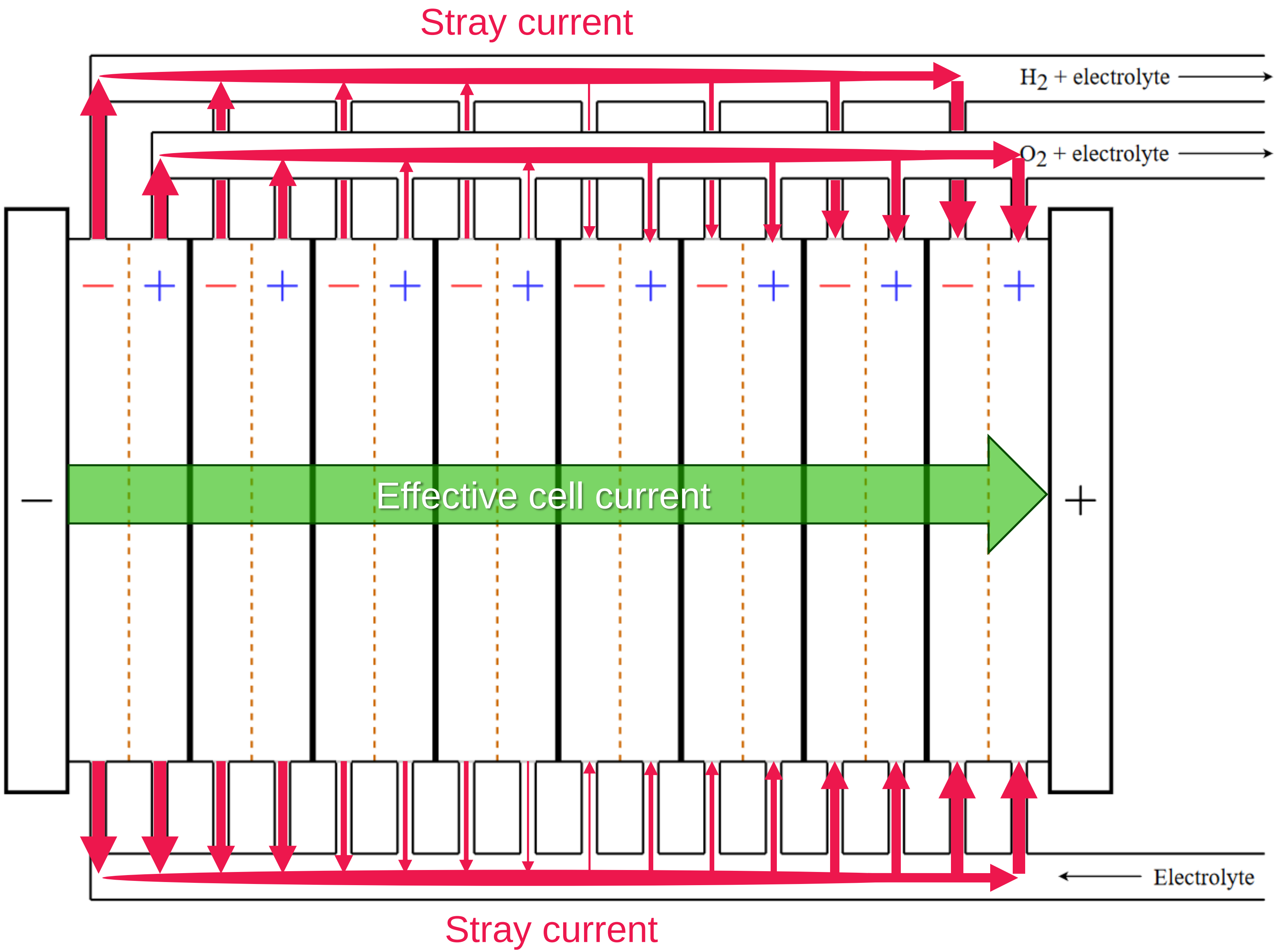
- Publication: Sakas et al, "Influence of shunt currents in industrial-scale alkaline water electrolyzer plants", Renewable Energy, 2024



- Efficiency drops as load is decreased
  - Cause: stray (or "shunt") currents, accounting for 16% to 41% of supplied DC power from 100% to 50% of nominal current load
- Half of lower explosion limit of H_2-in-O_2 content reached at 45.6% of nominal current
- These issues also reported in the industry:
  - "World's largest green hydrogen project 'has major problems due to its Chinese electrolysers': BNEF"
  - "Chinese hydrogen electrolyser makers are exaggerating their stacks' efficiencies by 10-20%"

Stray currents

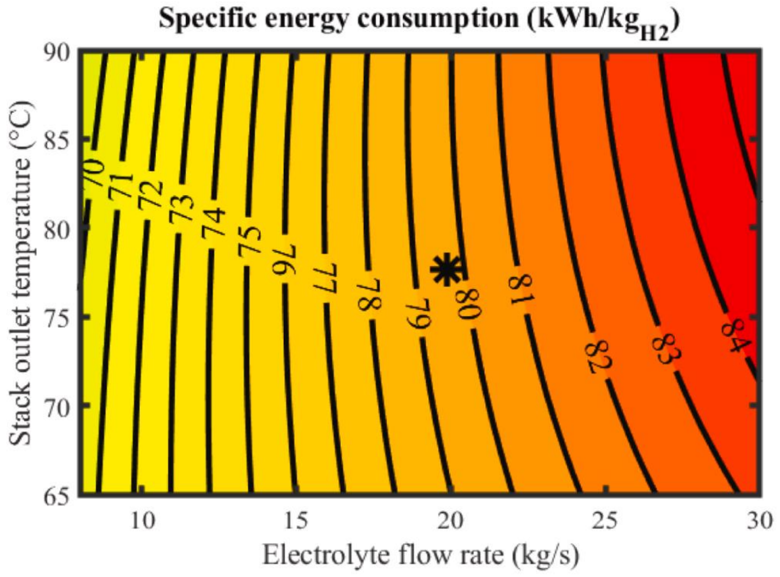
- Fluid channels present a parallel path for current in the cell stack, bypassing the electrochemical reaction
  - Total supplied current = effective cell current + stray current
  - Stray currents waste energy as heat



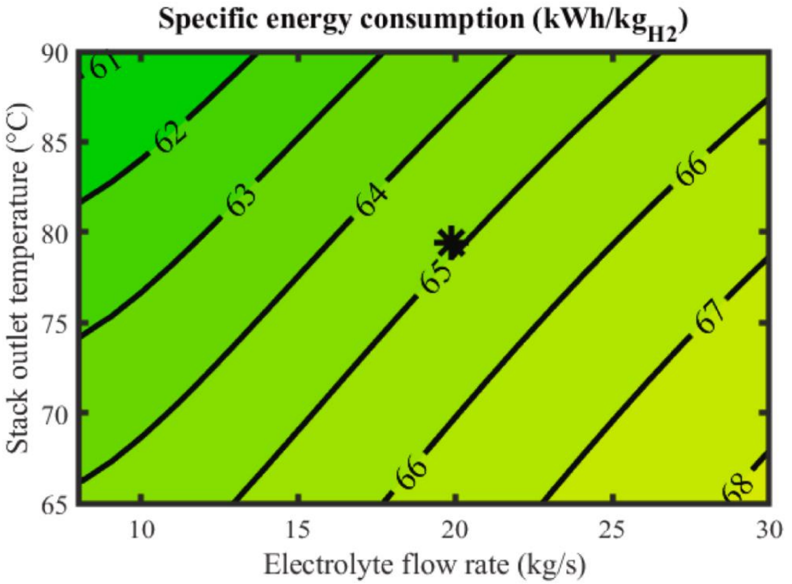
Task 1: Energy and cost-efficient industrial scale alkaline water electrolyzer (AWE) system

Results from modeling the 3-MW 16-bar system

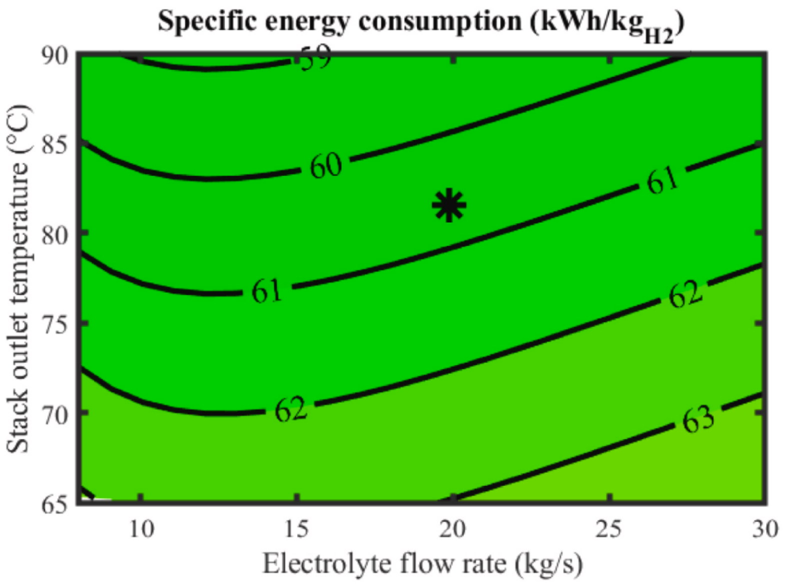
- Publication: Sakas et al, “Sensitivity analysis of the process conditions affecting the shunt currents and the SEC in an industrial-scale alkaline water electrolyzer plant”, Applied Energy, 2024
- Stray currents can be reduced by controlling electrolyte flow rate especially at partial loads



50% of nominal current



75% of nominal current

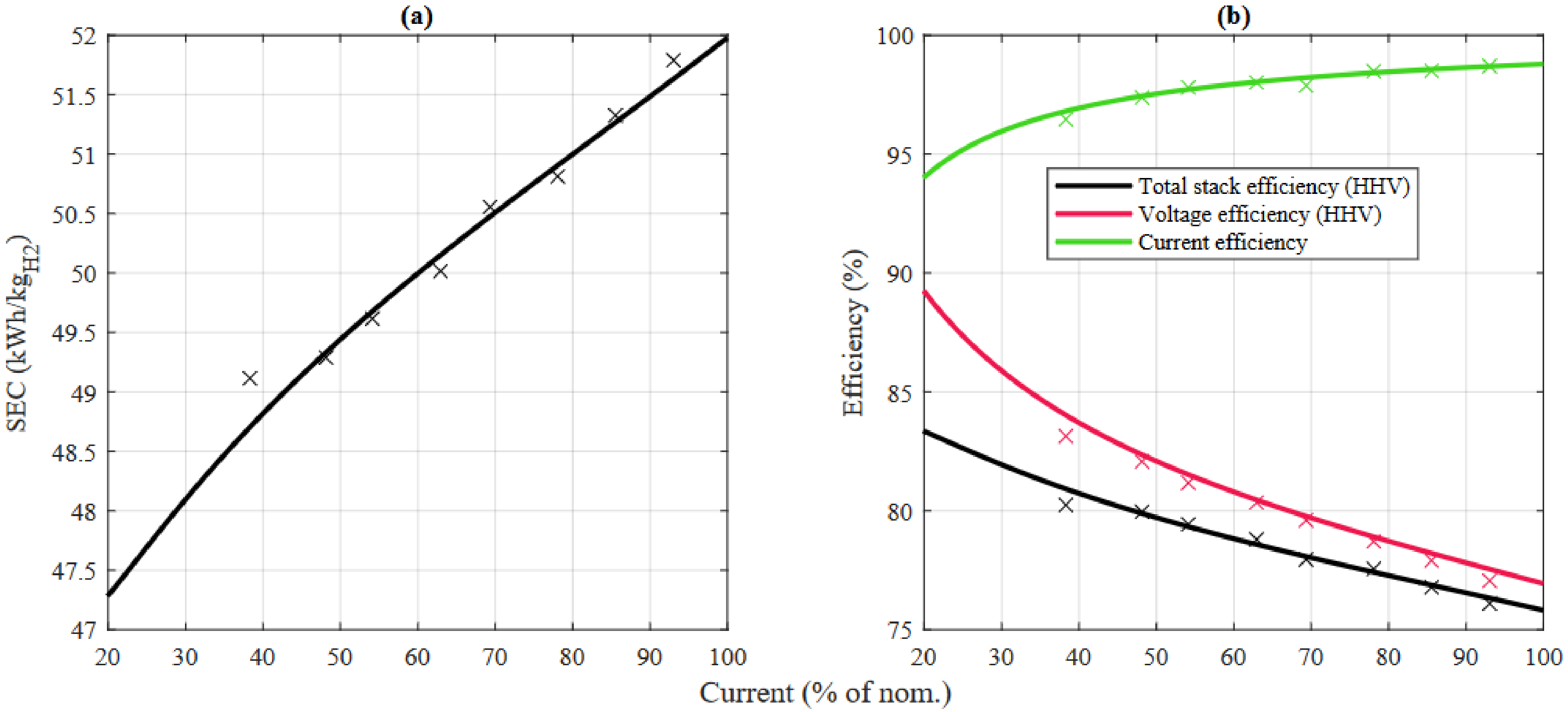


100% of nominal current

Task 1: Energy and cost-efficient industrial scale alkaline water electrolyzer (AWE) system

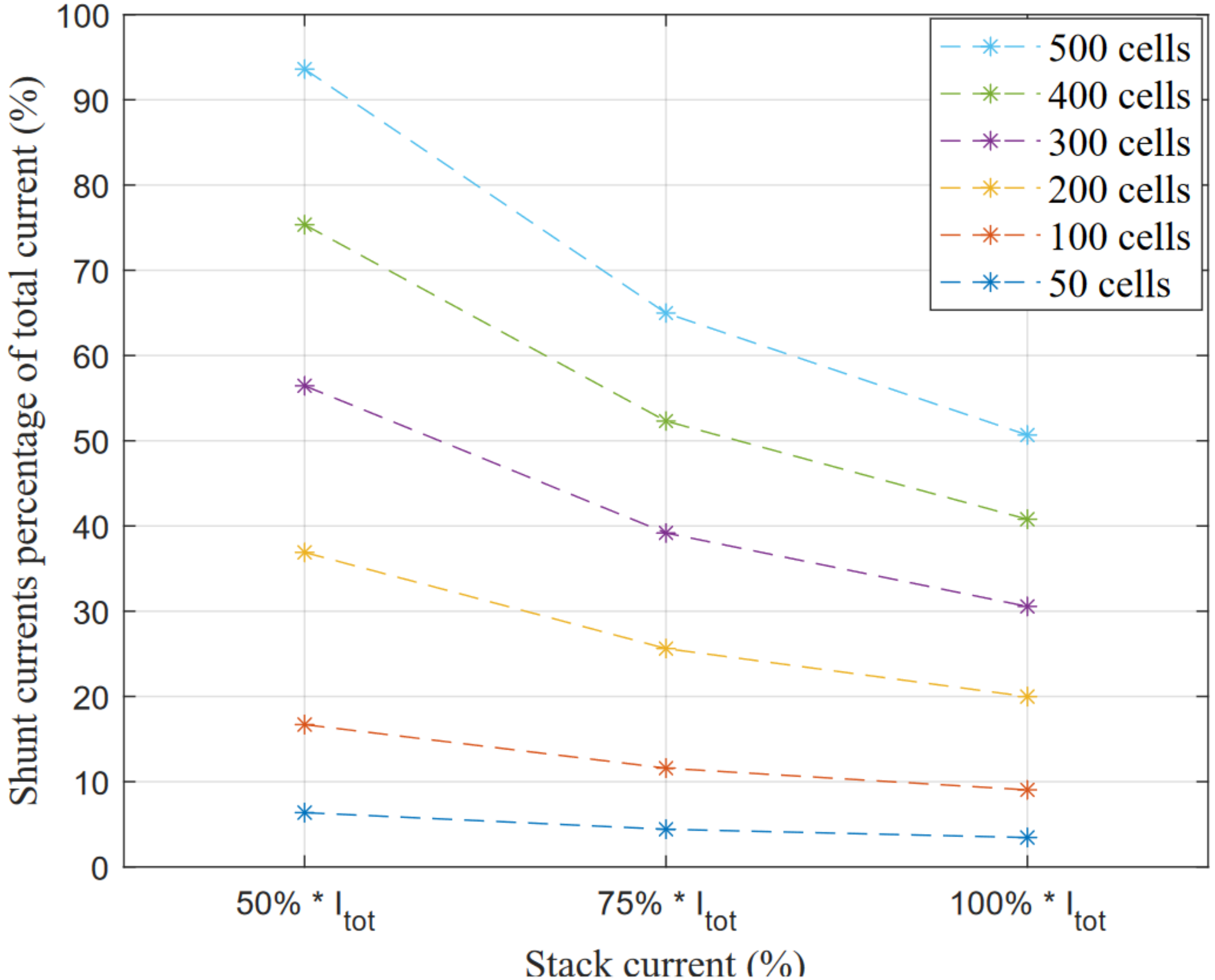
Results from modeling the 1-MW atmospheric system

- Publication: Pöyhönen et al, "Dynamic mass- and energy-balance simulation model of an industrial-scale atmospheric alkaline water electrolyzer" (under review in Energy)
- Efficiency improves towards lower loads
- Stray currents only 1% to 6% of supplied stack DC power from 100% to 20% of nominal current load
- Less stray currents than in the 3-MW 16-bar system because of:
  - ✓ More advanced manifold design
  - ✓ Outlet manifold channel more occupied by gas thanks to atmospheric pressure and lower electrolyte flow rate
  - ✓ Shorter stack (less voltage)



Task 2: Elevated-voltage and low-stray-current alkaline electrolyzer stack

- Premise: Higher stack voltage (>1000 V_{DC} vs. conventional <500 V_{DC}) allows H_2 production at lesser currents
  - Significant cost-reduction potential with less expensive power electronics
  - Stacking more cells in series to increase voltage increases stray currents
- Approach: Lumped-parameter simulation of an alkaline cell stack



Task 2: Elevated-voltage and low-stray-current alkaline electrolyzer stack

- 500-cell stack of approx. 1000 V_{DC} can be divided into substacks to limit stray currents
  - Substacks electrically in series, with separate fluid flow circuits

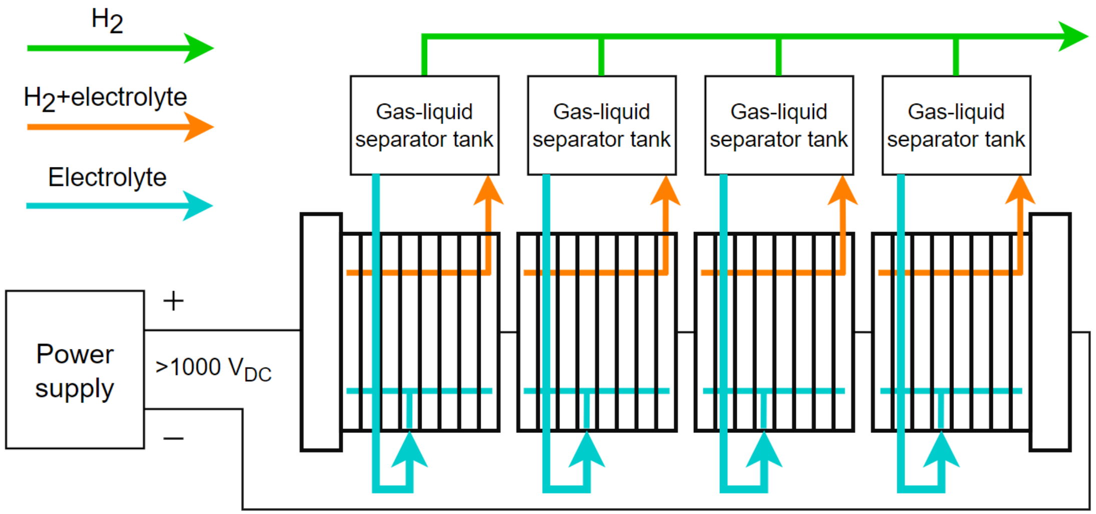


Figure: Substacking exemplified in principle.

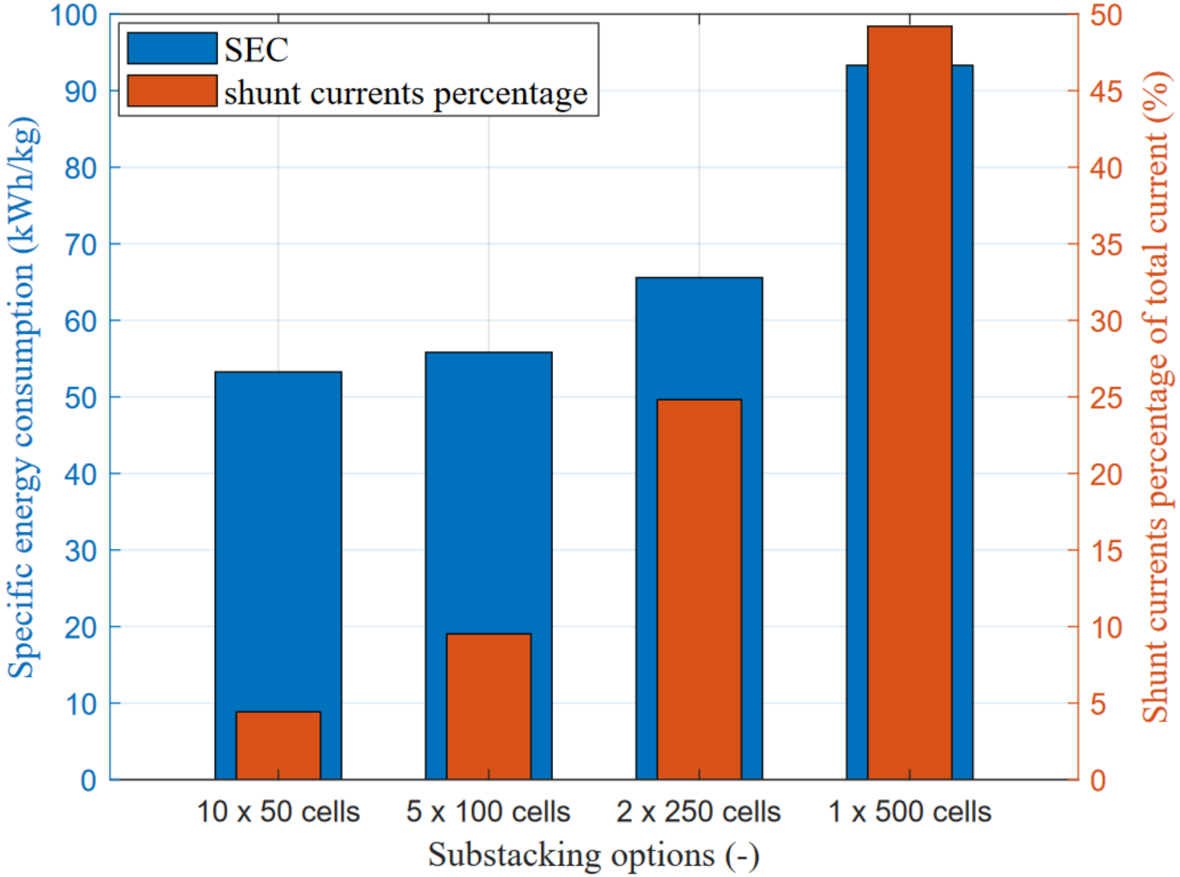
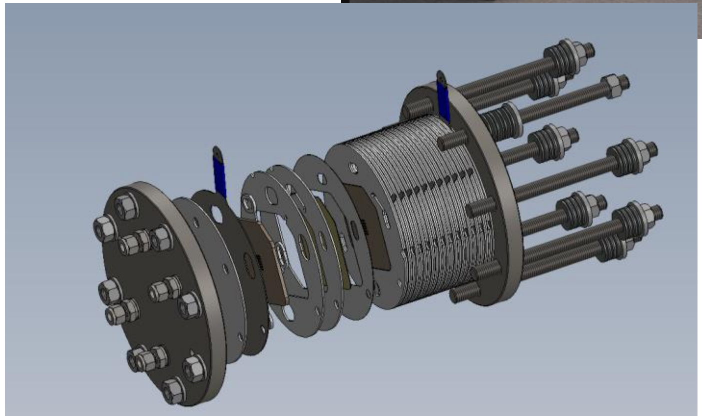


Figure: Shunt currents percentage of total current and SEC comparison of different substacking options at the nominal load operation.

Task 2: Elevated-voltage and low-stray-current alkaline electrolyzer stack

LUT laboratory infra

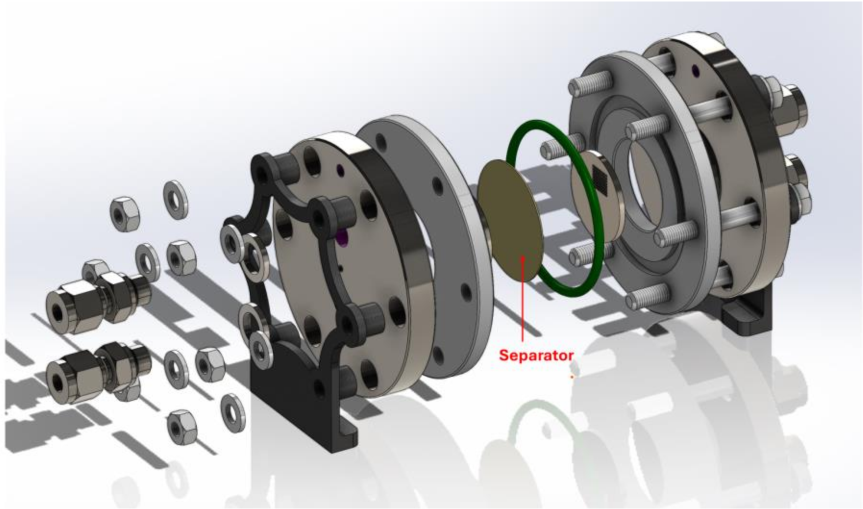
- LUT AWE stacks
  - Single-cell, 10-cell, and 12-cell stacks tested
    - At 30% nominal current, serial connection of 10+12 cells has current efficiency of 93%
    - Stray current between stacks <0.2% of total current
- High voltage AWE test environment
  - 2x48 cells (200 V, 10 kW) stray currents measured
  - 10x48 cells (1000 V, 50 kW) to be implemented in 2025

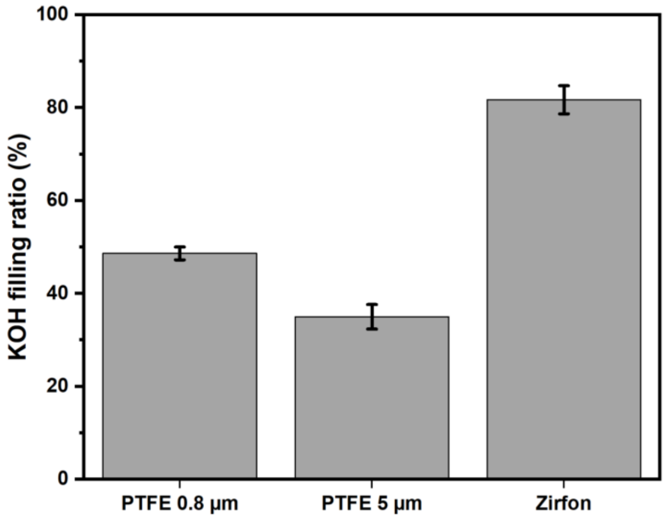


Task 3: Elevated-temperature alkaline electrolyzer cell

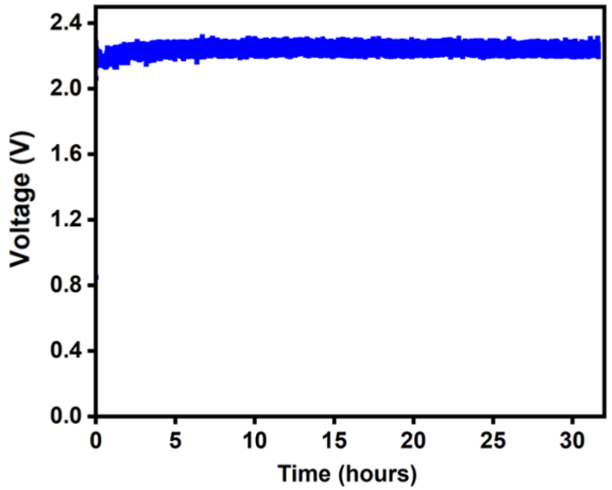
Stable separator material found:

- Electrolyte uptake of inherent hydrophobic PTFE was good enough to be used as a separator material after its hydrophilic modification
- Resistance offered by modified PTFE separator was 0.54 Ωcm^2 at 50°C (state-of-the-art Zirfon: 0.30 Ωcm^2 at 50°C)
- Stable voltage of 2.2 V when using PTFE 0.8 µm in a zero-gap alkaline electrolysis cell for more than 30 hours
- PTFE survived the alkaline stability test at 120°C; next target is to test it in higher temperature AWE setups at Technical University of Denmark (DTU)





Electrolyte uptake and filling ratio within the pores of separator



Separator stability in electrolytic cell using chronopotentiometry

Summary of key findings

- Stray currents cause a significant energy loss in pressurized alkaline water electrolyzers
  - Atmospheric electrolyzers at an inherent advantage
- Energy savings can be achieved by process control
- Stray currents can be limited efficiently by substacking
- High-temperature alkaline water electrolysis shows potential to increase energy efficiency

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