EXTRAORDINARY STORIES

From space to ocean floor…

Fuel Cells and Hydrogen in Maritime Applications

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NORWEGIAN HYDROGEN FORUM

hydrogen.no

www.hydrogen.no/h2guide

National association with approx. 75 members, and 20 partners from public sector

nel · A Member of The Linde Group | AGA · IFE · Statoil · Statkraft · BIL · AABY AUTO · HYUNDAI · TOYOTA

Uno X · cmr Prototech · Ruter# · HYSTORSYS · FLOW OFOTEN · Universitetet i Tromsø · Berkel O. Steen

HYOP · HEXAGON COMPOSITES · UiO Universitetet i Oslo · SINTEF · KUNNSKAPSBYEN LILLESTRØM · GREENSTAT

Sjøfartsdirektoratet Norwegian Maritime Authority · ZERO · CerPoTech Ceramic Powder Technology · EnergiNorge · NTNU Det skapende universitet · Mercedes-Benz

AIR LIQUIDE · OREEC KUNNSKAPSBYEN CENTRE OF INNOVATION · FFI Forsvarets forskningsinstitutt · Smøkraft Foreninga · EGN ENERGIGASS NORGE · BELLONA · DNV·GL · HSN Høgskolen i Sørøst-Norge · ZEG Power

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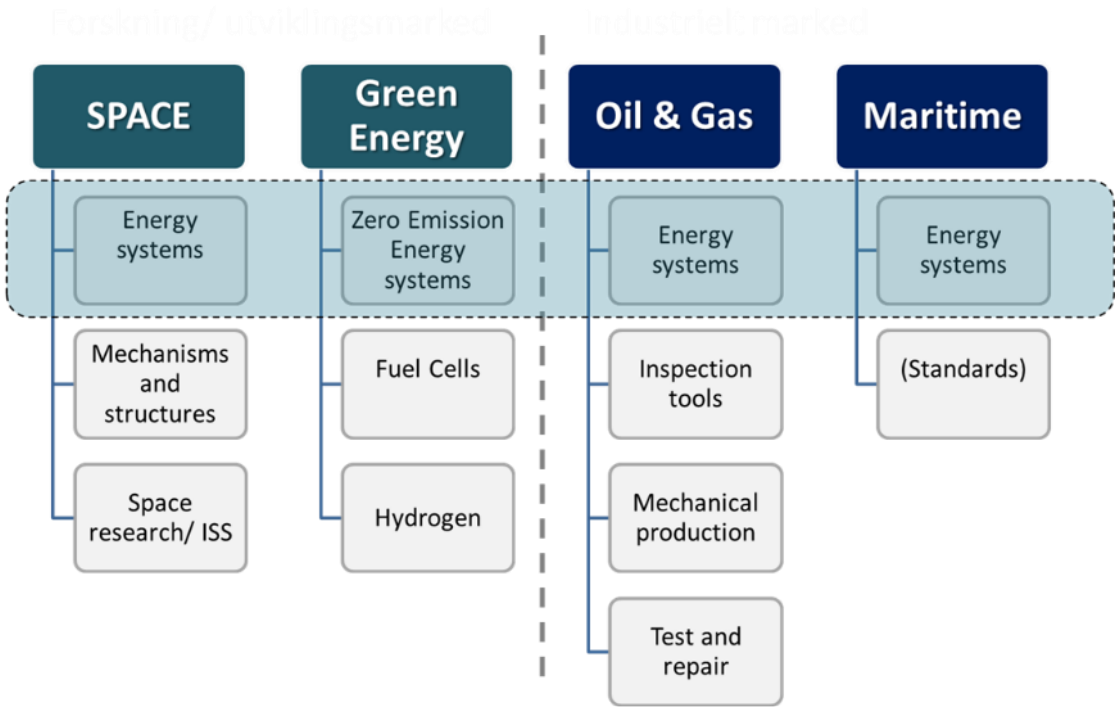
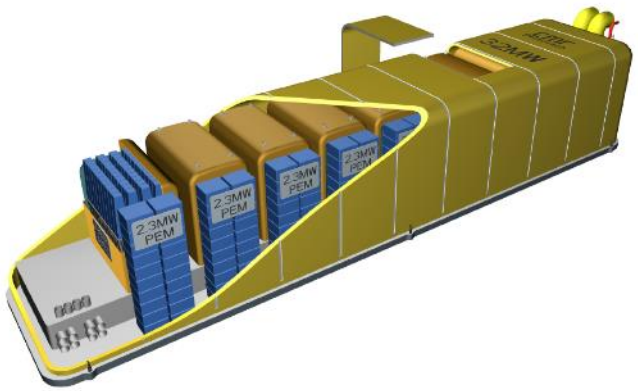
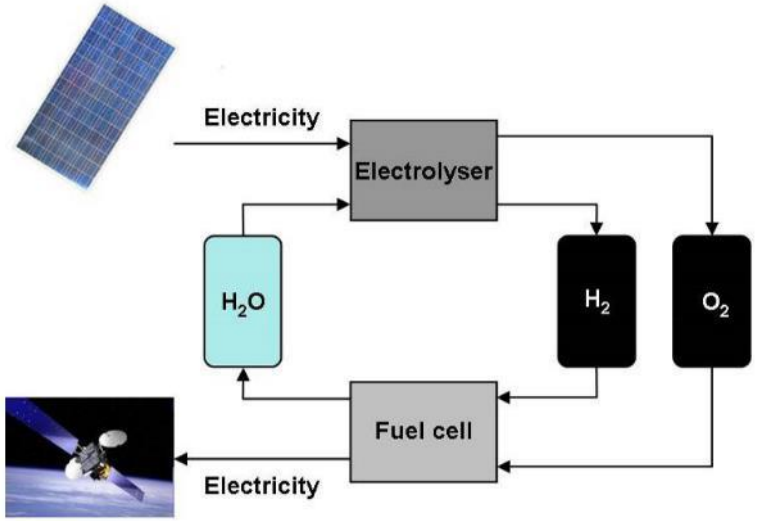
Background information

- Part of Christian Michelsen Research group
- Prototype development – from idea to product
- 25 years experience with research, development and testing of hydrogen and fuel cell technology
- Expertise in advanced design and manufacturing, system design and integration, and stack/complete system testing





CHEOP – Development of fuel cell system for offshore power supply and deep sea shipping applications



Development of Closed-loop Regenerative Fuel Cells Systems for space applications

Energy storage system for *Stratobus*

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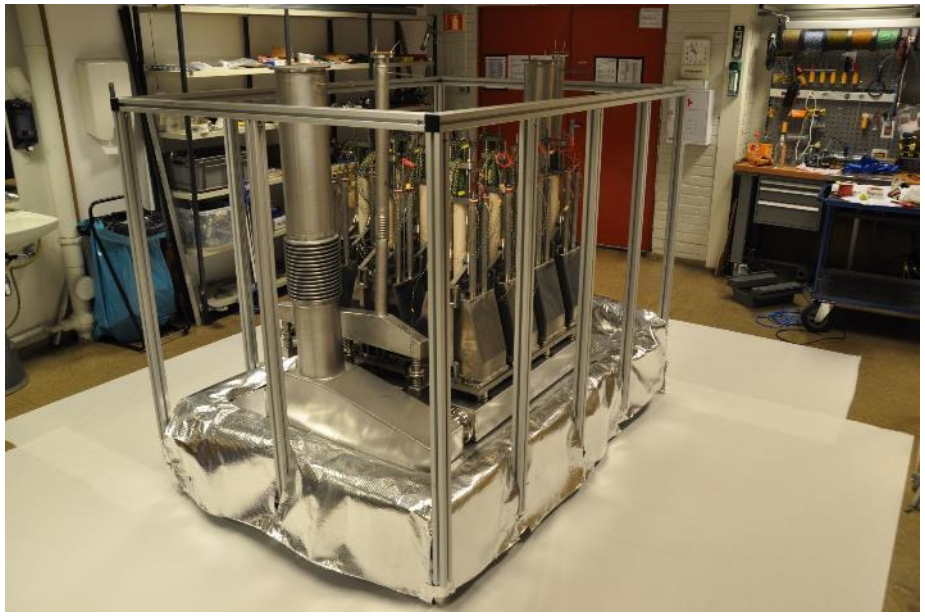
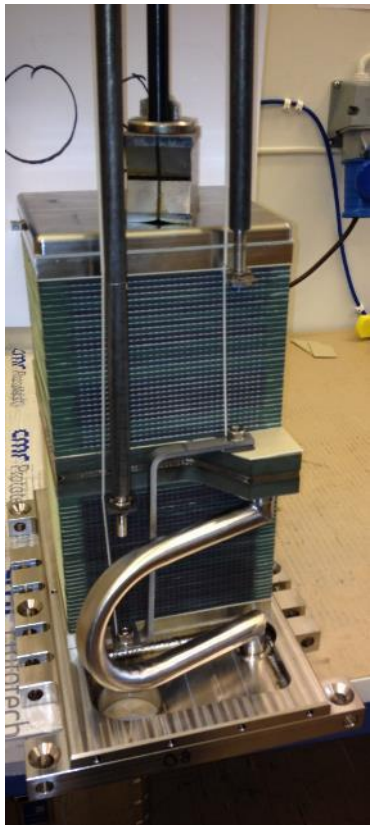
Solid Oxide Fuel Cells
Solid Oxide Electrolysis
PEM fuel cells
High Temperature PEM fuel cells
High pressure PEM electrolysis
Regenerative Fuel Cell Systems
Reforming



BioZEG - 20 kW SOFC

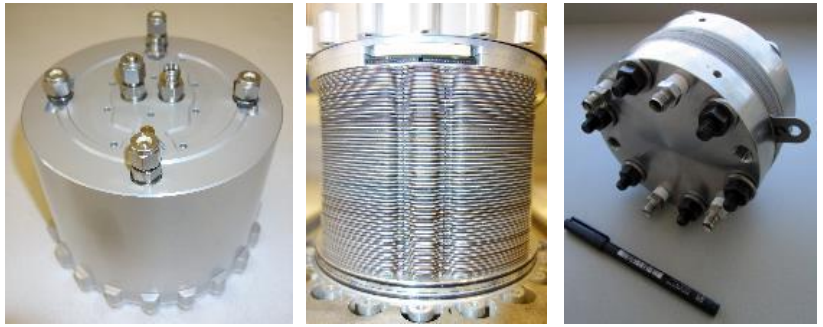


RSOFC stack

100 bar PEM electrolyser

Methane pyrolysis reactor

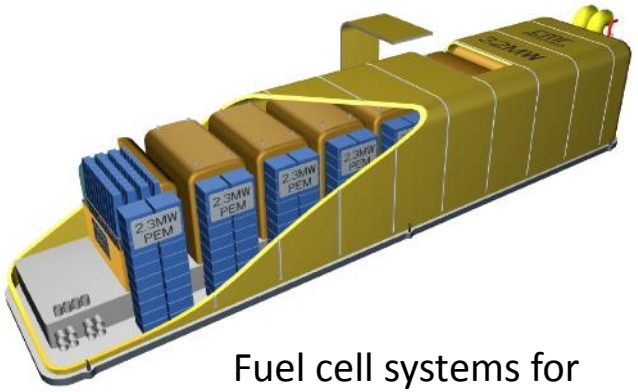
Space to Ocean Space



Light-weigh FC and ELY stacks for Space Applications.
15 years development for European Space Agency

H2 Viking – Zero emission Sunseeker Predator 95

Advanced manufacturing
- Ariane 5 structures



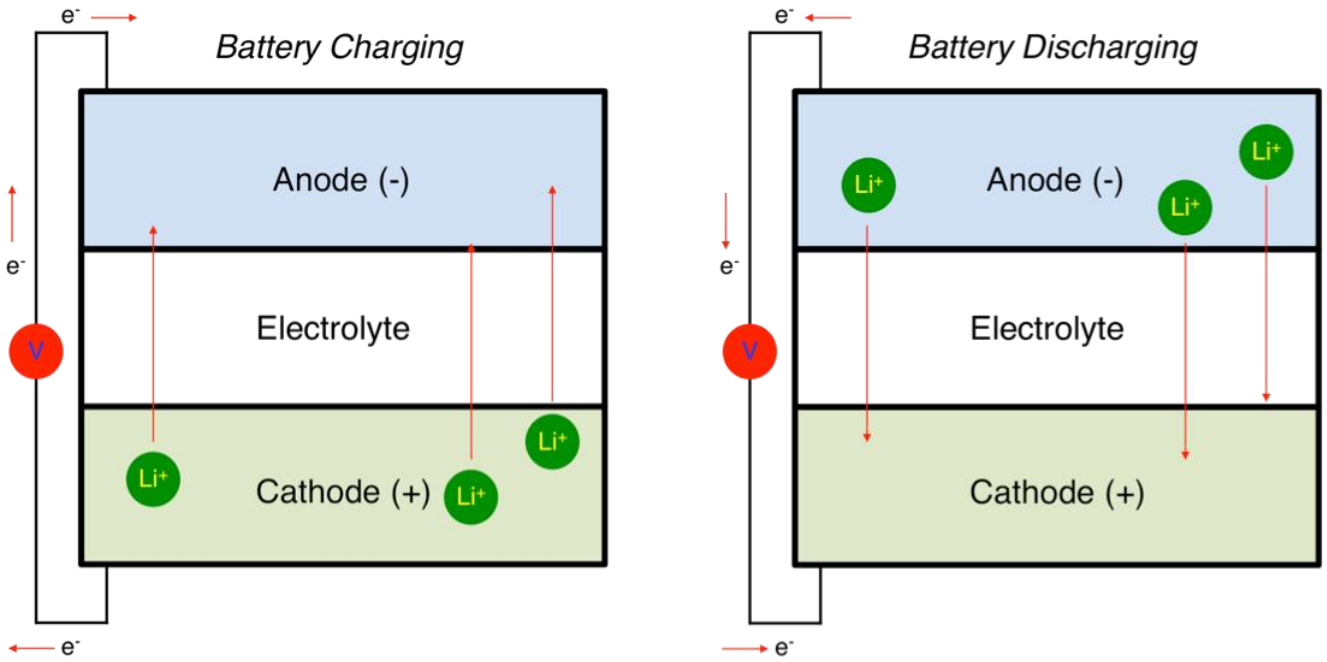
Fuel cell systems for
offshore power supply

H2 fueled 12,5 kW FC system incl batteries
and electric propulsion installed on MF
Vågen (2009-2011)

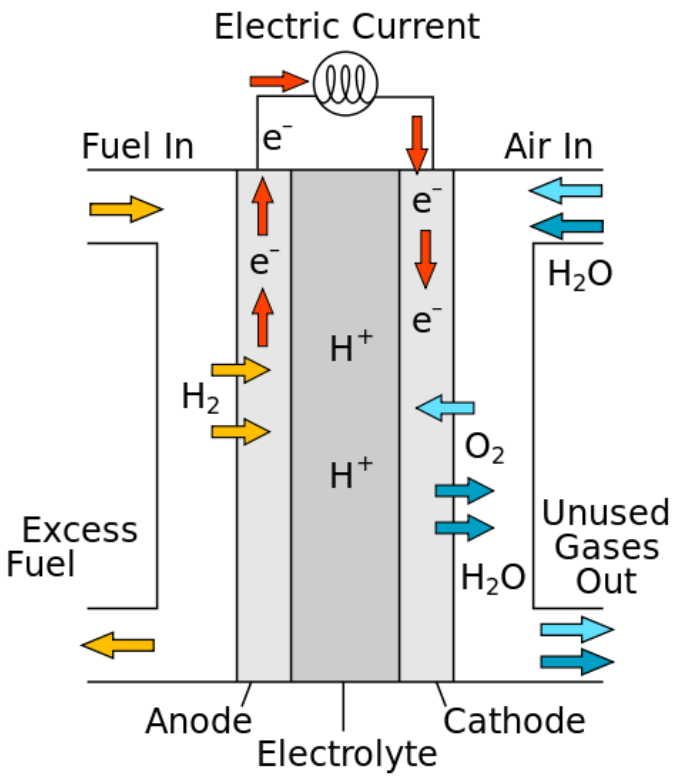
Foto: Siemens

- Maritime - obvious case for electrification
- Potential - significant reductions in energy consumption, emissions and total cost of ownership
- Optimization of zero emission electric powertrains
  - Aim is to design the most (cost) efficient solutions for a diversified energy scenario

Why Fuel Cells?



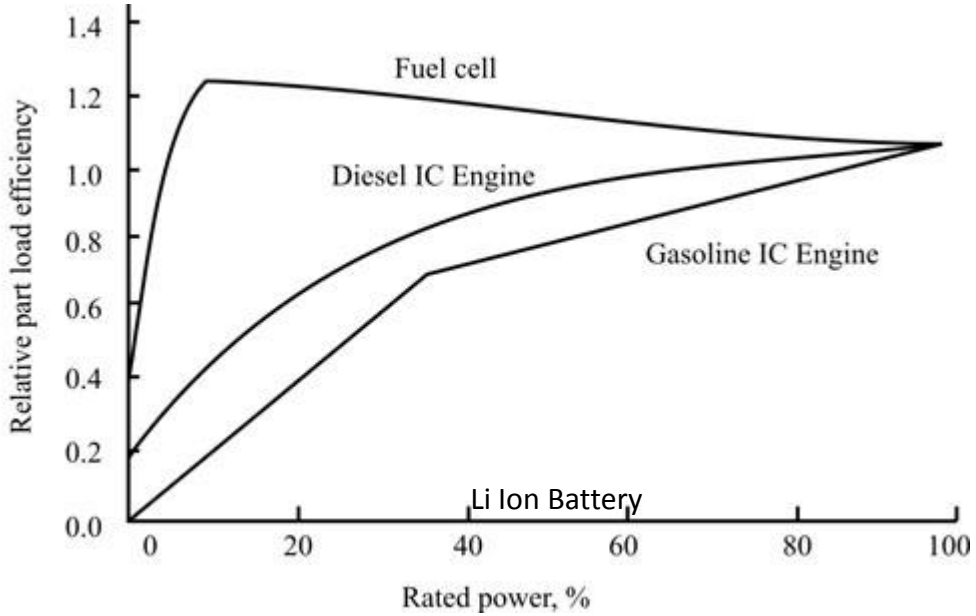
Li Ion Battery

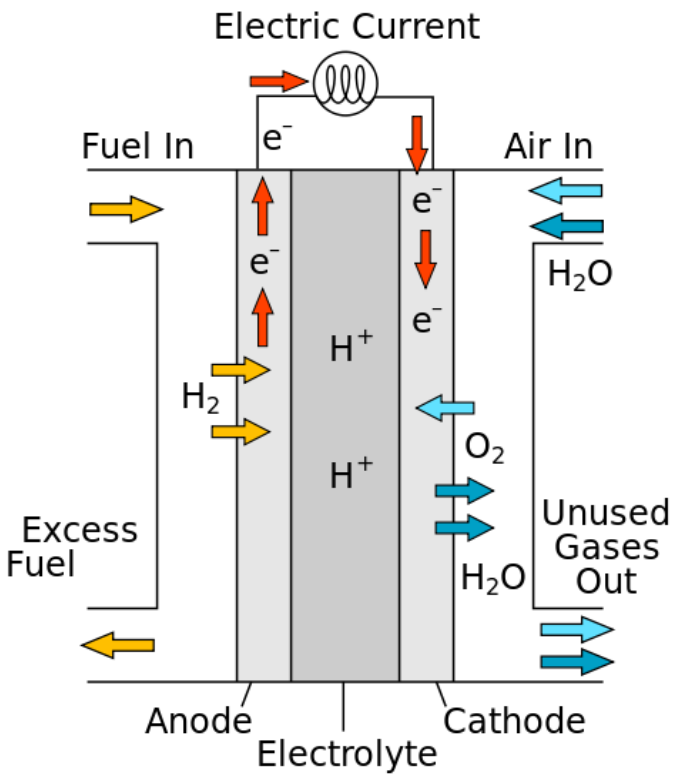


Proton Exchange Membrane FC

Why Fuel Cells?

- Enables zero emissions energy intensive applications with limited time/access to charging
- Low energy consumption $\eta_{FC} \sim 50 - 65\ \%$ + rest heat
- High part load efficiency

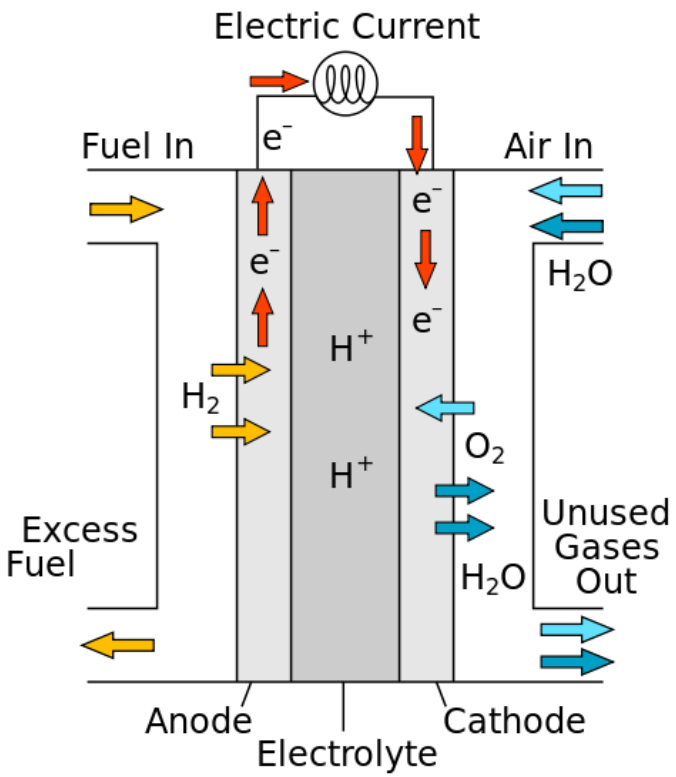




Proton Exchange Membrane FC

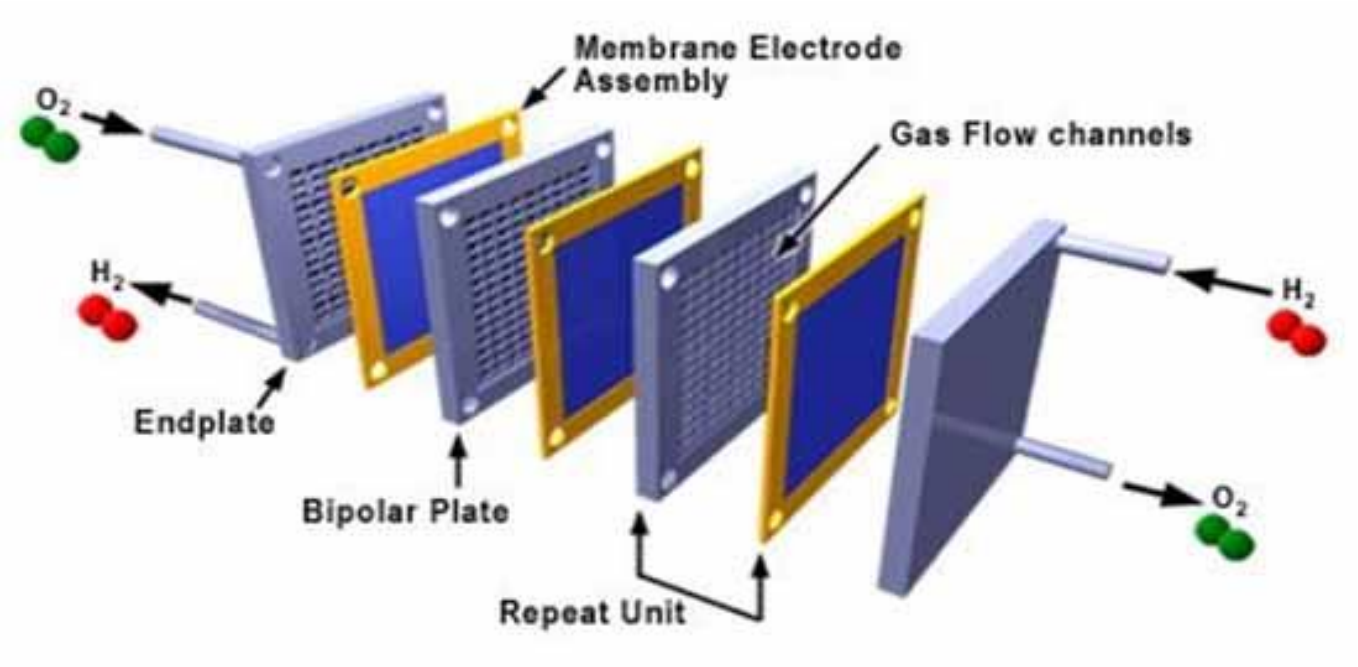
Why Fuel Cells?

- Enables zero emissions energy intensive applications with limited time/access to charging
- Low energy consumption $\eta_{FC} \sim 50 - 65\ \%$ + rest heat
- High part load efficiency
- No (significant) noise and vibrations
- Low complexity
- High level of redundancy
- High performance at low temperature
- Utilization of variable renewable energy sources – stabilizing power grids
- Fuel flexibility
  - Hydrogen, bio(m)ethanol, natural gas/biogas, ammonia



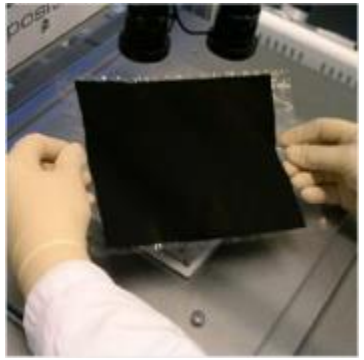
Proton Exchange Membrane FC

Fuel cell stack

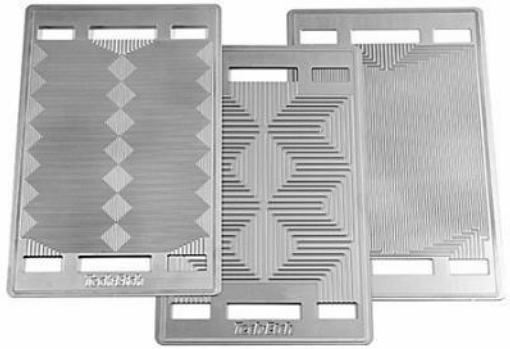


Proton Motor PEM automotive FC stack

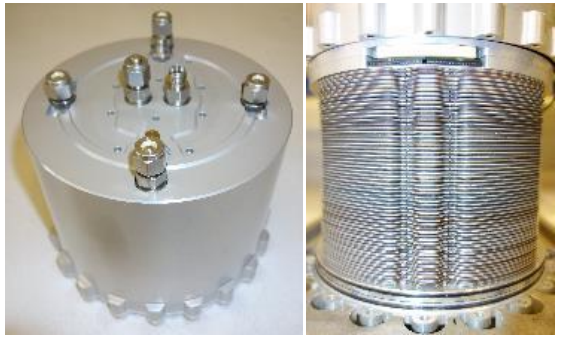
MEA



Bipolar plate



Prototech Space PEMFC stack



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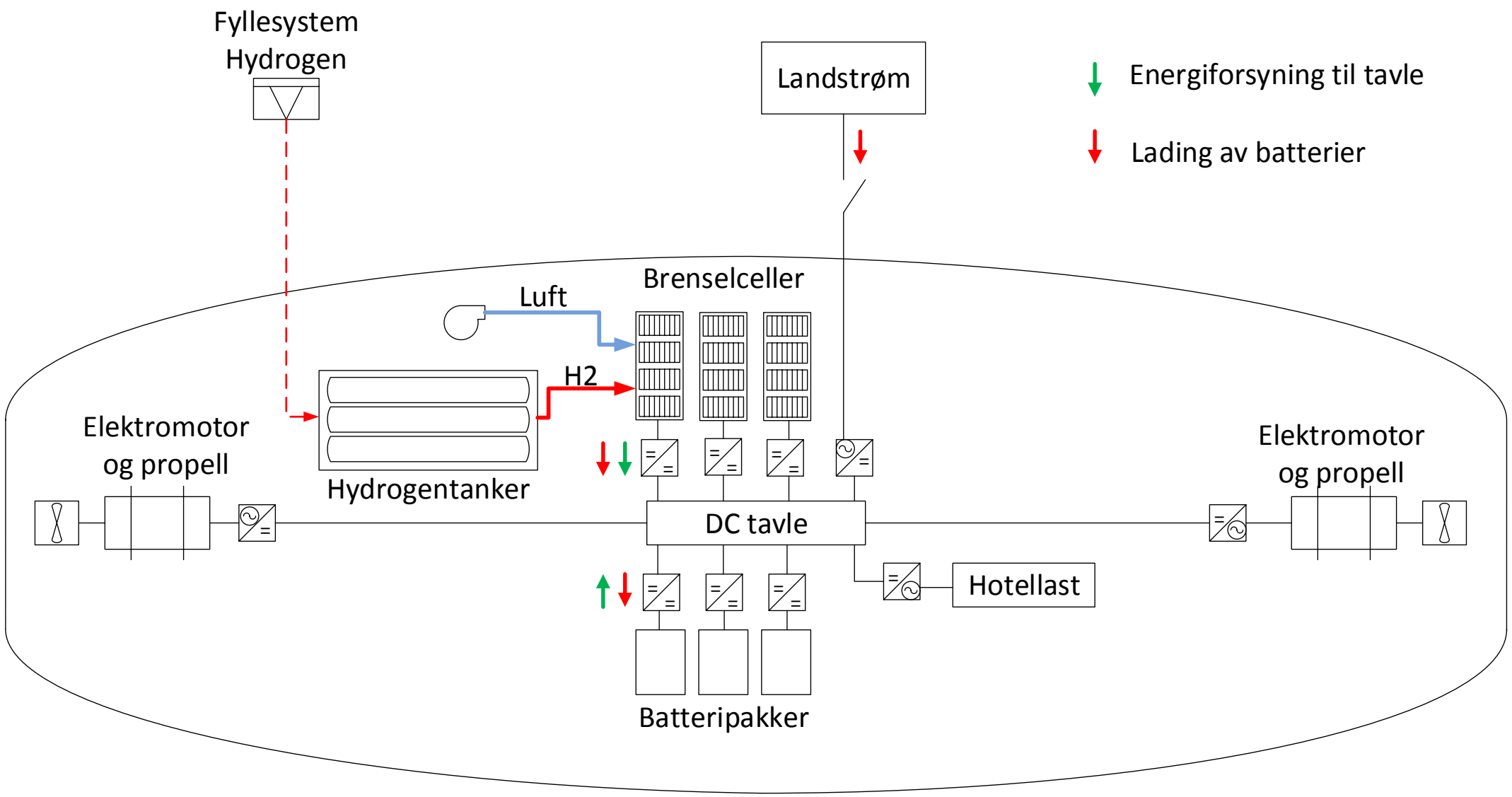
Fuel cell system – stack + Balance of Plant

Ballard FC module

Toyota Mirai FC system



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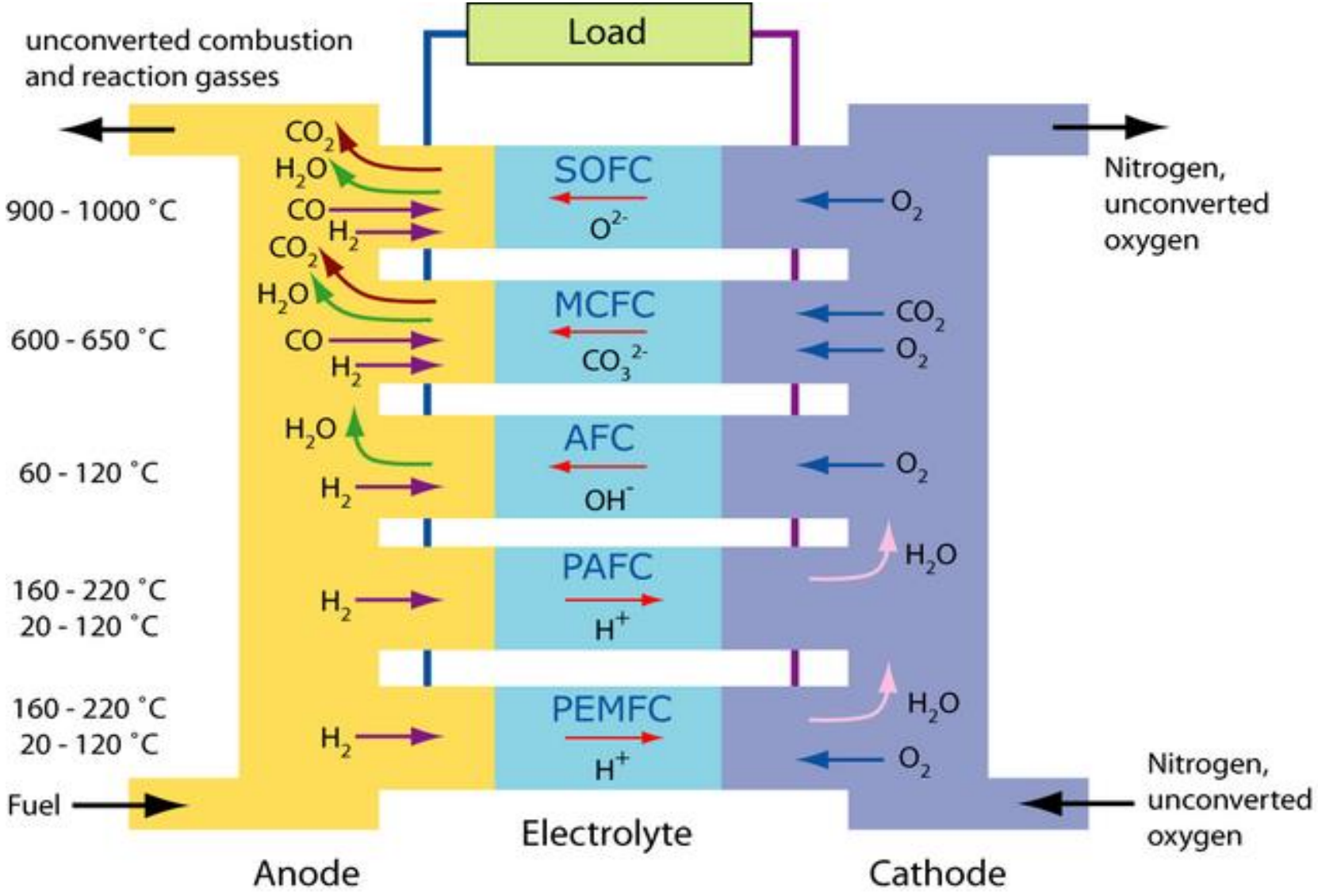
Fuel cell types

Proton Exchange Membrane and Solid Oxide Fuel Cells most relevant for maritime operations



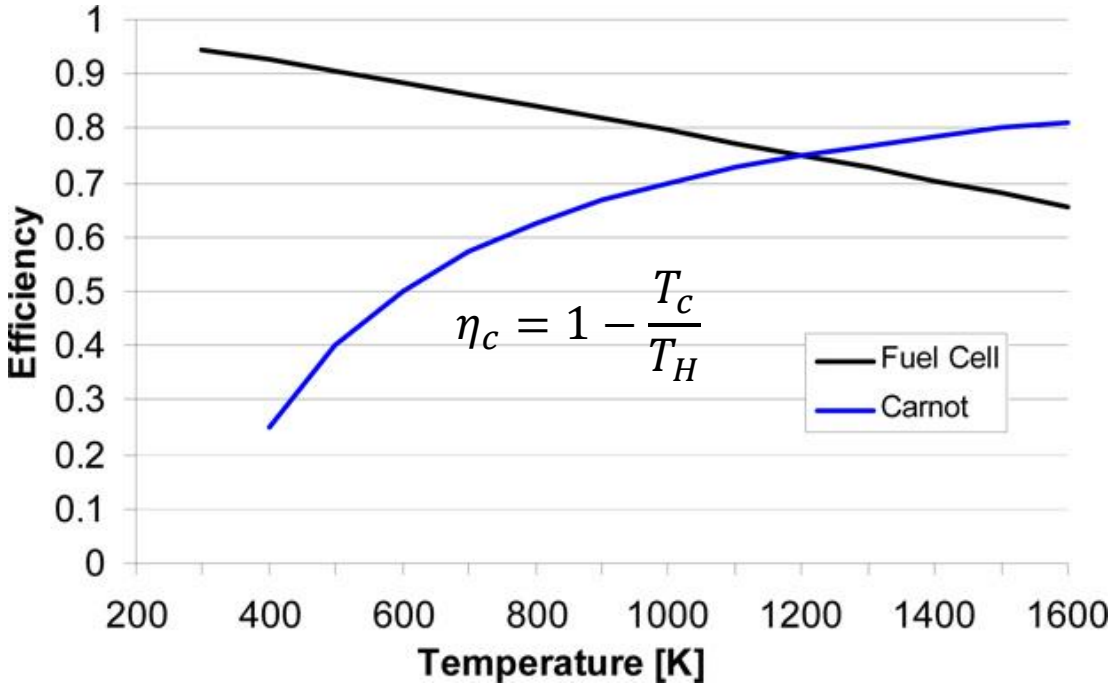
$$\eta_t = \frac{\Delta G}{\Delta H}$$

$$\Delta G = \Delta H - T\Delta S$$

- Theoretical efficiency varies with temperature
- Actual efficiency depends on
  - Activation polarization
  - Ohmic polarization
  - Concentration polarization
- Less losses for high temperature fuel cells

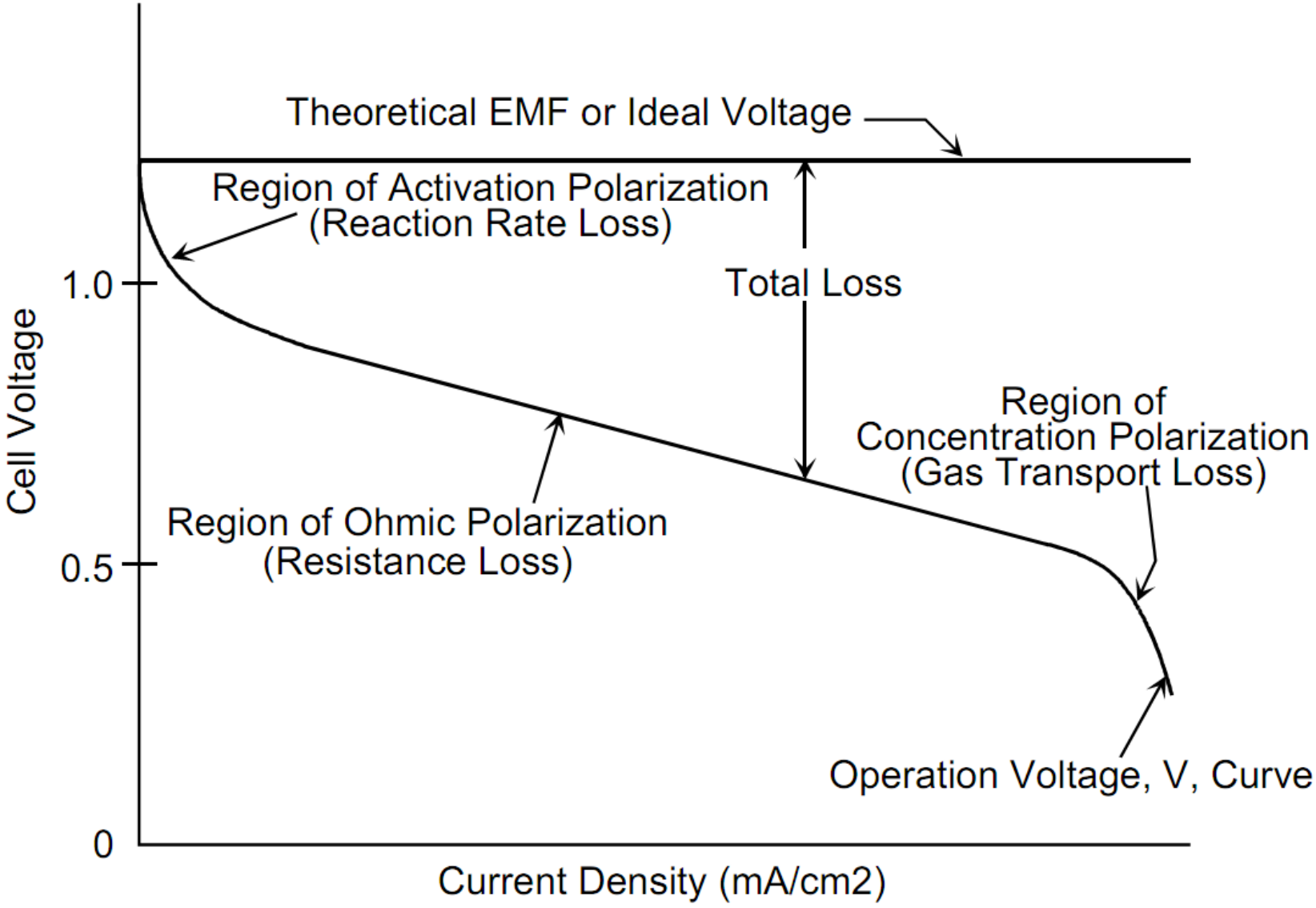
$$\eta = \frac{\text{Useful Energy}}{\Delta H}$$

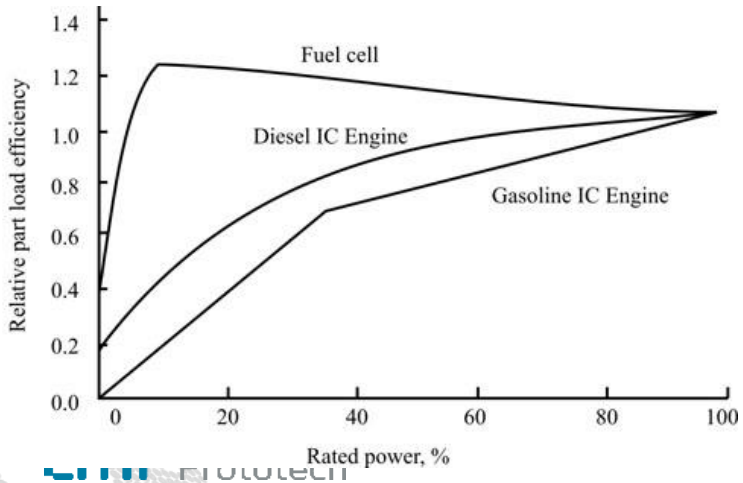
Theoretical efficiency FC vs. Carnot engine



Polarization curve

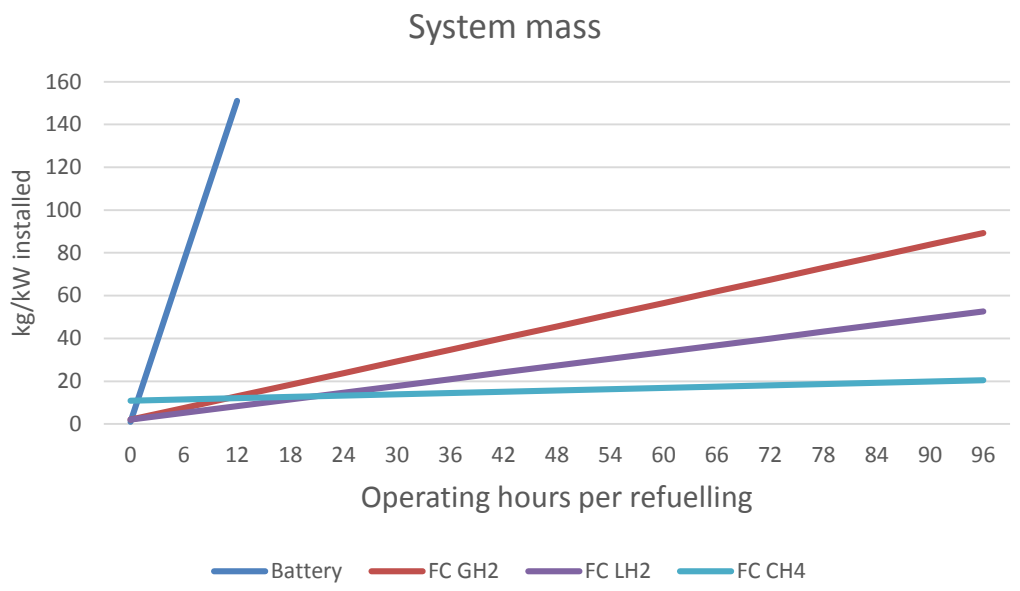
- Polarization curve describes performance of fuel cell stack

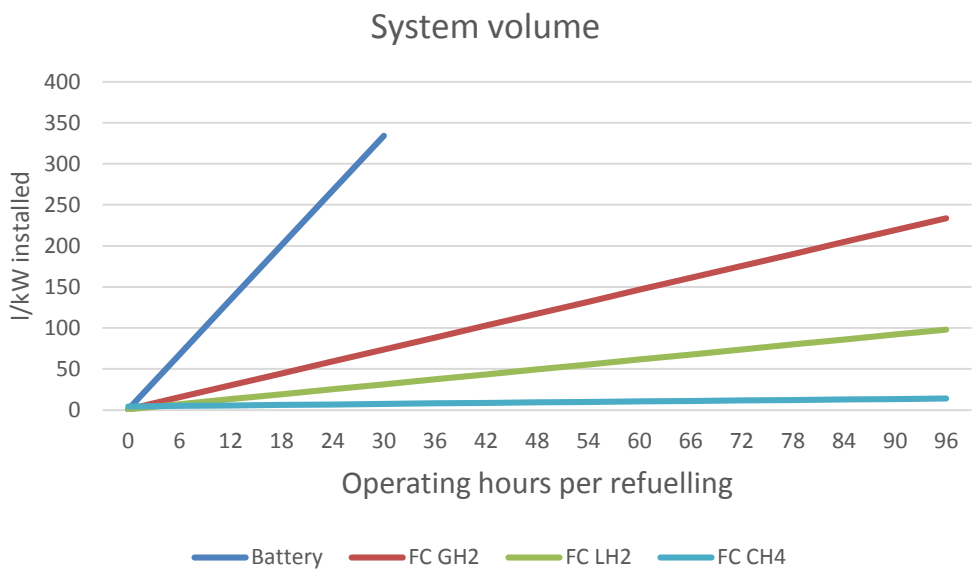


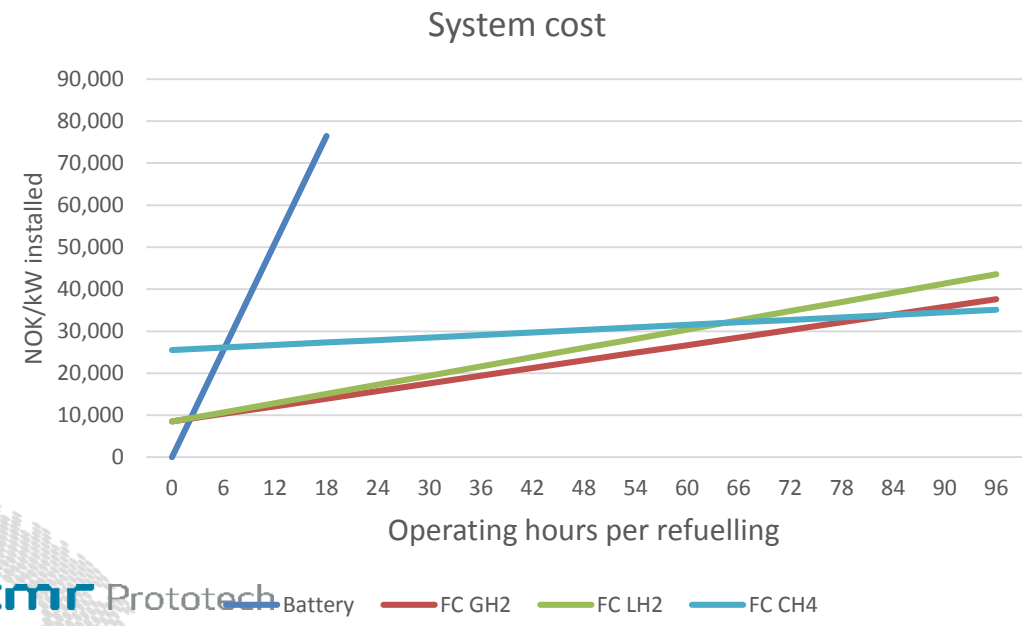


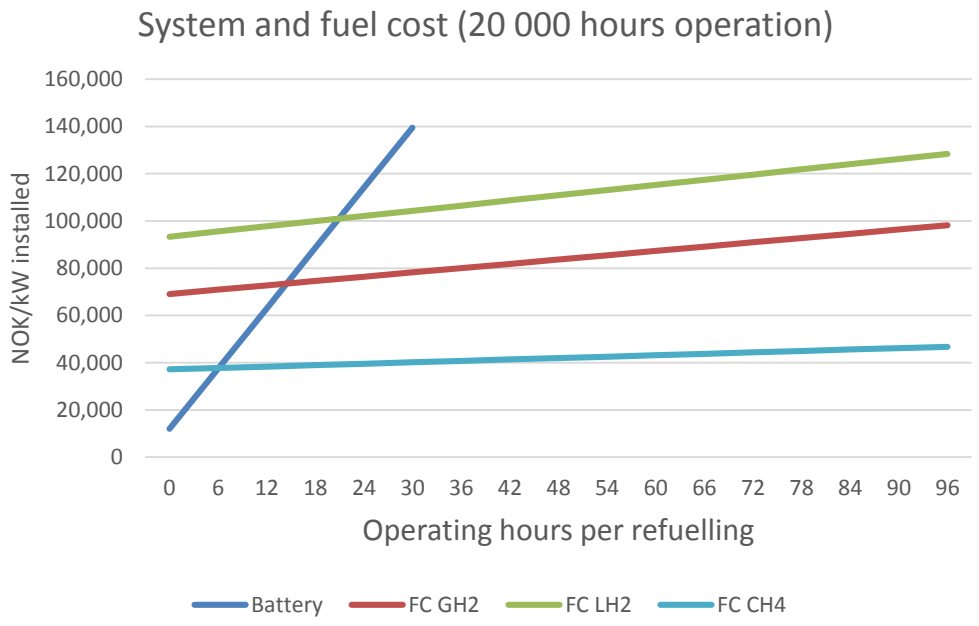
Overall efficiency assessment

- Power conversion efficiency higher for batteries than hydrogen FC
- However:
  - Efficiency of non-utilized VRE = 0%
  - Heat ≠ lost energy
  - Ship power need $\sim v^3$
    - Charging time may have significant implication on ship energy consumption
  - Ship power need dependent on weight
- Fuel cells and batteries are complementary technologies – need both to achieve emission free maritime sector
- Total cost of ownership and overall emissions probably more important than efficiency


System mass
kg/kW installed
160
140
120
100
80
60
40
20
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Operating hours per refuelling
Battery
FC GH2
FC LH2
FC CH4


System volume
l/kW installed
400
350
300
250
200
150
100
50
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Operating hours per refuelling
Battery
FC GH2
FC LH2
FC CH4


System cost
NOK/kW installed
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Operating hours per refuelling
Battery
FC GH2
FC LH2
FC CH4


System and fuel cost (20 000 hours operation)
NOK/kW installed
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Operating hours per refuelling
Battery
FC GH2
FC LH2
FC CH4

	Specific energy (kWh/kg)	Energy density (kWh/l)
Diesel (genset)	4,80	4,00
LNG (genset)	5,00	2,26
LNG (FC)	6,82	3,08
NH3 (FC)	3,11	2,39
250 bar GH2	1,32	0,30
350 bar GH2	1,16	0,41
700 bar GH2	0,99	0,66
LH2	1,65	1,07
Batteries	0,07	0,10

Maritime fuel cells - selected projects

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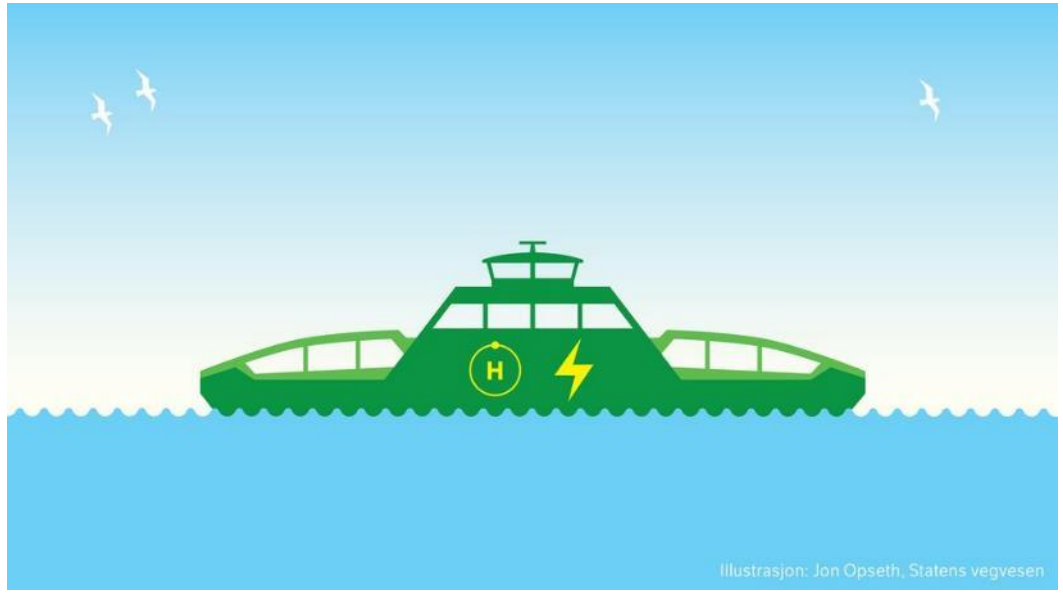
Maritime hydrogen projects in Norway

- NPRA hydrogen car ferry
  - In operation from 2021
  - Hjelmeland – Nesvik – Skipavik
  - 50% energy delivered by H2
  - Norled, Fjord1, Boreal qualified to bid
- Trondelag FK – Zero emission high speed vessel
- Norwegian value creation



NPRA Hydrogen car ferry project

HYBRIDskip – supported by Pilot E. Consortium led by Fiskarstrand Verft

UTSTYRS- OG TENESTELEVERANDØRAR

ANEL AS
APPLY TB
AQUAPRO
eta energi
Bostek
CFD marine
corvus energy
DALSEIDE SHIPPING SERVICES AS
Future Solutions
GRENLAND ENERGY
BLUEDAY TECHNOLOGY
LMG MARIN
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SERVOGEAR
palantir
THE SWITCH
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Servicebåt AS
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ZEM
WESTCON
WÄRTSILÄ

VERFT

APPLY LEIRVIK
KVÆRNER
Selfa
FJELLSTRAND
H Verft

REIARLAG

NORLED
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Østensjø Rederi
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BREMNES SEASHORE
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BRANSJE- OG INTERESSEORGANISASJONAR

GREENSTAT
Sjøfartsdirektoratet Norwegian Maritime Authority
BTO
Lloyd's Register
Kystrederiene

A wide range of Norwegian initiatives

Aquaculture vessels

Fjord tourism

Viking Cruises

LMG Marin, CMR Prototech

GKP7H2

Karoline

Hydrogen Viking – Sunseeker Predator 95

Osterøy ferry

Supply vessels

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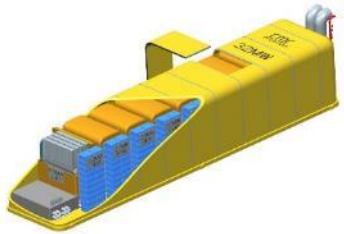
Potential market – *all* vessels

Urban Water Shuttle



Seasight
~1,5 MW

Sunseeker
Green Cruises
3 MW

Hydrogen ferry
0,5 – 2 MW

Work boat
0,2-1,2 MW

- Develop fuel cell power systems for high energy demand vessel types
- Various fuel types
  - GH2
  - LH2
  - Methanol
  - LNG
  - Ammonia
- *Marine CHEOP*

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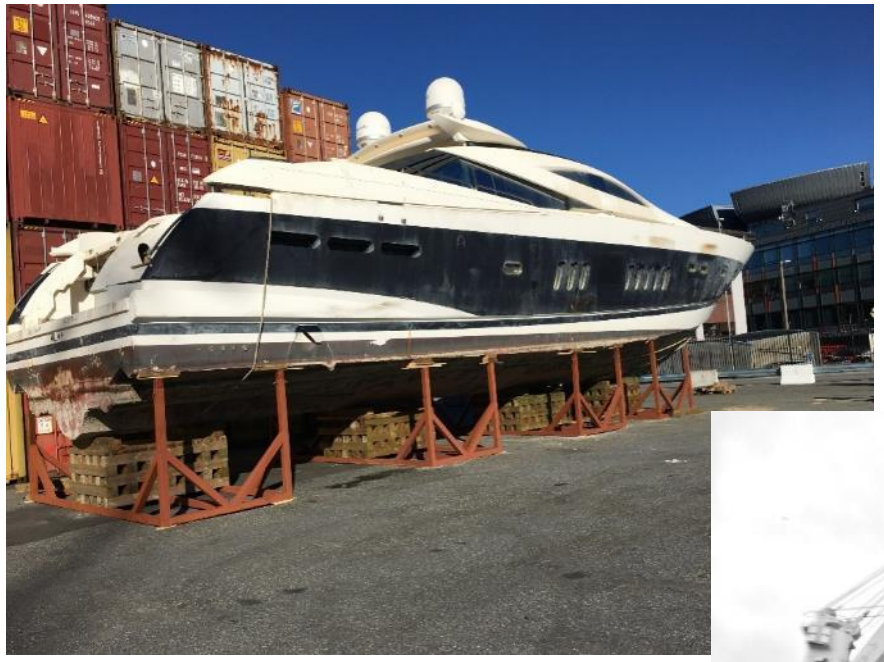
- Fuel cost and infrastructure
- Maritime adaption of fuel cell technology – optimization
- Rules and regulations

Figure: Waitbutwhy

Hydrogen Viking

- 100 ft Sunseeker
- ~40 knots
- Demonstration of zero-emission hybrid propulsion
- Education/meetings



The yacht in the port of Bergen

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JOTUN
HAGLAND
GREENSTAT
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Innovasjon Norge
HYDROGEN VIKING
- The world's first hydrogen powered superyacht
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Thank you for your attention !

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