FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

EMSA study “*Fuel Cells in shipping*” and TCO considerations

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San Francisco, 11th September 2019

Fuel Cells

EMSA Study on the use of Fuel Cells in Shipping

EMSA Study – Tasks and Objectives

Task 1 – PART A

Review of Recent Projects

FellowSHIP,
FCShip,
METAPHU,
Nemo H2,
FELICITAS,
SF-BREEZE,
Pa-X-ell,
US SSFC,
MC-WAP,
ZemShips,
SchIBZ and
RiverCell

Presentation of FC technologies

alkaline fuel cell (AFC),
proton exchange membrane fuel cell (PEMCF),
high temperature PEMFC (HT-PEMFC),
direct methanol fuel cell (DMFC),
phosphoric acid fuel cell (PAFC),
molten carbonate fuel cell (MCFC)
solid oxide fuel cell (SOFC)

Selection of the 3 best technologies based on individual merits

Task 2 – PART B

Regulatory Gap Analysis
Review of existing Standards

Task 3 – PART C

Safety Assessment on the use of the 3 selected FCs
(concept generic designs for RO-PAX and Cargo-Vessel)
Total of 6 Safety Assessment Cases.

Study available at:

http://emsa.europa.eu/main/air-pollution/alternative-fuels.html

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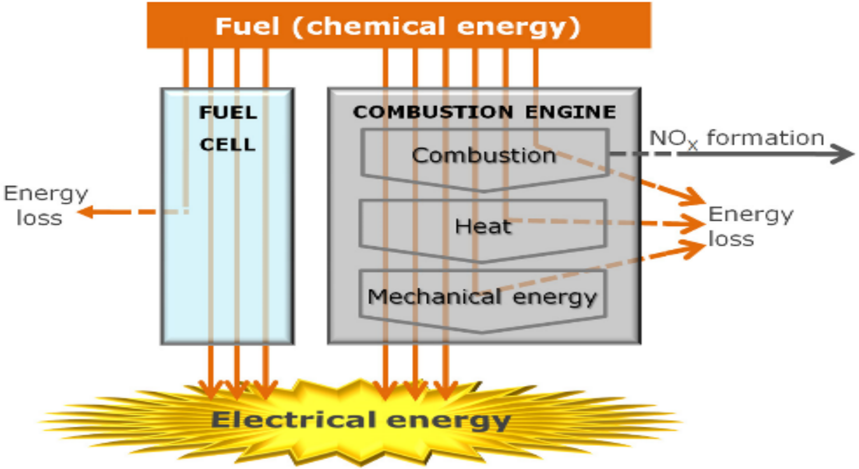
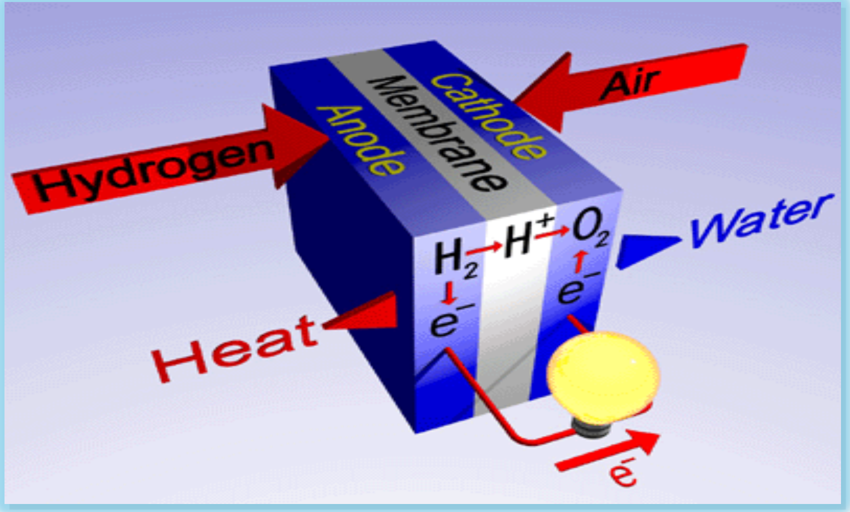
What is a Fuel Cell?





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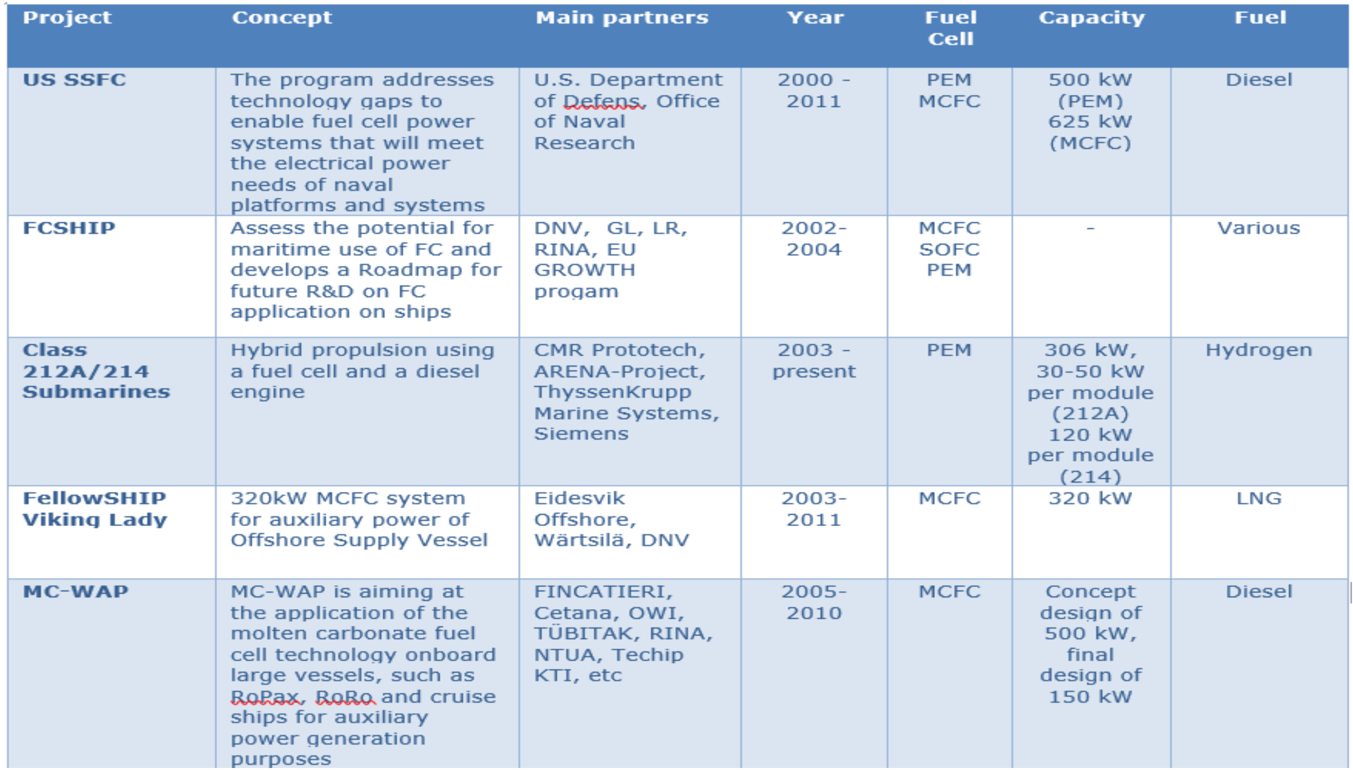
Introduction | **Technology and Projects** | Regulatory Gaps | Safety and Risk analysis



Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
US SSFC	The program addresses technology gaps to enable fuel cell power systems that will meet the electrical power needs of naval platforms and systems	U.S. Department of Defens, Office of Naval Research	2000 - 2011	PEM MCFC	500 kW (PEM) 625 kW (MCFC)	Diesel
FCSHIP	Assess the potential for maritime use of FC and develops a Roadmap for future R&D on FC application on ships	DNV, GL, LR, RINA, EU GROWTH progam	2002-2004	MCFC SOFC PEM	-	Various
Class 212A/214 Submarines	Hybrid propulsion using a fuel cell and a diesel engine	CMR Prototech, ARENA-Project, ThyssenKrupp Marine Systems, Siemens	2003 - present	PEM	306 kW, 30-50 kW per module (212A) 120 kW per module (214)	Hydrogen
FellowSHIP Viking Lady	320kW MCFC system for auxiliary power of Offshore Supply Vessel	Eidesvik Offshore, Wärtsilä, DNV	2003-2011	MCFC	320 kW	LNG
MC-WAP	MC-WAP is aiming at the application of the molten carbonate fuel cell technology onboard large vessels, such as RoPax, RoRo and cruise ships for auxiliary power generation purposes	FINCATIERI, Cetana, OWI, TÜBITAK, RINA, NTUA, Techip KTI, etc	2005-2010	MCFC	Concept design of 500 kW, final design of 150 kW	Diesel

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Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
FELICITAS – subproject 1	Application requirements and system design for FC in heavy duty transport systems	Lürssen, FhG IVI, AVL, HAW, Rolls-Royce, INRETS, VUZ	2005-2008	-	-	-
FELICITAS – subproject 2	Mobile hybrid marine version of the Rolls-Royce Fuel Cell SOFC system	Rolls-Royce, Uni Genoa, Lürssen, HAW, Uni Eindhoven	2005-2008	SOFC	250 kW (60 kW sub system)	LNG, other fuel also evaluated
						Hydrocarb n fuels and drogen
						-
						drogen

Stationary Power 1MW hybrid SOFC system and 250kW Generator module of Rolls-Royce Fuel Cell Systems

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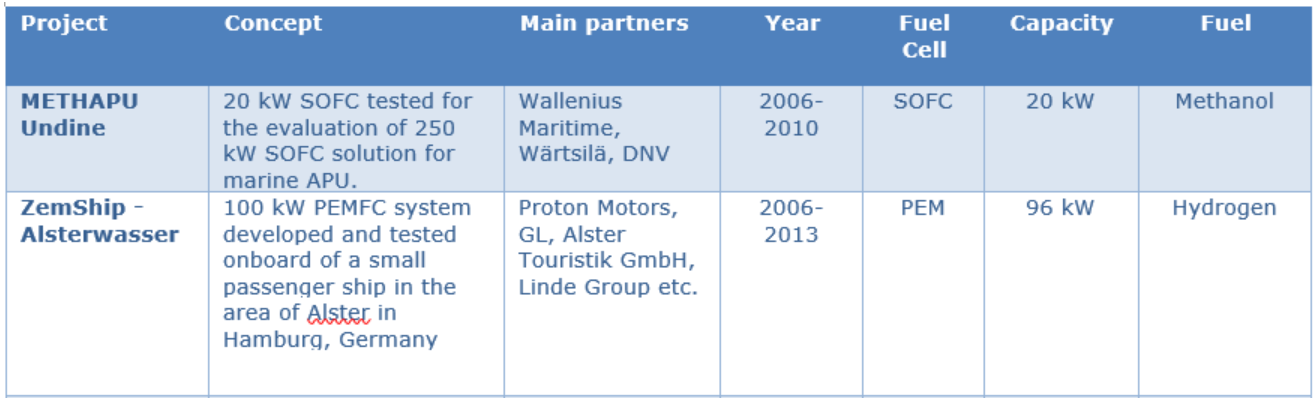

Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
METHAPU Undine	20 kW SOFC tested for the evaluation of 250 kW SOFC solution for marine APU.	Wallenius Maritime, Wärtsilä, DNV	2006-2010	SOFC	20 kW	Methanol
ZemShip - Alsterwasser	100 kW PEMFC system developed and tested onboard of a small passenger ship in the area of Alster in Hamburg, Germany	Proton Motors, GL, Alster Touristik GmbH, Linde Group etc.	2006-2013	PEM	96 kW	Hydrogen

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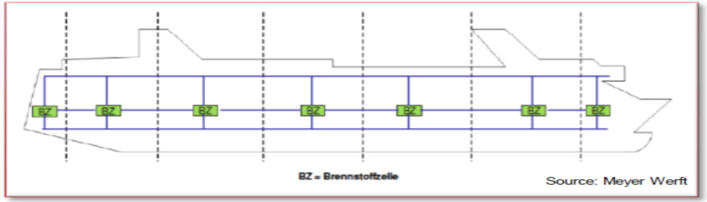
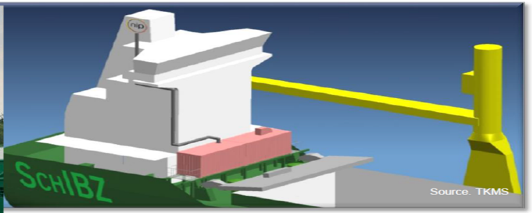
Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
E4Ships – Pa-X-ell MS MARIELLA	60 kW modularized HT-PEM fuel cell system developed and tested for the decentralized auxiliary power supply onboard passenger vessel MS MARIELLA.	Meyer Werft, DNVGL, Lürssen Werft, etc	Phase 1: 2009-2017 Phase 2: 2017-2022	HTPEM	60 kW (each stack is 30 kW)	Methanol
E4Ships - SchIBZ MS Forester	100 kW containerized SOFC system developed and tested for the auxiliary power supply of commercial ships. Scalable up to 500 kW units.	ThyssenKrupp Marine Systems, DNVGL, Leibniz University Hannover, OWI, Reederei Rörd Braren, Sunfire	Phase 1: 2009-2017 Phase 2: 2017-2022	SOFC	100 kW	Diesel



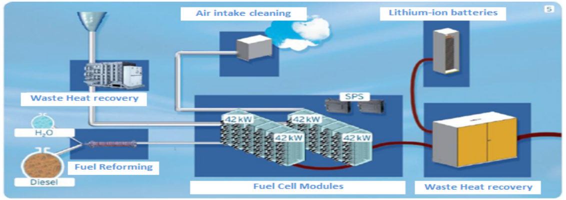
Source: Meyer Werft



Source. TKMS

PA-X-ELL

SCHIBZ



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Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
MF Vågen	Small passenger ship in the harbour of Bergen	CMR Prototech, ARENA-Project	2010	HTPEM	12 kW	Hydrogen
Hornblower Hybrid	Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell	Hornblower	2012-	PEM	32 kW	Hydrogen
Nemo H2	Small passenger ship in the canals of Amsterdam	Rederij Lovers etc				
Hydrogenesis	Small passenger ship which operates in	Bristol Boat Trips etc.				
		onal nd	2015 - present	PEM	120 k per modul Tota powe 2.5M	

SF-BREEZE

Nemo 2

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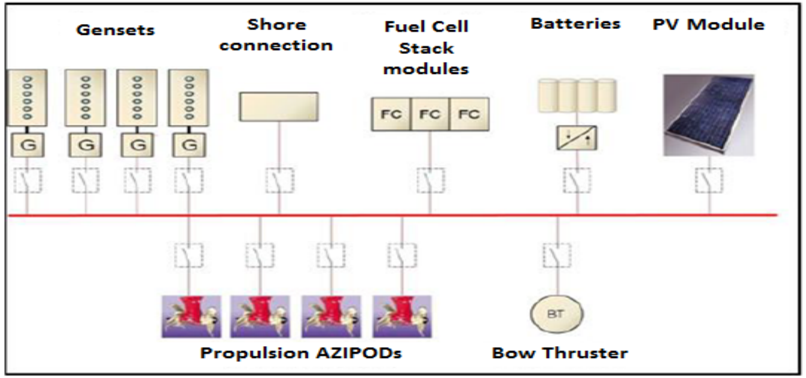
Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
RiverCell	250 kW modularized HT-PEM fuel cell system developed and to be tested as a part of a hybrid power supply for river cruise vessels	Meyer Werft, DNVGL, Neptun Werft, Viking Cruises	Phase 1: 2015-2017 Phase 2: 2017-2022	HTPEM	250 kW	Methanol
RiverCell – Elektra	Feasibility study for a fuel cell as part of a hybrid power supply for a towboat	TU Berlin, BEHALA, DNVGL, etc	2015-2016	HTPEM	-	Hydrogen



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7 fuel cell types were shortlisted and evaluated deeper
3 types were selected based on scores in predefined parameters

- Electro-galvanic fuel cell (EgFC)
- Enzymatic Biofuel Cells (EnzFC)
- Magnesium-Air Fuel Cell (Mg-AFC)
- Metal hydride fuel cell (MHFC)
- Protonic ceramic fuel cell (PCFC)
- Microbial fuel cell (MFC)
- Alkaline fuel cell (AFC)
- Direct borohydride fuel cell (DBFC)
- Direct carbon fuel cell (DCFC)
- Direct formic acid fuel cell (DFAFC)
- Direct methanol fuel cell (DMFC)
- Direct-ethanol fuel cell (DEFC)
- Molten carbonate fuel cell (MCFC)
- Phosphoric acid fuel cell (PAFC)
- Solid oxide fuel cell (SOFC)
- PEMFC
- High Temperature PEM
- Reformed methanol FC (R-MFC)
- Regenerative fuel cell (RegFC)
- RFC – Redox
- Solid acid fuel cell (SAFC)
- Upflow microbial fuel cell (UMFC)
- Zinc-air battery

Maturity and Relevance

- Solid Oxide Fuel Cell
- Molten Carbonate FC
- Phosphoric Acid FC
- HT PEM fuel cell
- Alkaline fuel cell
- PEM fuel cell
- Direct Methanol FC

Tolerance for cycling

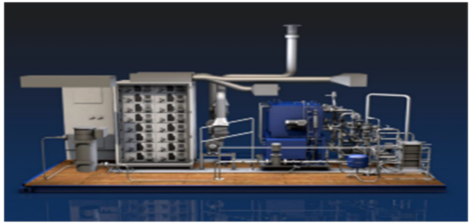
Lifetime

Efficiency

Emissions

Relative cost

Modular power levels



Safety aspects

Physical size

Flexibility towards type of fuel

Sensitivity for fuel impurities

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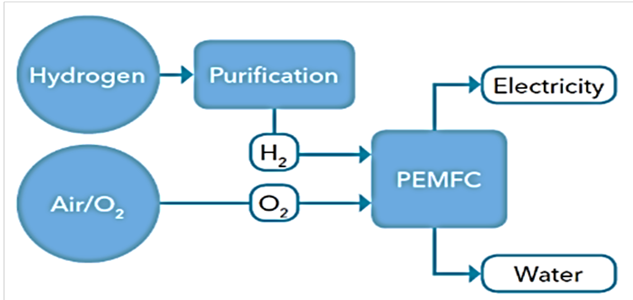
Technology selected: (a) PEM and (b) high-temperature PEM (HT-PEM)



PEM Technology
Mature Technology
Compact and lightweight
Relatively low cost
Tolerance for cyclic operation
Require very pure H2
Complex water mgmt system

HT-PEM Technology

Draws on the benefits of PEM, but address some of the cons:

- Fuel flexible
- Avoid complex water mgmt system
- Waste heat for heating purposes

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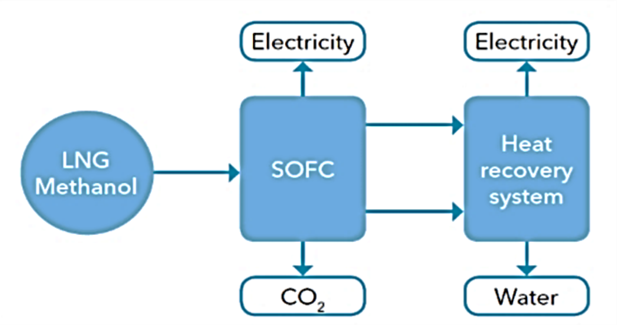
Technology selected: (c) Solid Oxide Fuel Cell (SOFC)



SOFC Technology	
Technology starting to become mature	
SOFC is highly efficient (up to 60%)	Opportunity for waste heat recovery
Moderately sized	Less flexible towards cyclic operation
Very fuel flexible	Good for battery hybrid solutions

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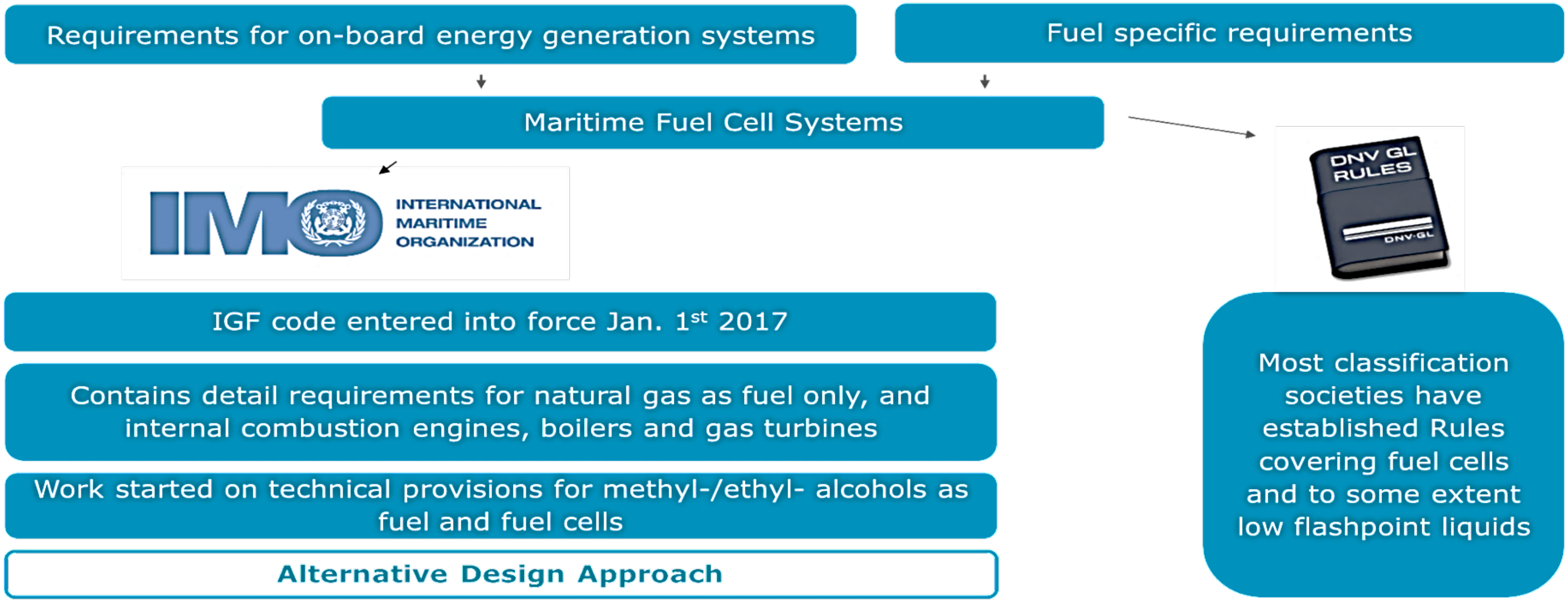
Short summary of regulative status



Requirements for on-board energy generation systems

Fuel specific requirements

Maritime Fuel Cell Systems

INTERNATIONAL MARITIME ORGANIZATION

IGF code entered into force Jan. 1st 2017

Contains detail requirements for natural gas as fuel only, and internal combustion engines, boilers and gas turbines

Work started on technical provisions for methyl-/ethyl- alcohols as fuel and fuel cells

Alternative Design Approach

Most classification societies have established Rules covering fuel cells and to some extent low flashpoint liquids

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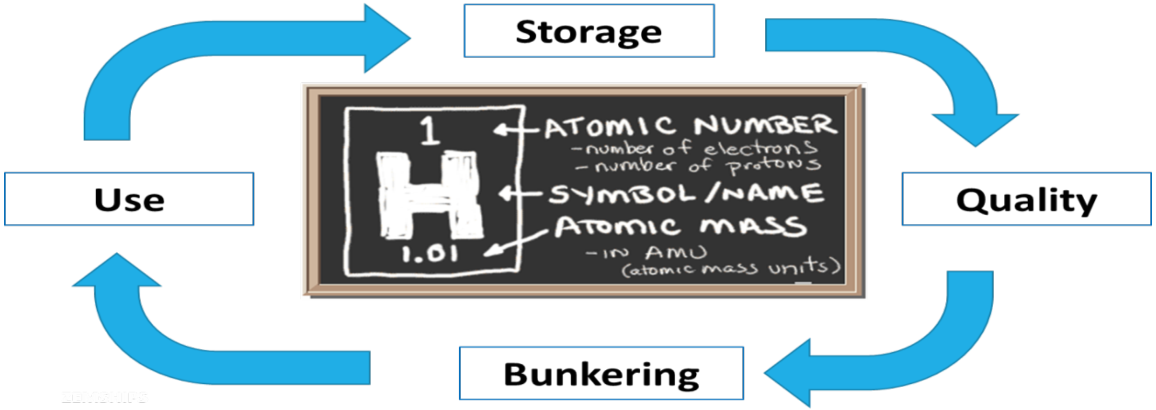
Key Regulatory Challenge

- **For a zero pollutant emission Fuel Cell installation**
- **For the use of Hydrogen as Energy Carrier**



Storage

Quality

Bunkering

Use

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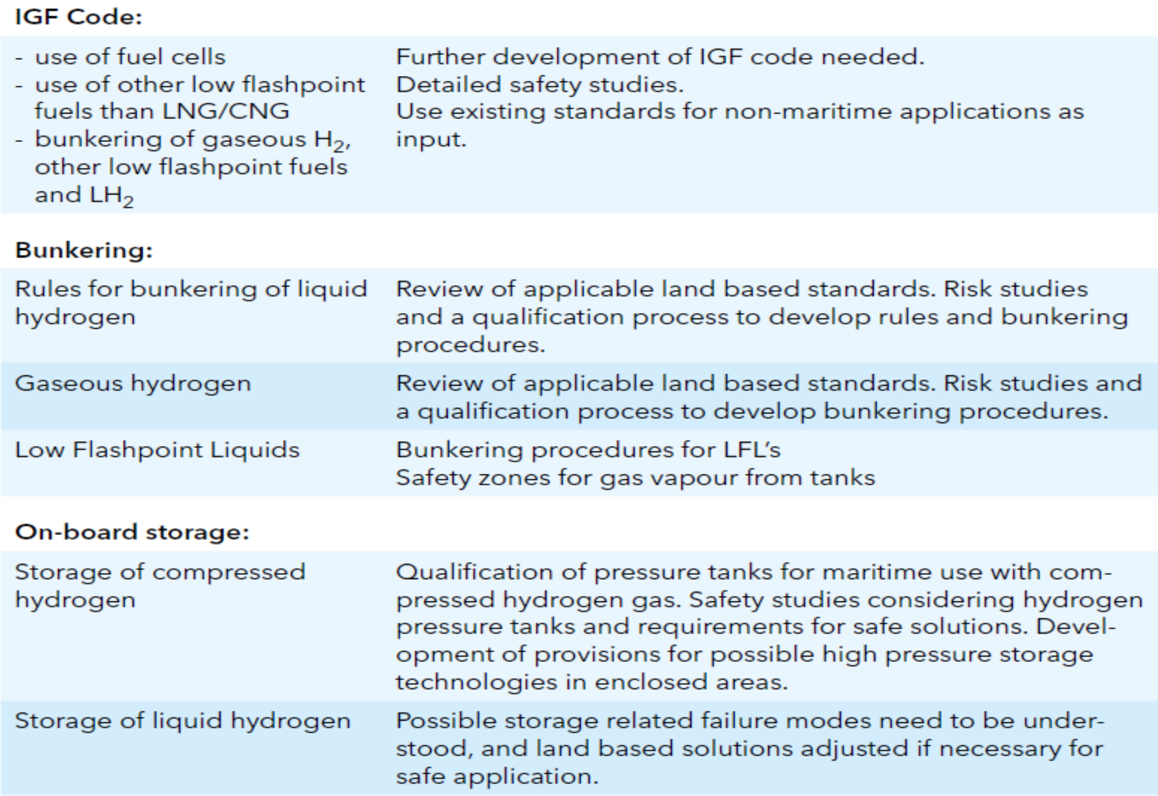

IGF Code:	
- use of fuel cells - use of other low flashpoint fuels than LNG/CNG - bunkering of gaseous H_2, other low flashpoint fuels and LH_2	Further development of IGF code needed. Detailed safety studies. Use existing standards for non-maritime applications as input.
Bunkering:	
Rules for bunkering of liquid hydrogen	Review of applicable land based standards. Risk studies and a qualification process to develop rules and bunkering procedures.
Gaseous hydrogen	Review of applicable land based standards. Risk studies and a qualification process to develop bunkering procedures.
Low Flashpoint Liquids	Bunkering procedures for LFL's Safety zones for gas vapour from tanks
On-board storage:	
Storage of compressed hydrogen	Qualification of pressure tanks for maritime use with compressed hydrogen gas. Safety studies considering hydrogen pressure tanks and requirements for safe solutions. Development of provisions for possible high pressure storage technologies in enclosed areas.
Storage of liquid hydrogen	Possible storage related failure modes need to be understood, and land based solutions adjusted if necessary for safe application.

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Fuel cell System:

Safe handling of hydrogen releases	Review of and update of fuel cell rules and regulations. Risk studies to improve understanding of possible safety critical scenarios including fire and explosion to recommend risk controlling measures.
Ventilation requirements	The fuel specific properties must be considered. Relevant and realistic hydrogen dispersion simulations needed to evaluate and/or update ventilation requirements.
New arrangement designs	Need for improved understanding of system design issues, new technology challenge existing regulations
Piping to fuel cell system	Knowledge and safety assessments needed to identify needs to adjust LNG requirements for the use of LH.
Reforming of primary fuel	Reformer safety issues should be explored and documented

Ship life phases:

Best practices/Codes for hydrogen, LFL fuels and fuel cell installations	Procedures should be developed for commissioning, docking, maintenance to reflect the properties of hydrogen and other LFL fuels.

Fuel specific:

Hydrogen	Comprehensive safety studies considering hydrogen specific properties, behaviour and conditions needed for the use of hydrogen in shipping applications

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Scenario	Ship type	Fuel Cell type
1	Ro-Pax ferry	SOFC with reformer and WHR LNG as primary fuel
2		HT PEM FC with reformer Methanol as primary fuel
3		PEM FC fueled with hydrogen
4	Gas Carrier	SOFC with reformer and WHR LNG as primary fuel
5		HT PEM FC with reformer Methanol as primary fuel
6		PEM FC fueled with hydrogen

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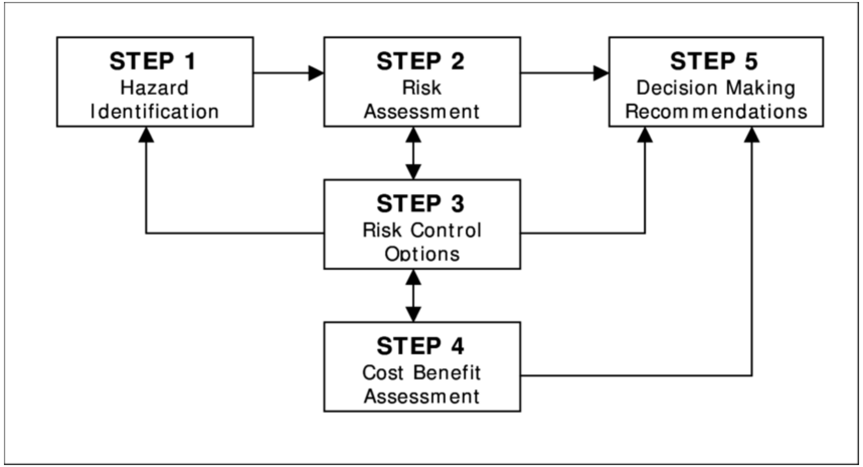
HAZID Team

Company	Expertise / Function
EMSA	Observer
TKMS	FC Design and arrangement
Meyer Werft	FC Design and arrangement
Meyer Werft	Methanol Fuel System design
Meyer Werft	Electrical Integration
Serenergy	FC Manufacturer
sunfire	FC Manufacturer
TUB	FC Design and arrangement
TKMS	Electrical Integration
ATG	FC boat operator
DNV GL	Project manager
DNV GL	Facilitator
DNV GL	IMO Rules, Fuels and Fuel Cells
DNV GL	Hydrogen Risk Assessment
DNV GL	Fuels and Fuel Cells
DNV GL	Risk Assessment



STEP 1 Hazard Identification

STEP 2 Risk Assessment

STEP 3 Risk Control Options

STEP 4 Cost Benefit Assessment

STEP 5 Decision Making Recommendations

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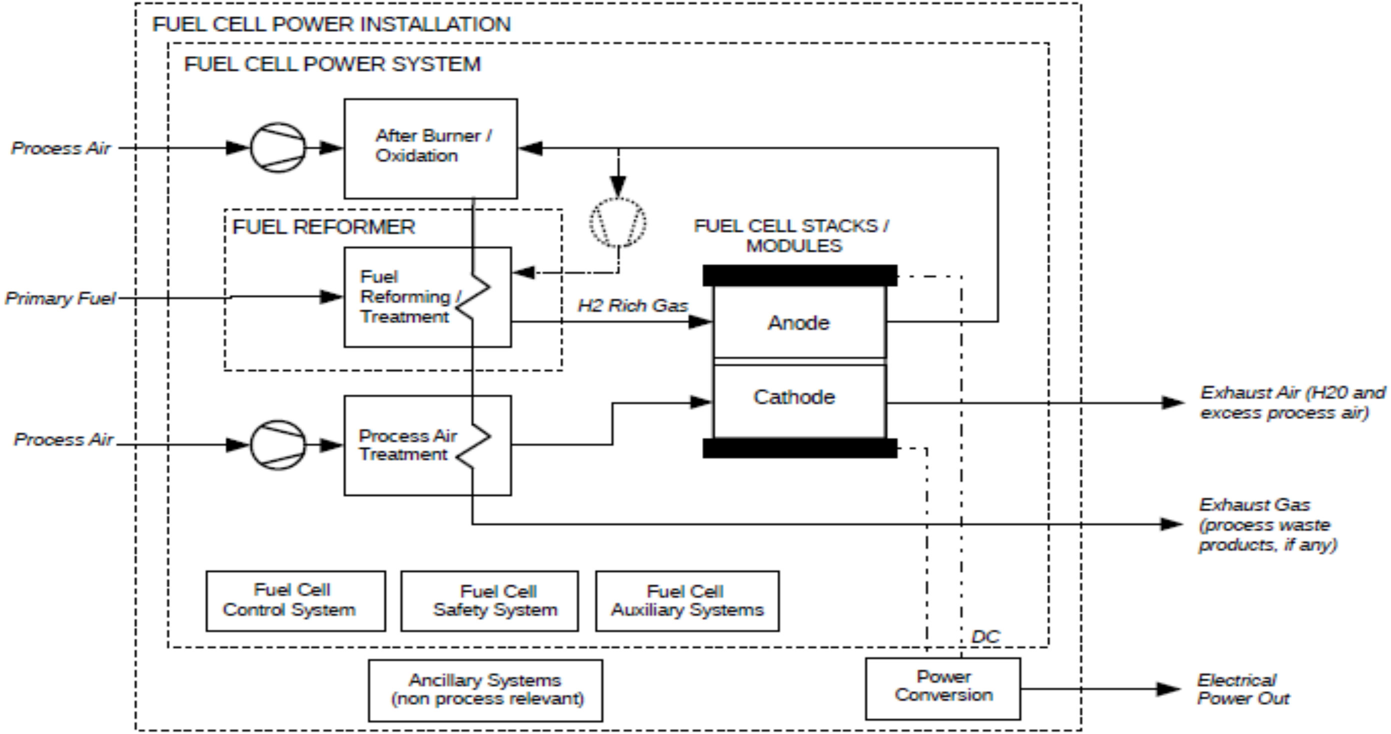
First things first! – Need to define adequately the Boundaries of different elements



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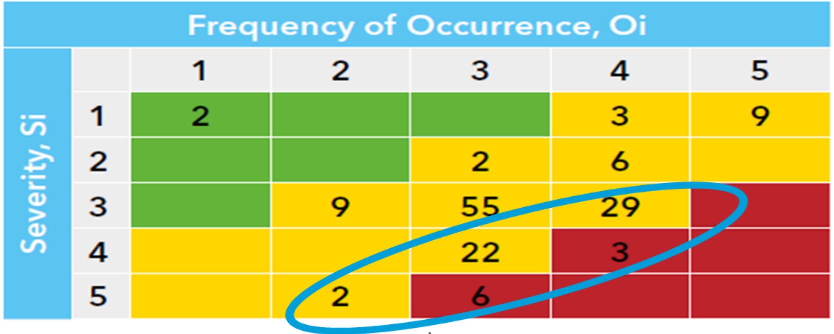
Results

Risk matrix from initial evaluation



	Frequency of Occurrence, Oi				
Severity, Si	1	2	3	4	5
1	🟩 2	🟩	🟩	🟨 3	🟨 9
2	🟩	🟩	🟨 2	🟨 6	🟨
3	🟩	🟨 9	🟨 55	🟨 29	🟥
4	🟨	🟨	🟨 22	🟥 3	🟥
5	🟨	🟨 2	🟥 6	🟥	🟥

Figure C.6: Criticality Matrix of overall 146 initially rated failure scenarios

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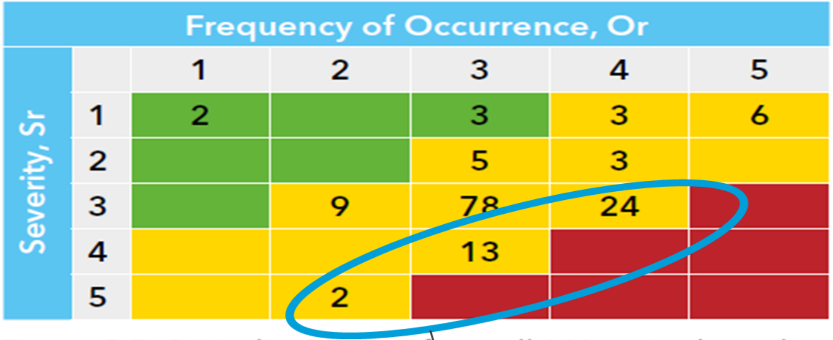
Risk matrix with safeguards implemented



	Frequency of Occurrence, Or				
Severity, Sr	1	2	3	4	5
1	🟩 2	🟩	🟩 3	🟨 3	🟨 6
2	🟩	🟩	🟨 5	🟨 3	🟨
3	🟩	🟨 9	🟨 78	🟨 24	🟥
4	🟨	🟨	🟨 13	🟥	🟥
5	🟨	🟨 2	🟥	🟥	🟥

Figure C.7: Criticality Matrix of overall 146 revised rated failure scenarios

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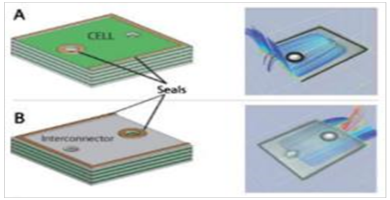
Results – most critical findings

Strong Exothermic reaction of reformer material

Picture courtesy of Oel-Waerme-Institut GmbH

Internal leakage in FC Module



Picture courtesy of Ecole Polytechnique Fédérale de Lausanne

High energy collision penetrating LH2 tank

Rupture of tank with compressed H2

Picture courtesy of ASME

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Results – most critical findings

Leakage of hydrogen rich gases

Failure of pressure reduction

Picture Courtesy of Long Tsuen Industria

Failure of electrical power conditioning system

Thermal runaway of energy buffer (Battery)

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Results – most critical findings

Loss of inert gas system

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🟨	🟨	🟥	🟥	🟥

Vehicle crash penetrating Fuel Cell System

Picture courtesy of Peter MacDiarmid/Getty Images

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Leakage during bunkering of hydrogen

🟩	🟩	🟩	🟨	🟨
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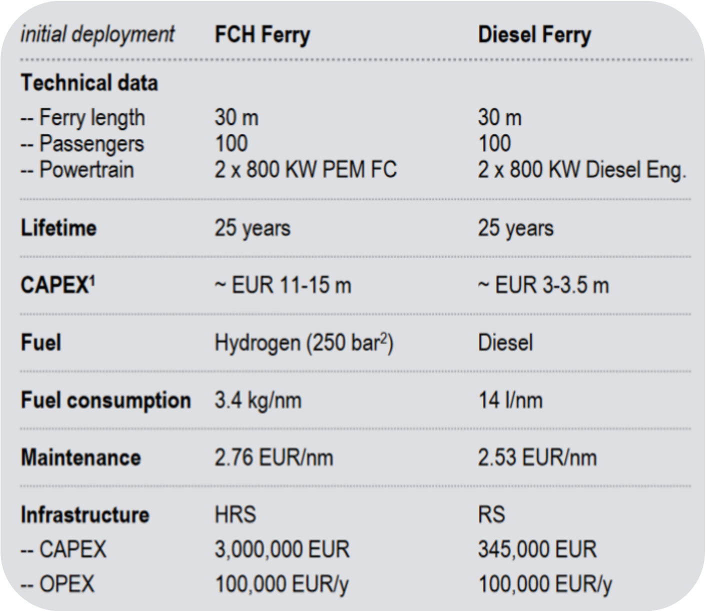
Picture Courtesy of Seatrade Maritime News

Preliminary business case – FC Ferry use in Europe

Assumptions and key parameters

Applications and technologies



initial deployment	**FCH Ferry**	**Diesel Ferry**
Technical data		
-- Ferry length	30 m	30 m
-- Passengers	100	100
-- Powertrain	2 x 800 KW PEM FC	2 x 800 KW Diesel Eng.
Lifetime	25 years	25 years
CAPEX[1]	~ EUR 11-15 m	~ EUR 3-3.5 m
Fuel	Hydrogen (250 bar[2])	Diesel
Fuel consumption	3.4 kg/nm	14 l/nm
Maintenance	2.76 EUR/nm	2.53 EUR/nm
Infrastructure	HRS	RS
-- CAPEX	3,000,000 EUR	345,000 EUR
-- OPEX	100,000 EUR/y	100,000 EUR/y

1) Incl. cost of initial development, testing, permitting/licensing/approvals (excl. possibly necessary fuel cell stack replacements)

2) Alternative tanks pressure between 200-700 bar

Use case

- Starting in 2021, a fuel cell powered passenger ferry will offer daily public transportation between to cities along the costal line of a European province with ~100,000 inhabitants
- With a top speed of ~28 kn and average speed of ~22 kn, the ferry will offer 360 round trips à 115 nm per year, requiring one (overnight) refuelling at the home port
- Resulting annual operations in this use case:
  - Total annual distance travelled: ~ 33,800 nm
  - Annual energy requirements: ~1,870,000 kWh (~6,300 kWh/d)
  - Annual hydrogen consumption: ~122,500 kg (~390 kg/d)

Exogenous factors

- Source of hydrogen: electrolysis from (low-cost) hydropower
- Cost of hydrogen: 3.5 EUR/kg
- H2 refuelling infrastructure: one refuelling station at the home port, synergies with other port-related FCH applications (e.g. forklift trucks)
- Cost of Diesel: 1.01 EUR/l
- CO2 footprints of green / grey hydrogen : 0 / 9 kg CO2/kg
- CO2 footprints of diesel : 2.64 kg CO2/l
- NOX footprints of diesel: 0.004 g/l

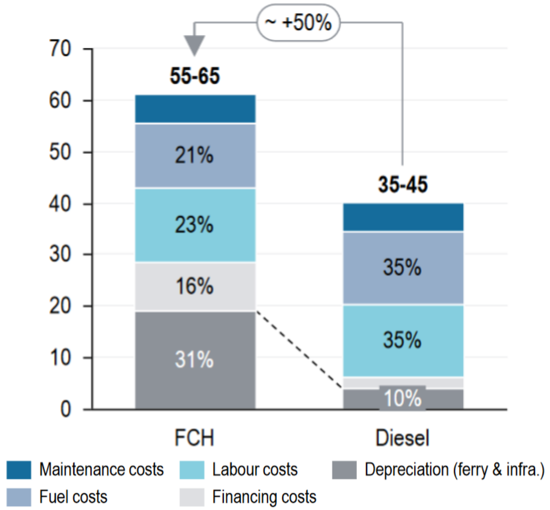
Source: Roland Berger

Business case and performance overview

FCH ferry would likely yield a significant cost premium over a diesel ferry – significant CO2 savings expected, esp. with green H2

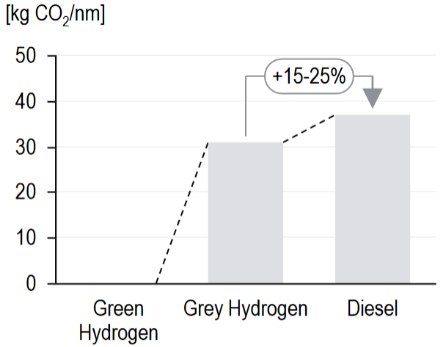
Economic

Estimated annualised Total Cost of Ownership [EUR/nm]



Environmental

- Zero local emissions of CO2, pollutants such as NOx, fine dust particles when using green hydrogen
- CO2 emissions well to wheel dep. on fuel source and fuel efficiency; in this example, a green hydrogen fuel cell ferry saves nearly 1,250 t CO2 p.a.
- **Comparison of CO2 emissions**



Technical/Operational

- Pure FCH electric ferries are currently in a development phase, first pilot demonstration projects with prototypes will be starting within the next 5 years
- Medium-term commercialisation unlikely, initial priorities are successful demonstration projects in areas with high need for decarbonisation of maritime public transport, e.g. Scandinavia, Mediterranean
- Challenges: initial regulatory framework and permitting (e.g. refuelling protocols, FCH powertrain for maritime appl.), hydrogen supply (quantities, cost efficiency)
- Potential to meet same operational requirements (range, refuelling time) – like diesel/MGO ferries

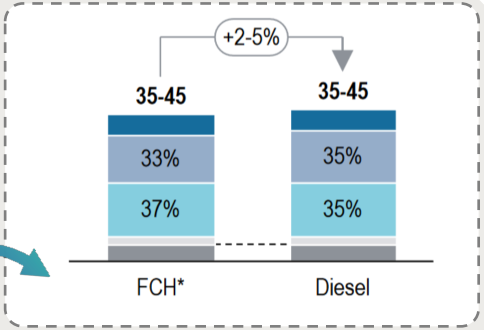
Source: Roland Berger

CAPEX of ferry and infrastructure as well as cost of hydrogen are key determinants for the business case at hand

Capital cost of FCH ferry and hydrogen infrastructure

- Highly dependent on the **technical specifications** which in turn derive from the **deployment use. Strong regional differences**; initial costs for development, testing and permitting/certification as well as cost of refuelling infrastructure are decisive factors

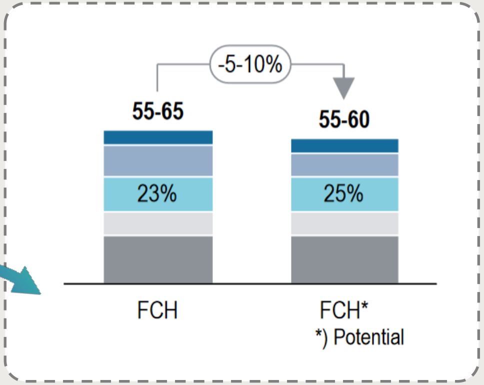
If capital cost of ferry and refuelling infrastructure were reduced to diesel levels, TCO would fall below diesel levels



Hydrogen supply and cost of hydrogen

- Relatively **high volumes of hydrogen** consumption (e.g. here nearly 400 kg per day and vessel) require large supplies, storage and refuelling capacities – supplying green hydrogen from large-scale electrolysis with cheap renewable electricity might be the ideal long-term solution

Reducing the price of hydrogen to 2.50 EUR/kg leads to a reduction in TCO of 2-5 EUR/nm (or -5-10%) - strong regional differences



Source: Roland Berger