AMMONIA TO POWER

Efficient ammonia-based fuel cell systems and impact

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NH_3
AMMONIA TO POWER

Why ammonia as a fuel?

Why use the SOFC technology with ammonia?

What are the challenges?

Solutions

The competitors

Techno-economic analysis and comparison

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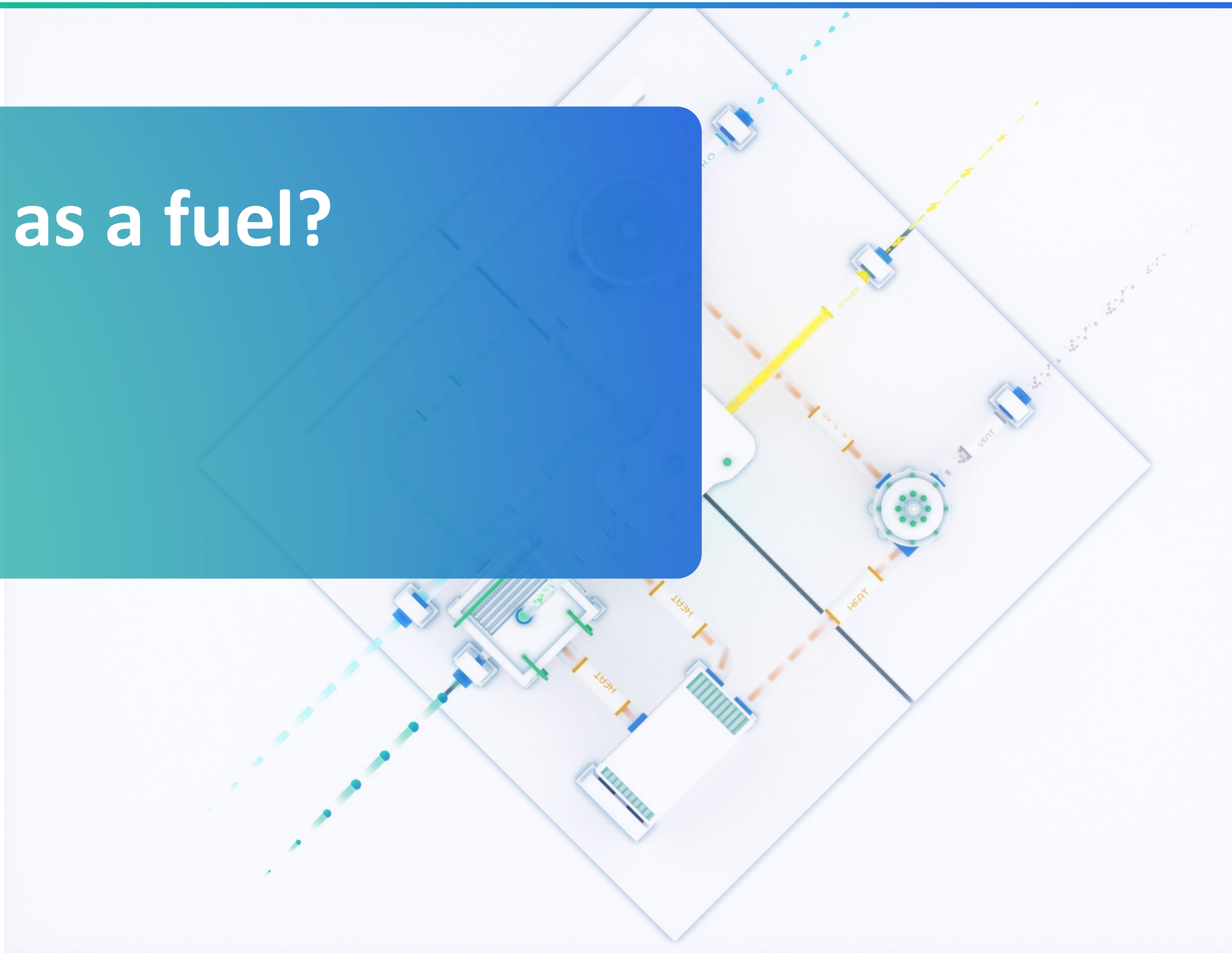
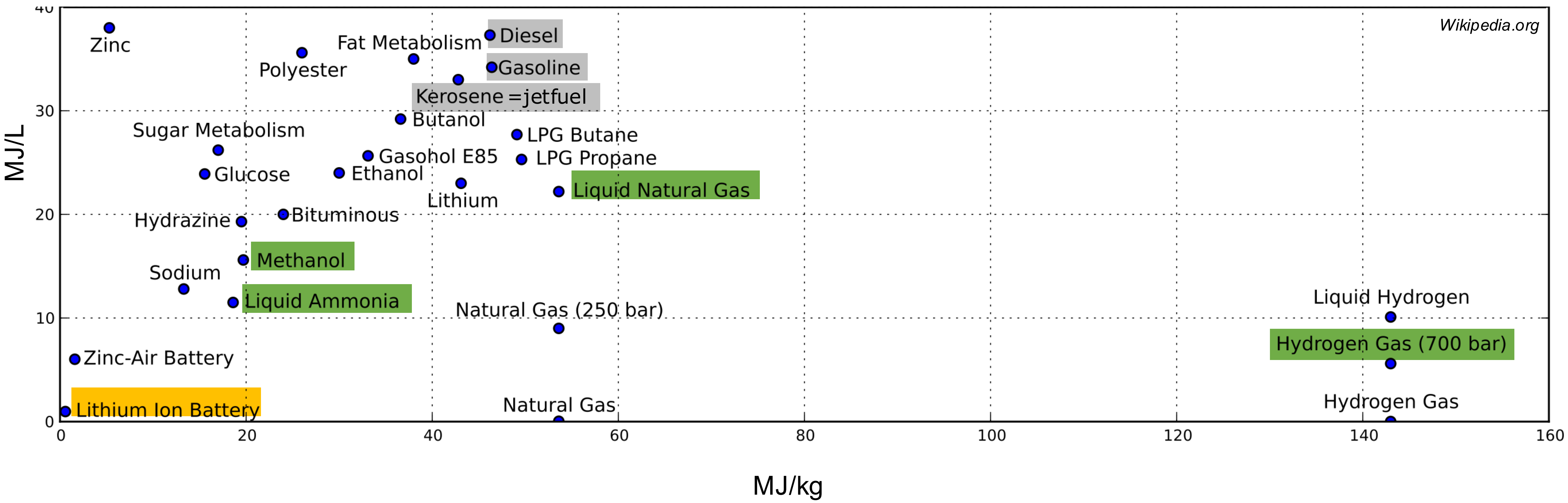
Why ammonia as a fuel?



Energy density



Biomass availability

Sustainable biomass, globally[2] 200 EJ			
33 EJ Wood & residues	61 EJ Agricultural waste	33 EJ Wet waste, oils & manure	73 EJ Energy crops

Biomass seems to be scarce!

Direct air capture very costly due to energy need (CO_2 0.04 % of atmosphere)

Preferably a fuel without need for biogenic carbon

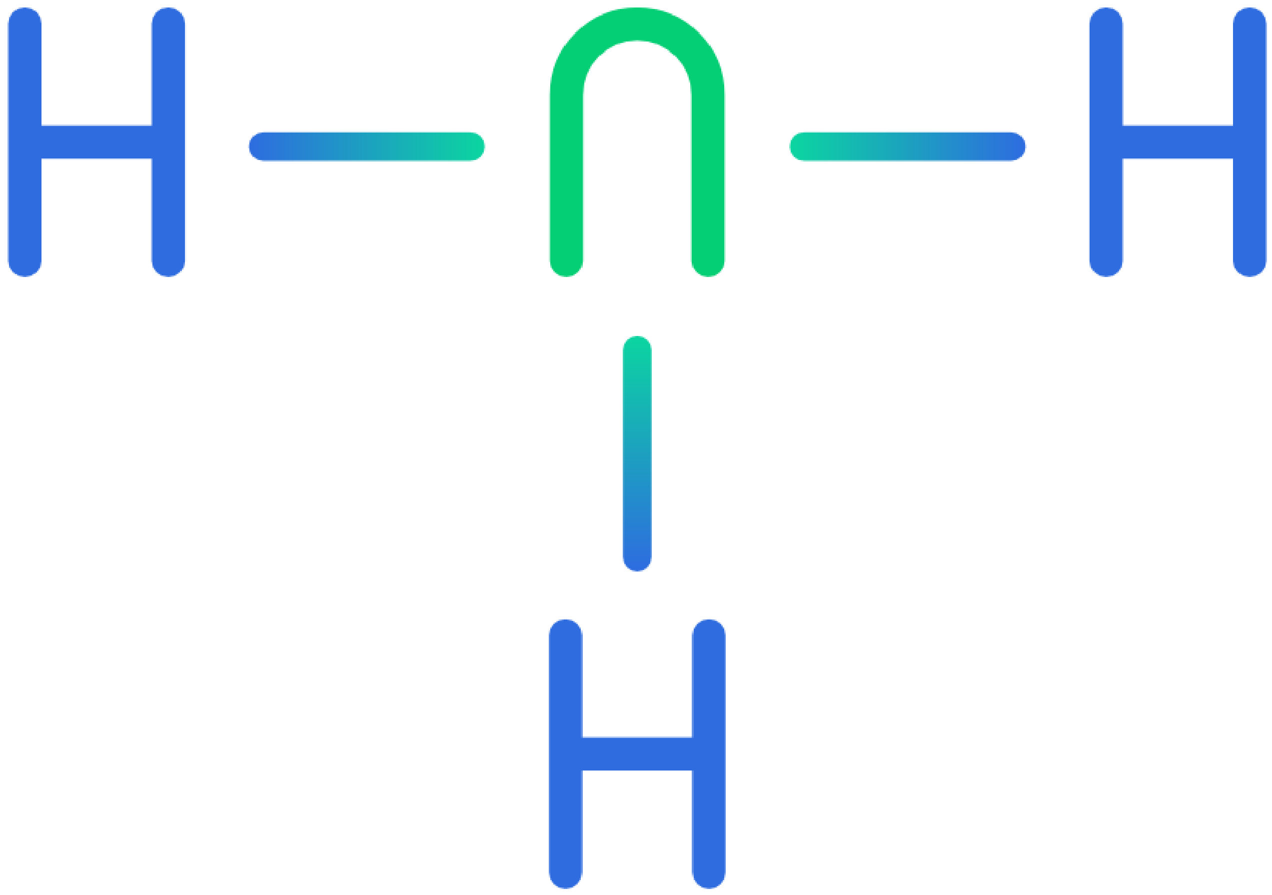
Demand for carbon-based fuels [EJ][1]

	Low scenario	High scenario
Shipping	Up to 20	Up to 20
Plastics	60	120
Peak heating	30	50
Buildings	30	40
Industry	20	40
Aviation	15	20
Cement	0	30
Electricity balancing	10	20
Steel	5	20
Road transport	5	10
Total	**175**	**370**

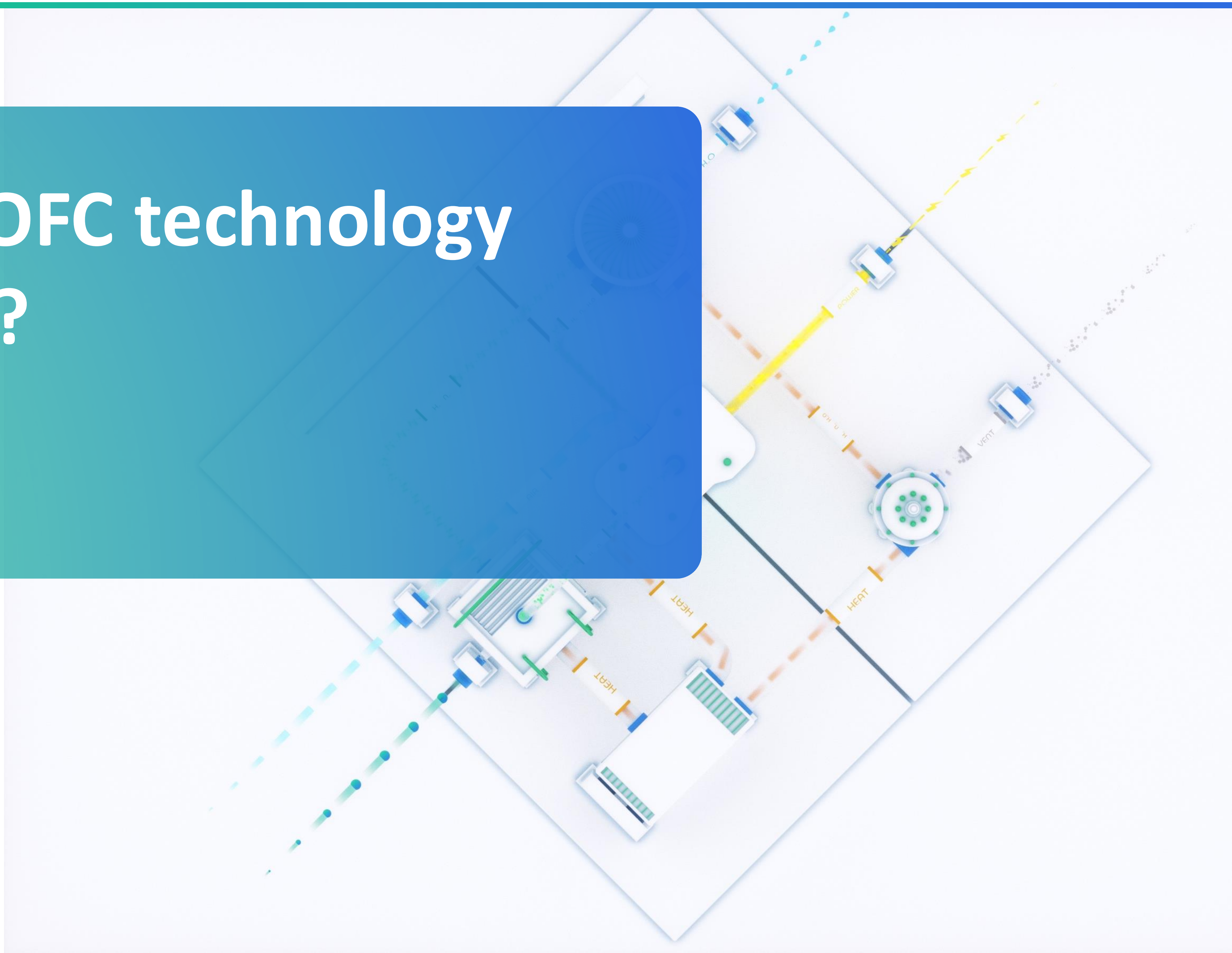
Decarbonization – using green ammonia

- No carbon sources needed
- Can be easily liquified
- Toxic – but has been transported safely for +100 years

AMMONIA



Why use the SOFC technology with ammonia?



Cost aspects

- In maritime transportation: CAPEX / **OPEX**: ~10 / **90 %**
  - The **fuel cost** is significant
- Future **green fuels** will be relatively more **expensive**
  - Energy **efficiency improvements likely to pay** off
- Current maritime engines reaches efficiencies between **~45 – 54 %** (LHV)
- Ammonia fed SOFC is expected to reach efficiencies of: **~65 - 70 %**

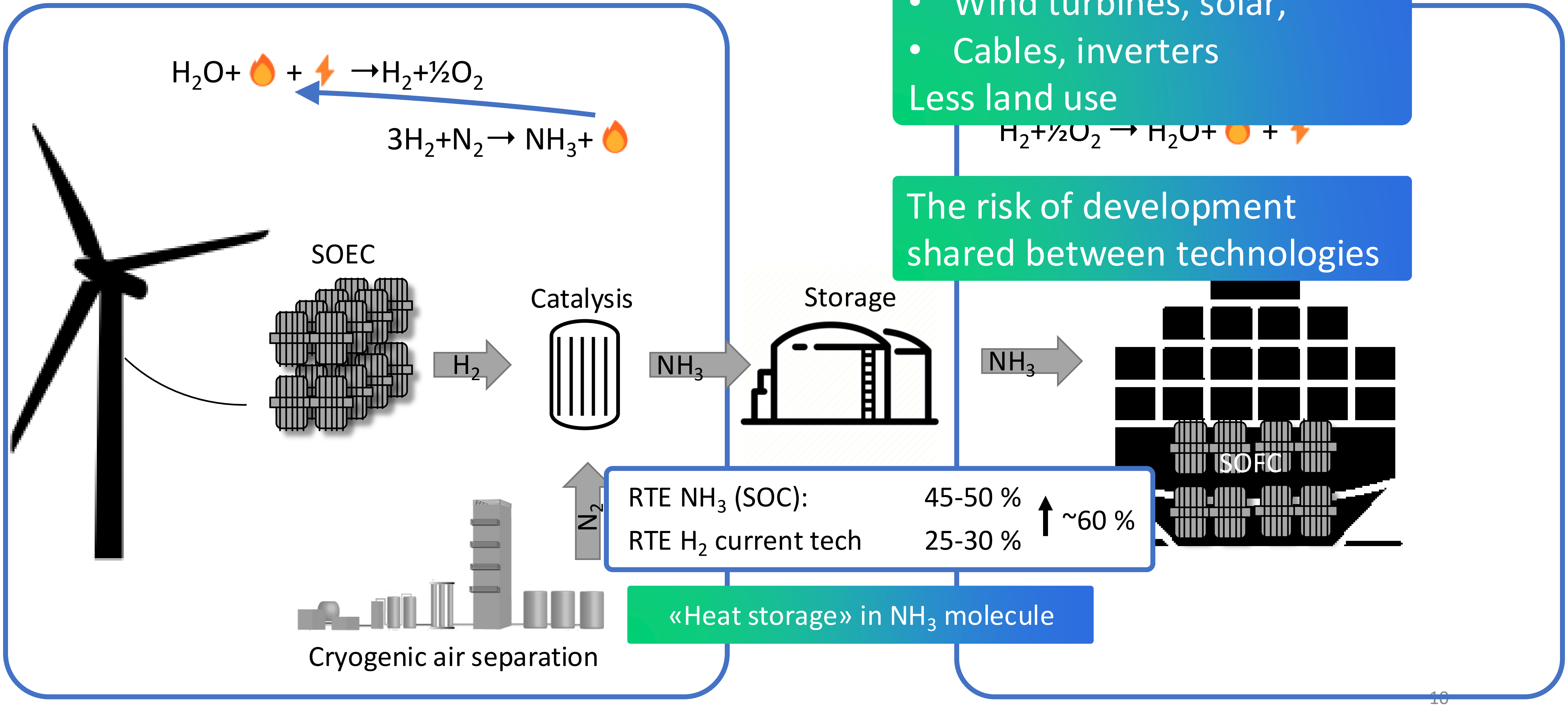
+ 35 %

Other aspects

Less materials for
- Wind turbines, solar,
- Cables, inverters

Less land use

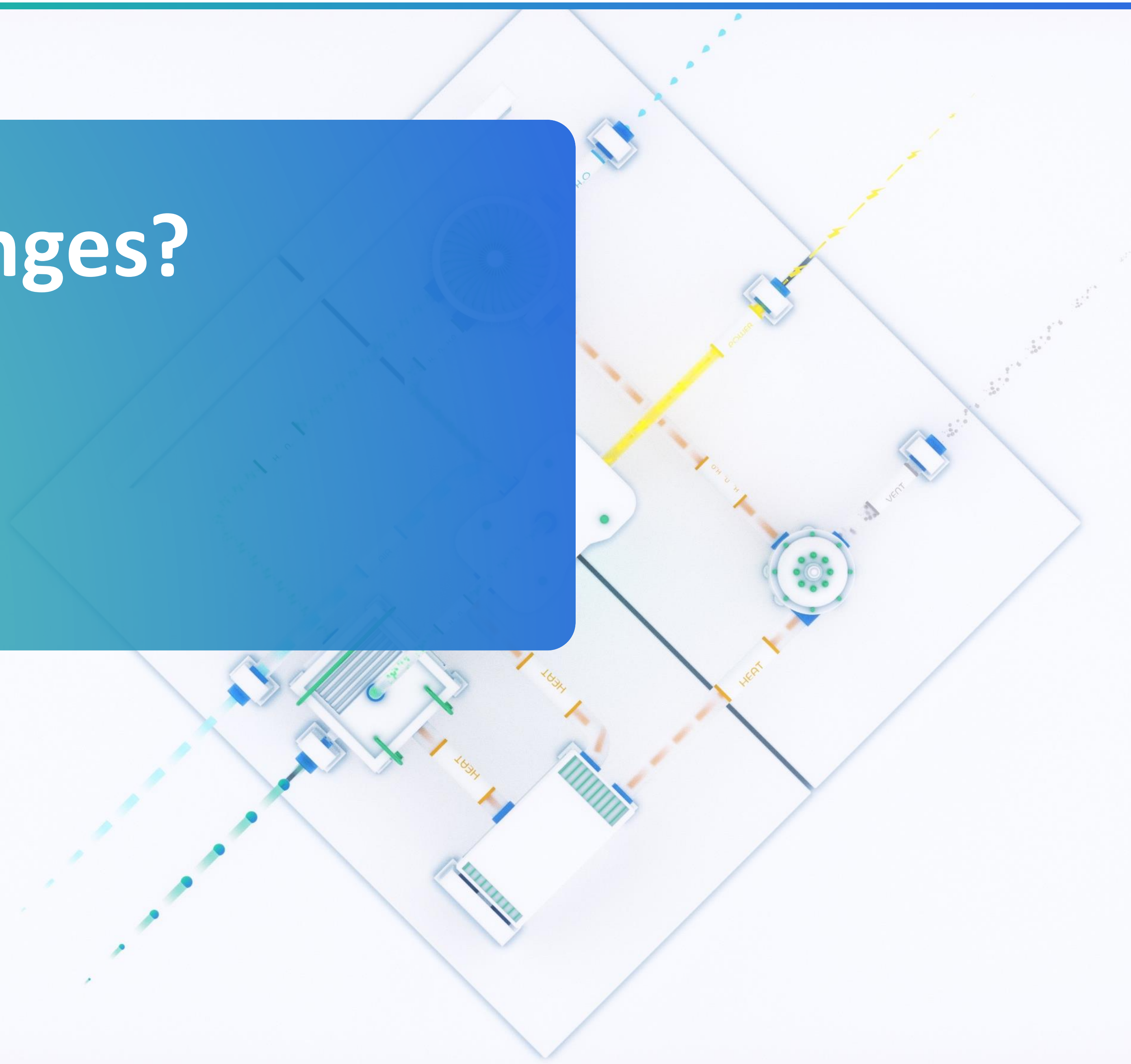
The risk of development shared between technologies



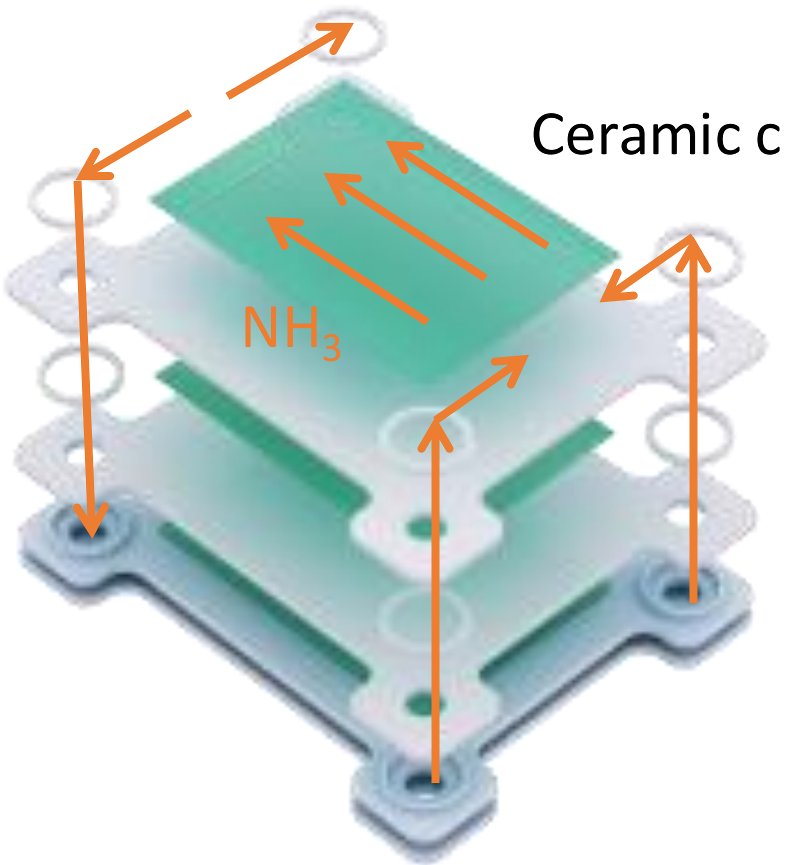
RTE NH_3 (SOC):	45-50 %	↑	~60 %
RTE H_2 current tech	25-30 %		

«Heat storage» in NH_3 molecule

What are the challenges?



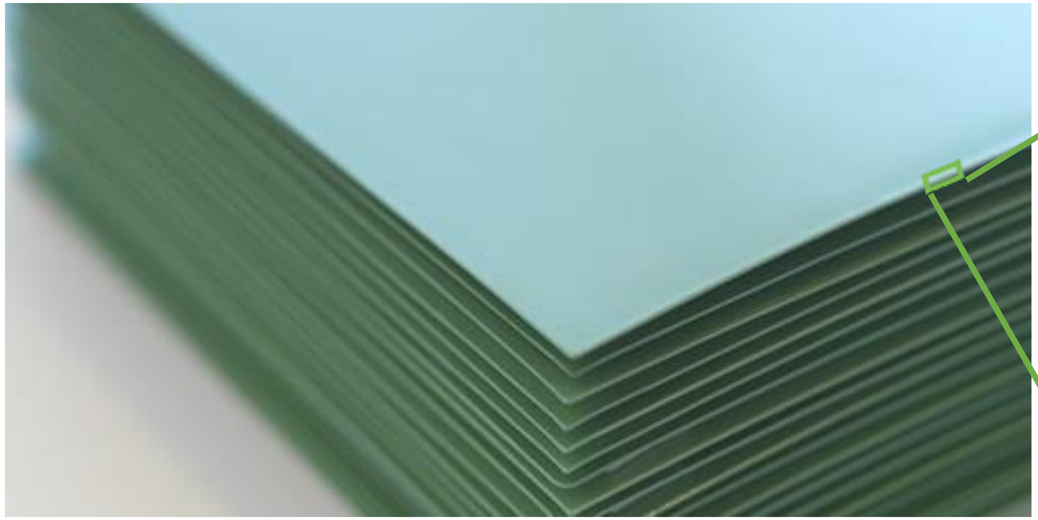
The solid oxide cells and stacks

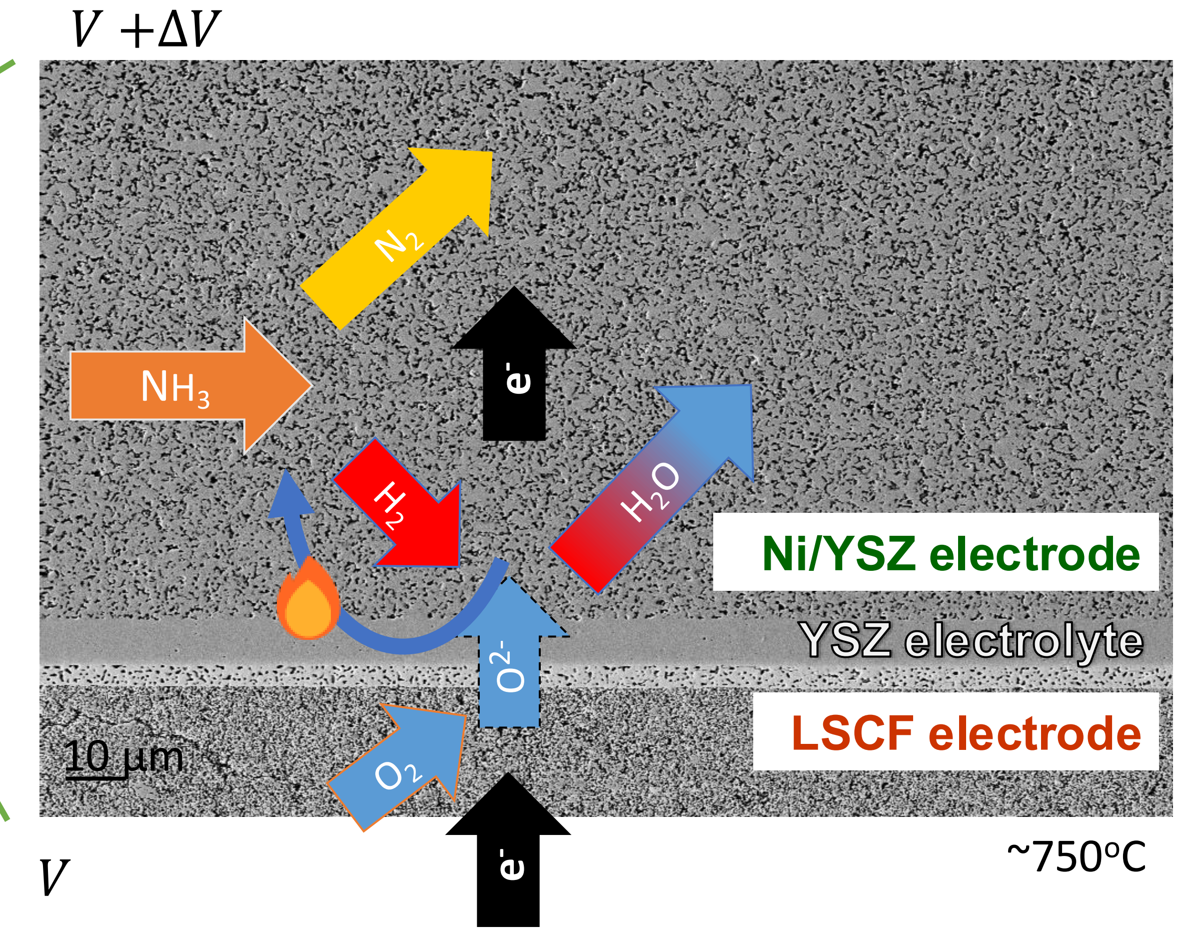


Ceramic cell

Metallic “interconnect”

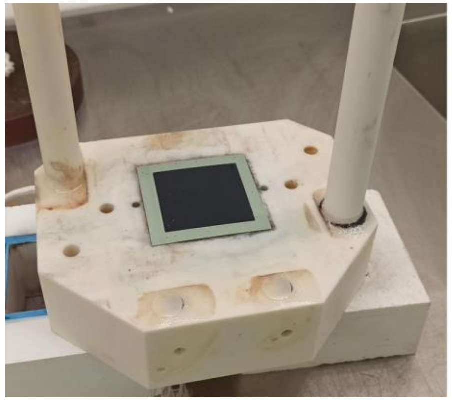
Ammonia in the Solid oxide fuel cells



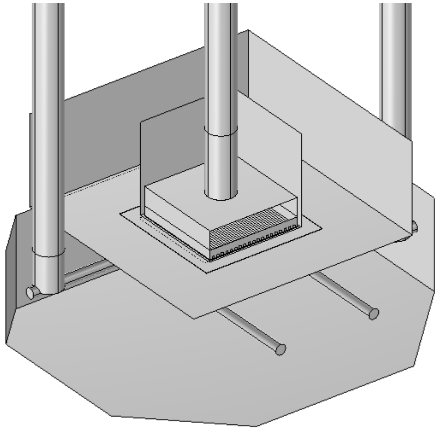


Testing and modelling of cells with NH_3

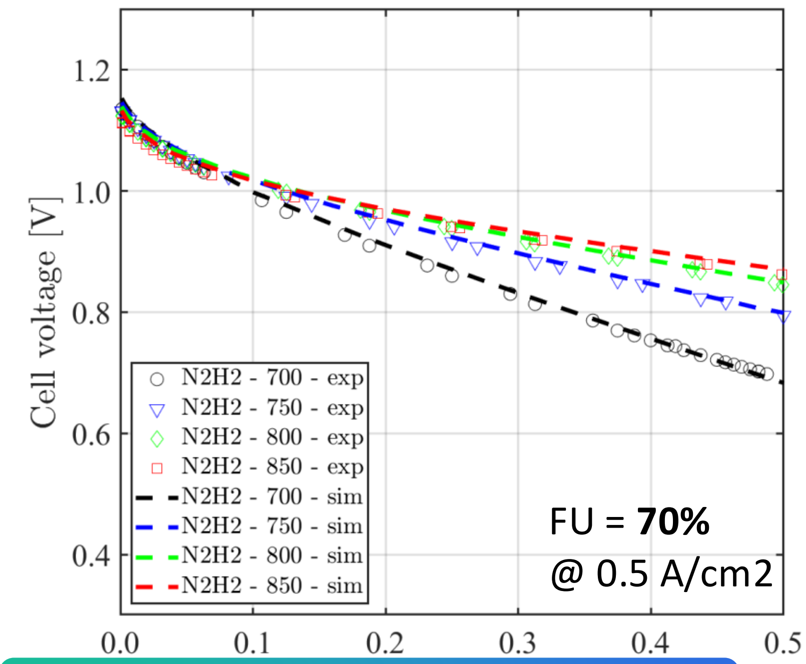
Testing



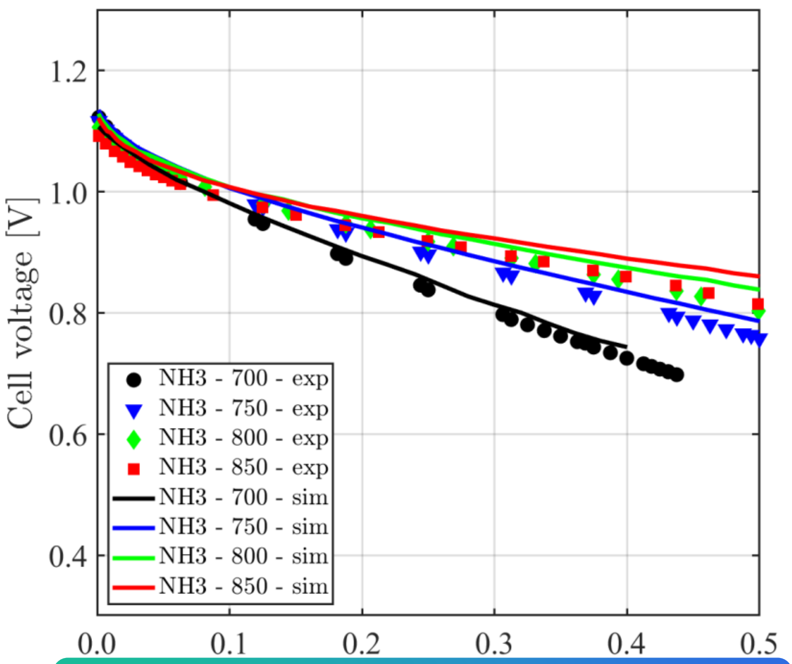
Modelling



(a) pre-cracked ammonia



(b) direct ammonia



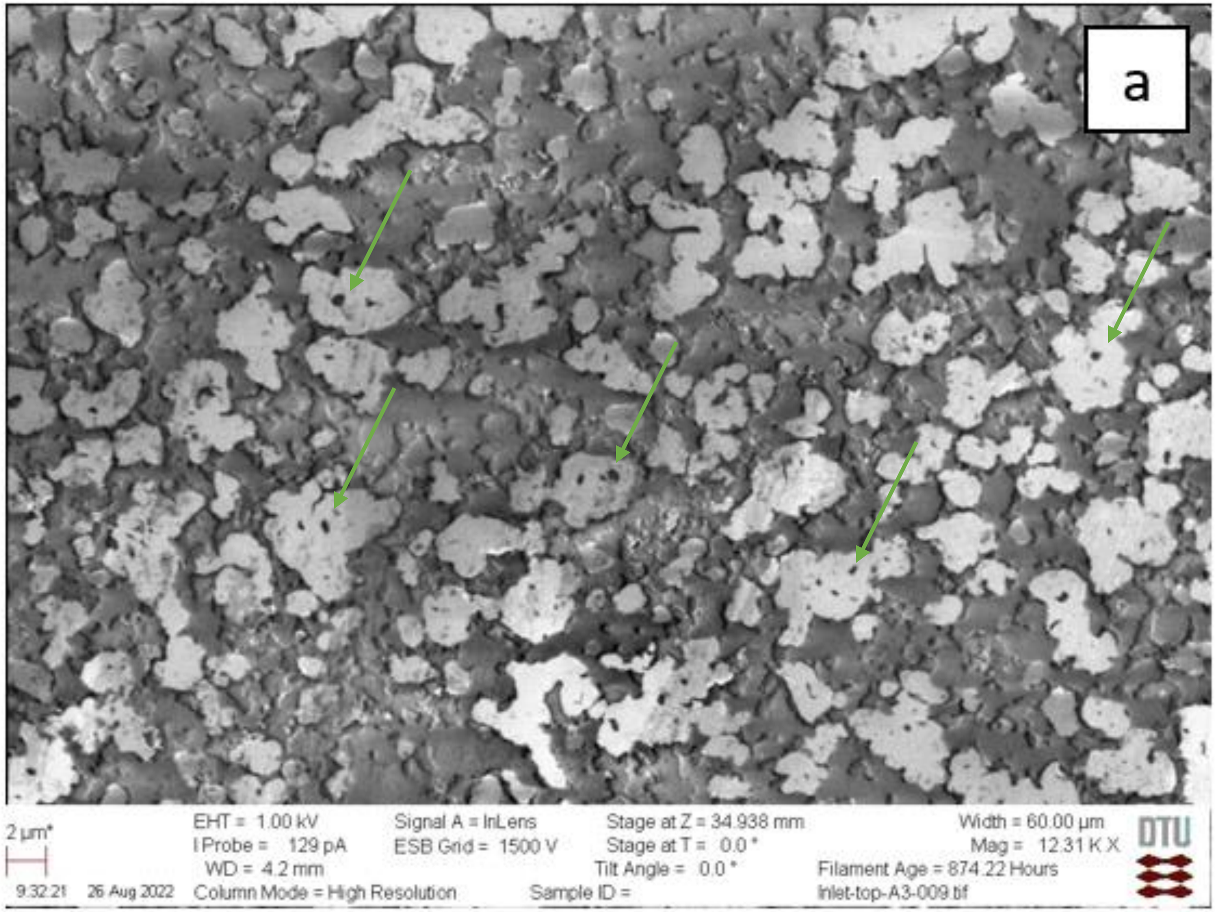
Current stack technologies – max 70-80 % fuel utilization

Solid understanding of combined cracking and electro-chemical reactions

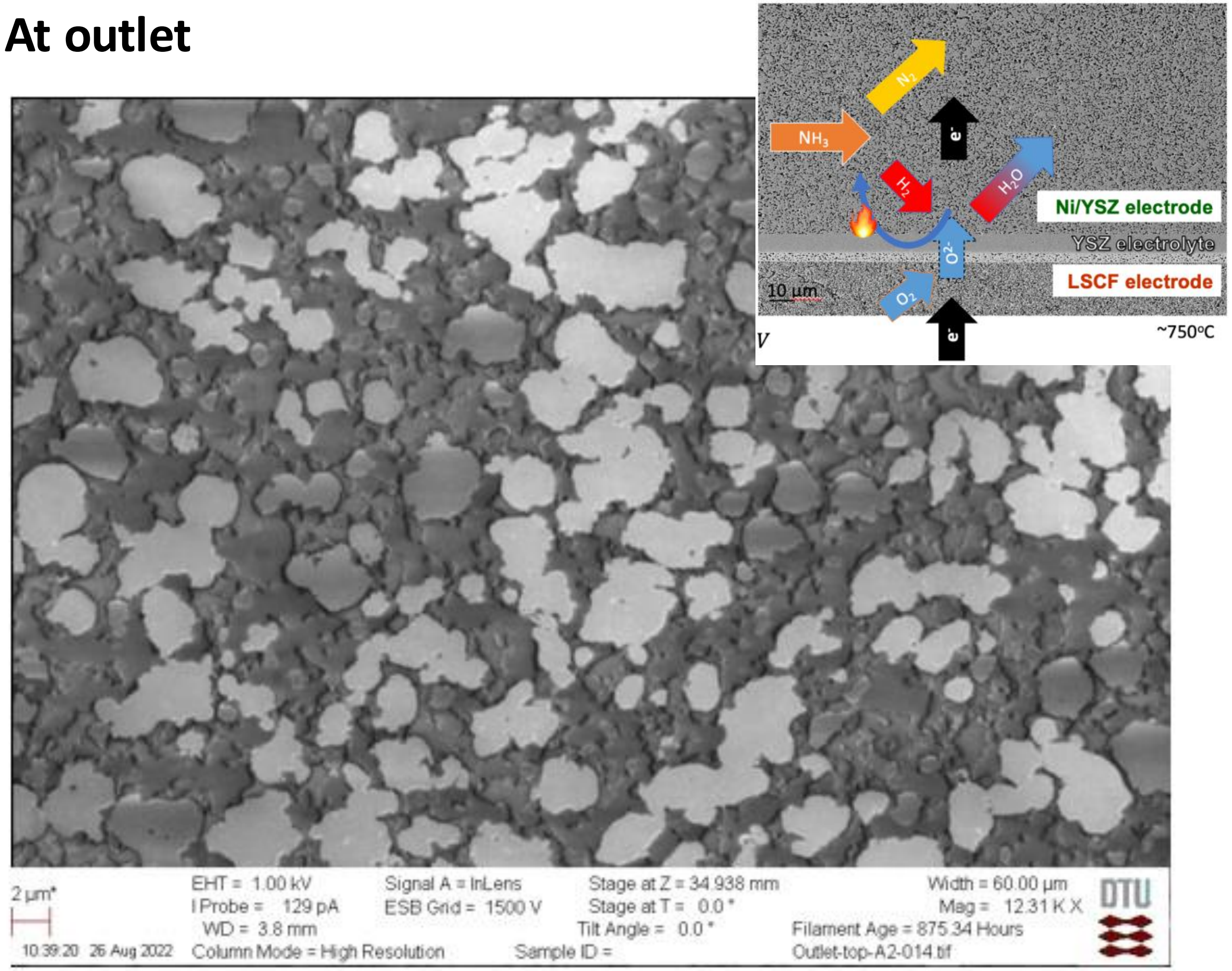
Nemati, A., Rizvandi, O. B., Mondi, F., & Frandsen, H. L. (2024). *Energy Conversion and Management*, *308*, 118396.

Nitriding – might be an issue@ 600-800 ºC

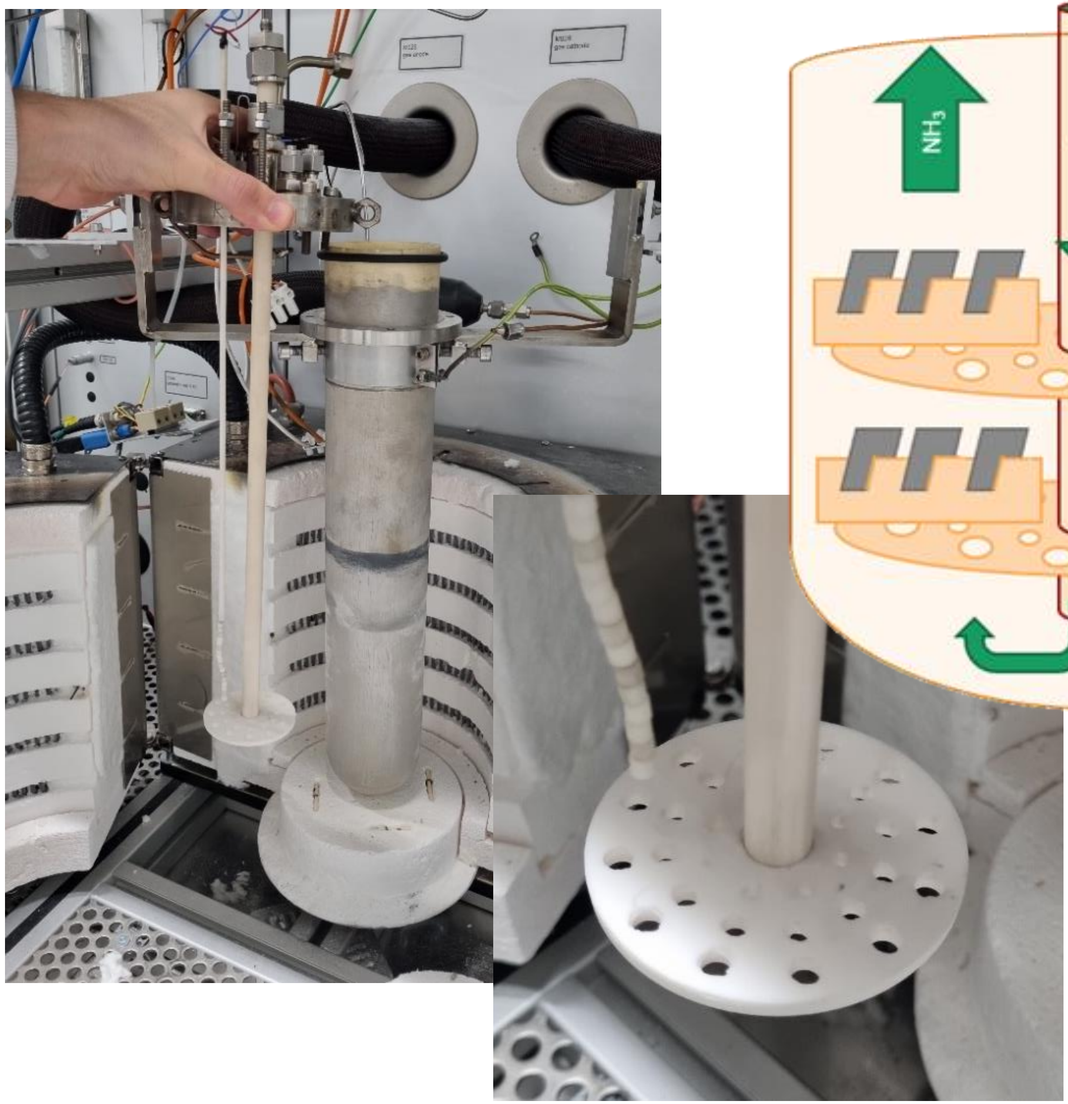
At inlet

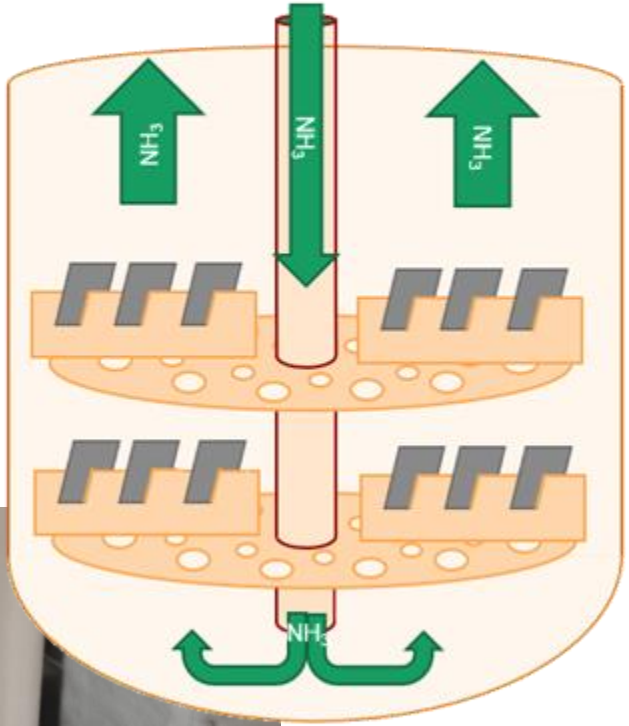


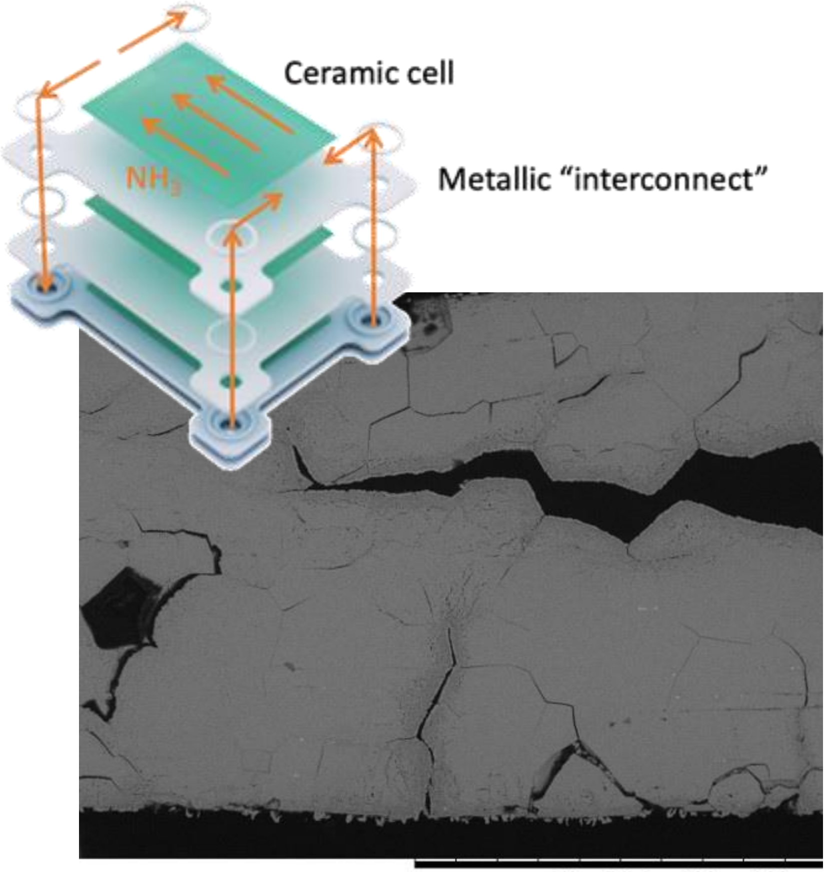
At outlet



Nitriding of interconnect







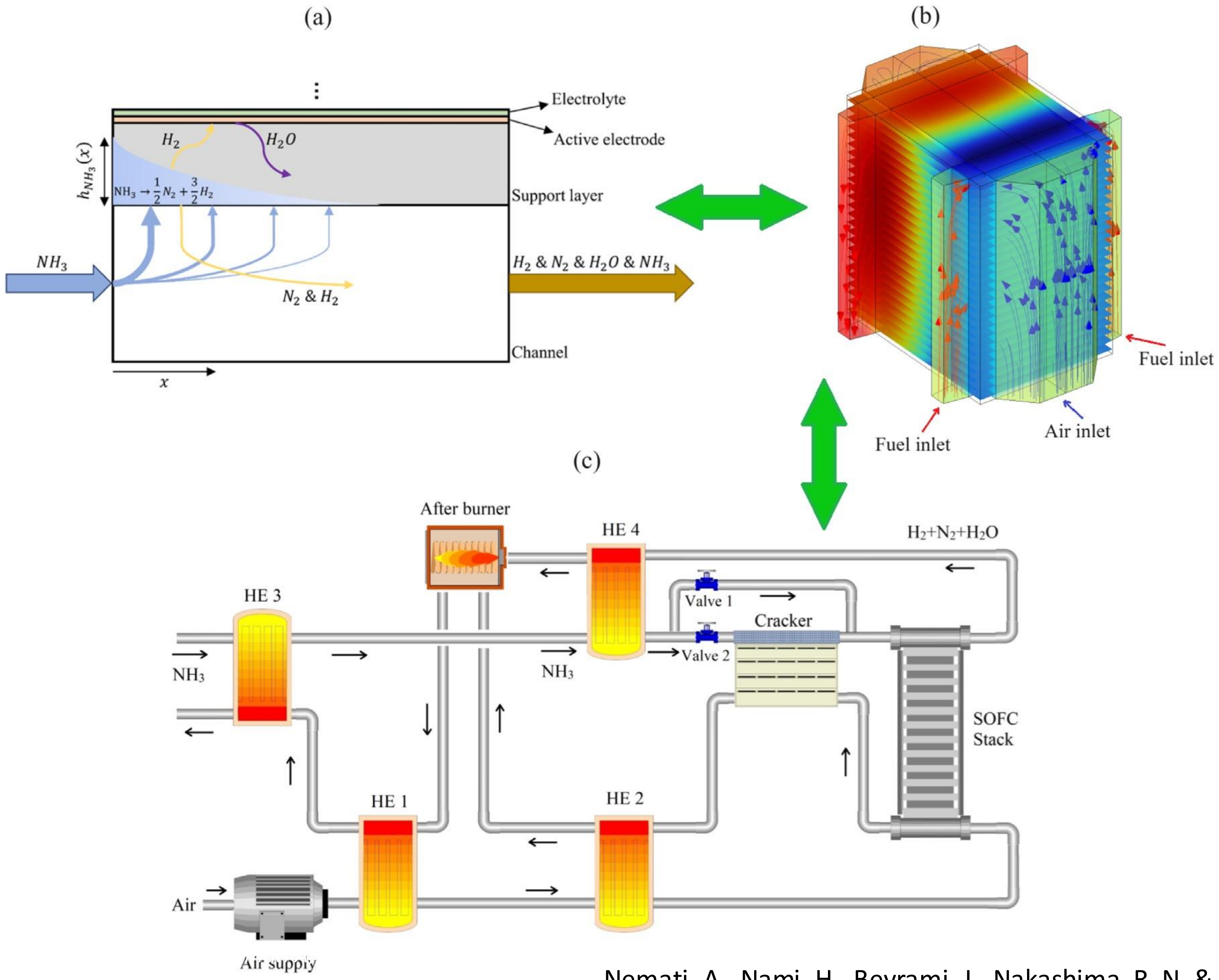
Crofer 22 H – 650C –
with ammonia

Nitriding of typical steels worse – even when using typical coatings

Unpublished work, A. B. Jacobsen, P. V. Hendriksen, X. Sun, A. Nemati, H. L. Frandsen

Solutions

How to deal with the devil in the detail



Multi-scale simulations

Covering material to system level

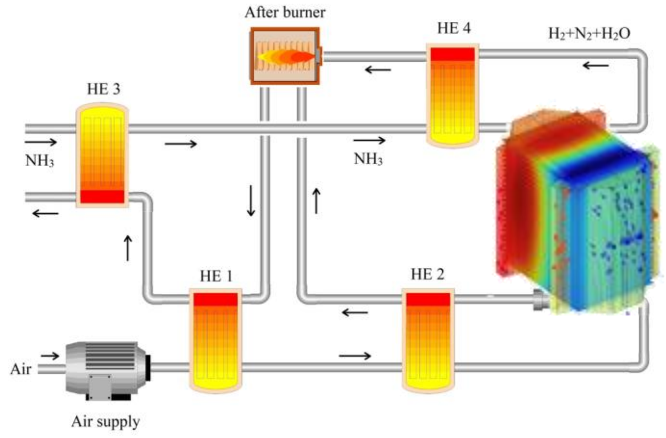
Validated with:

- Materials testing
- Cell measurments
- Stack measurements

Nemati, A., Nami, H., Beyrami, J., Nakashima, R. N. & Frandsen, H. L., 2025, In: Fuel. 392, 14 p., 134837.

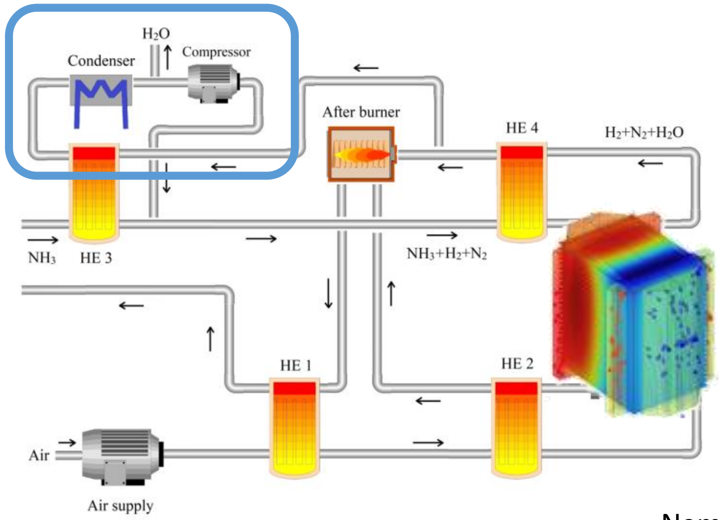
Conceptual system designs

Base configuration



~ 53 %

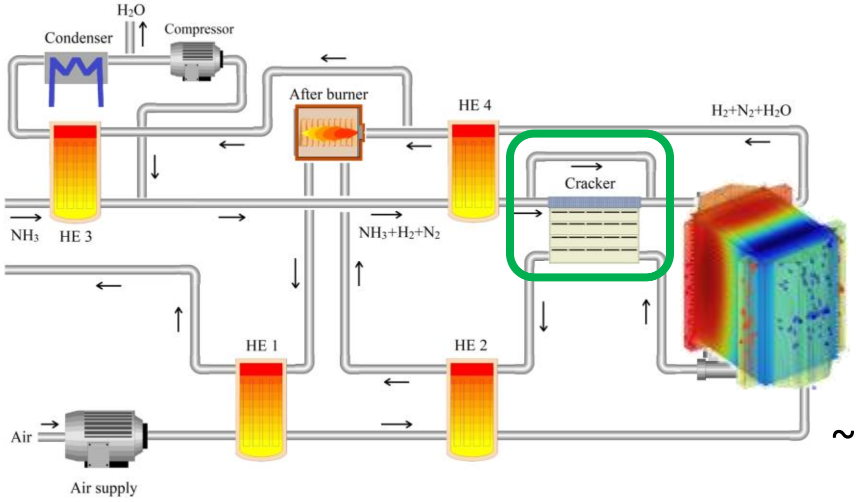
Recirculation



~ 74 %

External cracker

Additional air flow

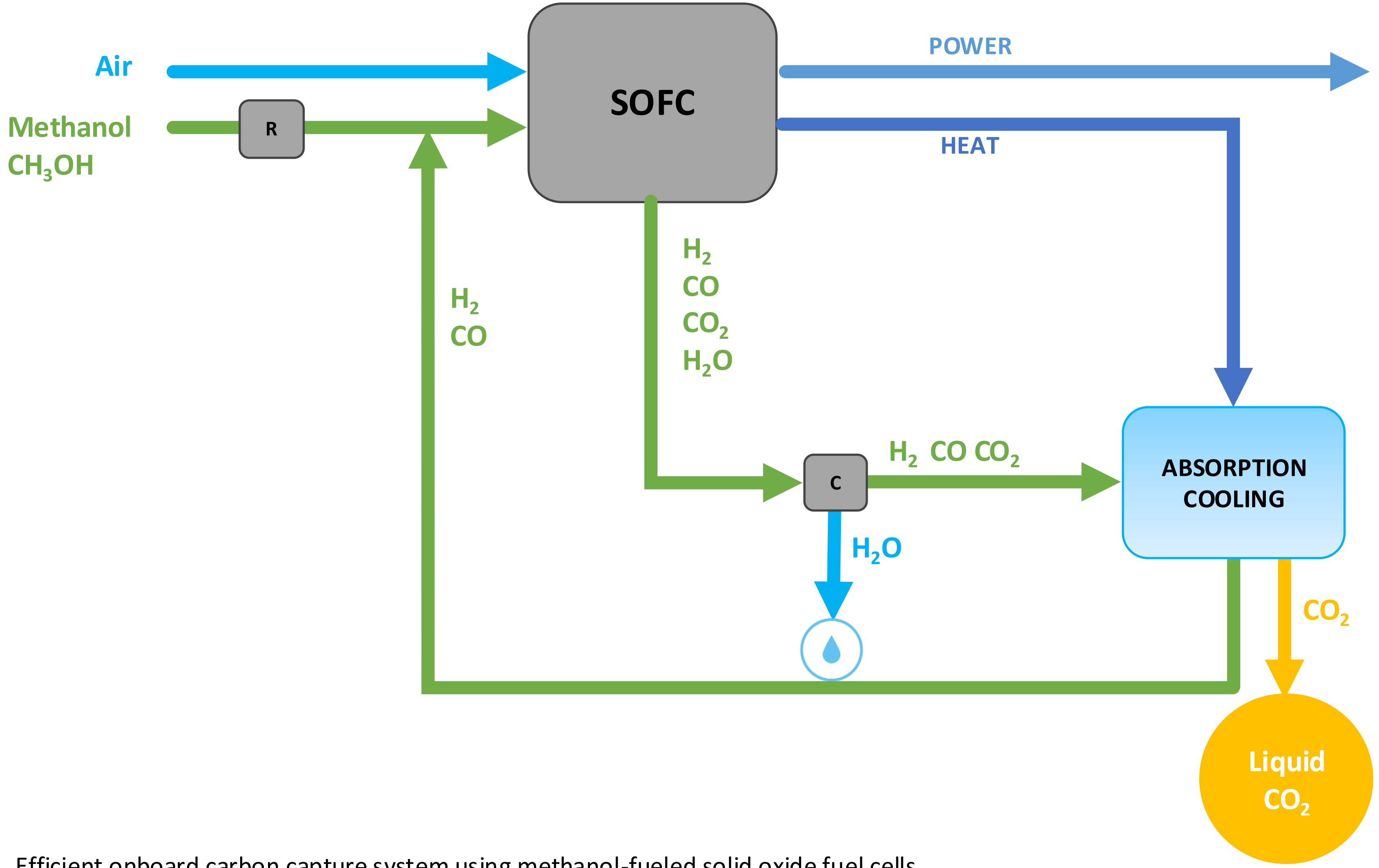


~ 72 %

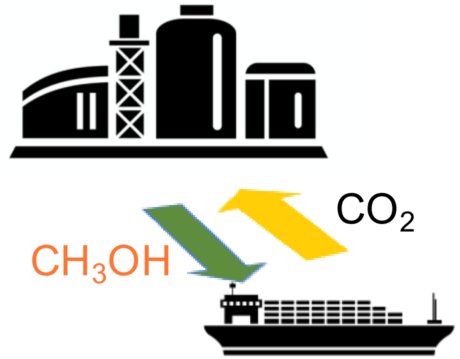
Nemati, A., Nami, H., Beyrami, J., Nakashima, R. N. & Frandsen, H. L., 2025, In: Fuel. 392, 14 p., 134837.

Alternative solutions

A new methanol fuel cell concept



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

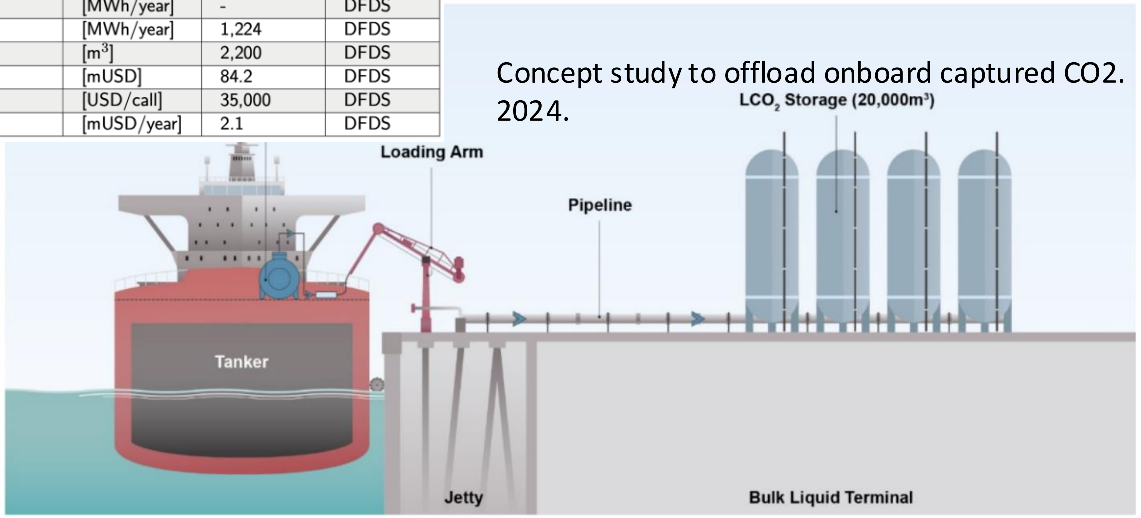


Efficient onboard carbon capture system using methanol-fueled solid oxide fuel cells
Johnsen, V. G., Bornemann, F. B., Nemati, A., Linderoth, S. & Frandsen, H. L., 2024, In: International Journal of

Techno-economic comparison

The study

Measure	Unit	VLA-IMM	Source
Lifetime	[year]	35	DFDS
Sailing days	[days/year]	365	DFDS
Active hours	[h/year]	4,745	Estimated
Hours at port	[h/year]	4,015	Estimated
Avg. speed	[nm/h]	20.0	DFDS
Avg. distance	[nm]	260.0	Estimated
Avg. duration	[h]	13.0	DFDS
Avg. duration at port	[h]	11.0	Estimated
Main power system (MP) power	[MW]	28.3	DFDS
Auxiliary power system (AP) power	[MW]	4.0	DFDS
Avg. energy consumption, MP	[MWh/year]	107,427	Estimated
Avg. energy consumption, AP sea	[MWh/year]	-	Estimated
Avg. energy consumption, AP port	[MWh/year]	3,975	Estimated
Boiler energy cons. at sea	[MWh/year]	-	DFDS
Boiler energy cons. at port	[MWh/year]	1,224	DFDS
Tank size	[m^3]	2,200	DFDS
Base CAPEX	[mUSD]	84.2	DFDS
Port call costs	[USD/call]	35,000	DFDS
Ancillary costs	[mUSD/year]	2.1	DFDS

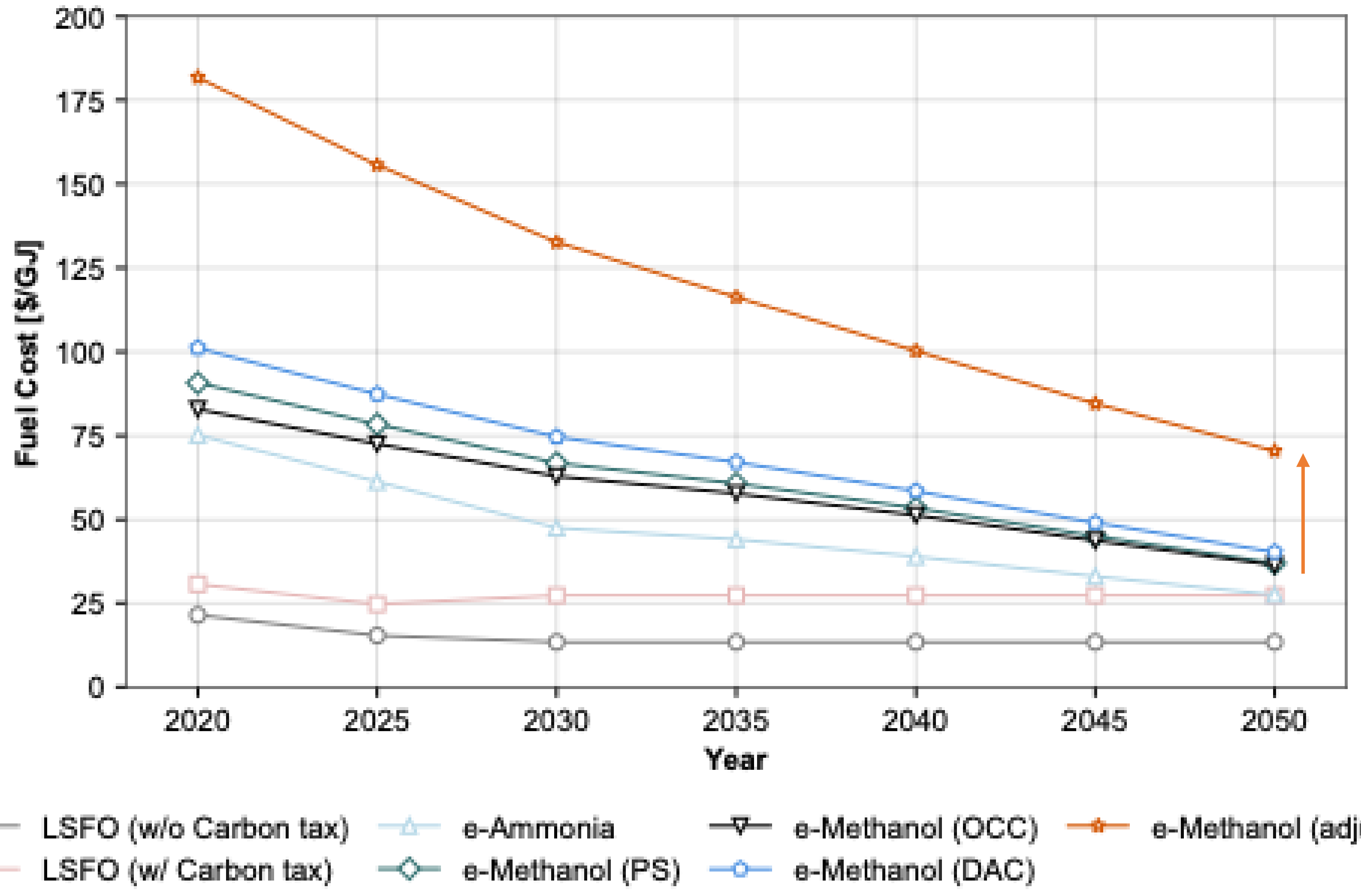


Concept study to offload onboard captured CO2. 2024.

Total cost of owership: MMMCZCS NavigaTE
Fuel cost: MMMCZCS Fuel Cost Calculator
Operational data: DFDS
CO2 infrastructure data: Rambøll
CO2 offloading cost data: GCMD, LR and Arup

Techno-economic analysis of methanol fuelled solid oxide fuel cell systems with energy efficient carbon (in preparation) capture in maritime transportation, Y K Pochareddy, K R Sørensen, A Nemati,∗, L H Costa Sousa, A Andreasen, G Agustsson, H Silva, S Linderoth, H L Frandsen

Cost of Fuel



Ammonia is the cheapest »green fuel»

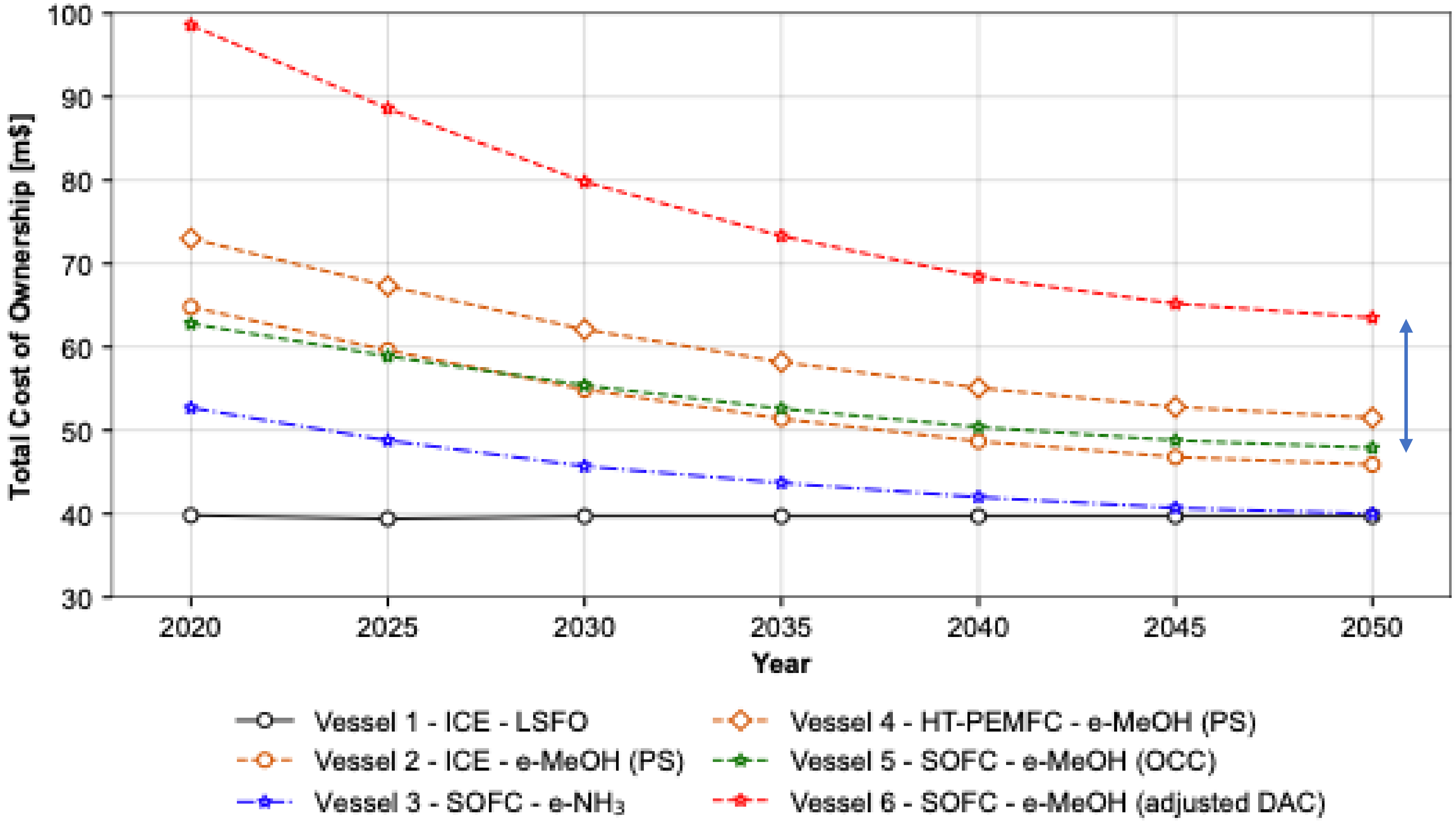
Methanol OCC second
- No scarcity of biomass

If biomass scarce, cost approach methanol DAC

Fossil fuels cheapest
- Even with carbon tax

Techno-economic analysis of methanol fuelled solid oxide fuel cell systems with energy efficient carbon (in preparation)
capture in maritime transportation, Y K Pochareddy, K R Sørensen, A Nemati,∗, L H Costa Sousa, A Andreasen, G Agustsson, H Silva, S Linderoth, H L Frandsen

Total cost of ownership

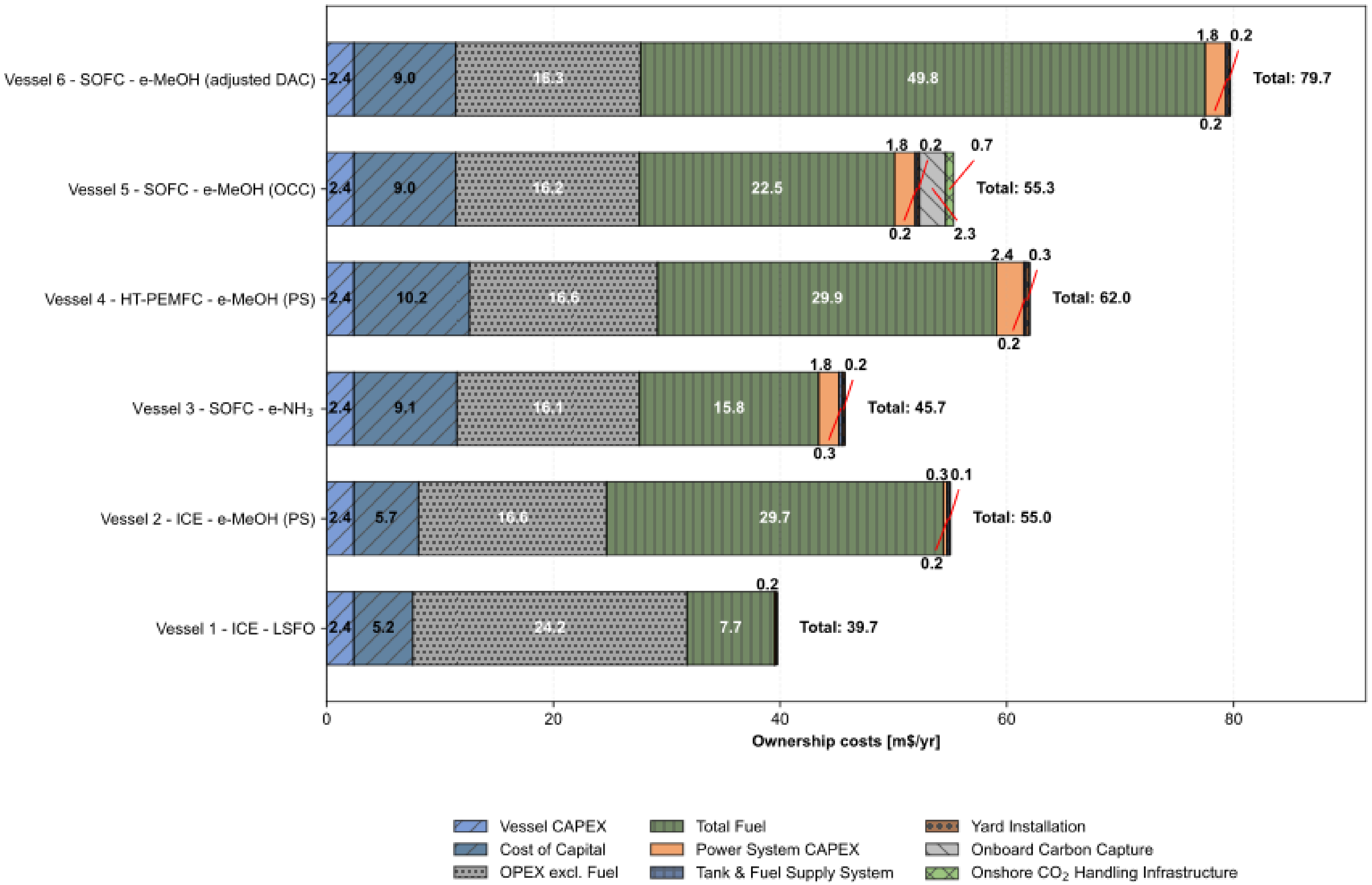


DAC based MeOH is easily outcompeted by OCC

TCO for SOFC-NH_3 is cheapest (no safety cost)

Techno-economic analysis of methanol fuelled solid oxide fuel cell systems with energy efficient carbon (in preparation) capture in maritime transportation, Y K Pochareddy, K R Sørensen, A Nemati,∗, L H Costa Sousa, A Andreasen, G Agustsson, H Silva, S Linderoth, H L Frandsen

TCO break-down, y2030



MeOH OCC CO_2 infrastructure is neglegible compared to DAC

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Conclusions

- SOFCs fed with NH3 can result in very high efficiencies (~72 %)
  - Current materials requires pre-cracking of ammonia
- Avoiding a cracker will gain ~2 % of efficiency (~74 %)
  - Material research needed (promising results)
- Alternative: on-board carbon capture (OCC) of CO2 from methanol
  - Reasonably high efficiencies (~68 %)
  - ~100 % fuel utilization
- Cost comparison
  - Ammonia is the cheapest fuel
  - Ammonia SOFC is the lowest TCO solution, long-term (no safety cost)
  - Methanol OCC provides the cheapest carbon based green solution

Clean Hydrogen Partnership

Co-funded by the European Union

The project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research, under Grant Agreement No 101101521

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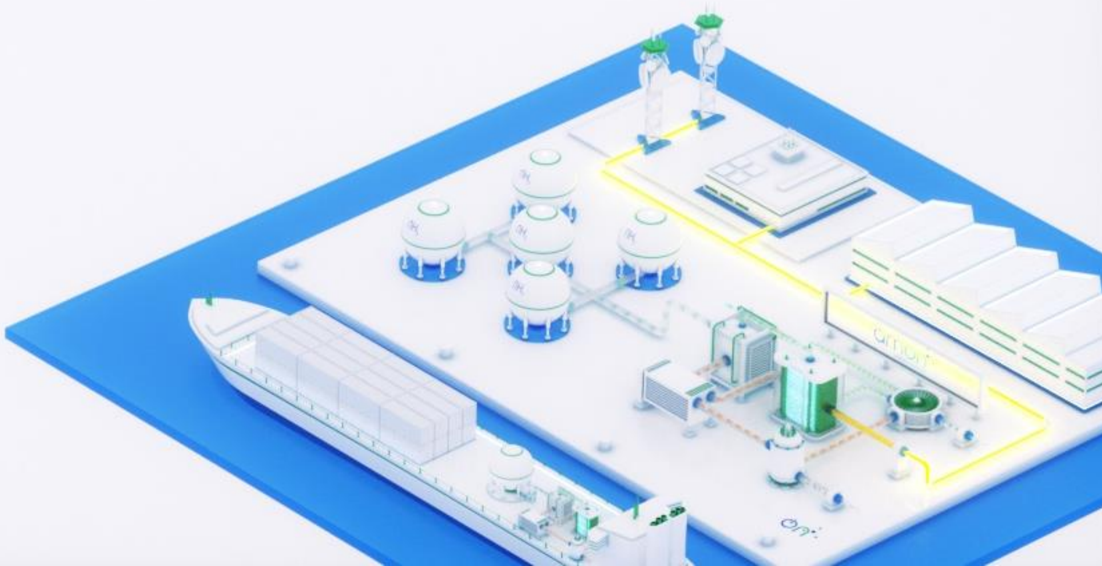

THANK YOU

more info www.amon.eu