DLR INSTITUT FÜR MARITIME ENERGIESYSTEME

EINSATZ VON PEM- UND SOFC BRENNSTOFFZELLEN IN MARITIMEN ANWENDUNGEN

Markus Mühmer, Thanapol Poojitganont

24.09.2024

Summer School 2024 – Brennstoffzellen und Batterien

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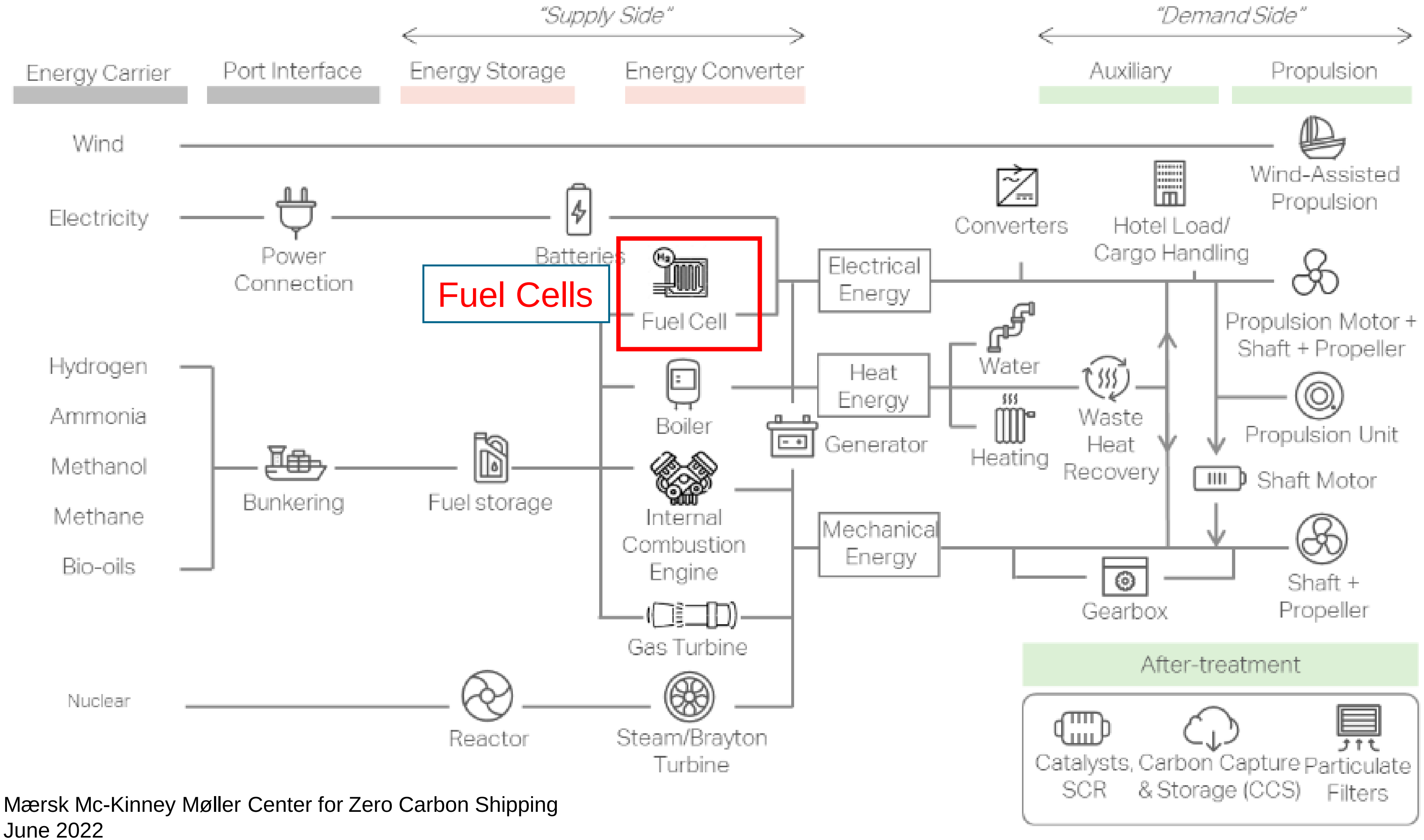
Figure 1: Vessel technology pathways



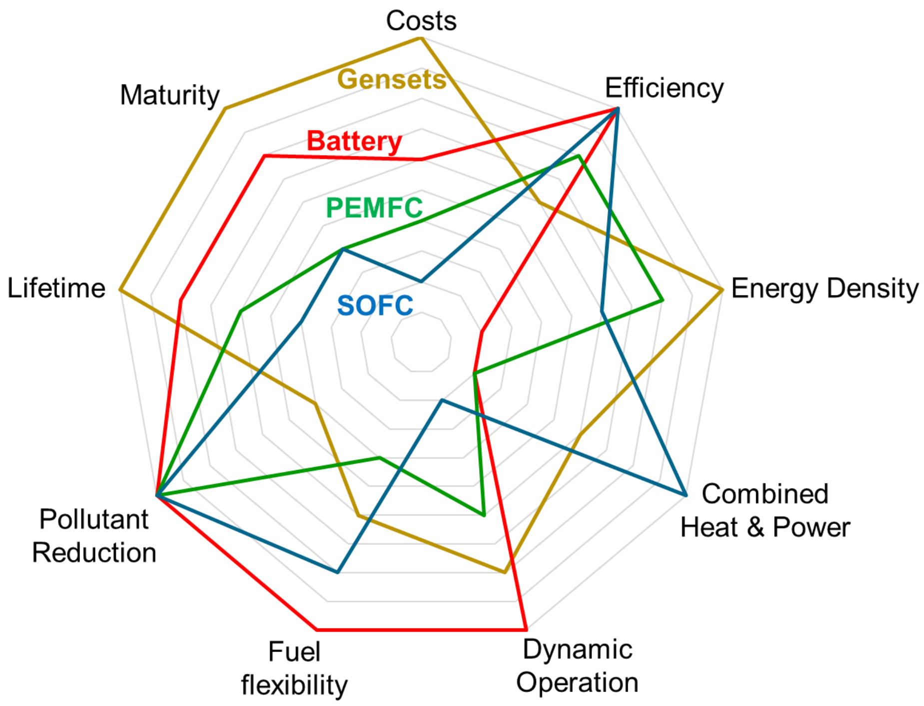
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
June 2022

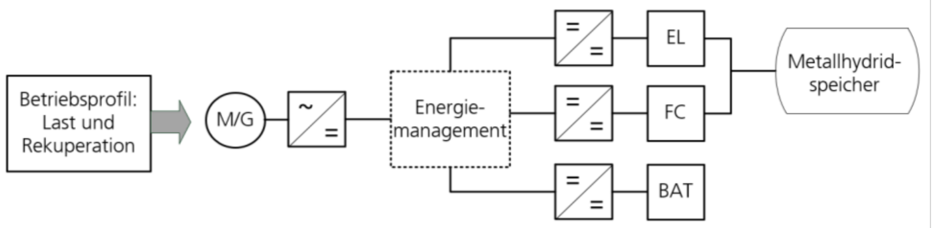
Energiekonverter und -systeme

Welche Konzepte der Erzeugung elektrischer, thermischer und mechanischer Energie aus erneuerbaren Quellen sind am effizientesten?

Optimierung von Energiesystemen an Bord

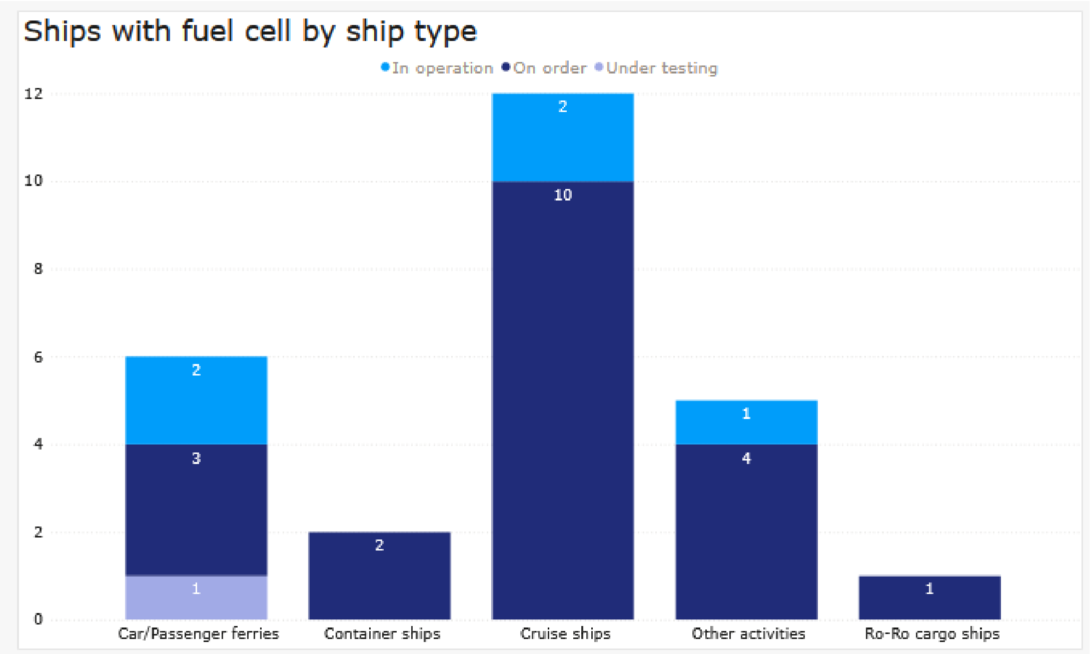
- **Energiewandler:** Integration von effizienten Energieerzeugern (Brennstoffzellensysteme, hybride Systeme mit flexiblen Kraftstoffen)
- **Elektrische Systeme:** Entwicklung zuverlässiger Bordnetze (Gleichstromnetze für effiziente Energieverteilung, Stabilität und Fehlermanagement für hybride Energiesysteme, Regelung & Hardware für Umrichter der neuen Generation)
- **Energiespeichersysteme:** Einsatz hocheffizienter Speicher (maritime Batteriesysteme, Degradation)
- **Thermische Systeme:** Optimierung der Gesamteffizienz (Nutzung von Abwärme, kombinierte Wärme- und Stromerzeugung, Integration von Wärmepumpen)
- **Systemanalyse & Optimierung:** Expertise für den effizienteren Betrieb (Messung & Analyse von Lastprofilen und AIS-Daten, Systemsimulation & Optimierung des Energie-Managements, Routenoptimierung & Windunterstützte Antriebe)





Herausforderungen in maritimer Umgebung?

- Treibstoff der Zukunft?
- Investmentkosten (PEM ~ 1.500 – 1.800 € / kW)
- Leistungsklasse: Kommerzielle Brennstoffzellensysteme haben erreichen Leistungen im mittleren dreistelligen Bereich
- Keine bindenden Regularien für Brennstoffzellenanwendungen → Sehr aufwendiger – Prozess



Quelle: DNV Alternative Fuel Insight (20.09.2024)

~ 100.000 Schiffe in Betrieb weltweit
5 Brennstoffzellen in Betrieb / 20 in Bestellung

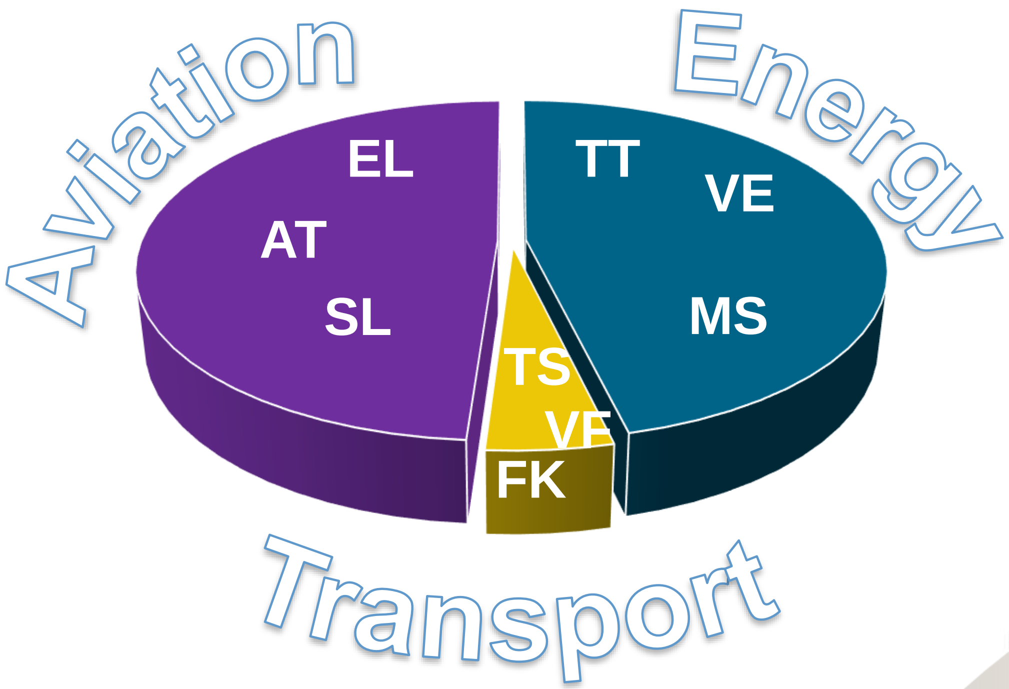
PEMScale 1.5

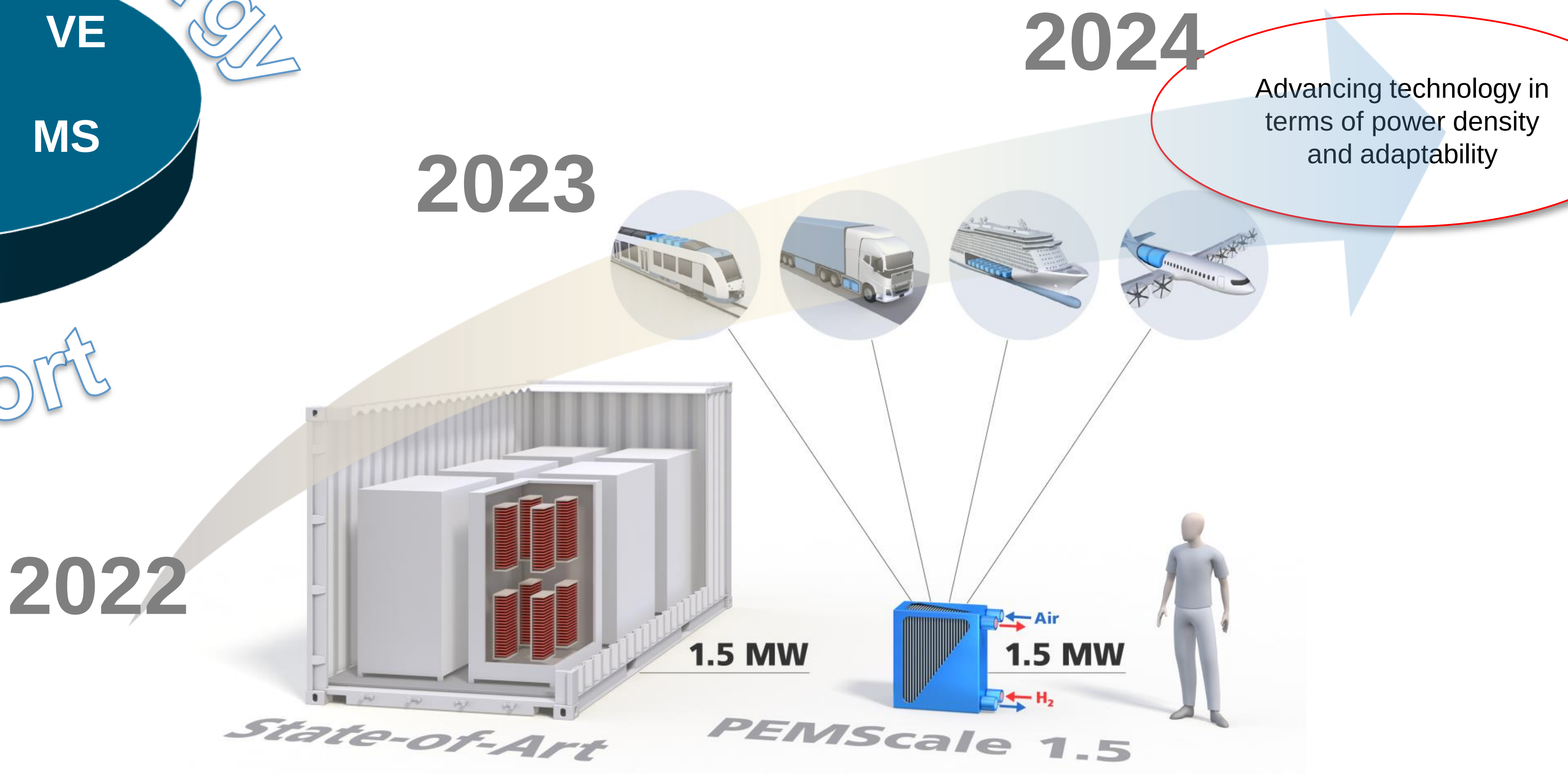
Sector Coupling

Hydrogen

Fuel Cells

System Analysis

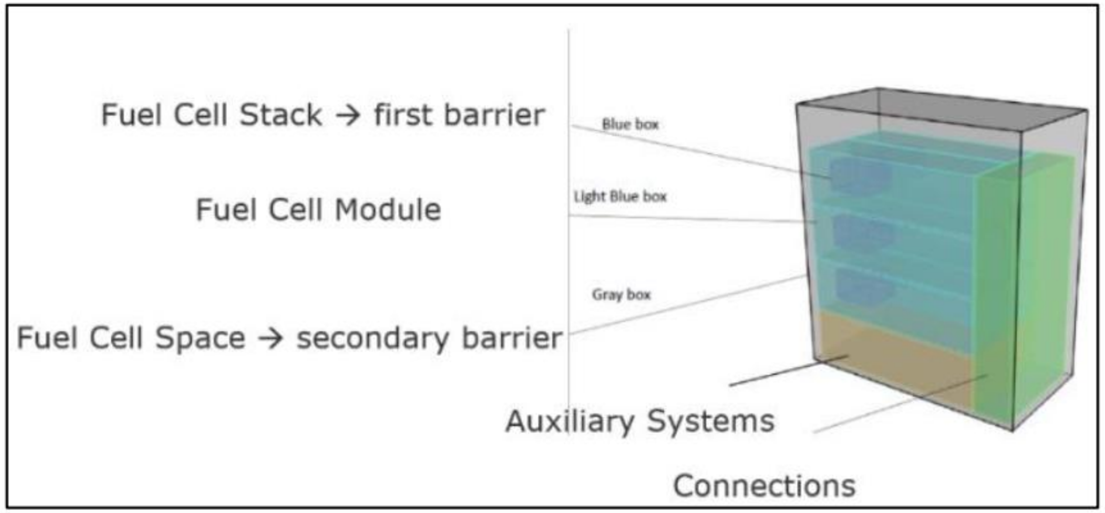




Forschungsprojekt LP II (Coriolis) – Sicherheitsanforderungen

- IGF – Code (Low Flashpoint fuels) – mainly designed for LNG applied for hydrogen fuel cells
- IMO-MSC.1-Circ.1647_Interim Guidelines For The Safety Of Ships Using Fuel Cell Power Installations

- Gekapselter Bereich um wasserstoffführende Komponenten
- Kontinuierliche Belüftung der Kapselung
- Die Belüftung muss ausreichen, um max. 25 % H_2 Konzentration der unteren Explosionsgrenze in jeglichen Leckageszenarien zu gewährleisten



Quelle: DNV_2021_Maritime_Regularien_fuer_Brennstoffzellen_und_alternative_Brennstoffe_WZZN2021_Vogler

EINSATZ VON BRENNSTOFFZELLEN IN MARITIMEN ANWENDUNGEN

SOFC

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Summer School 2024 – Brennstoffzellen und Batterien

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Content

- Overview of fuel cell, i.e. SOFC
- Maritime and fuel cell related project at DLR : HELENUS
- Research aspect in HELENUS

EINSATZ VON BRENNSTOFFZELLEN IN MARITIMEN ANWENDUNGEN
OVERVIEW OF FUEL CELL

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Overview of Fuel Cells

- Fuel cells -> a promising solution for low-emission power generation on ships [1–2, 4-6].
- **Advantages** for marine applications compared to diesel engines [2]:
  - Low emissions
  - Good part-load characteristics
  - High redundancy
  - Low maintenance
  - Low noise and vibrations
- **Struggles** of implementing fuel cells in combination with alternative fuels [3]:
  - High capital expenses
  - Large fuel storage
  - Lack of alternative fuel infrastructure
  - Short lifetime
  - Slow transient behavior

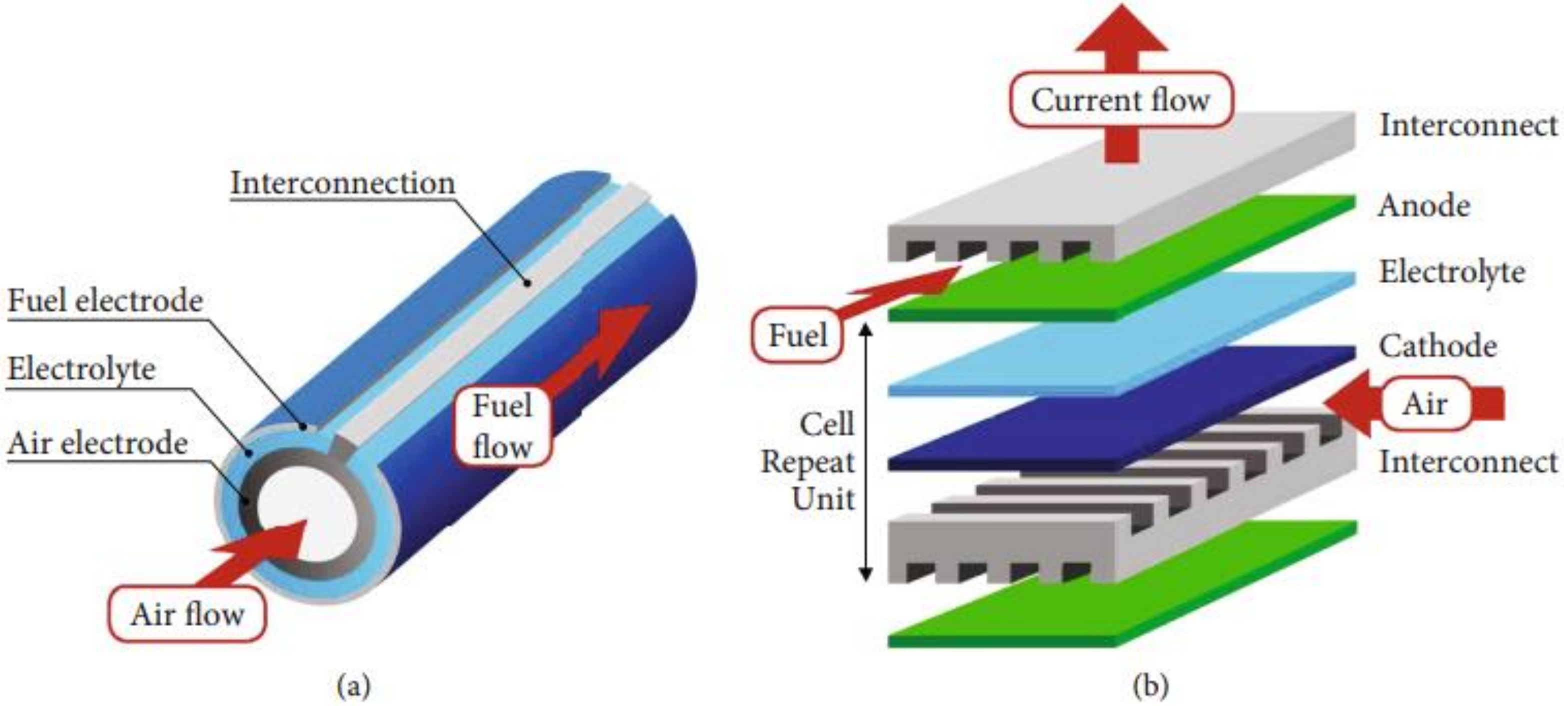
SOFC

- Solid oxide fuel cells (SOFCs) are characterized by a
  - **Higher fuel impurity tolerance** than LT-PEMFCs [1, 2].
  - Natural gas (NG) and ammonia can be **fed directly** to SOFC systems [8]
  - SOFC has demonstrated **high system efficiencies** of 50-65%, which can be even **increased to 70%** with combined gas turbine cycles [9, 10].
  - **SOFC struggles** with low power density, high investment cost, limited lifetime, and slow response to dynamic loads [1, 2].

- **Mitigated challenges** of SOFC on :
  - High efficiency compensates for the low power-to-volume ratio -> **Smaller fuel tanks** [11]
  - SOFC's **fuel flexibility** makes it possible to use a fuel with a higher energy density at high efficiency -> further decreasing the required ship volume
  - Investment costs are expected to drop when production increases [12]
  - **The lifetime of SOFCs, 30000 to 60000 hours** [13], is sufficient to reach the typical five-year docking interval for most ship applications
  - SOFCs can be **combined with batteries or ICE** to ensure the dynamic capabilities of the power plant [2, 14, 15] -> Power generation solution for long-haul marine applications [1–2,4,15]

SOFC Power Plants

- **SOFC Stacks**
  - SOFC stack design is distinguished into planar (PSOFC) and tubular (TSOFC); the former is most often researched [17] and is dominantly used in commercial products

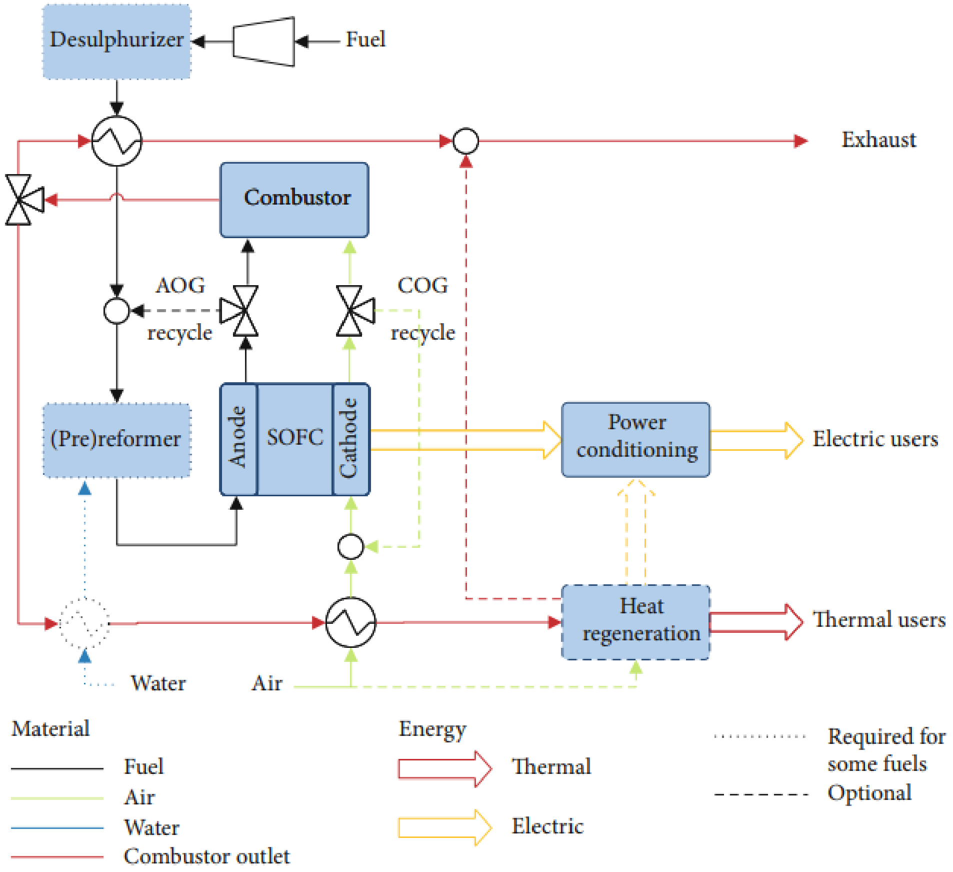


SOFC System

- **Balance of Plant Components** -> significant effect on system efficiency, power density, cost, and transient capabilities
- Components that support the fuel cells in power generation are called balance of plant (BoP) components, including:
  - Fuel processing equipment
  - Airflow control
  - Thermal management systems
  - Water management systems
  - Power conditioning equipment [18].
- These systems contain many different components:
  - Reformers
  - Burners
  - Blowers
  - Evaporators
  - Heat exchangers
  - Generators
  - Sensors, and valves

SOFC System

- Overview of SOFC power plants. AOG: anode off-gas; COG: cathode off-gas



SOFC System

- Related processes in BoP of SOFC:
  - Desulphurisation
    - The most suitable desulphurisation method depends on the fuel type and the sulphur tolerance of the fuel cell. Researchers and suppliers state that **SOFCs require a sulphur content below 1 to 10 ppm**
  - Reforming Strategy
    - Steam reforming is the most efficient for SOFC [19].
    - The conversion can occur in an **external reformer**. Alternatively, the heat and steam produced by the electrochemical reaction in the SOFC can be used to reform the fuel internally.
    - **Internal reforming** significantly decreases system capital cost and system complexity since no external reformer is needed [10].
  - Anode Off-Gas Recirculation
    - The anode off-gas of an SOFC already contains steam since water is produced at the anode during the electrochemical reaction.
    - **Recycling the fuel** also leads to **lower local fuel utilisation** [20] and a more homogeneous temperature and particle concentration distribution through the stack [21] -> beneficial for the cell lifetime [22].

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EINSATZ VON BRENNSTOFFZELLEN IN MARITIMEN ANWENDUNGEN
HELENUS

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HELENUS

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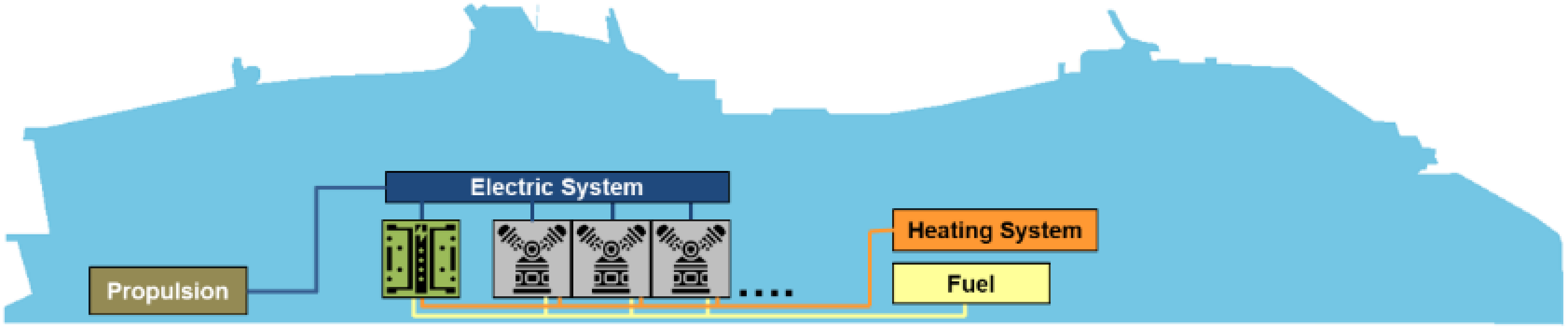
Key Objectives (1/3)

- **HELENUS Concept**: Demonstration of the **applicability**, **scalability**, and **fuel flexibility** of solid oxide fuel cells (SOFCs) in various maritime applications
- Installation and field trials of a **500 kW** SOFC operating in cogeneration mode, on an ocean cruise vessel
  - Full integration (spatial, electrical & thermal) into ship design, reaching **TRL7 by 2027** (project end)
  - Extended field testing planned after the project to reach **TRL8 by 2029**
- Creation of a pathway to **scale-up onboard SOFC installations up to 20 MW**
  - **23% overall efficiency improvement** expected over a conventional energy system

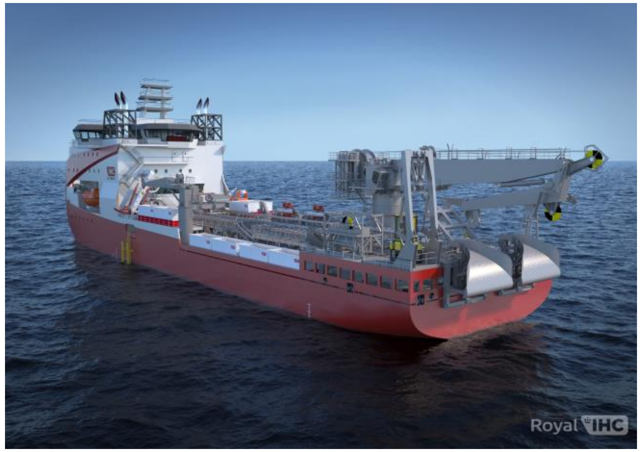


Full integration of SOFC in the machine area onboard cruise ship (background schematic from MSC)

Key Objectives (2/3)

Funded by
the European Union

- Evaluation of SOFCs in **various other maritime applications** (e.g. dredgers & offshore vessels)
    - Experimental laboratory validation using a 80 kW SOFC module over a transient hardware-in-the-loop (HiL) test setup
    - Assessment and optimization of system sizing, transient controls, and supervisory controls



Key Objectives (3/3)

Funded by
the European Union

- Enabling **fuel-flexibility of SOFCs with future renewable maritime fuels**
  - e.g. **ammonia**, **methanol**, renewable diesel, or hydrogen
  - Experimental laboratory validation using a 80 kW SOFC module

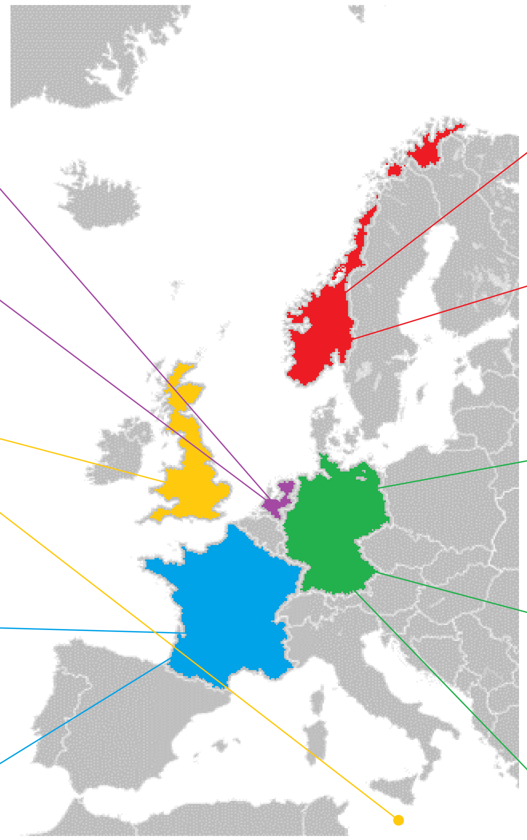
- Creation of a **technological and regulatory roadmap** for the widespread adoption and upscaling of SOFCs operating with renewable fuels in future maritime applications

Consortium

Funded by
the European Union

Active and coherent involvement of stakeholders from all sections of the maritime value chain from six different EU and associated countries

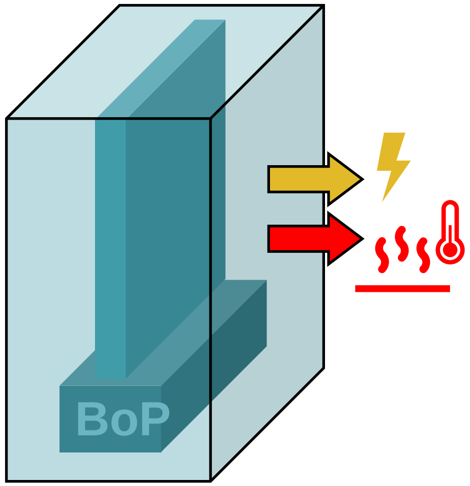
Fuel Cell Developer	**Alma Clean Power**	
Shipyards	**Chantiers de l'Atlantique**	
	IHC	
Ship Integrator	**Wärtsilä**	
Classification Society	**Bureau Veritas**	
Ship Operator	**MSC Cruises**	
Research Institutes	**DLR**	
	TU Delft	
Consulting	**BALance**	
	ifeu	



Scaling up SOFCs in cruise ships

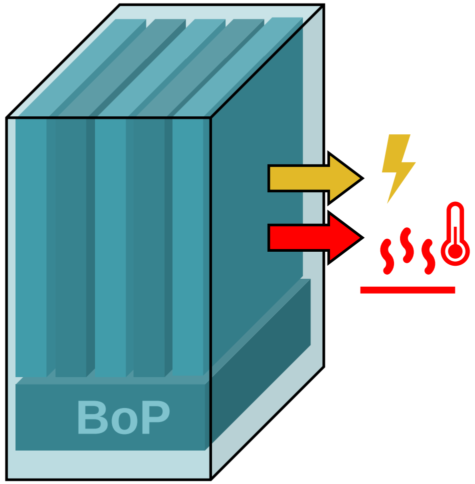
Funded by the European Union

80 kW module



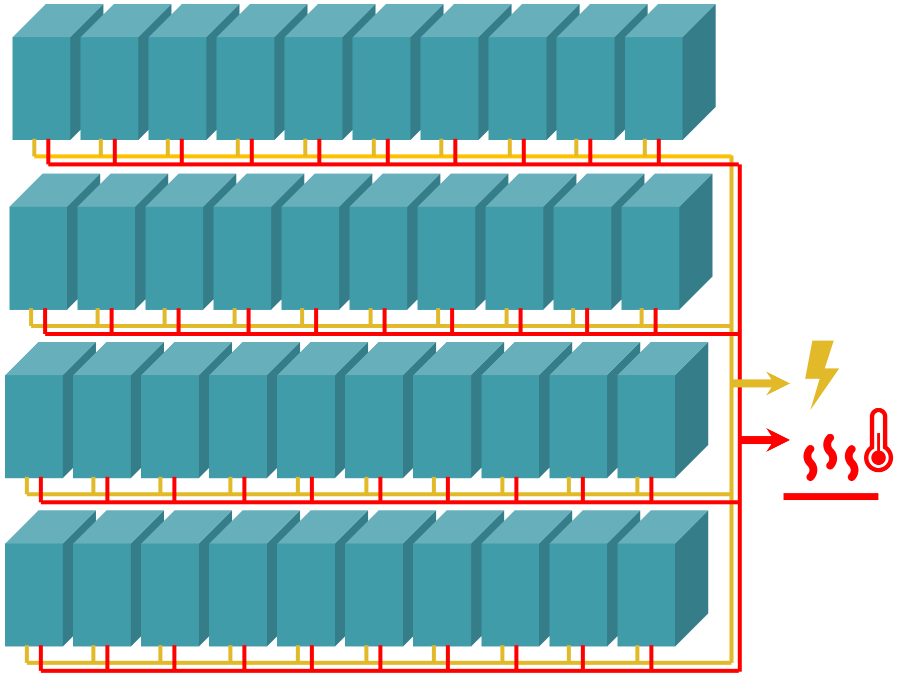
→ Lab testing at DLR (WP4)
→ Testing over various maritime duty cycles
→ Testing fuel-flexibility of the SOFC system

500 kW module



→ Ship installation and field testing onboard CdA/MSC cruise ship (WP5)
→ TRL7 solution
→ Evaluation in view of certification
→ >60% electrical efficiency
→ >85% cogeneration efficiency

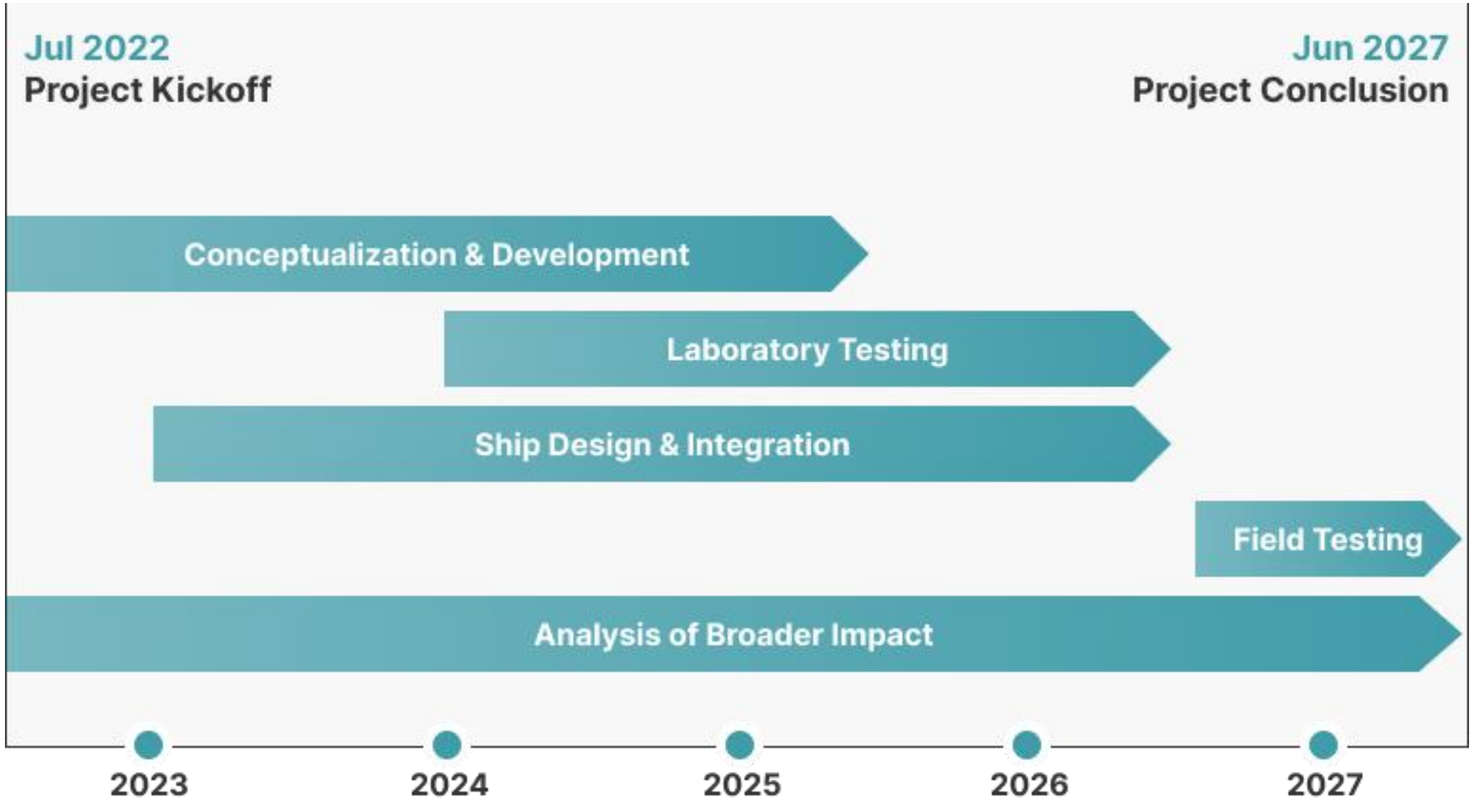
20 MW installation

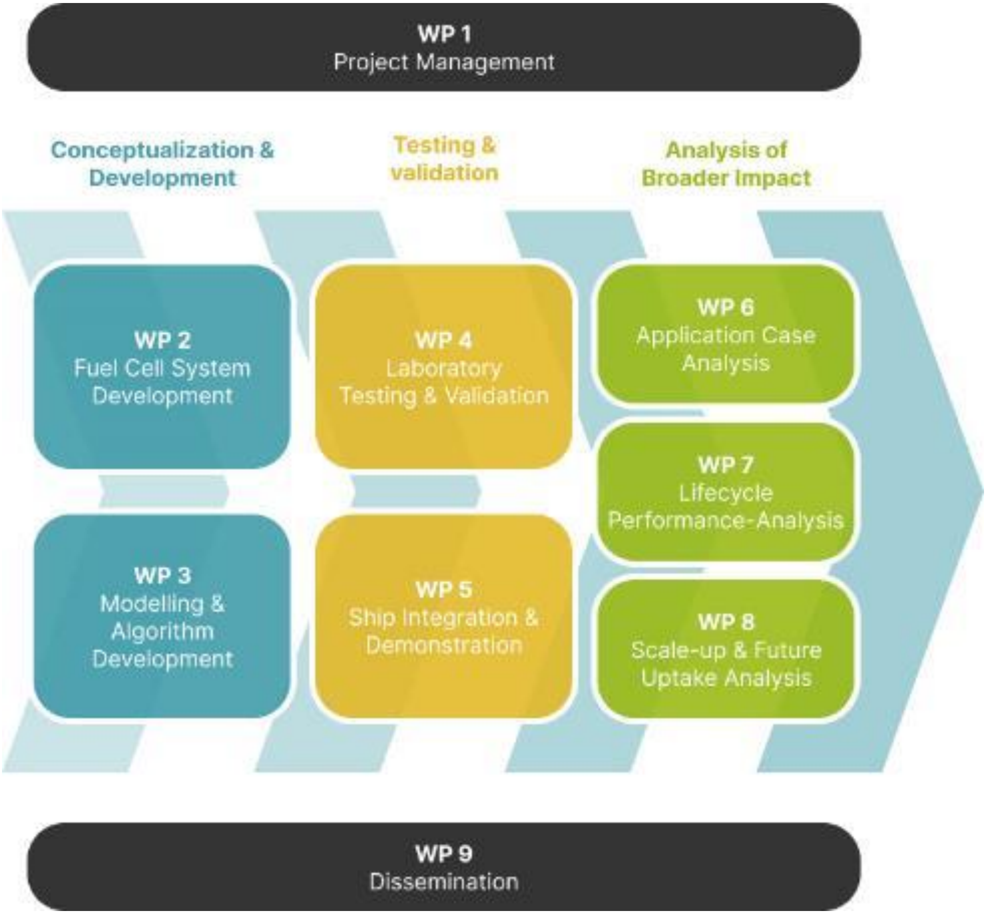


→ Future scaled-up scenario enabled by HELENUS
→ 23% overall efficiency gains over conventional ICE-Genset system

Project Organization

- Total Budget: 14,8 M€
- Duration: 5 years, Jul 2022 – Jun 2027





EINSATZ VON BRENNSTOFFZELLEN IN MARITIMEN ANWENDUNGEN
RESEARCH ASPECT IN HELENUS

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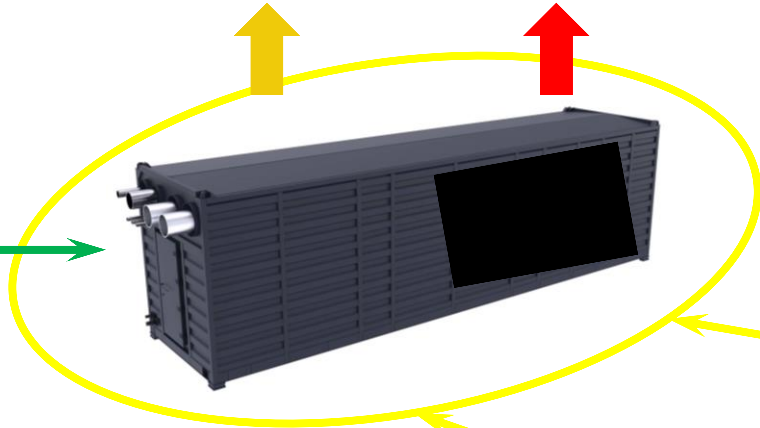
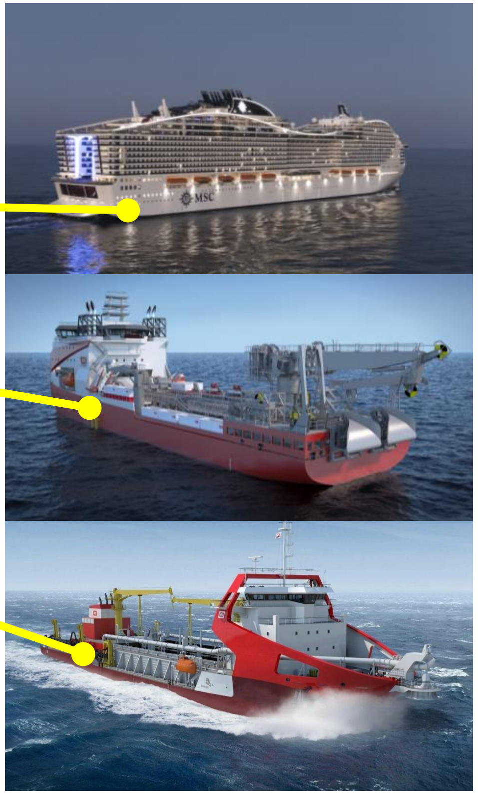
Motivation/ Fundamental Idea

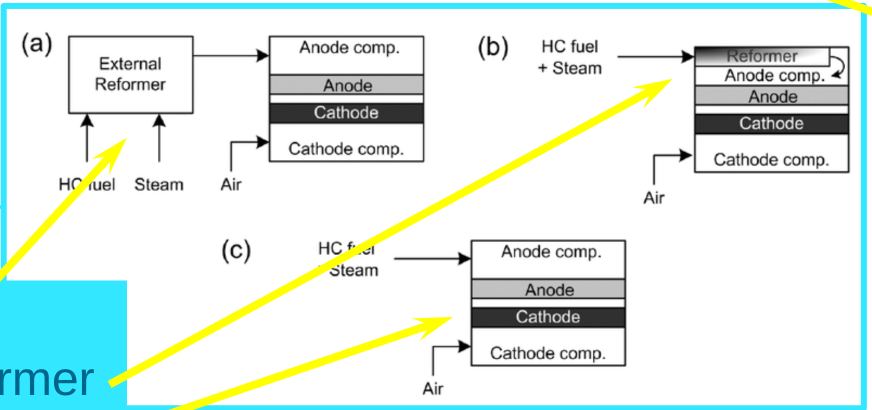
Electricity Heat

i.e. Natural gas,
Ammonia,
Methanol, etc.

Reformer

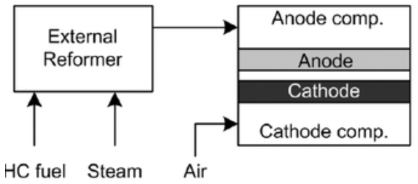




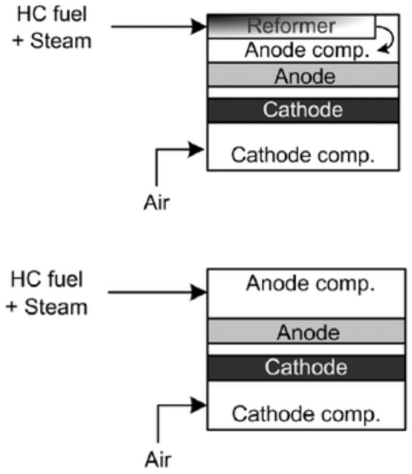


(a) External reformer
(b) Indirect internal reformer
(c) Direct internal reformer

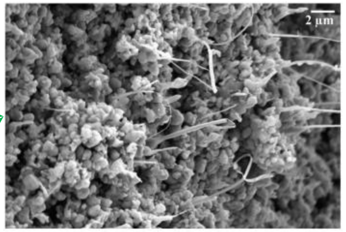
Motivation/ Relevant



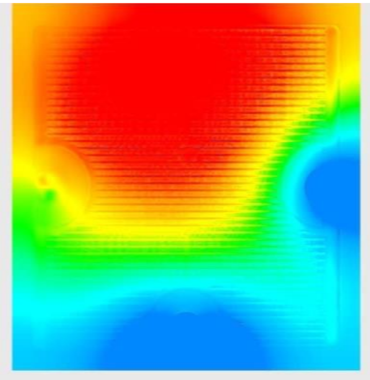
External Reformer



Internal Reformer



Coking



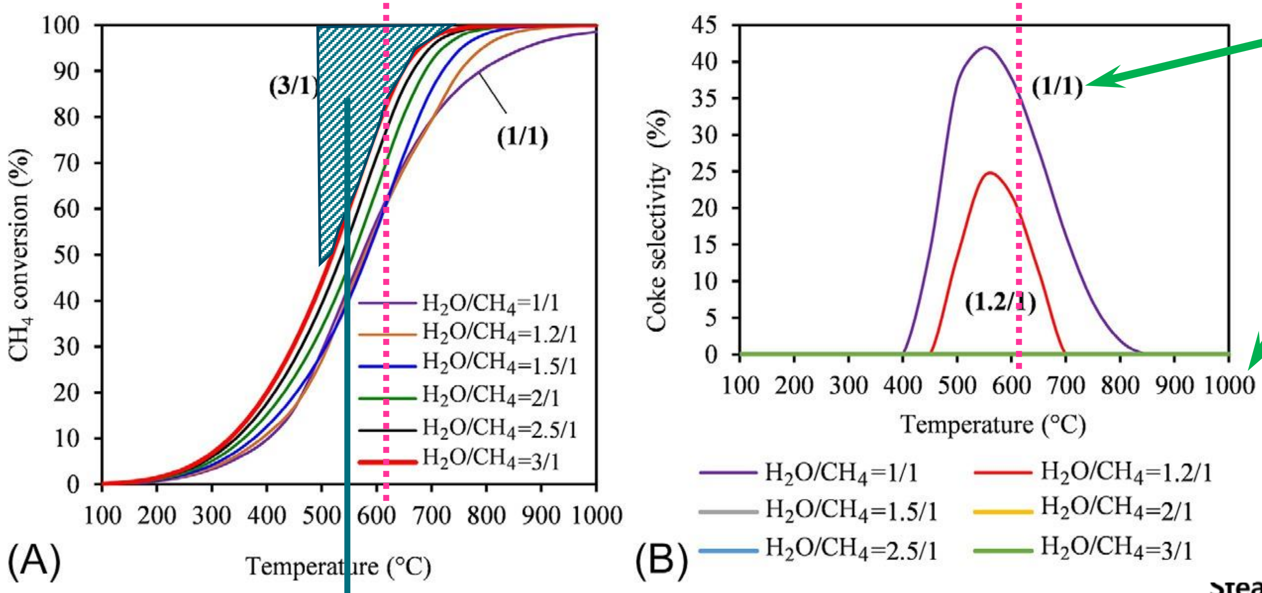
Dramatically temperature distribution

Resulting in:
- Overall efficiency drop-off
- Cell/ stack degradation
- Physical damage

Due to occurrence of both endothermic and exothermic simultaneously

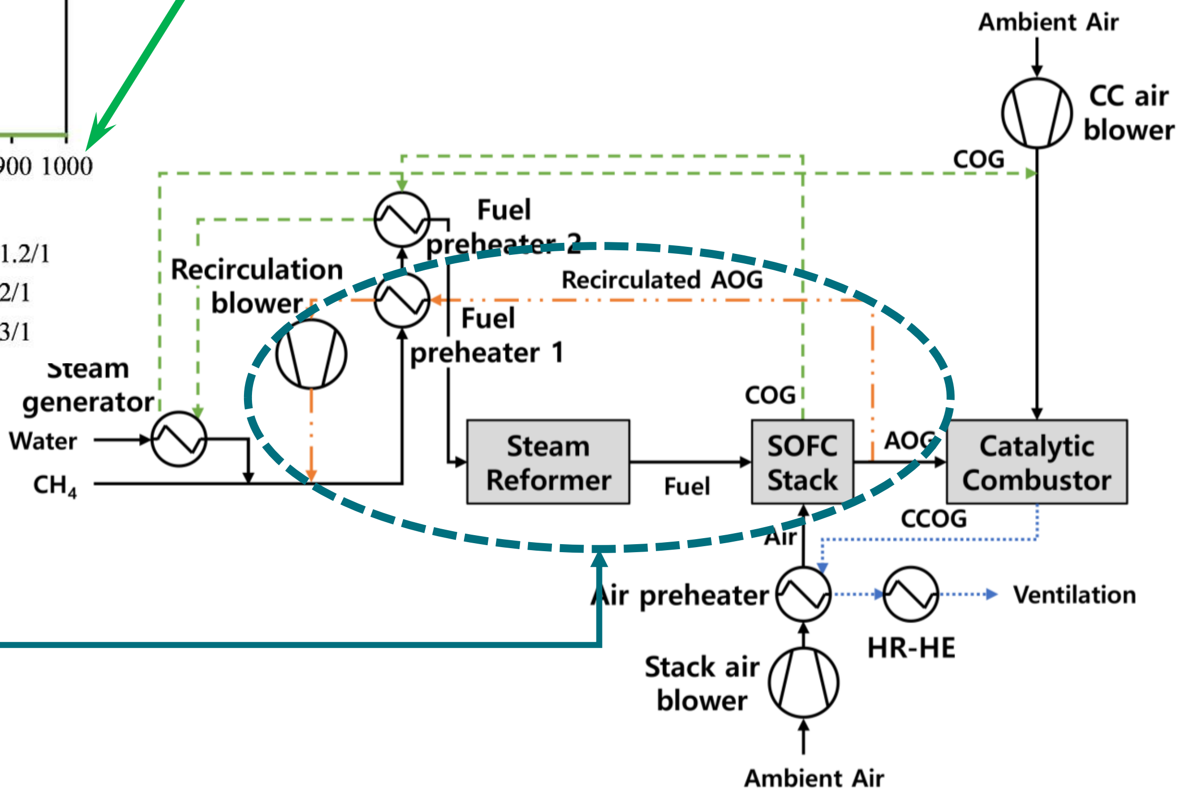
Motivation/ Challenge

HELENUS‘ SOFC operating temperature



How to avoid coking?
- Adjust operating temperature
- Adjust Steam/Carbon ratio

What is the behavior of Methanol?

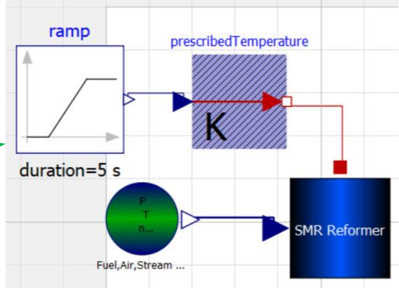


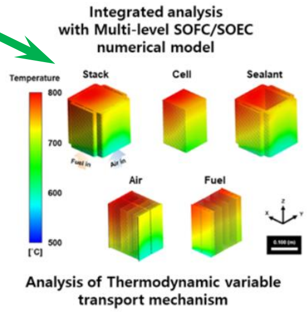
Motivation

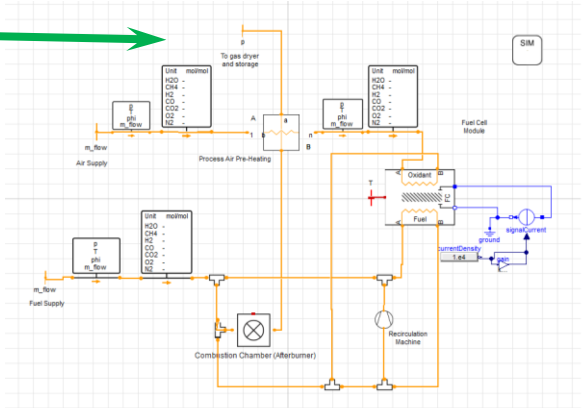
- Goals:
  - Study the **behavior of SOFC fueling with alternative fuel** both on stationary and transient loads
  - Consider **effects of using selected alternative fuels** in SOFC, i.e. **coking**
  - Explore the **temperature distribution inside internal reforming** SOFC
  - Investigate the **emission in anode-off gas** as well the characteristic of **anode-off gas recirculation**
  - Understand the **degradation mechanism of SOFC** via endurance tests

Methodology and scientific approach

- Tools
  - Experimental Investigation:
    - NAUTILUS demonstrator
    - HELENUS teststand
    - Emission measurement system
    - Developed emulator(s) supporting experimental investigation
  - Numerical Simulation:
    - Dymola/ Modelica based SOFC & BoP fueling with alternative fuels and CH3OH Toolbox & Emulator
    - CFD/ FEM tool for temperature distribution study







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- Galactica @DLR-TT
- AVL SESAM i60 FT SII | AVL
- Cooperation tasks with KMUTNB, Thailand
- Heat/mass transport – 연세대학교 기계공학부 (yonsei.ac.kr)

THANK YOU & QUESTIONS

Bildquelle hier angeben

Internship „Data-driven fuel cell control“

Development of a real-time data clustering technique for a fuel cell system control

Start: Jan 2025
DLR Institute of Maritime Energy Systems
Düneberger Straße 108 | D - 21502 Geesthacht

Rationale
Reliable operation of a fuel cell system requires robust control of gas supply, thermal management and power electronics. As the amount of processed data grows together with increasing number of sensors and actuators, the control logic becomes cumbersome and error-prone. By means of a data clustering technique, one could reduce a dimension of the parameter space and characterize an operation of a fuel cell system in terms of states and state-to-state transitions. This creates an abstraction logical layer, which simplifies the reasoning about the system behavior and allows for a simple yet robust data-driven control system.

Tasks

- Develop a graph-based model for resilience analysis of a fuel cell system
- Validate the model in a laboratory environment

Requirements

- Strong mathematical background (data clustering)
- Some knowledge of fuel cell systems would be a plus

Contact person
Dr.-Ing. Igor Sokolov
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Internship „Analysis of Fuel Cell System Resilience using Graph Theory“

Development of graph-based mathematical framework for fuel cell system resilience assessment

Start: Jan 2025
DLR Institute of Maritime Energy Systems
Düneberger Straße 108 | D - 21502 Geesthacht

Rationale
A commercial fuel cell system consists of numerous components (called BoP), which must work cohesively in order to ensure a reliable power delivery to an application. The BoP components expose mechanical, electrical and network interfaces, which collectively form interlinked operational layers. Since every BoP component is a node in several layers simultaneously, its fault propagates across all layers and affects negatively the system performance. In order to improve a fuel cell system resilience, one can use a graph-based model which describes the relationship between the operational layers and identifies weak points in system architecture.

Tasks

- Develop a graph-based model for resilience analysis of a fuel cell system
- Validate the model in a laboratory environment

Requirements

- Strong mathematical background (graph theory)
- Some knowledge of fuel cell systems would be a plus

Contact person
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