Hybridization and Electrification of Propulsion Systems for Inland Waterways

CIMAC CASCADES - September 22, 2021

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Green Image and Stringent Legislation are pushing New Technologies in Marine Industry

CO_2

40% reduction in 2030

70% reduction in 2050

compared to 2008

SO_2

Global fuel limit of 0.5% in 2020

Greenhouse Gases

50% reduction in 2050

compared to 2008

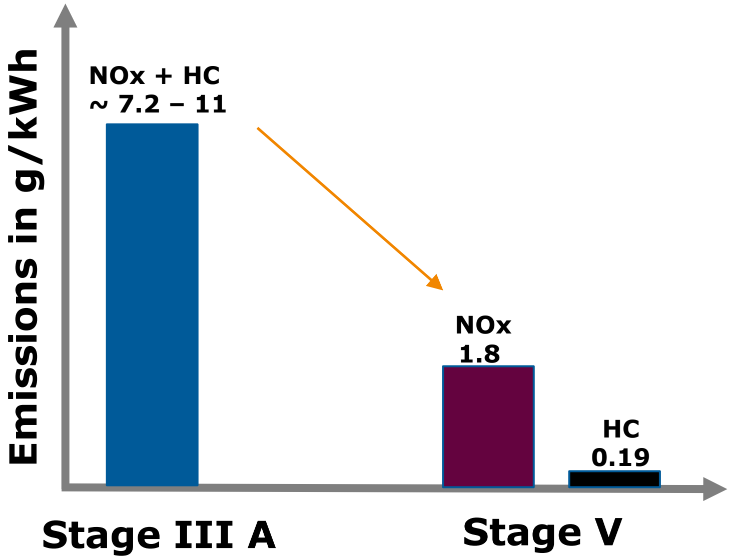
Heavy Fuel Oil

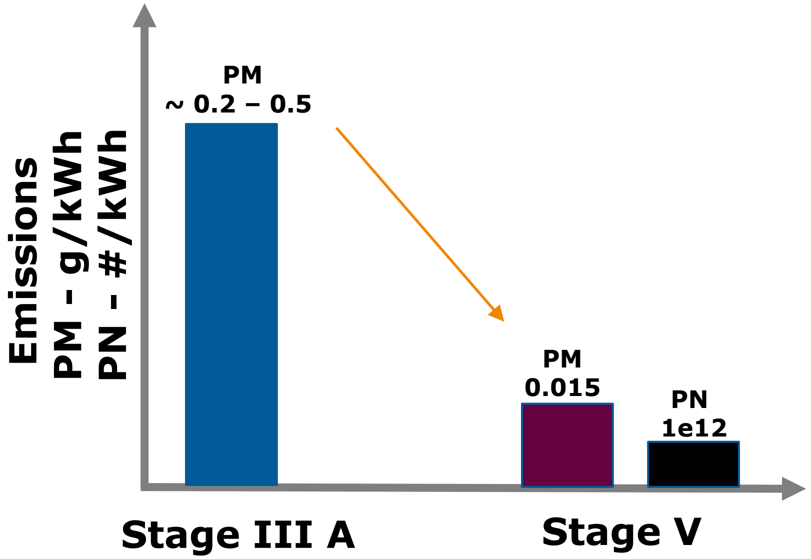
Ban on the use and carriage of heavy fuel oil (HFO) in the Arctic

Fuel consumption data collection by authorities started in 2019

EU Stage V - Inland Waterway Vessels (IWV)

Stage V regulation, mandatory date of application:

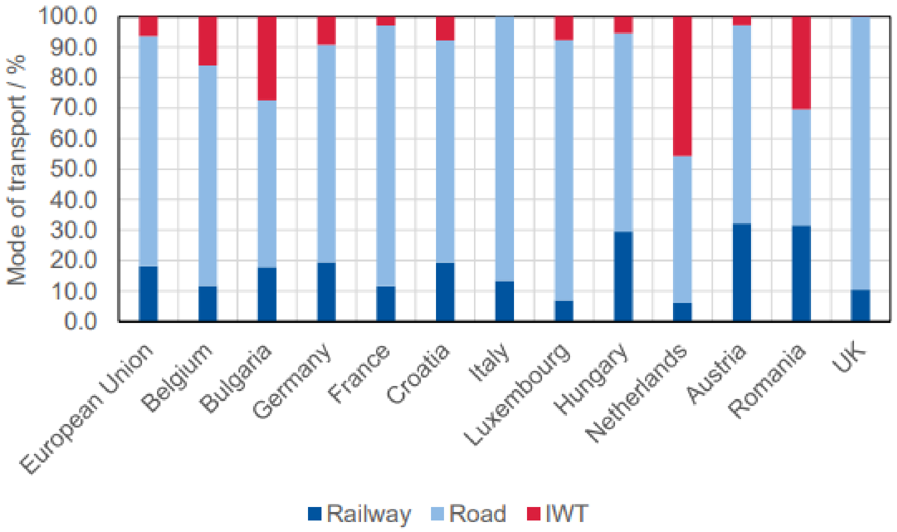




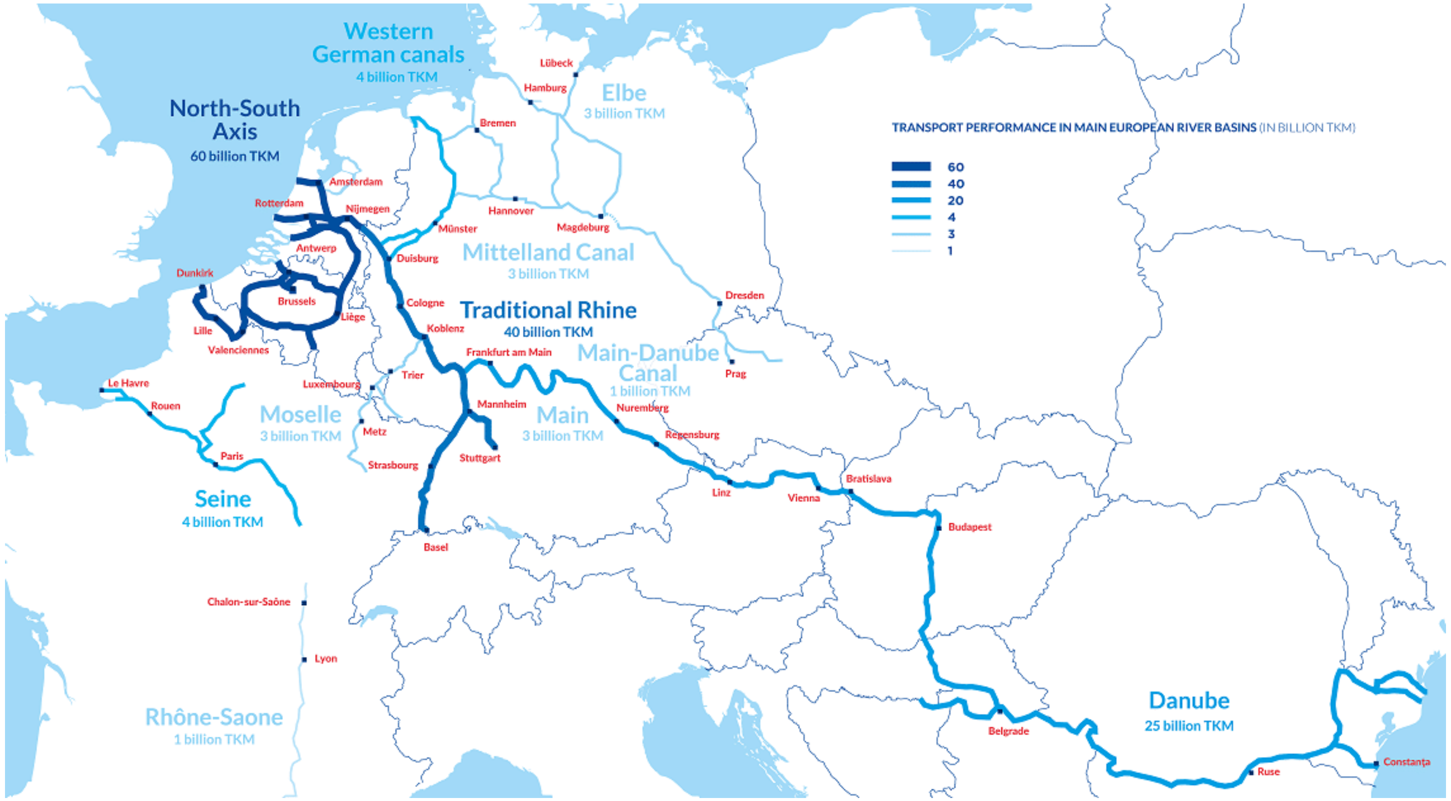
- Apart from the reduction in allowable PM emissions, Stage V introduces PN limits for mid to large engines (P ≥ 300 kW)
- Introduction of PN limit makes the application of DPF mandatory
- Emissions regulations are defined for both propulsion and auxiliary engines

The European Inland Waterway Network

- The European inland waterways cover a length of over 41.500 km, divided into navigable rivers and lakes and artificial canals.



Split of freight transport per country as percentage of ton-kilometers in 2015 [1] [10]



Freight traffic on European inland waterways [8]

European Inland Waterway Fleet

- More than 17000 vessels are operated on the European inland waterways
- Pure battery-electric propulsion systems can only cover smaller distances within short-sea shipping and transportation on urban waterways
- Hydrogen and fuel cells considered as a viable zero-emission solution for inland waterway transport, coastal and short-sea shipping

Country	Dry cargo vessels	Tanker vessels	Push boats	Tug-boats	Cargo-boats	Tank barges	Total
Belgium	806	216	94	10	230	8	1364
Germany	916	419	285	140	789	44	2593
France	860	44	93	0	383	47	1427
Luxem-bourg	8	16	11	0	0	2	37
Netherlands	3993	1240	649	479	1135	51	7547
Switzerland	17	55	0	2	4	3	81
Rhine countries	**6600**	**1990**	**1132**	**631**	**2541**	**155**	**13049**
Bulgaria	26	4	38	13	161	5	247
Croatia	8	5	10	32	98	21	174
Hungary	78	2	26	53	300	4	463
Moldova	8	5	1	10	26	0	50
Austria	6	5	10	0	54	15	90
Poland	109	2	-	-	431	0	542
Romania	75	4	183	69	984	97	1412
Serbia	62	5	40	82	345	37	571
Slovakia	26	4	41	1	119	32	223
Czech Re-public	44	0	-	-	145	0	189
Ukraine	44	3	73	15	472	22	629
Central and East-ern Europe	**486**	**39**	**422**	**275**	**3135**	**233**	**4590**
Total	**7086**	**2029**	**1554**	**906**	**5676**	**388**	**17639**

European inland waterway fleet [2]


[4]


[6]

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Why Hydrogen and PEM Fuel Cells for Marine Applications

Zero Emission

With hydrogen produced from renewable energies, PEM (Proton Exchange Membrane) fuel cells are a zero-emission solution for marine powertrains

High Efficiencies

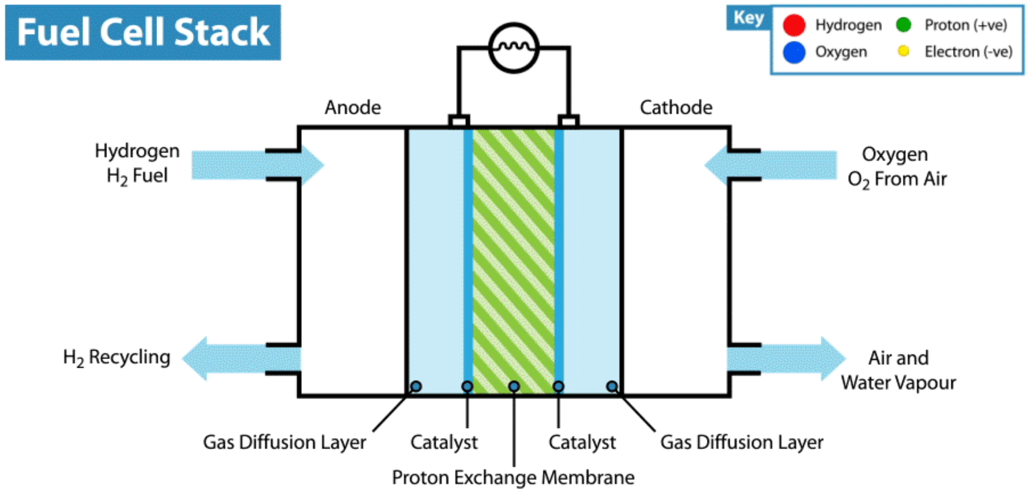
Peak Fuel Cell System efficiencies[1] of >60 % at low loads and e.g. 47 % at rated power
→ H_2 consumption has a dominating influence on TCO in heavy duty and marine applications

High Power Density

High power densities of PEM fuel cell stacks allow to package the required target power within a compact enclosure

High Dynamic Capabilities

Dynamics of t_{90} <1 s for automotive passenger car and ~3…5 s for HD applications allow to reduce the required battery capacity within a hybrid powertrain



[1] Efficiencies based on LHV (Lower Heating Value) of H_2 (25 °C)

AVL PEM Fuel Cell Stack & Fuel Cell System

Unit Cell

- The bipolar-plate and the MEA (Membrane Electrode Assembly) form a unit cell

Fuel Cell Stack

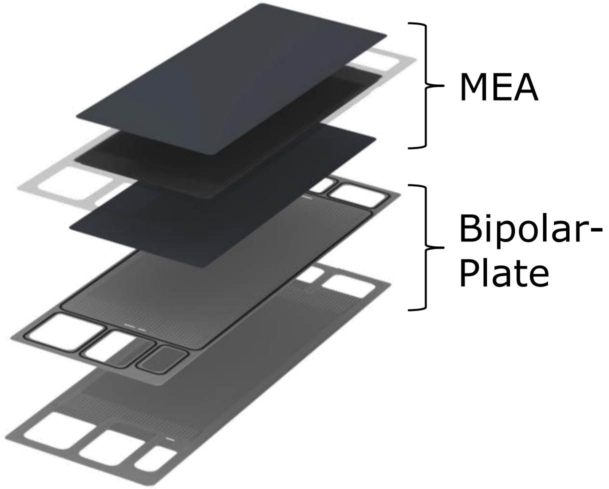
- The unit cell block (stacked unit cells) including end plates and compression hardware form a fuel cell stack

Fuel Cell System

- The fuel cell stack(s) incl. the Balance of Plant (BoP) components required for the supply and conditioning of reactants as well as cooling are called a Fuel Cell System

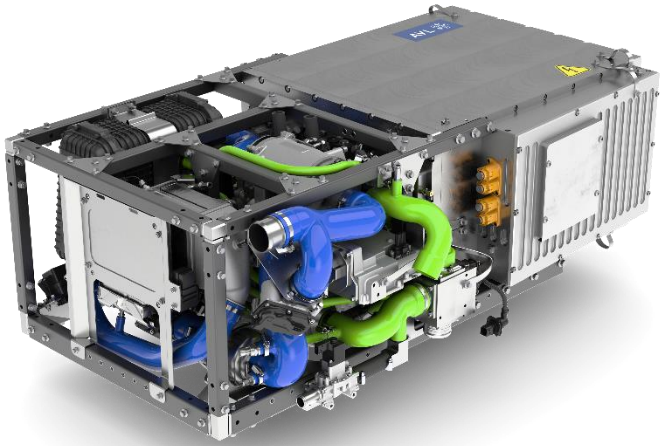
TECO Marine Fuel Cell System
https://teco2030.no/

Unit Cell



Fuel Cell Stack

150 kW HD Fuel Cell System (HyTruck)



Generic Marine PEM Fuel Cell System

FC Stacks

H_2 and O_2 are converted to electrical energy in an electrochemical reaction

Ox (Oxidant) System

Supply and conditioning of ambient air to the FC stacks

Fx (Fuel) System

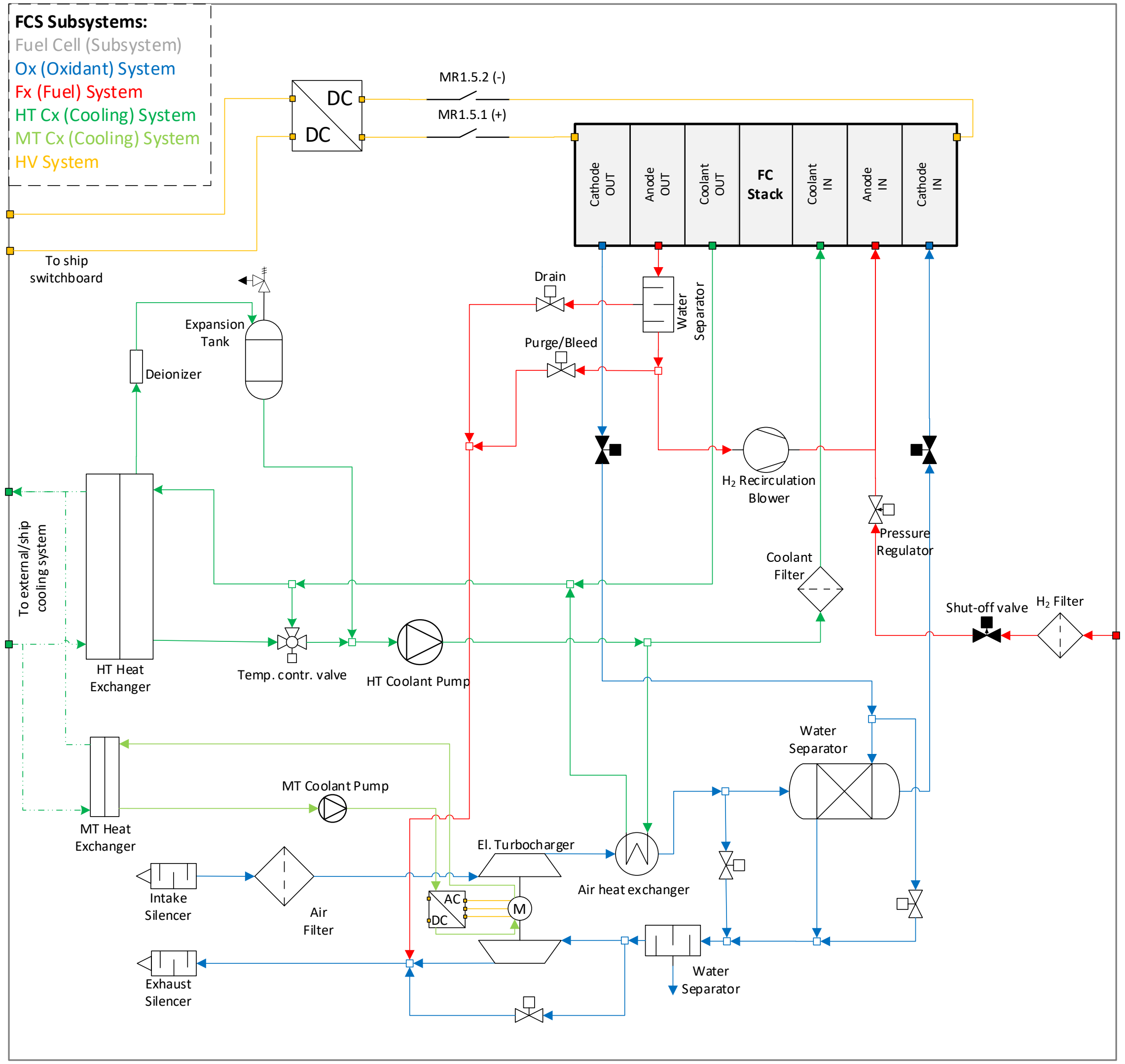
Hydrogen from a compressed gaseous (CGH2) or liquid (LH2) storage system is supplied to the FC stacks. Recirculation of excess H_2 and control of gas concentrations within the closed anode loop.

Cx (Cooling) Systems

Waste heat of the FC stacks and BoP components is rejected to an external cooling system or ambient

HV System

The target operating point of the FC System is controlled with power electronics (e.g. DC/DC converter) and electrical energy is supplied to the powertrain



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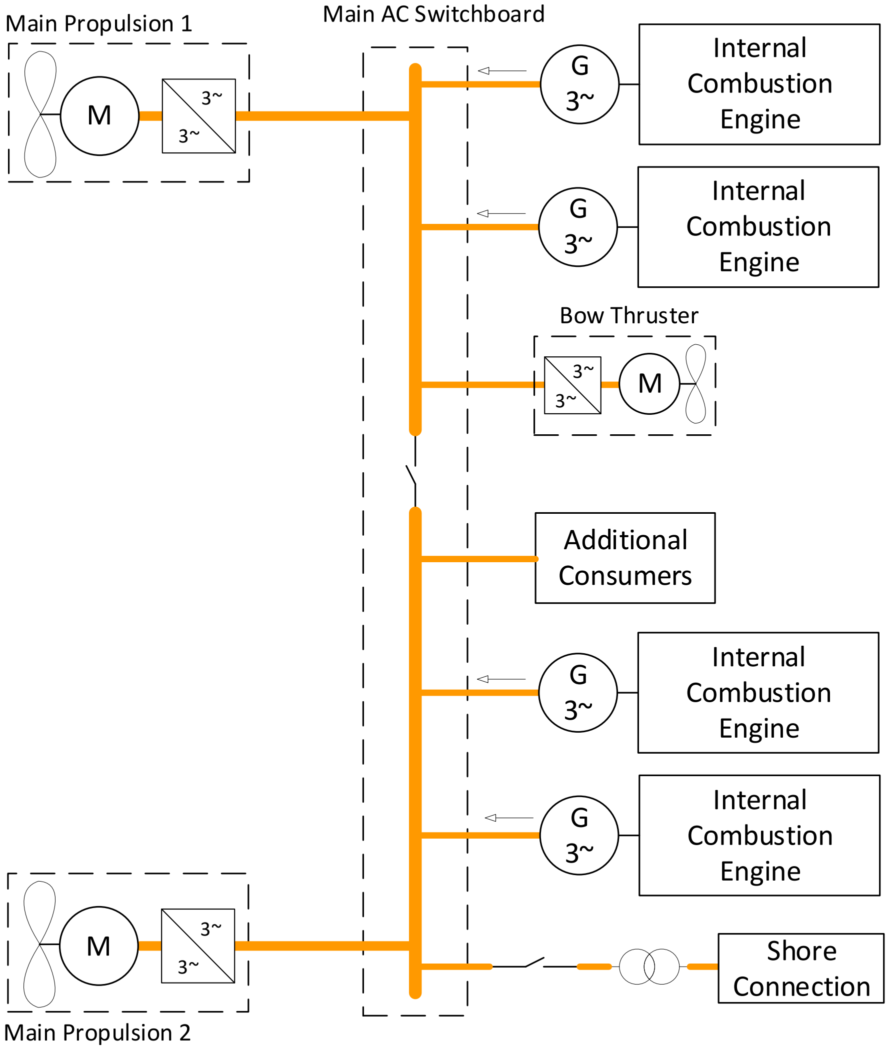
Hybrid Powertrain – Inland Waterway Vessels (1)

- Some vessels for inland waterways are **already equipped with a diesel-electric powertrain** → Diesel generators connected to e.g. a 690 VAC 60 Hz switchboard

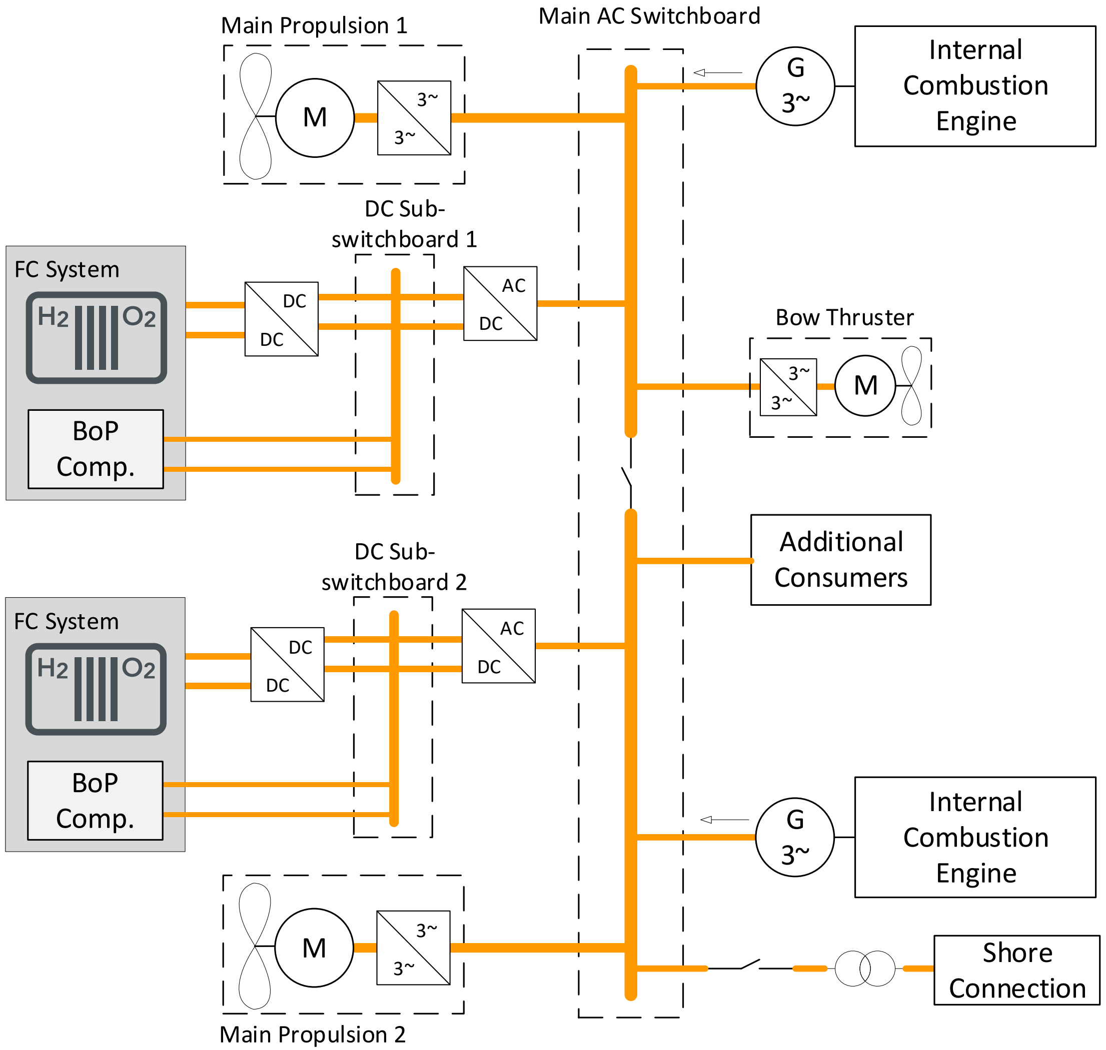
Simplified, generic Diesel-Electric Powertrain



Hybrid Powertrain – Inland Waterway Vessels (2)

- Some vessels for inland waterways are **already equipped with a diesel-electric powertrain** → Diesel generators connected to e.g. a 690 VAC 60 Hz switchboard
- As **retrofit**, **fuel cell systems** can be installed into the powertrain, replacing single ICE generators

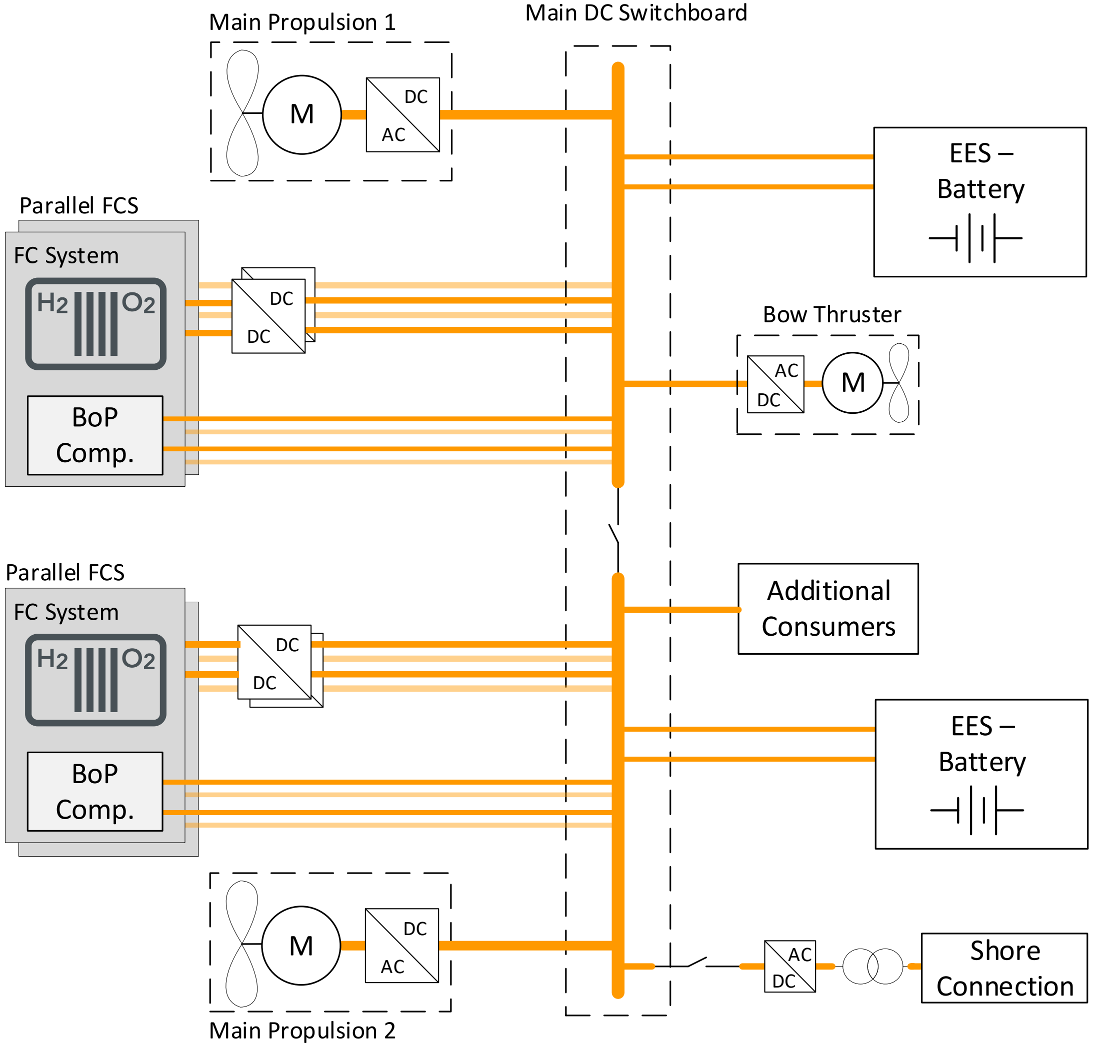
Simplified, generic hybrid ICE/FCS powertrain



Hybrid Powertrain – Inland Waterway Vessels (3)

- Some vessels for inland waterways are **already equipped with a diesel-electric powertrain** → Diesel generators connected to e.g. a 690 VAC 60 Hz switchboard
- As **retrofit**, **fuel cell systems** can be installed into the powertrain, replacing single ICE generators
- A **pure electric powertrain** can consist of **multiple parallel FCSs** to reach the target power and an **EES system (battery) for peak shaving** connected to a DC switchboard

Simplified, generic hybrid FCS/EES powertrain



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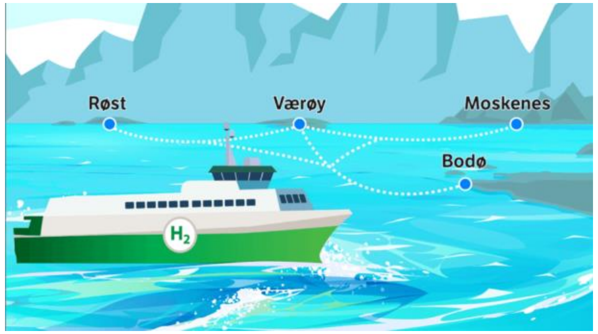
Hydrogen & Fuel Cell Projects in Shipping - Examples

Vestfjorden Ferry, Norway [7]

- Longest ferry connection in Norway with 278 km
- Vessels to go in operation 2025
- Tender specification: 85 % of the fuel must be hydrogen-based, remaining 15 % zero- or low-emission fuel



Flagship Project – H_2 Ferry MF Hidle [3]

- Route: Judaberg-Helgøy on the west coast of Norway (260 km/d)
- 3×200 kW PEM fuel cell modules
- Battery capacity planned 0-500 kWh (need for batteries is under consideration)

ELEKTA Push Boat [5]

- Experimental vessel for use in Berlin-Brandenburg region
- FC Systems: 3x100 kW
- Photovoltaic System: 2.7 kWp
- Electric Motors: 2x210 kW
- Accumulators: 2x1025 kWh
- H_2 Fuel Bundle: 750 kg

Green Hydrogen at Blue Danube [9]

- VERBUND project for production, transportation and use of green hydrogen
- Goal is to create a trans-European green hydrogen value chain
- Hydrogen produced in Austria, Bavaria and south-eastern Europe is transported via Danube to users in Austria and Germany

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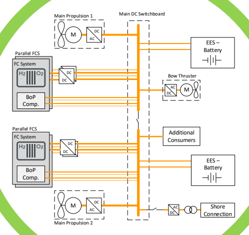
Challenges for Fuel Cells in Marine Applications



Legal Provision

- No satisfactory rules and/or requirements for hydrogen-powered ships from IMO, Flag States, or Class Societies
- IMO has however initiated a process to develop rules for fuel cells in the IGF Code.

Integration

- Challenging for different electric vessel powertrains → "standard" solution vs. purpose built
- Different voltage classes and interface requirements depending on the specific vessels and the power demand

System Complexity

- High target power require multiple FCS in parallel
- New challenges arise for complex FCS architectures, e.g. insulation resistance
- Hybridization leads to higher system complexity but also offers more degrees of freedom for optimization

Durability

- Marine specific requirements incl. lifetime of >35 000 h
- Challenge not only for FC stack but also BoP components → new development for marine applications
- But less demanding op. profile compared to automotive applications for e.g. dynamic operation

Costs

- Increased production volumes can significantly decrease CAPEX
- H_2 consumption has a dominating influence on total cost of ownership → Increased system efficiency and optimized powertrains required

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Summary

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- Green Image and Stringent Legislation are pushing new technologies in the marine industry
- Stage V introduced a significant reduction of allowed emissions for inland waterway vessels

- With H_2 produced from renewable energies, PEM fuel cell systems are a zero-emission propulsion solution for marine propulsion systems

- PEM fuel cell systems offer high efficiencies, high power density and high dynamics
- Hybrid powertrains with fuel cells and e.g. batteries lead to higher system complexity but also offer more degrees of freedom for optimization

- Multiple hydrogen and FC projects for marine applications are currently elaborated
- Marine PEM FCS are entering the market and first vessels with PEM FC are available

- Challenges like non-satisfactory rules, high system complexity, durability are to be solved
- This requires a close collaboration of system developers, integrators and regulatory bodies

Thank you

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HYTRUCK has received funding from the Austrian Climate and Energy Fund’s Energy Model Region programme under grant agreement No. 868790.

Abbreviations

AC	Alternating Current
BoP	Balance of Plant
CAPEX	Capital Expenditures
CGH2	Compressed Gaseous Hydrogen
DC	Direct Current
DNV	Det Norske Veritas
DPF	Diesel Particulate Filter
EE	Electrical and Electronics
EES	Electrical Energy Storage
FC	Fuel Cell
FCS	Fuel Cell System
HD	Heavy Duty
HT	High Temperature
HV	Hazardous Voltage or High Voltage
ICE	Internal Combustion Engine
IMO	International Maritime Organization
IWT	Inland Waterway Transportation
IWV	Inland Waterway Vessel
LHV	Lower Heating Value
LH2	Liquid Hydrogen
MEA	Membrane Electrode Assembly
MT	Medium Temperature
PDU	Power Distribution Unit
PEM	Proton Exchange Membrane
TCO	Total Cost of Ownership

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