NAUTILUS

Sustainable shipping with SOFCs

Experience from the NAUTILUS project and future outlook

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AMPS Workshop

May 30th 2025

This project has received funding from the European Union's Horizon 2020 research and innovation program under the grant agreement No 861647

Shipping is Hard-to-Abate Sector

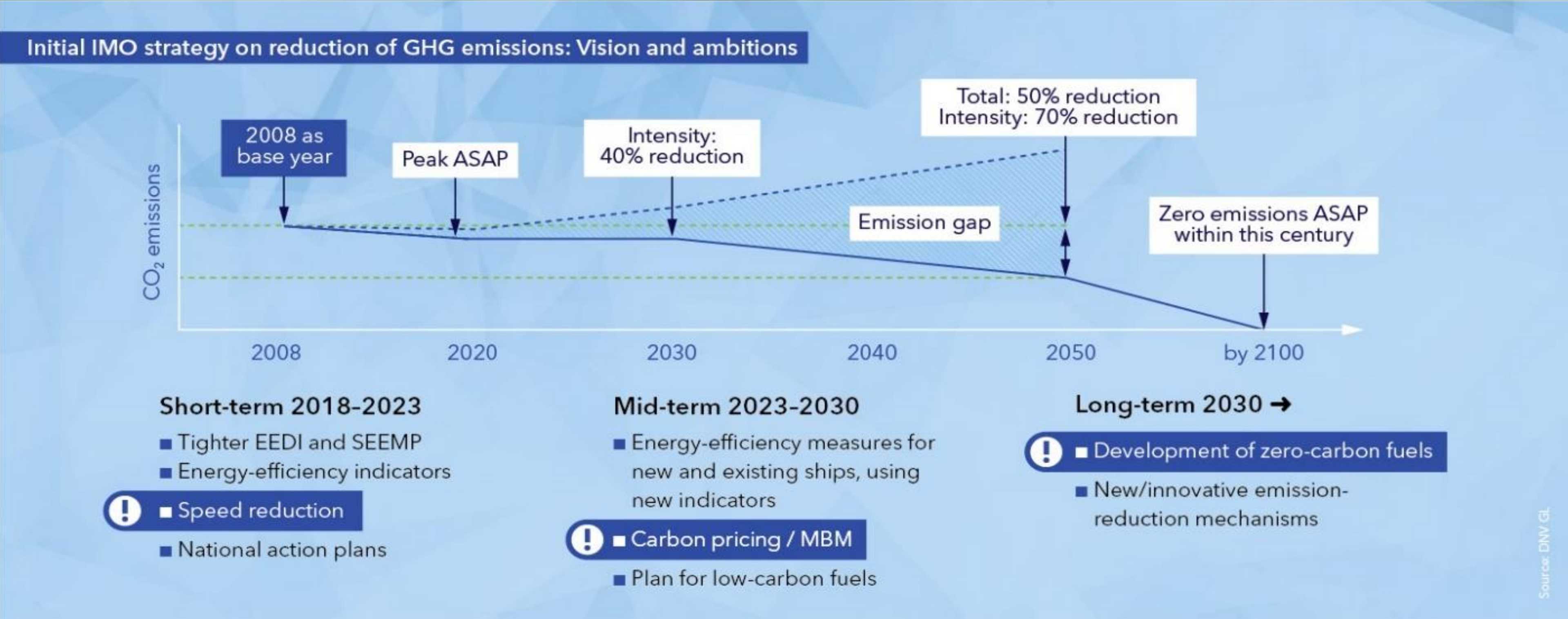
GHGs Globally:

- Shipping 0.93 billion tons (2.6%)

Other Pollutants in EU:

- SO_x 11%
- NO_x 16%
- PM2.5 7%

Shipping is Hard-to-Abate Sector



40% reduction of CO_2 by 2030 compare to 2008 pursuing 70% reduction by 2050

SOx, NOx and Black Carbon emissions as much as 80% and higher in Tier III Emission Control Areas (ECAs)

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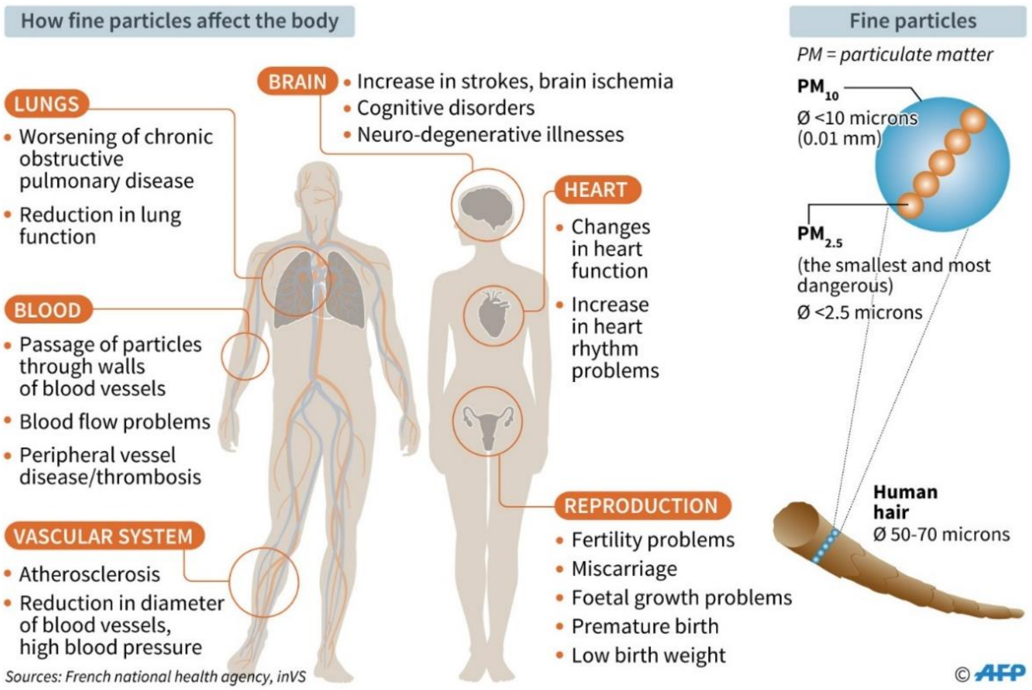
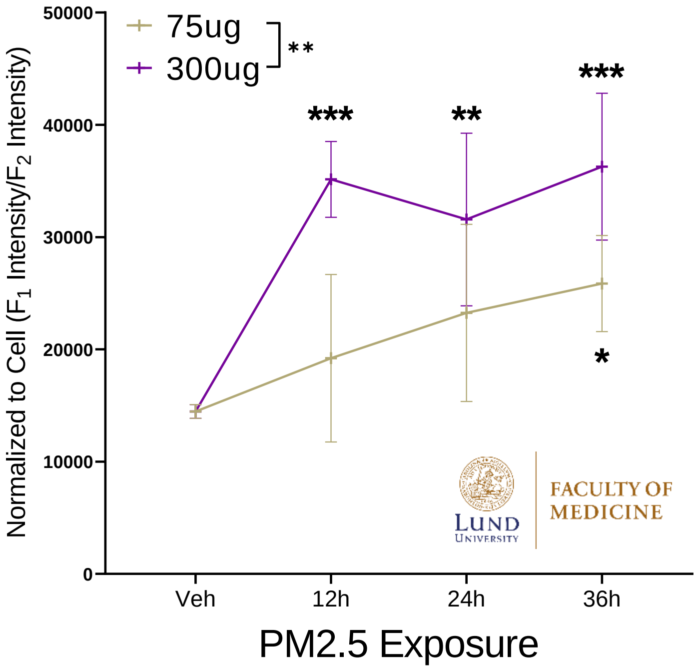
Beyond GHGs: Health Impact of Air Pollution





Higher PM2.5 dose and exposure time intensifies inflammation and toxicity in human tissue

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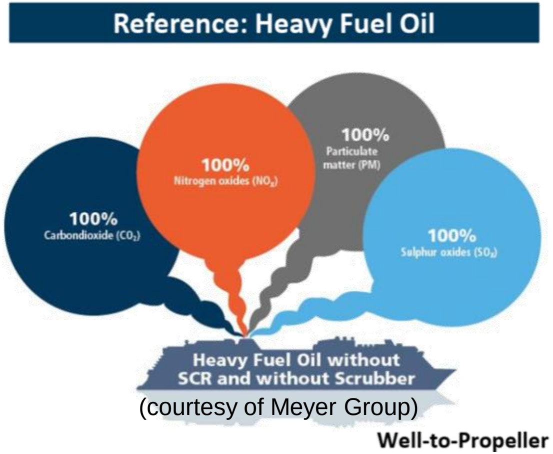
First phase of transition

2008 reference

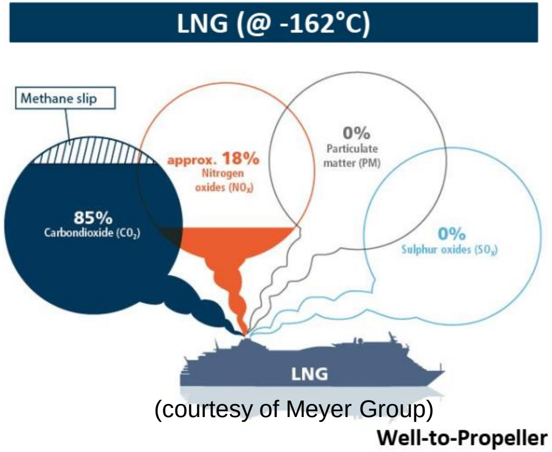
- Fuel: Heavy Fuel Oil (HFO)
- Engine: HFO generators
- Exhaust treatment: None

State of the Art

- Fuel: LNG
- Engine: Gas motors
- Exhaust treatment: SCR or not needed



(courtesy of Meyer Group)



(courtesy of Meyer Group)

Source: Ansar, A. (2020), "*Electrochemical processes and energy systems towards step-wise emission reduction of the marine sector*", LEC Sustainable Shipping Technologies Forum, 27-28.04.2021

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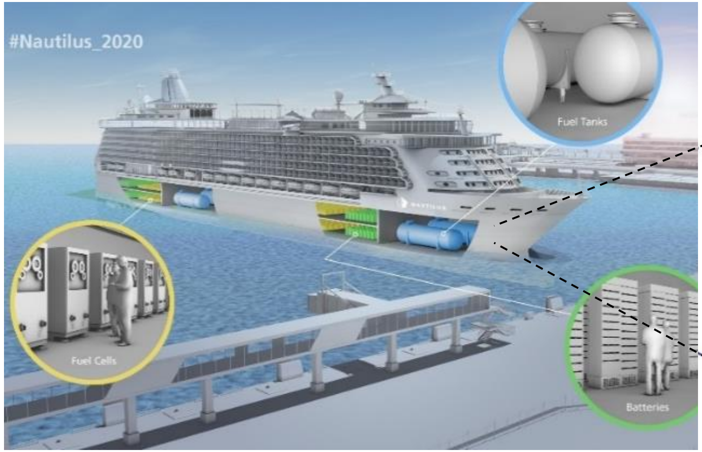
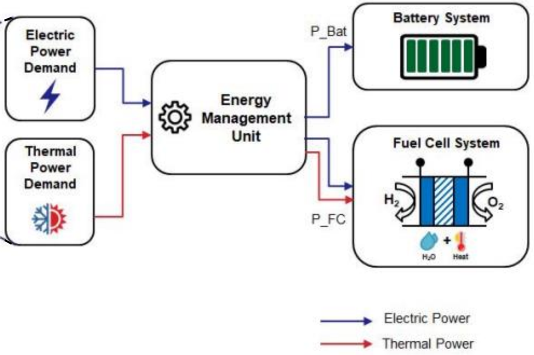
NAUTILUS concept

- Nautilus genset SOFC/battery
  - Gradually replace ICE
  - Modular genset, high combined efficiency
  - Less or no LNG slip
  - Increased redundancy factor
- Genset to cover a transient power demand





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Project pillars

Proof of concept	Functional demonstrator	Technology impact
Sizing, optimisation and *system engineering* of SOFC system. and ship integration.	Design and operation of 80kW *containerized demonstrator*	*Genset analysis* of future fuels
Steady-state and dynamic *testing* of 30kW large stack module (LSM) with battery.	*Inclination testing* to test ability to withstand ship motions	*Techno-economic analysis* including future fuels
Digital demonstrator for energy simulation on cruise ships with operation of SOFCs, batteries, and diesel generators.	*Emission measurements* of greenhouse gases and pollutants	*Life cycle analysis* including future fuels

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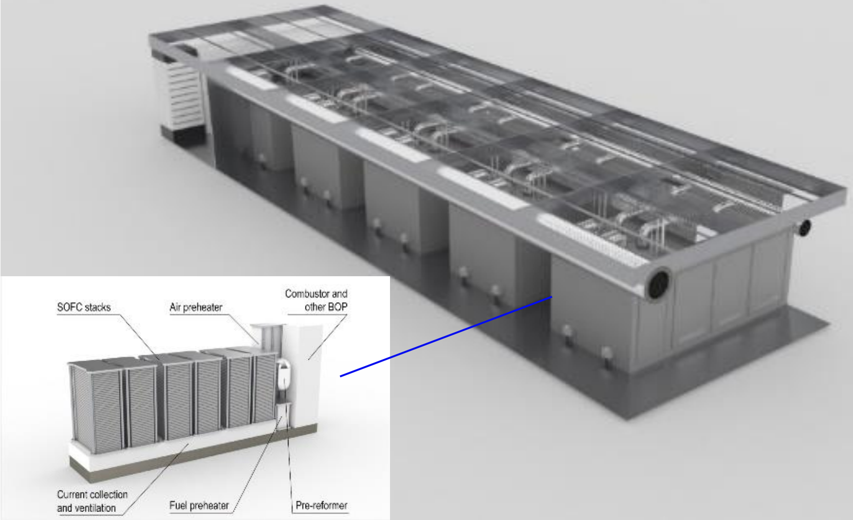
1 MW building block of NAUTILUS Genset

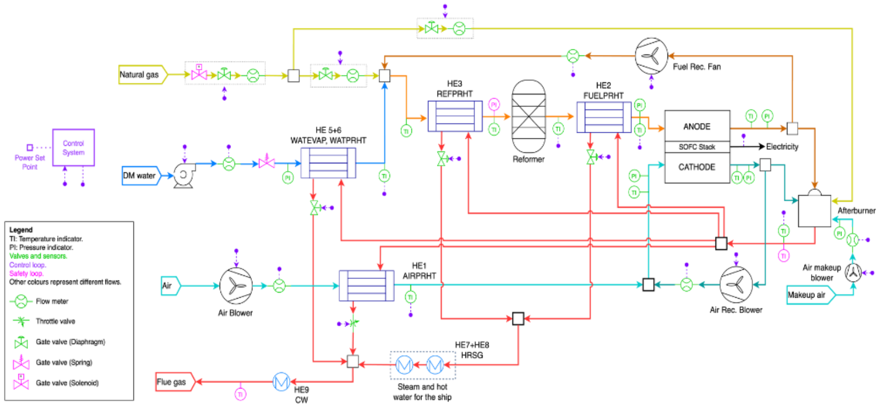


Integrated System Design

- SOFC unit for MW integration

- El. efficiency **60.2 %-LHV**
- Net comb. eff. **76.8 %-LHV** (ship hot water)

➔ cathode, anode off-gas recirculation blowers
➔ HEX network optimization
➔ Beginning of life, end of life approach (constant power)



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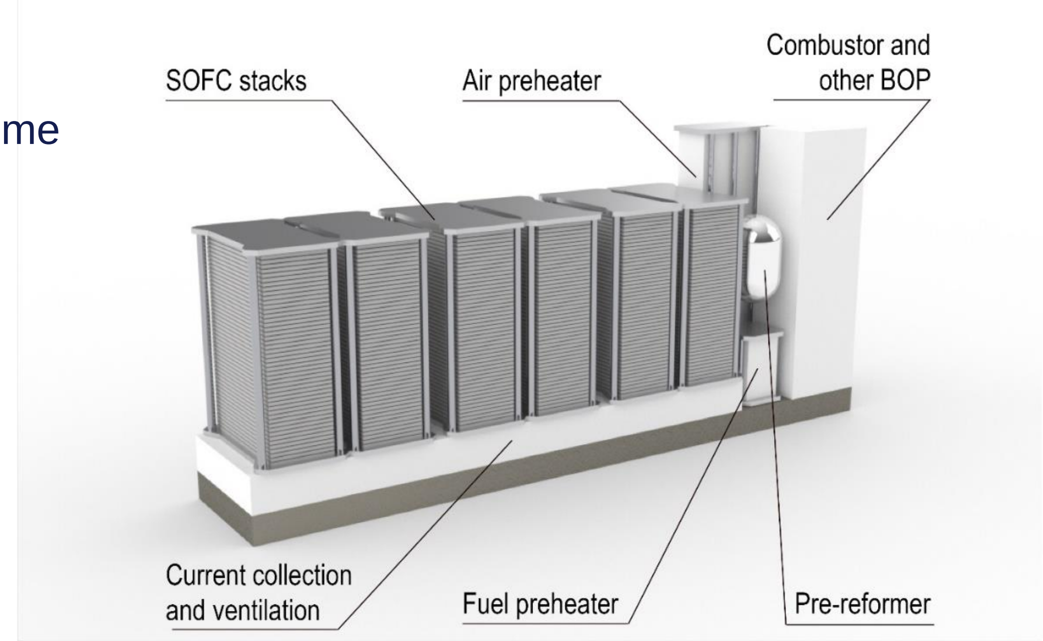
Concept design 110 kW unit

Operational concept

- Constant power production over lifetime
  → degradation in efficiency
- Modulation per unit
- Replaceable stack
  - 0.75x0.45x1m and 370 kg
- Nitrogen purging system for start-up and shut down



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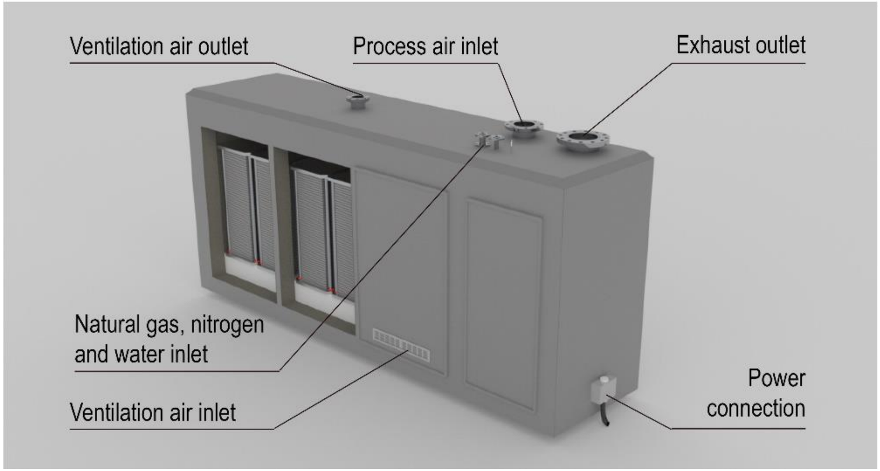
Concept design 110 kW unit

Components included in unit	Components excluded in unit
6 SOFC Stacks	LNG evaporator
Compression system	Desulphuriser
Current collection	Air blower
Insulation	Air filter
Fuel preheater	Waste heat recovery
Pre-reformer	(DC/DC booster)
Air preheater	AC/DC inverter
AOG recirculation loop	PLC
COG recirculation loop	Energy management system
Start-up evaporator/steam boiler	



Unit characteristics	Value	Unit
Length of unit	4	m
Width of unit	1	m
Height of unit	1.8	m
Weight of the unit	6.8	ton

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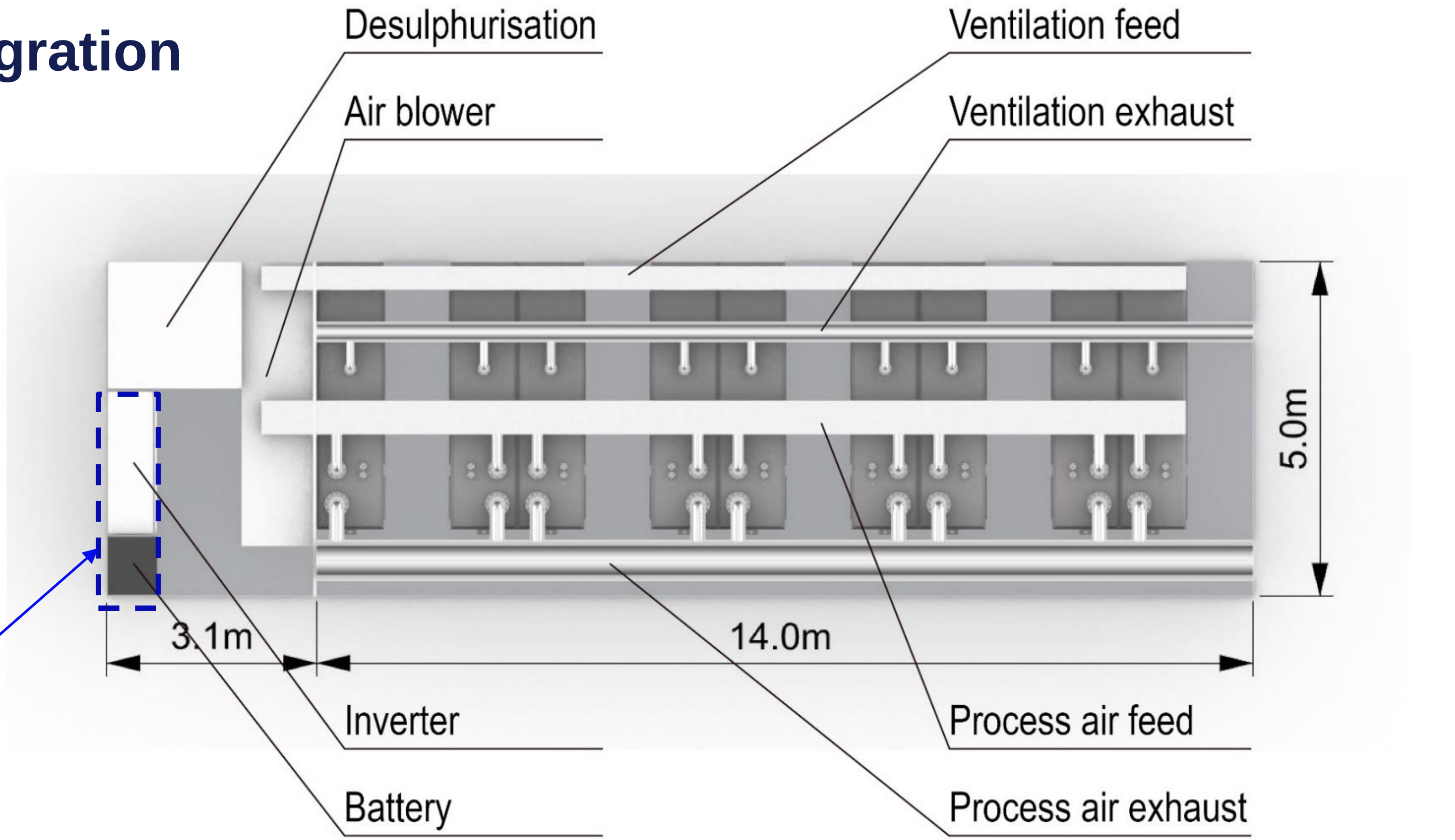
Room integration



separate battery room in ship integration

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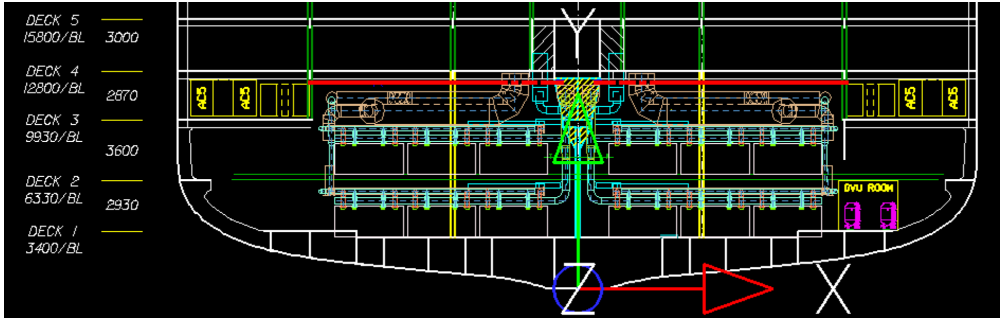
Ship integration



Space reservation for auxiliaries and supply systems

Ratio of fuel cell power installed to battery packs dimensioned

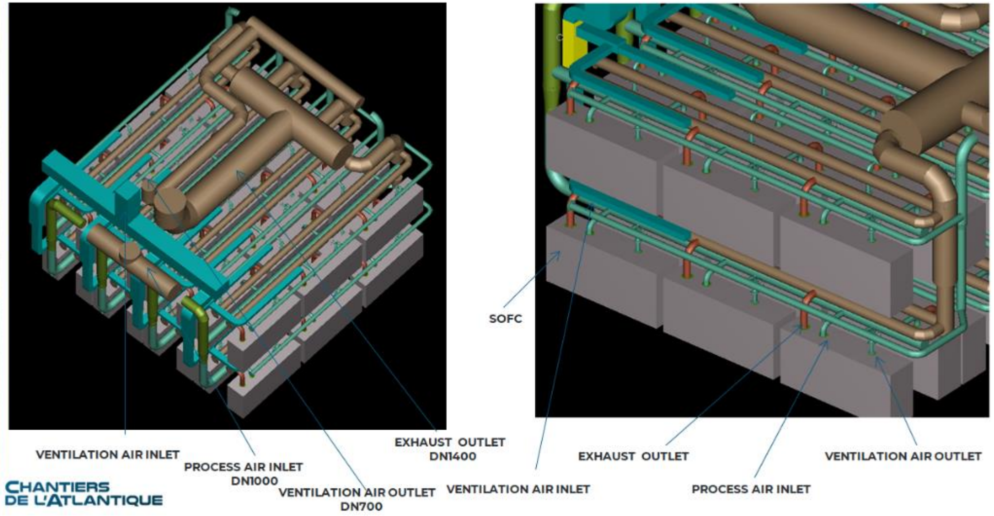
Safety aspects screening

Interfaces between SOFC and ship specified

Subsystem dimensioning

Sizing of the different auxiliaries : Air fans, EL room equipment, GVU units, desulfurization units

Redundancy via modularity required to ensure no significant loss of electrical generating capacity on ship propulsion / steering and safe return to port



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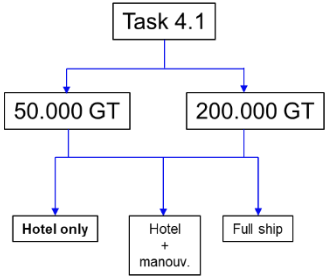
Design scenarios and maintenance key considerations

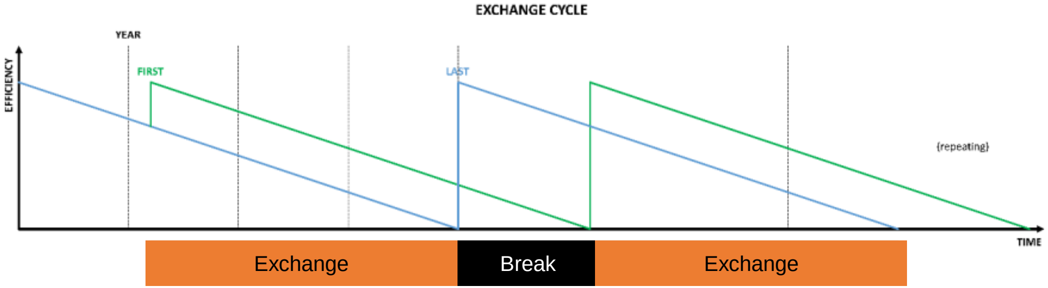
- Any improvement in the field of compacity (power density) will have a profound effect on multi-MW integration, especially for full-SOFC
  - Nautilus SOFC room 1,3-1,4 kW/m³ (incl. maintenance paths, piping,...)
  - Nautilus battery units 4,1-7,7kWh/m³ (optimized, well known technology)
- Stack exchange strategy required

Ship design scenarios



Design	1	2	3
Hotel only	FC+Battery	FC+Battery	FC+Battery
Manoeuvring	ICE	FC+Battery	FC+Battery
Propulsion	ICE	ICE	FC+Battery

increasing total installed power



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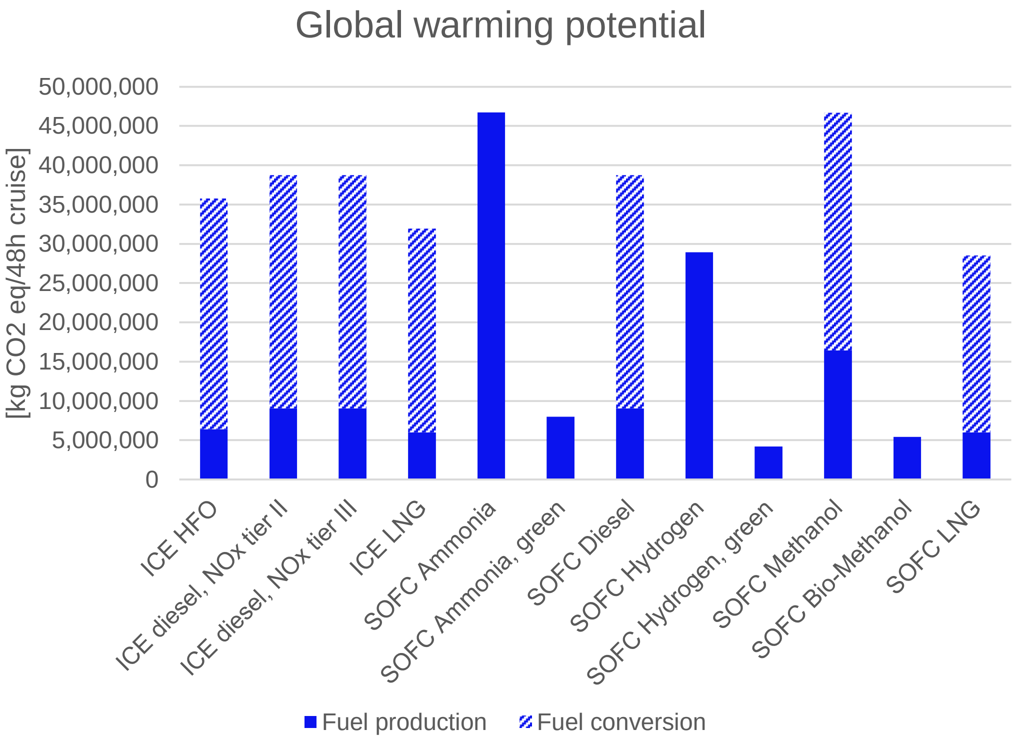
30% CO_2 reduction in Operation

Further increase in electrical efficiency and blending with synthetic fuel to get to 40% CO_2 emissions reduction



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Inclination test

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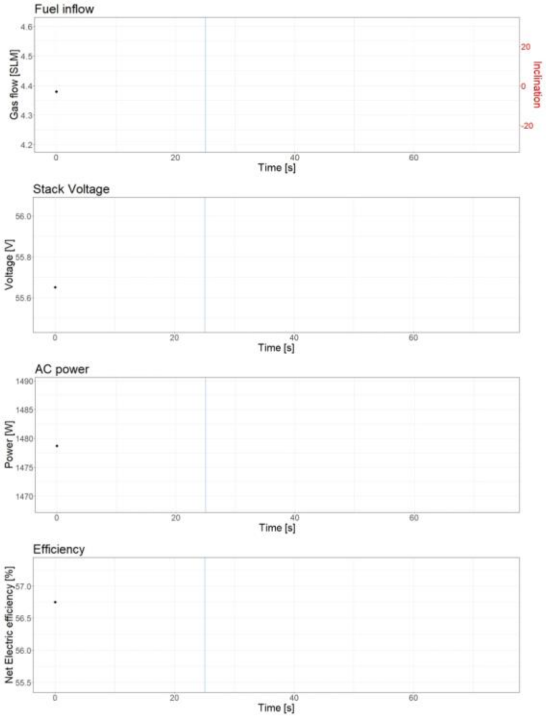
Van Veldhuizen et al., J. Power Sources 585 (2023) 233634



Deviations caused by proportional solenoid valve

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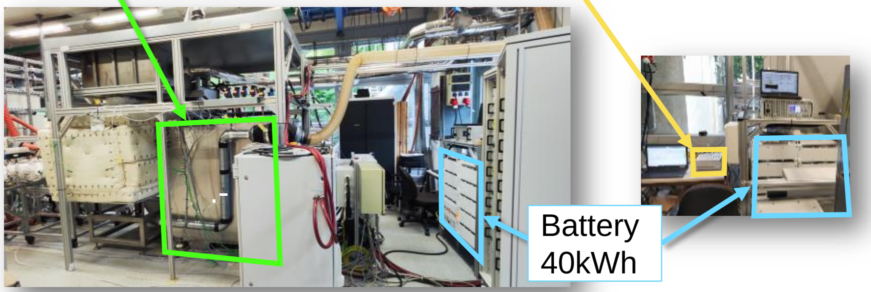
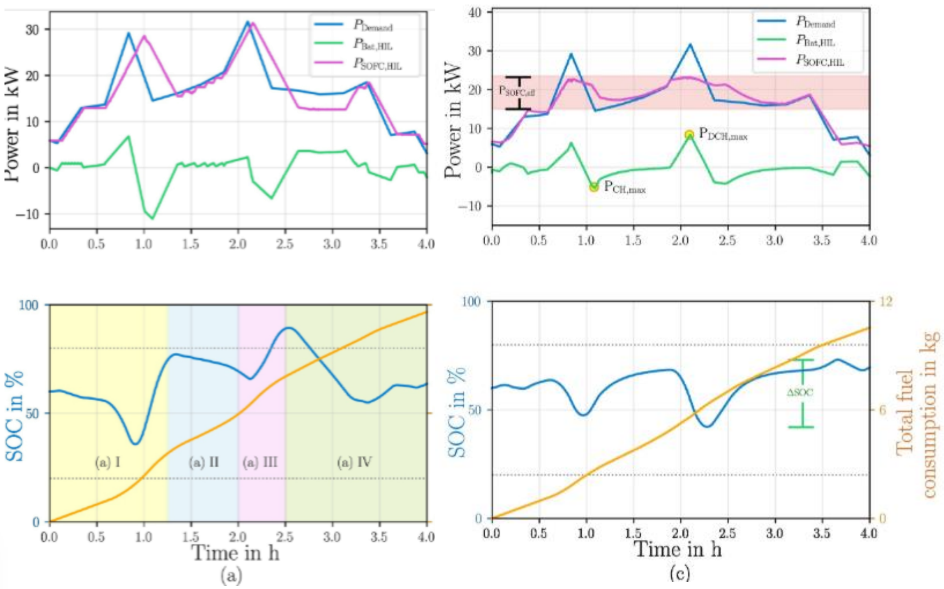
Proof of Concept Test

- 2400 h hot, 260 h under load
- SOFC module characterization
- Different fuel compositions
- Multi-control strategies
  - Additional fuel saving w. genset control





Ünlübayir et al., Applied Energy 376 (2024) 124183

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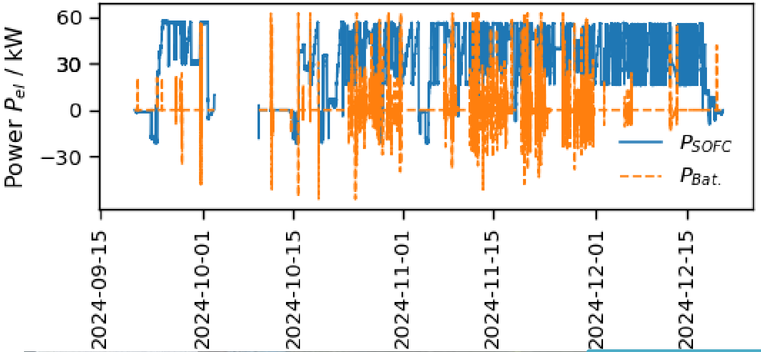
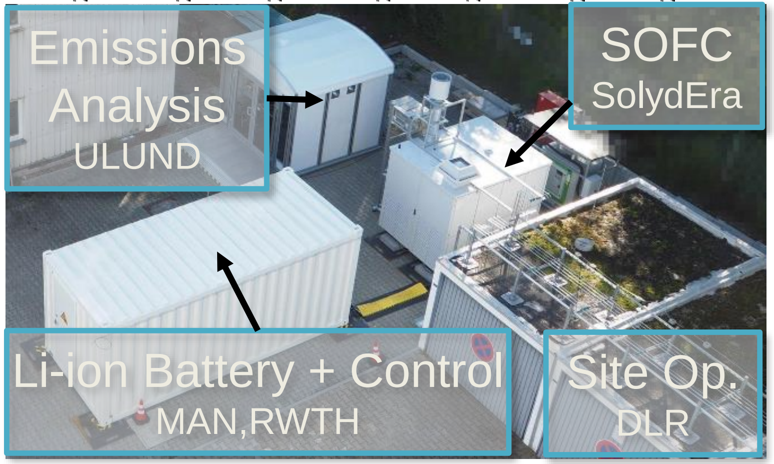
Functional demonstrator 2024

- Commissioning 29.10.2024

- 80 kW is demonstrated
- 62.6 MWh delivered in 2024

- Efficiency curves characterized
- Static, dynamic operation
  - 0.5%/min, 2%/min, 4%/min
- Real Profile tests, EMS strategies
- Edge cases
  - 240 cycles at 4%/min
  - E-Stops
  - Load drop





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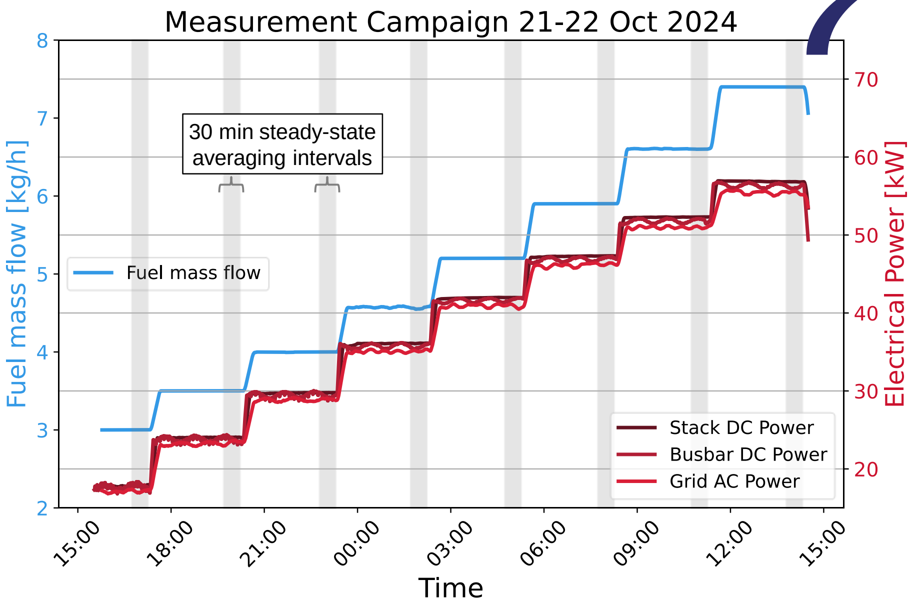
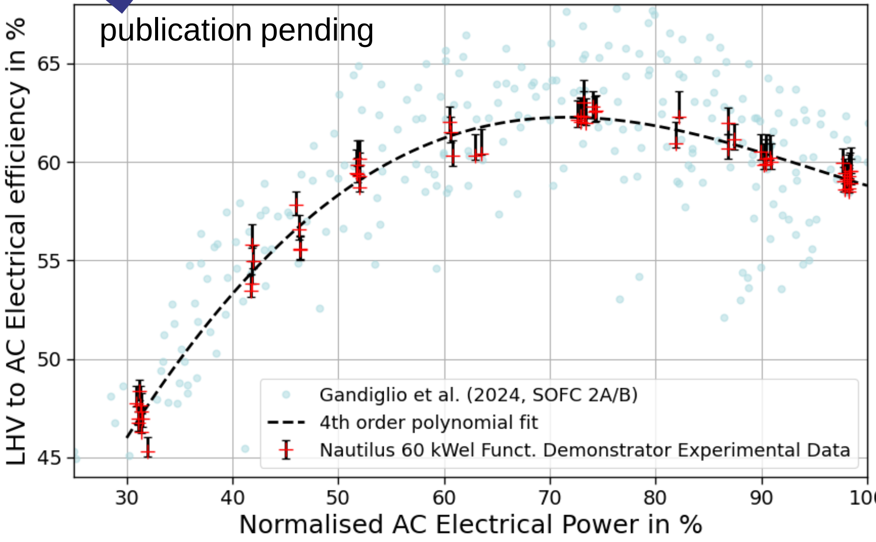
Functional Demonstrator: SOFC Steady-state Efficiency





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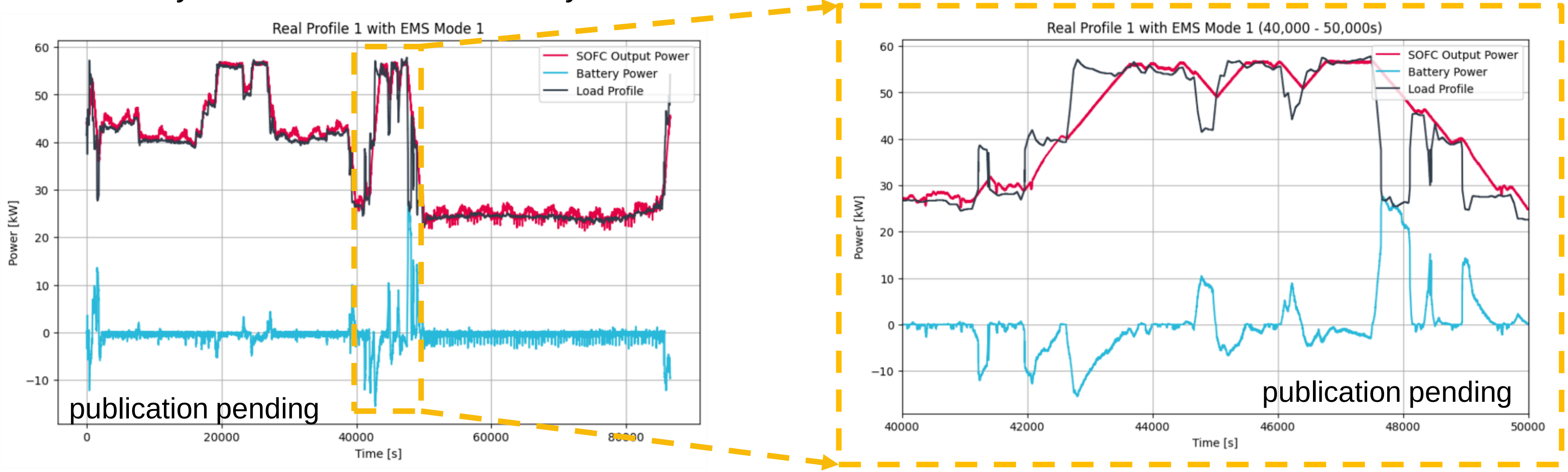
Functional Demonstrator: Dynamic operation

Real Profile Day 1; linearly compressed to the boundary conditions of the SOFC system



- The SOFC power output closely follows the load profile but struggles with highly dynamic changes
- The battery compensates for load peaks and drops

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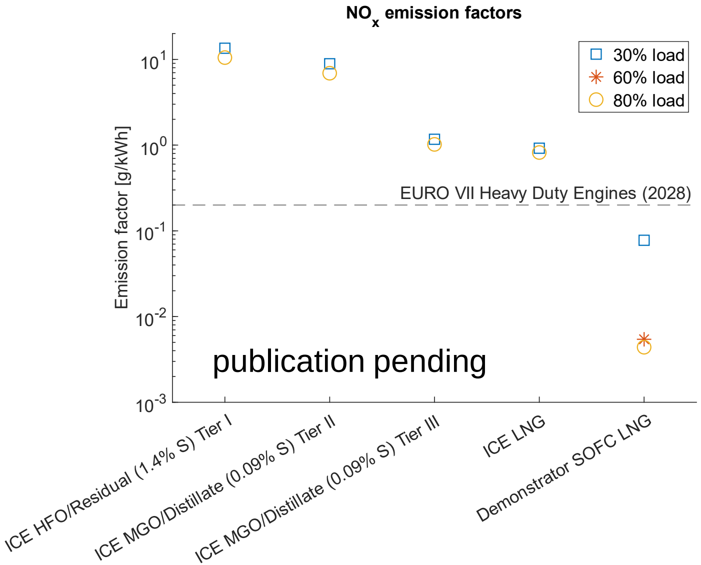
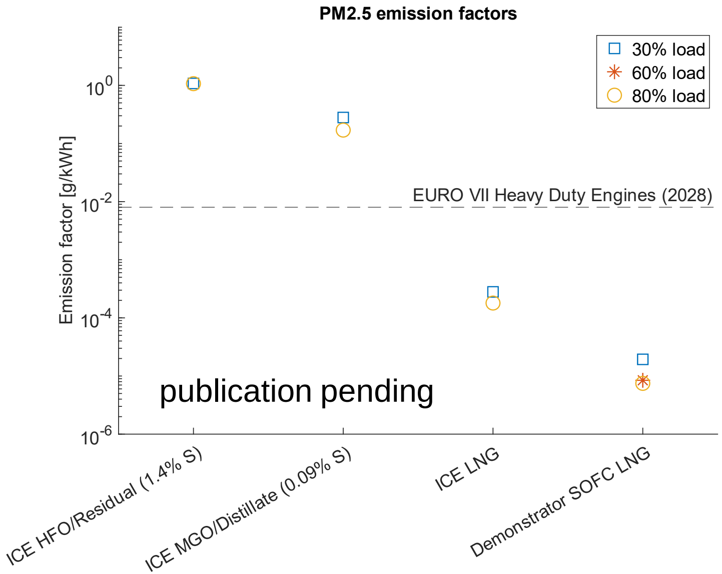
More than 95% emissions reduction for six pollutants





✓ negligible CH_4
✓ CO, SO_2, eBC
✓ dynamic operation

Comparisson of SOFC NOx emissions with baselines for different ICE Technologies and Fuels[1].
1. Grigoriadis, A. et al. (2021)

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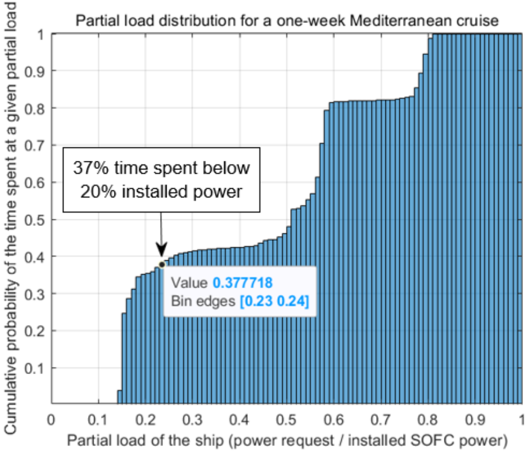
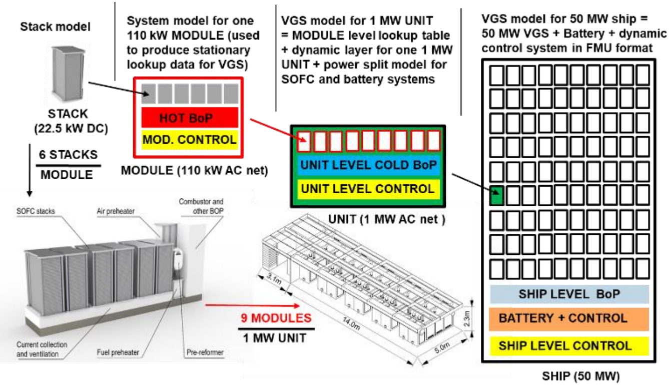
Modular genset at the MW-scale

- Operation at 15% of installed SOFC capacity 25% of the time
- Units should sustain high temperature to reduce temperature cycling
- High efficiency in broad part range by leveraging hot standby

Design	1	2	3
Hotel only	FC+Battery	FC+Battery	FC+Battery
Manoeuvring	ICE	FC+Battery	FC+Battery
Propulsion	ICE	ICE	FC+Battery

increasing total installed power





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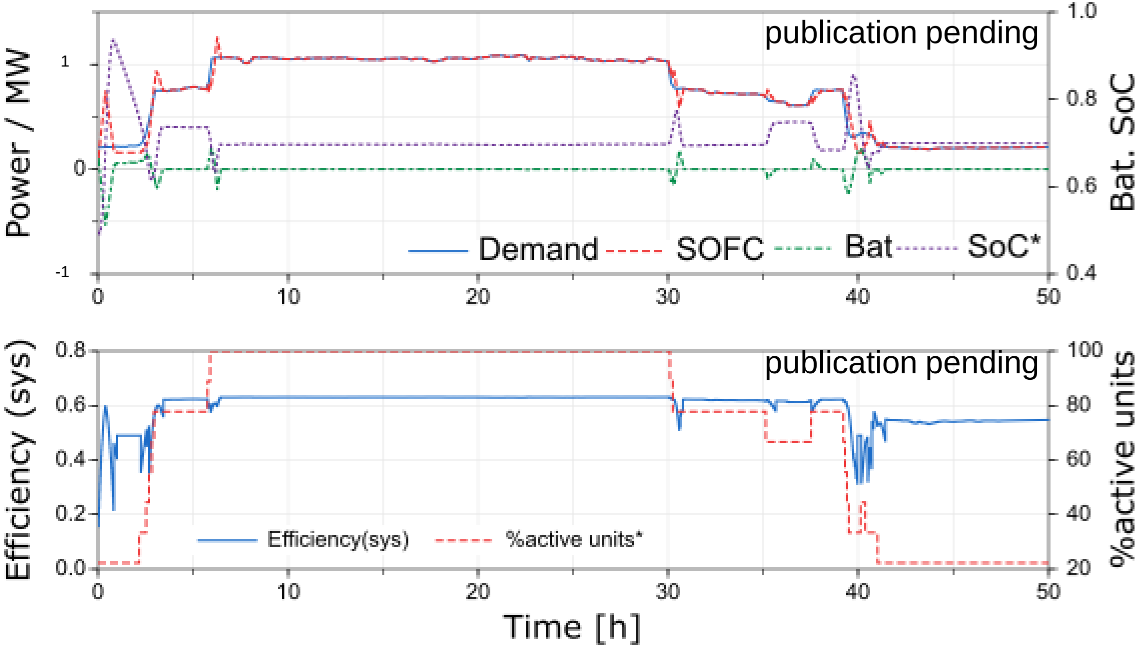
Virtual genset simulator (VGS)

- Several scenarios for power demand
- Optimal system level efficiency in broad load range (15% - 100%)
- Multi-module units leverage hot standby for optimal genset efficiency



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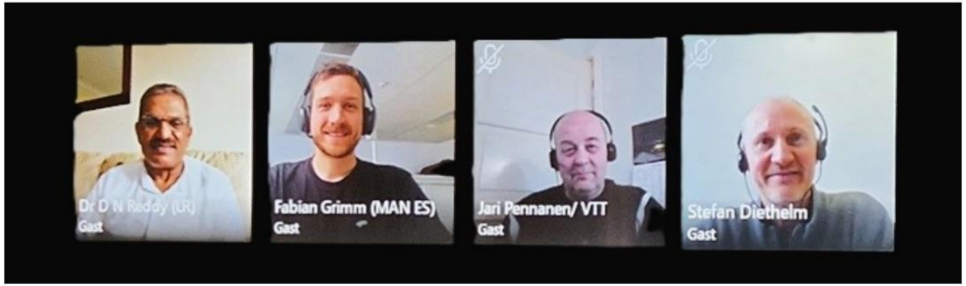
Q&A



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