Overcoming sustainability challenges of fuel cell maritime applications: ammonia and methanol cases

Rafael Nogueira Nakashima, Arash Nemati, Henrik Lund Frandsen & Peter Vang Hendriksen

Outline

- Sustainable fuels for maritime applications.
- Boosting fuel conversion efficiency with solid oxide fuel cells: ammonia example.
- Improving onboard carbon capture with fuel cells methanol example.
- Concluding remarks

Sustainable fuels for maritime applications

Sustainable fuels for maritime applications

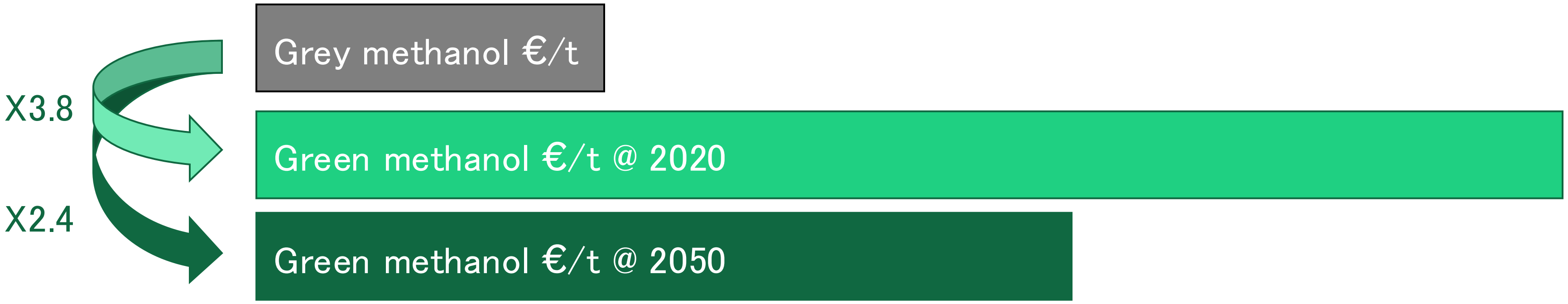
The green energy allocation challenge

- The **infrastructure** for attaining 2050 decarbonization targets is **enormous**:
  - Road: 20 EJ
  - Aviation: 25–50 EJ
  - **Shipping: 15 EJ**
  - Chemicals: 15 EJ

Bioenergy is a limited resource ≈ 65 EJ !

NH_3, H_2 by SOEC → 800 GW
- 250.000 6MW
- 25 years * 60 GW/y

- The **cost** of green alternatives is **3–4 times higher** than NG-based ones:



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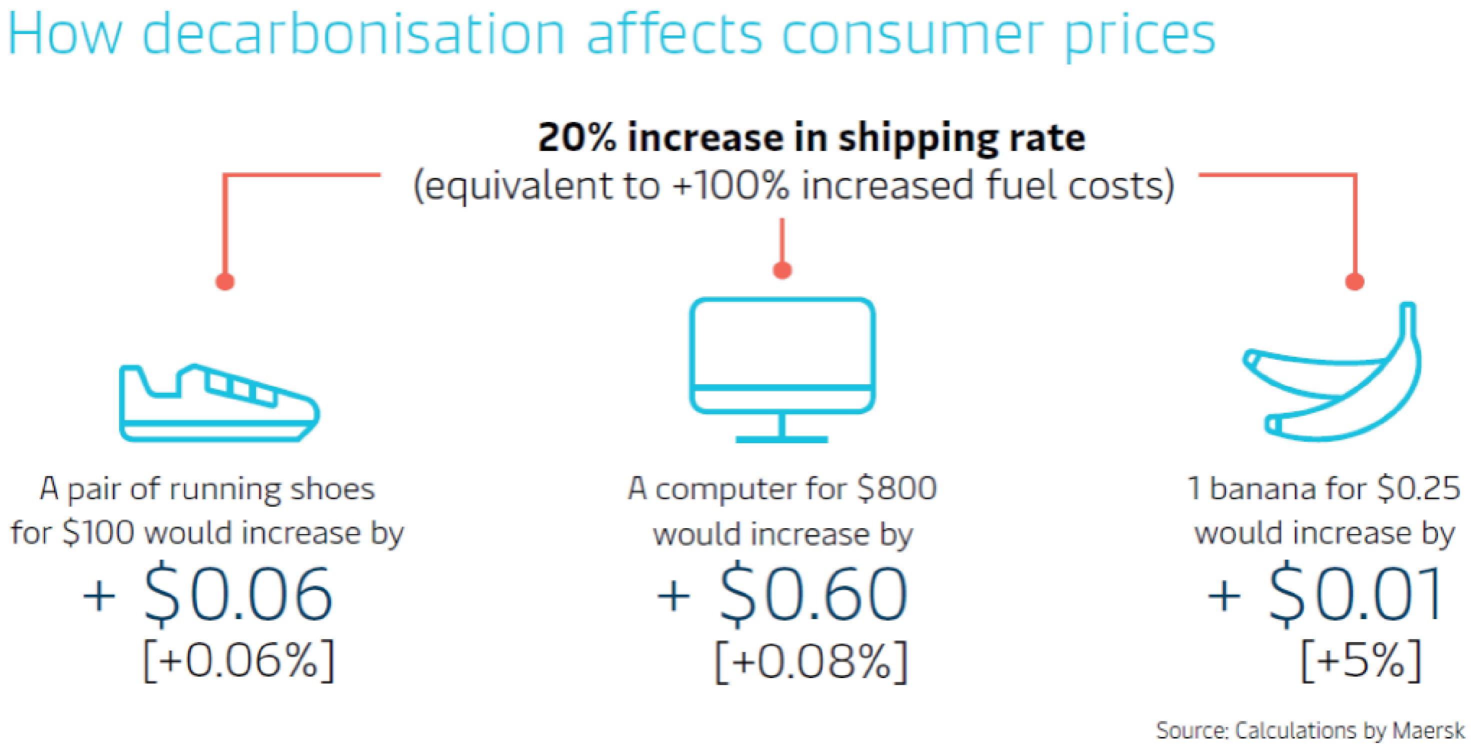
MarE-Fuel report

Sustainable fuels for maritime applications

Estimates on the impact of consumer prices

- The higher fuel costs are estimated to have **limited impact on the price of goods** transported



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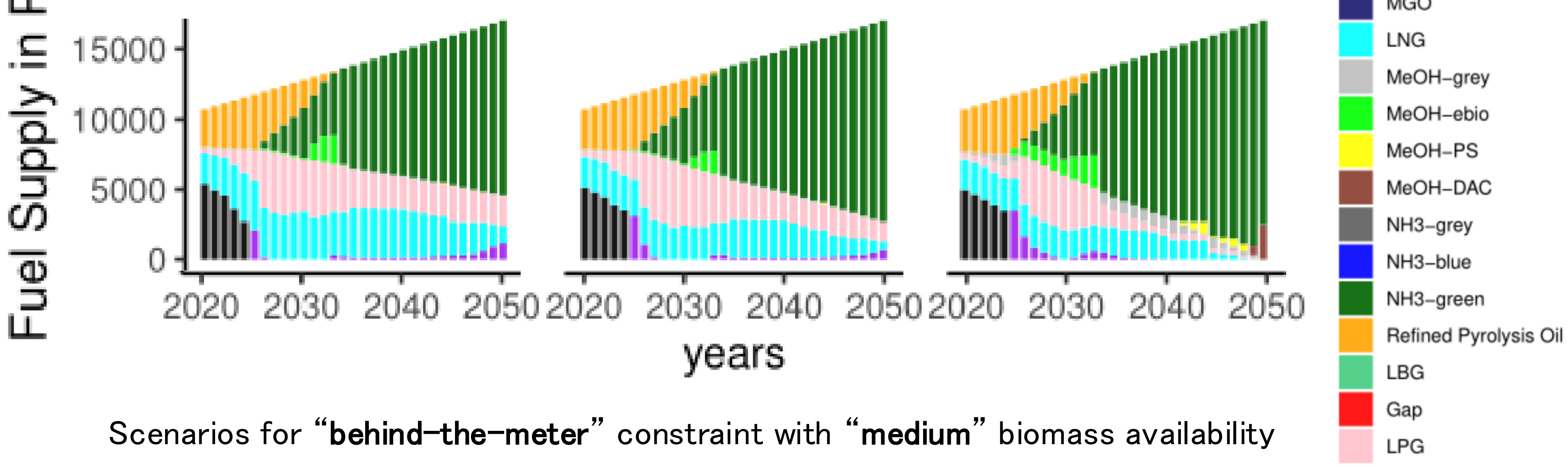
Mærsk sustainability 2020 report

Sustainable fuels for maritime applications

The roadmap for meeting decarbonization targets

- In an example scenario:
  - Initial reliance on bio-based alternatives and LNG/LPG.
  - Green ammonia gradual adoption and later dominance.

50% GHG emissions reductions by 2050 | **70%** GHG emissions reductions by 2050 | **99%** GHG emissions reductions by 2050



Scenarios for "**behind-the-meter**" constraint with "**medium**" biomass availability (full list of assumptions can be check in report ->)

More details and scenarios

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MarE-Fuel report

Boosting fuel conversion efficiency with solid oxide fuel cells: ammonia example

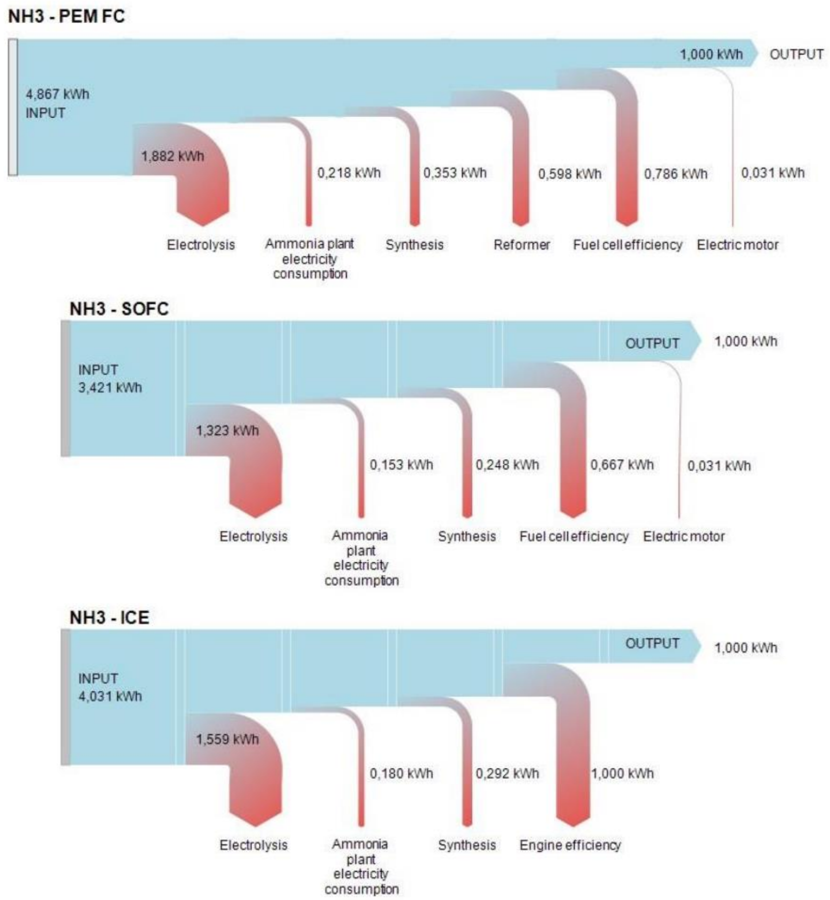
Comparison between different fuel cells

SOFCs outcompetes ICE efficiency for H_2 and green fuels

- SOFCs can reduce emissions of maritime transportation by increasing efficiency of ship propulsion

Figure 19. Electrical efficiency comparison of an internal combustion engine with PEMFCs and SOFCs

Source: Comparative report on alternative fuels for ship propulsion. Interreg North-West Europe. H2SHIPS. 2020



Recent NH3 SOFC projects at DTU Energy

SOC4NH3

HALDOR TOPSØE, equinor, ENERGINET, Ørsted, Vestas, AARHUS UNIVERSITET, DTU Energy

Prof. Peter Vang Hendriksen

AEGIR

COORSTEK MEMBRANE SCIENCES, BALLARD, VARD a Fincantieri company, VTT, SINTEF, DTU Energy

Prof. Anke Hagen

SOFC4Maritime

ALFA LAVAL, HALDOR TOPSØE, SVITZER, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, ABS, DTU Energy

Prof. Henrik Lund Frandsen

AMON

FONDAZIONE BRUNO KESSLER, SolydEra, SAPIO, VTT, HSLU Hochschule Luzern, ALFA LAVAL, kiwa, EPFL, EFCF est. 1994, DTU Energy

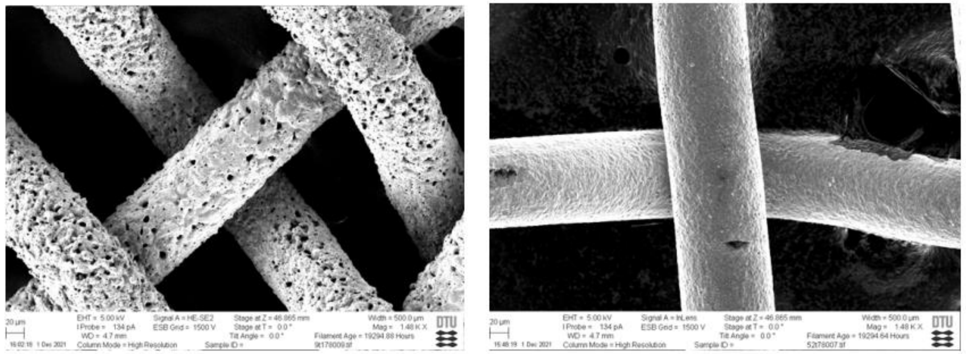
Prof. Henrik Lund Frandsen

Challenges of ammonia-SOFCs

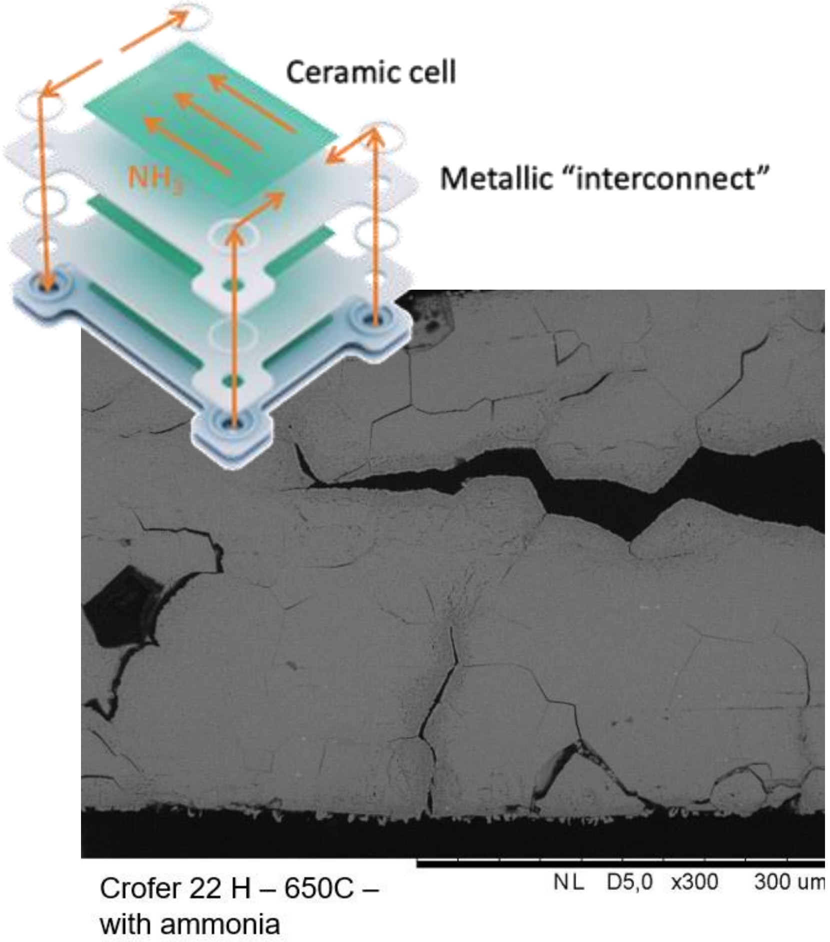
Nitriding of metallic components

- Significant reduction of stack lifetime due to the nitriding process

Ammonia | Hydrogen/Nitrogen



SEM of the Ni-mesh used for current collection in the long-term cell test experiments [1].



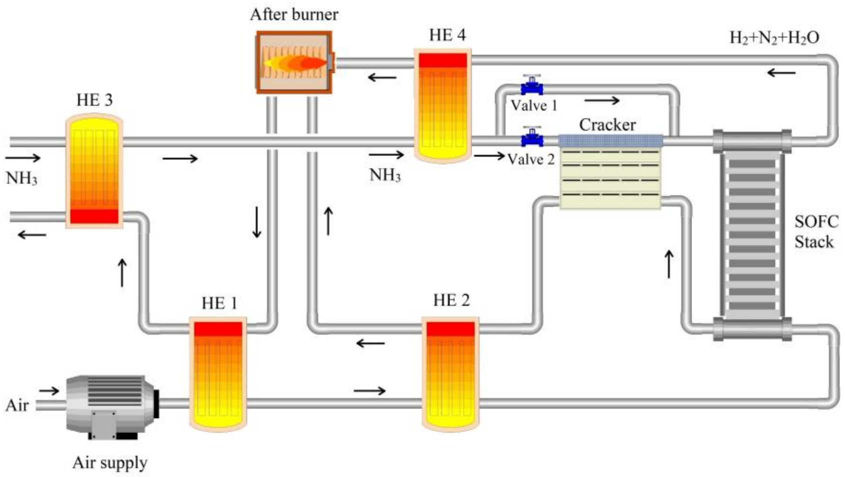
Interconnect after exposure to ammonia

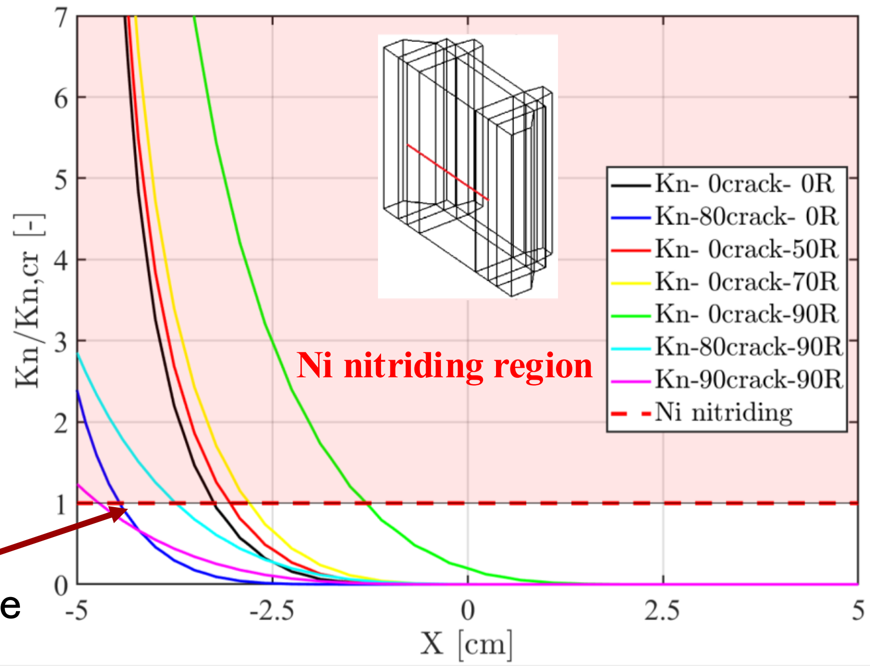
[1] Hendriksen, P. V., Mondi, F., Sun, X., Caldogno, R., Frandsen, H. L., Rizvandi, O. B., ... & Hansen, J. (2023). Ammonia as an SOFC Fuel. ECS Transactions, 111(6), 2085.

Solutions for ammonia-SOFCs

Ammonia pre-cracking and anode recirculation

- To protect the stack, we need an **external cracker**.
- To obtain high efficiency we need **recirculation**.
- External cracker reduces the efficiency (high airflow for cooling).





Description	System efficiency[%]
0% crack, 0% R	~ 53.4
80% crack, 0% R	~ 51.4
0% crack, 50% R	~ 63.5
0% crack, 70% R	~ 68.7
0% crack, 90% R	~ 74.2
90% crack, 90% R	~ 72.4

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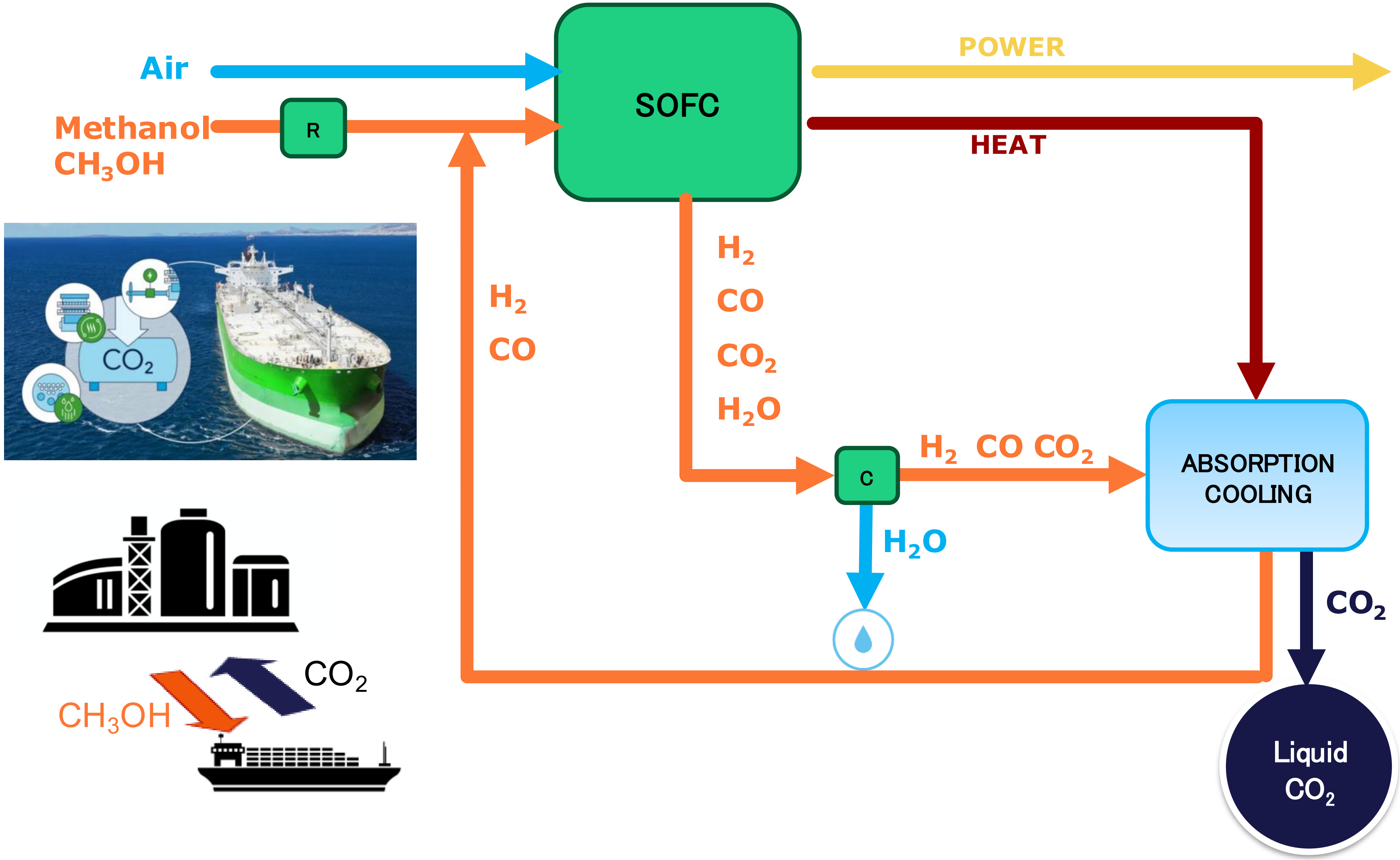
Full research article

Fuel / Elsevier

Improving onboard carbon capture with fuel cells methanol example

Integrating SOFCs with onboard carbon capture

Novel onboard carbon capture solutions enabled by fuel cells



- ~ **68 % efficiency**
- "**free**" capture and liquifaction of CO_2
- CO_2 can be re-used for methanol

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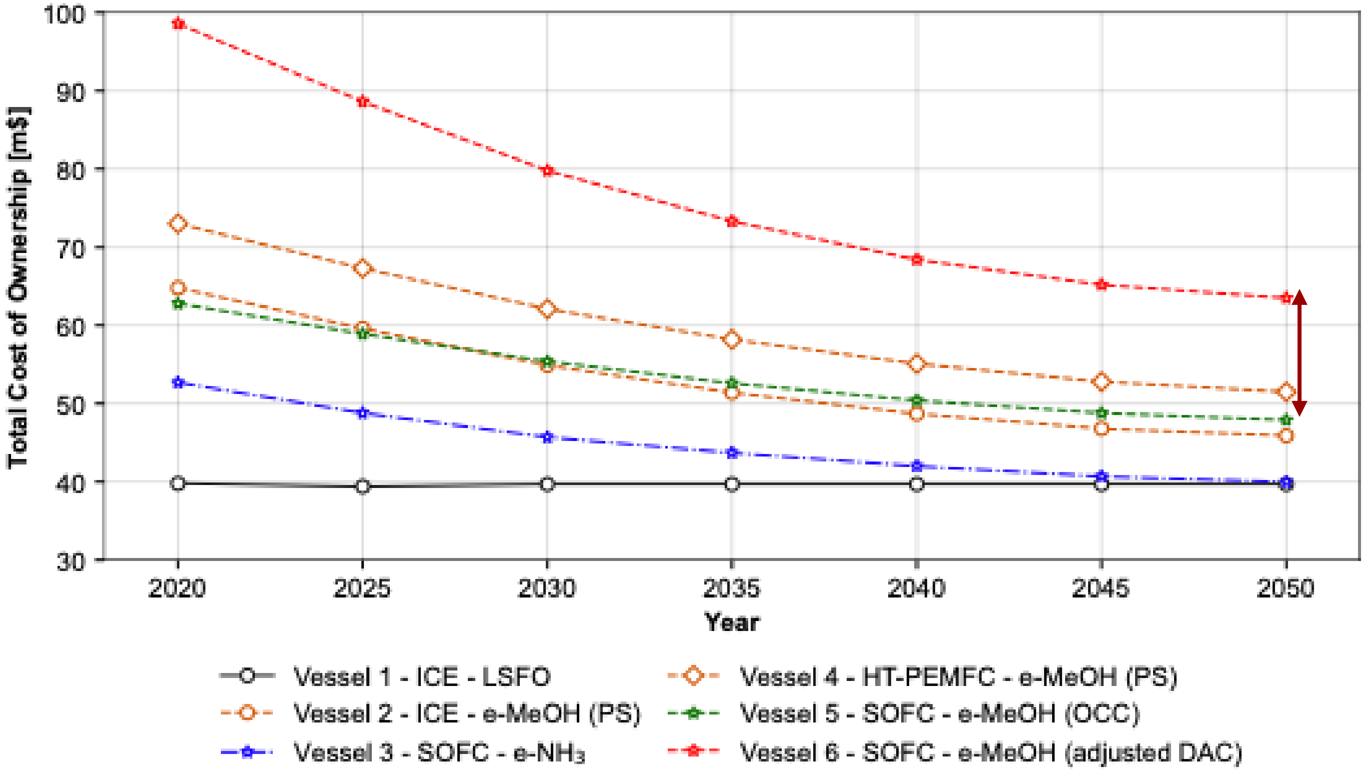
Full research article

IJoHE / Elsevier

Integrating SOFCs with onboard carbon capture

Total cost of ownership benchmark

- Ammonia–SOFC is still the **cheapest solution** for decarbonization.
- Onboard carbon capture is **significantly cheape**r than direct air capture alternative.



Source: Techno-economic analysis of methanol fueled solid oxide fuel cell systems with energy efficient carbon capture in maritime transportation (in preparation)

Closing remarks and acknowledgements

Concluding remarks

Future perspectives

- Decarbonization of maritime transport will call for (i) sustainable fuels (ii) efficient systems (iii) onboard carbon capture solutions.

- Main insights from DTU Energy:
  - Sustainable fuels are predicted to **cost 2–4 time more** until 2050
  - Limited bioenergy calls for **ammonia** and onboard carbon capture.
  - Only **SOFCs** can outcompete ICEs **efficiency-wise**.
  - Ammonia problems can be solved by **pre-reforming** and **anode recirculation**.
  - Fuel cells enable **efficient onboard carbon capture**.

Acknowledgements

Thanks for your attention

LinkedIn profile

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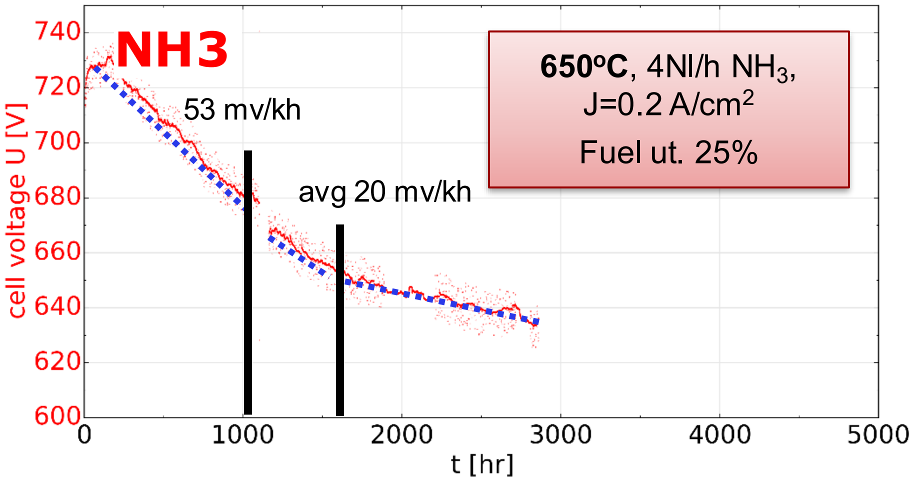
Among other contributors from DTU Energy

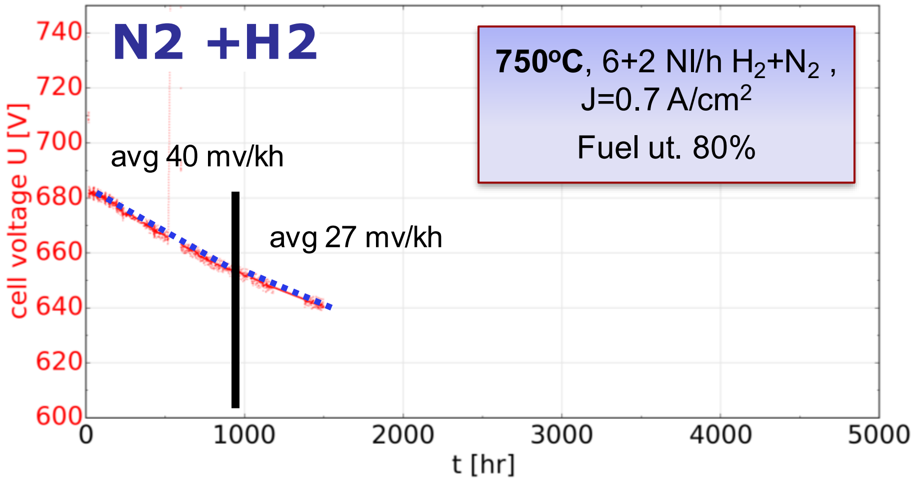
DTU

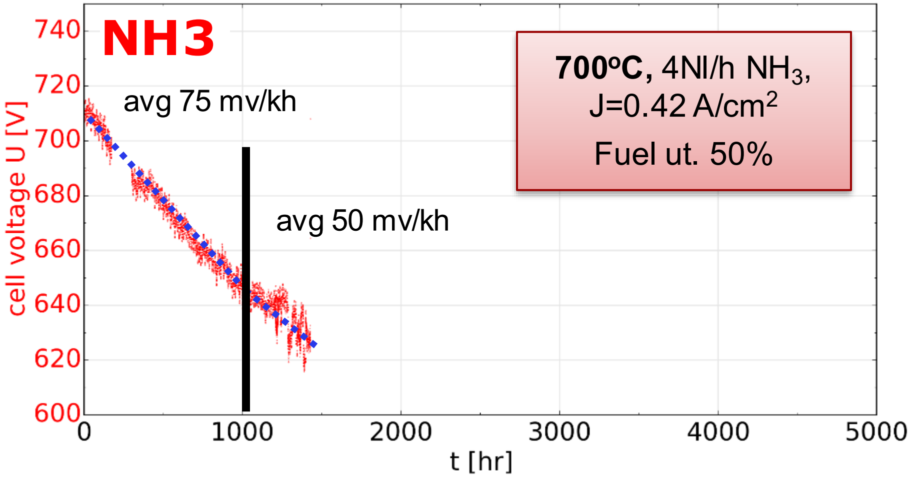
Backup slides

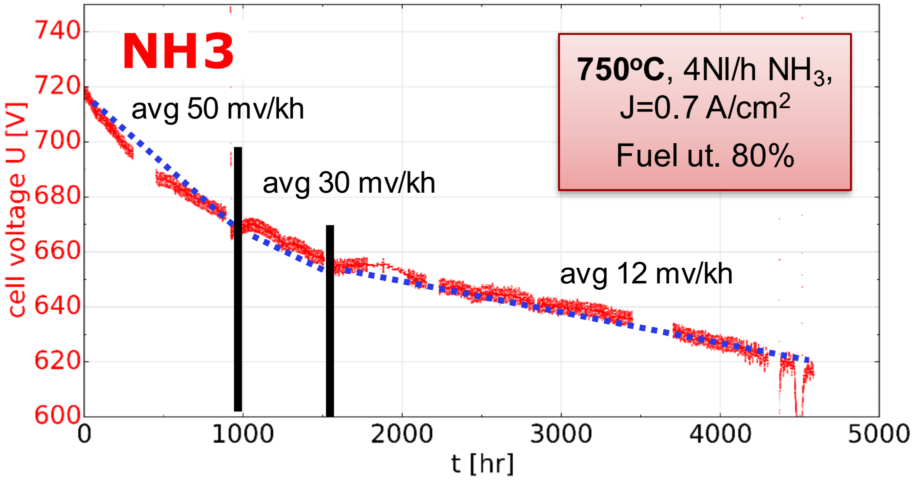
Cell operation with NH3

Use of ammonia in SOFC -> Durability at various T





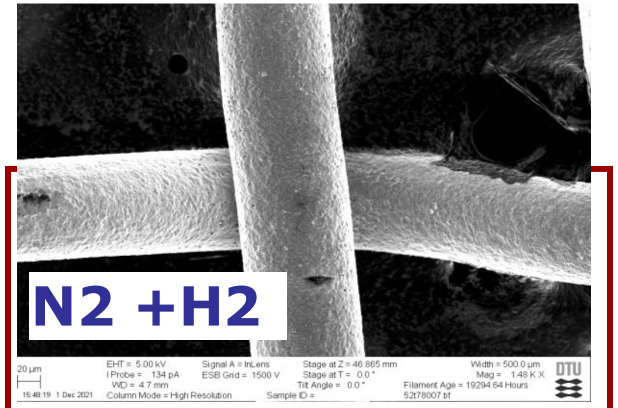




→ No dramatic effect on durability of ammonia

→ 2 - 3 %/1000 hr, FU ~ 80%

Auxiliary Ni mesh



- Damage to Ni mesh
- No damage at active part

Results from EUDP project; "SOC4NH3", project no. 64018-0546

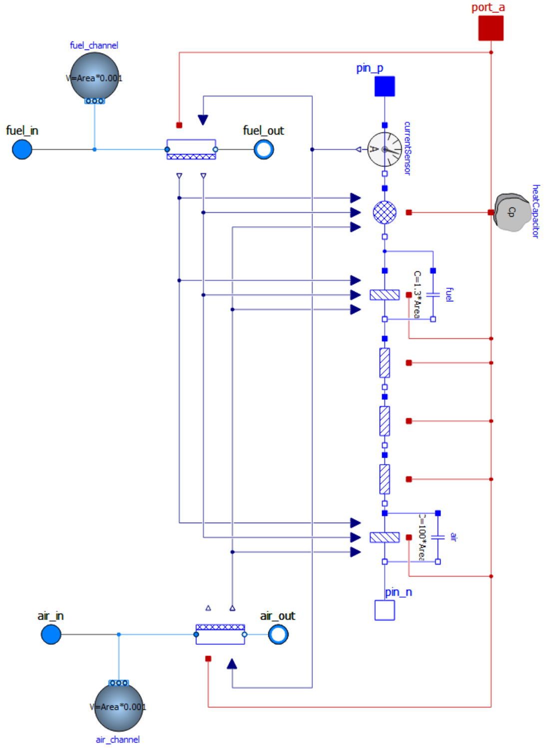
Backup slides

Open-source initiative: NEST

Vision: Modelica simulation

Work in progress

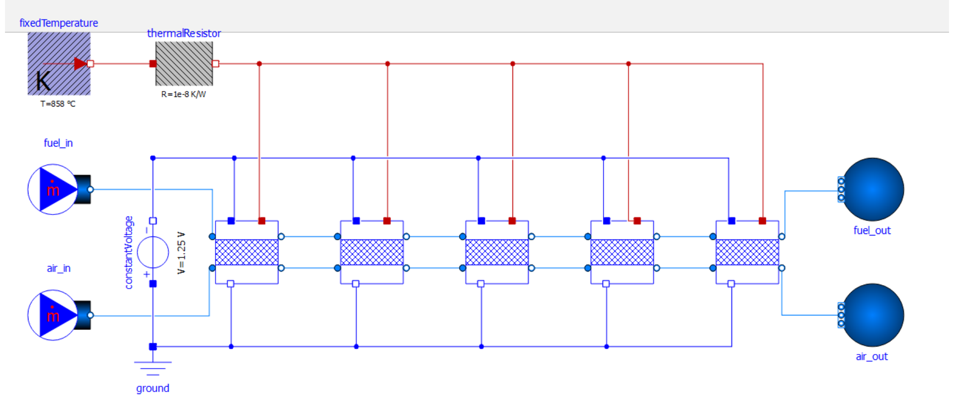
Detailed description of overpotential sources for each cell segment



Cell segment unit

Equivalent circuit representation

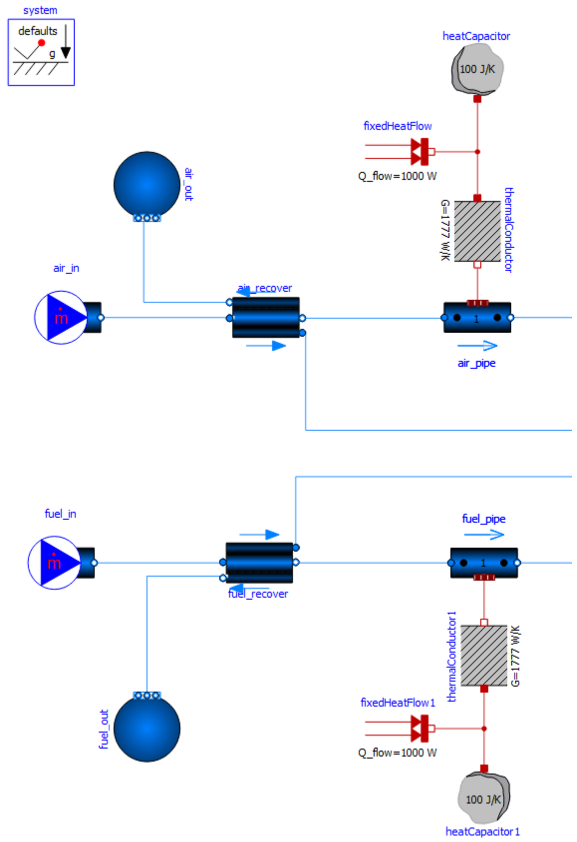
Finite element methods to convert PDE into multi-ODE problem reusing cell segments



Single repeating unit

Finite element representation

Module balance of plant integration using Modelica library

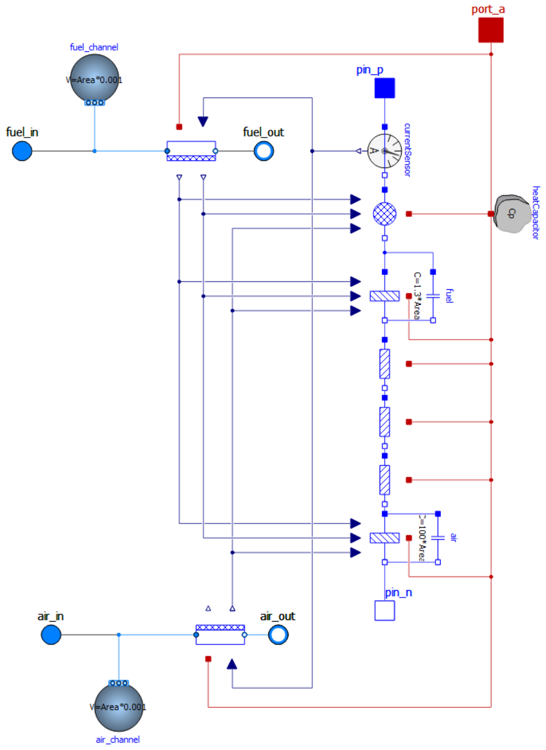


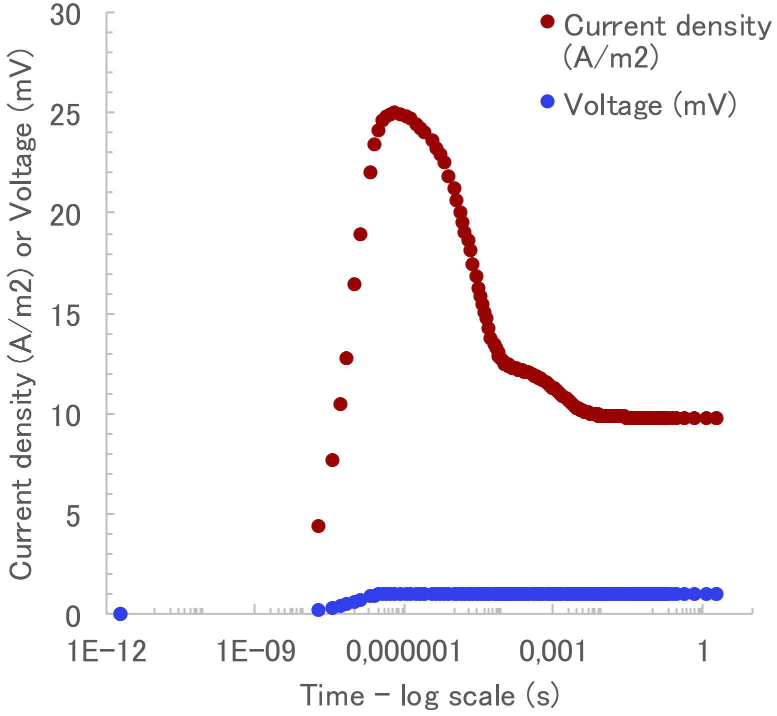
Module unit

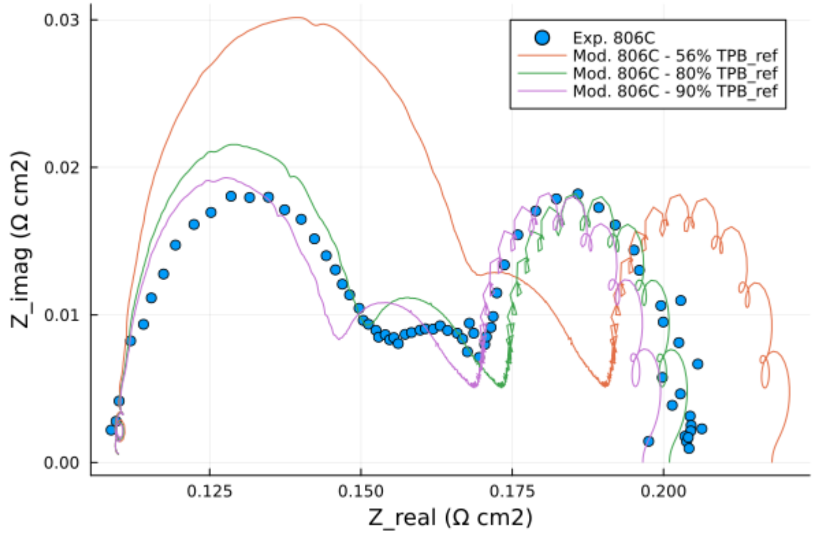
Conventional components

Vision: Modelica simulation

User case example: EIS validation and parameter inference







Cell segment unit

Equivalent circuit representation

→

Dynamic response in time domain

Potential step with current relaxation

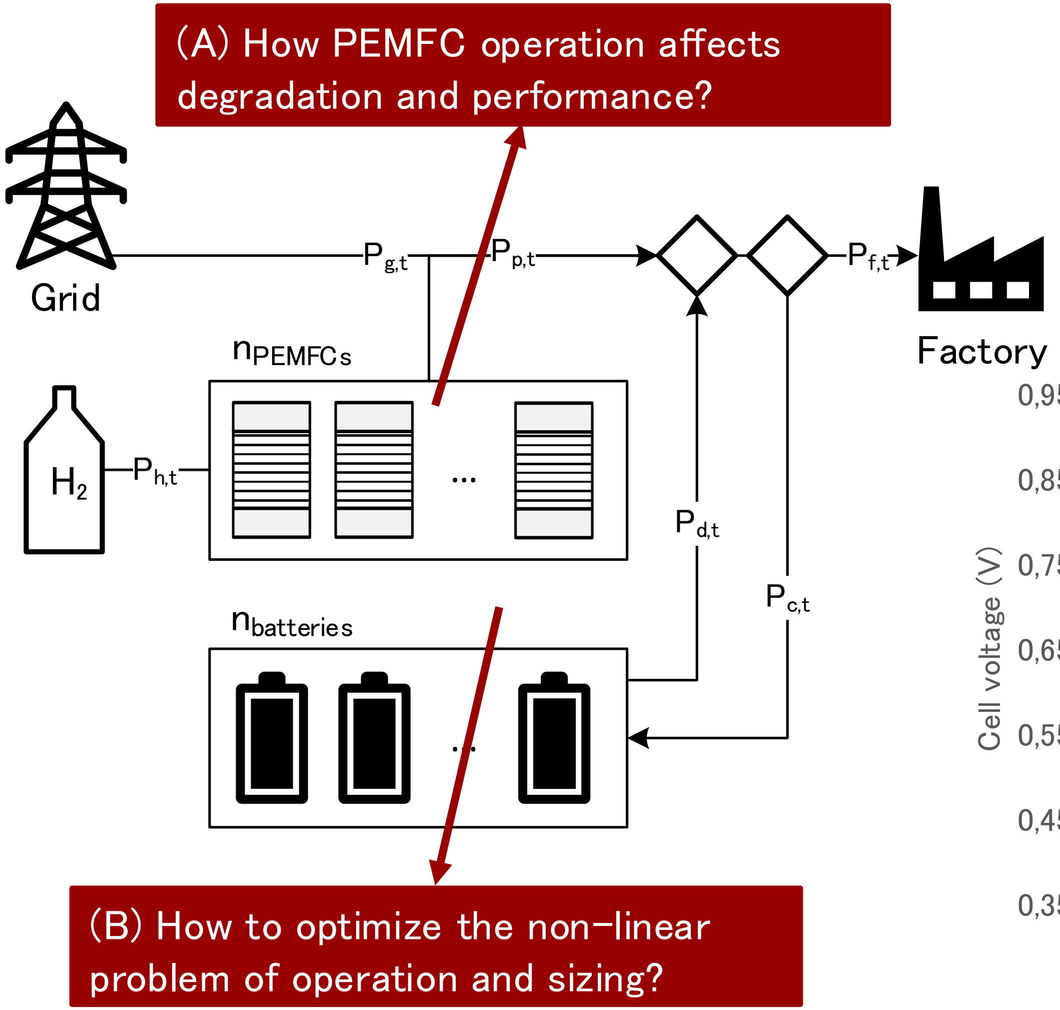
→

EIS simulation

Identification of modeling parameters compared with experiments

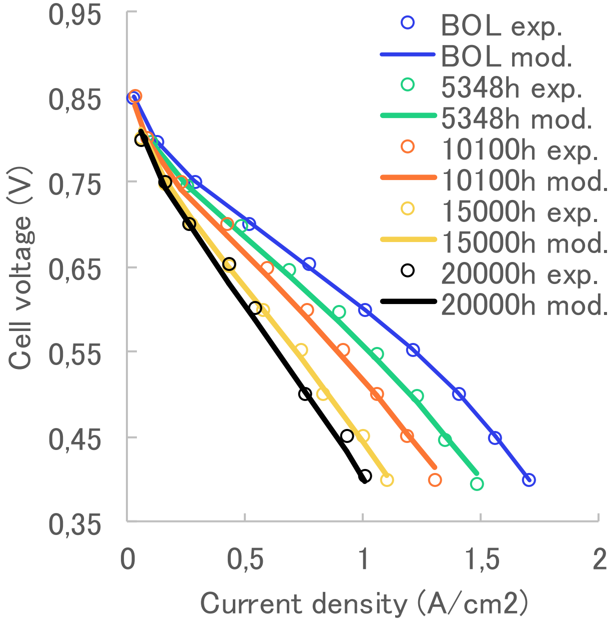
Fuel cell degradation and open science

dEMS – Degradation-aware EMS



Degradation model

Simplified model for EMS



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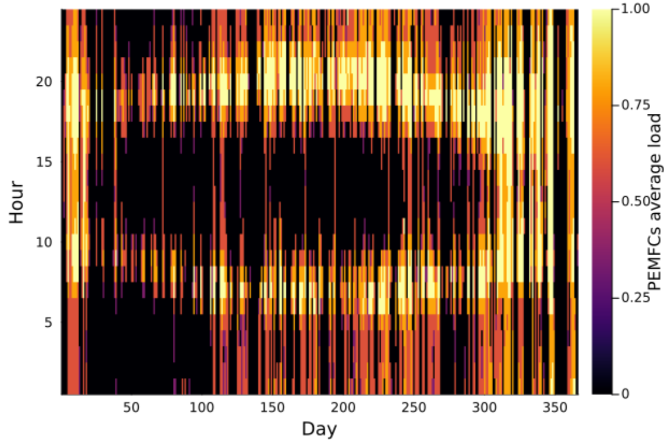
dEMS

Open-source software



Operation optimization