HySeas III: Progress on the World's First Sea-going H_2-powered RoPax ferry

4th of November 2020
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Funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no: 769417

HySeasIII

Agenda

1. About DLR and the HySeas III consortium
2. Motivation for decarbonisation
3. About HySeas III: Current state and future Steps
4. Environmental and economic assessment
5. Addressing the economic challenges: H_2 production availability and costs
6. Conclusions

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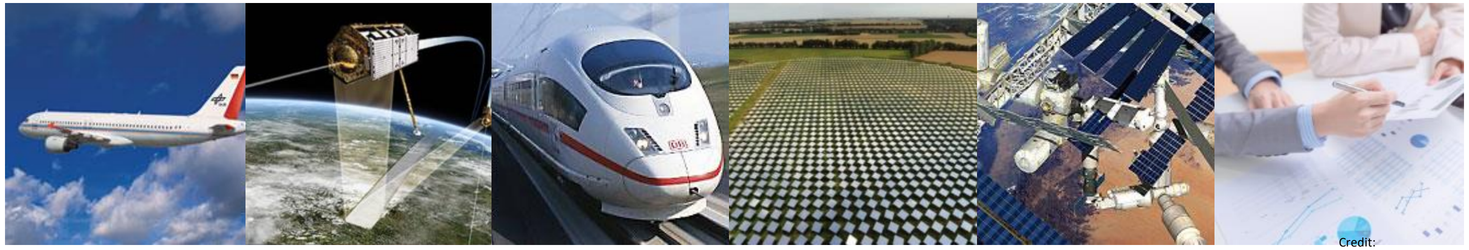
German Aerospace Center (DLR)



Credit: Nonwarit/Fotolia

- Research institution, space agency, project management agency
- Aeronautics, space, energy, transport, digitisation and security
- Approximately 8,000 staff in 40 institutes and facilities in 20 locations; offices in Brussels, Paris, Tokyo and Washington
- Member of the Helmholtz Association

DLR Institute of Networked Energy Systems, Oldenburg
Department: Energy Systems Analysis

Multidimensional and prospective assessment

- Multidimensional approaches that integrate economic, ecological, technical and social aspects
- Prospective assessments of technologies as a basis for system modelling

Energy Scenarios and Technology Assessment

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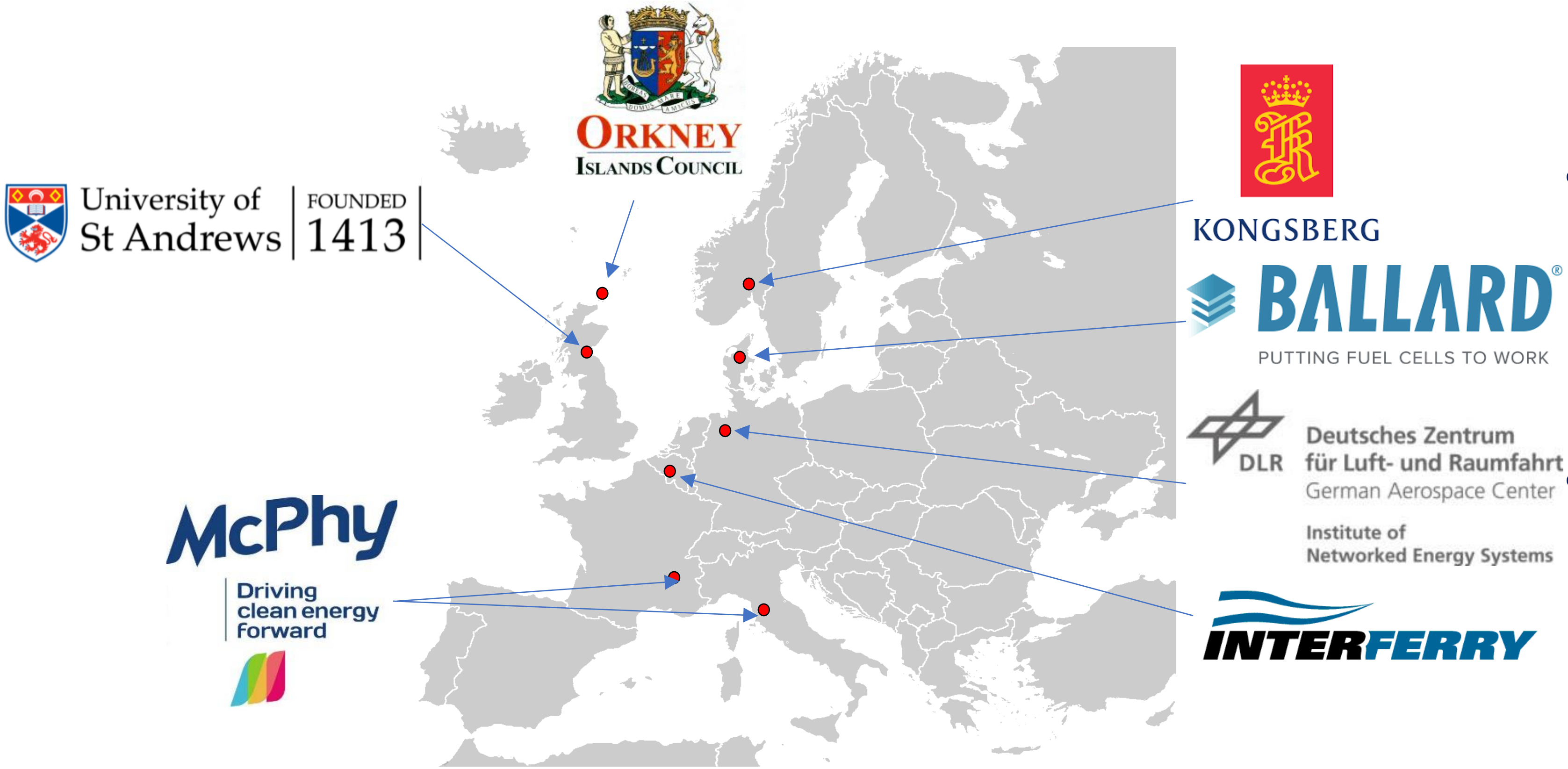
About the HySeas Consortium



- Develop, construct, certify and validate a hydrogen fuel cell drive and construct, launch and monitor a sea-going RoPax ferry
- Develop innovative business models and encourage replication by dissemination of exploitable lessons
- DLR contributes to HySeas III with environmental, economic, social and market assessments

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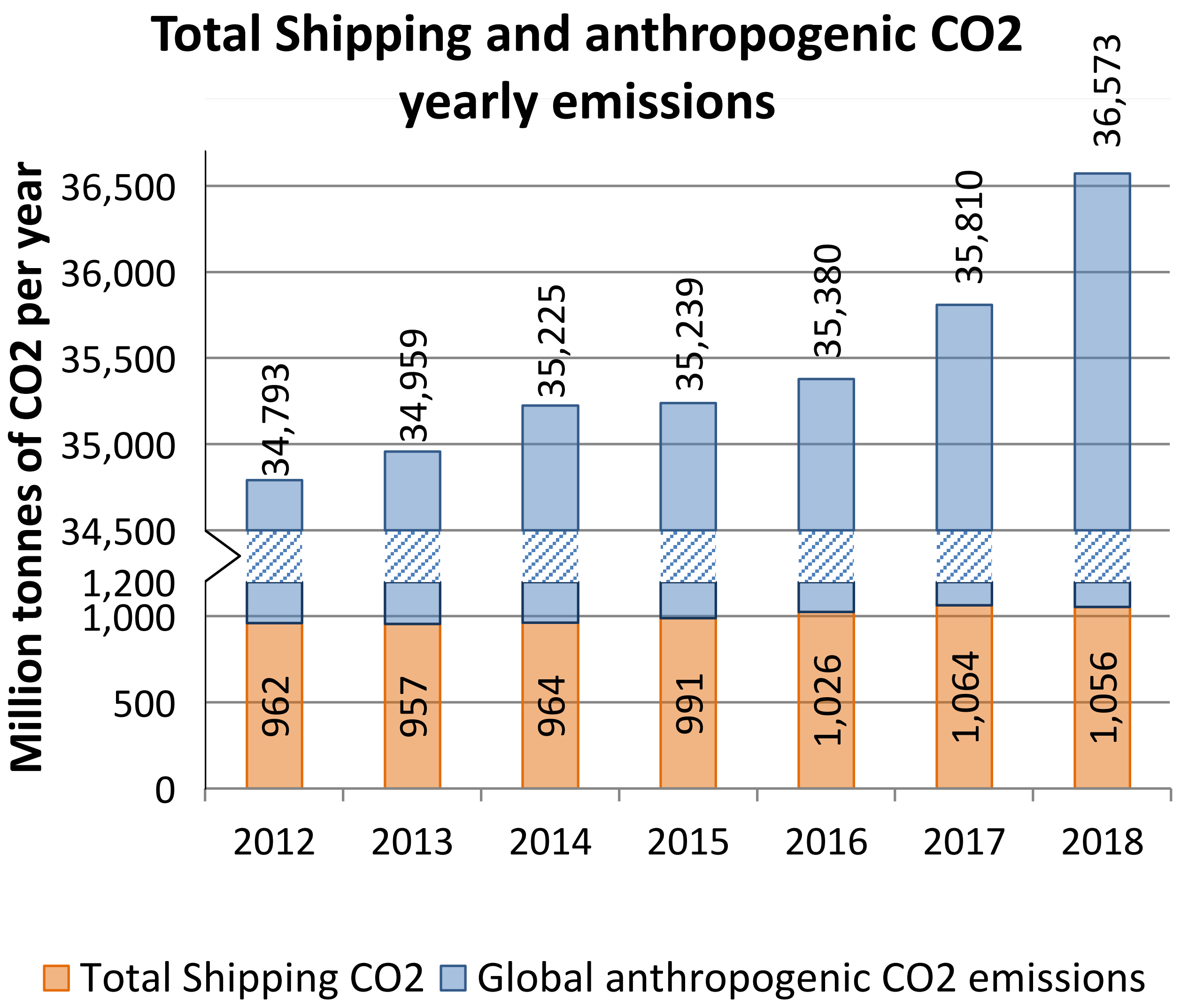
Motivation

- **Total Shipping contribution to GWP: 2.89% of total anthropogenic yearly CO_2 emissions (2018)**
- **IMO MEPC 72: Long-term measures: *„pursue the development and provision of zero-carbon or fossil-free fuels“***
- **...but first this has to be implemented in a small scale**
- **RoPax ferries have regular routes and some sizes are interesting for the implemention of new solutions**



Data: Jasper Faber, S. H., Shuang Zhang, Paula Pereda, Bryan Comer, Elena Hauerhof, Wendela Schim van, et al. (2020). Fourth IMO GHG Study 2020.

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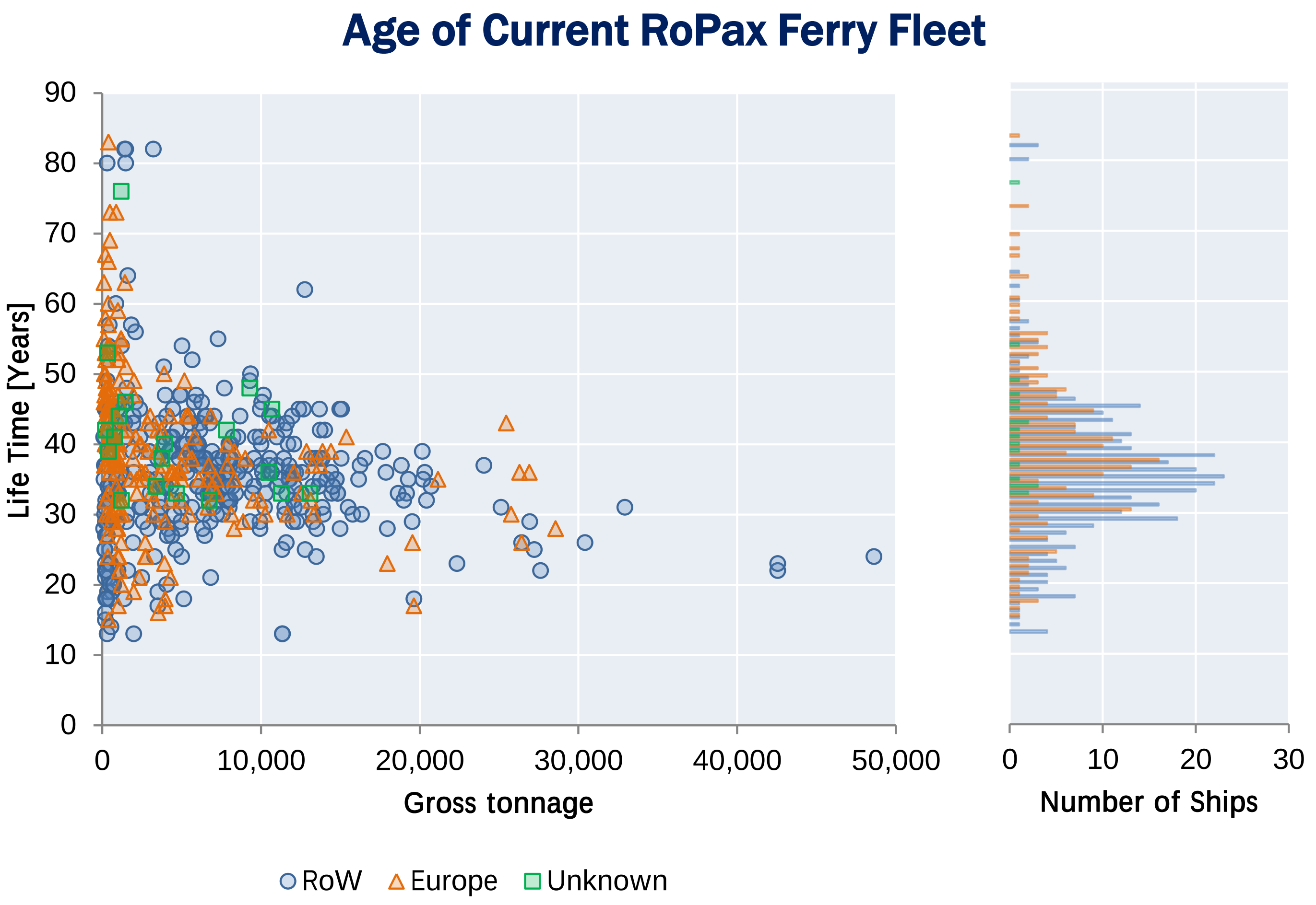
Motivation

- Although the long-term seems to be far away, ships are relatively long-lived (RoPax ferries more than 30 years).
- Future starts now if we want to reduce green house gases by 2050!



Gomez J.C., Vogt, T., Brand, U., Wilken, D., Remler, M. (2019). Market Potential Analysis of RoPax Ferry Market in Europe. Deliverable 6.1 Project HySeas III
Based on data of IHS Markit SeaWeb.

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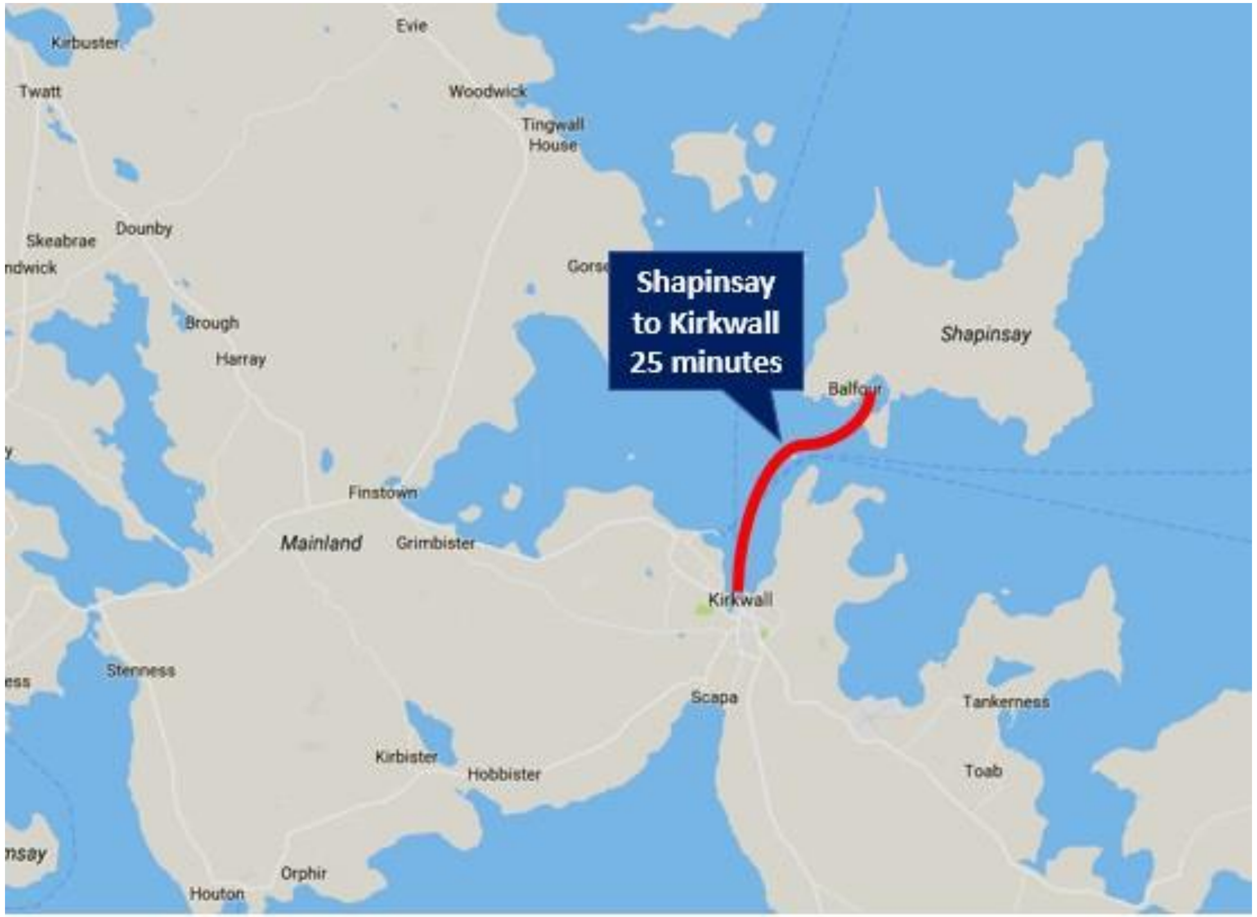
HySeas III: Location

- Operating profile – 25 minute crossing, continuous operation – 12 voyages a day, 1.5 hour lunch break and at berth all night.

Considering the route:

- Build the drivetrain on land for full scale testing first
- Integration into a newly built vessel design



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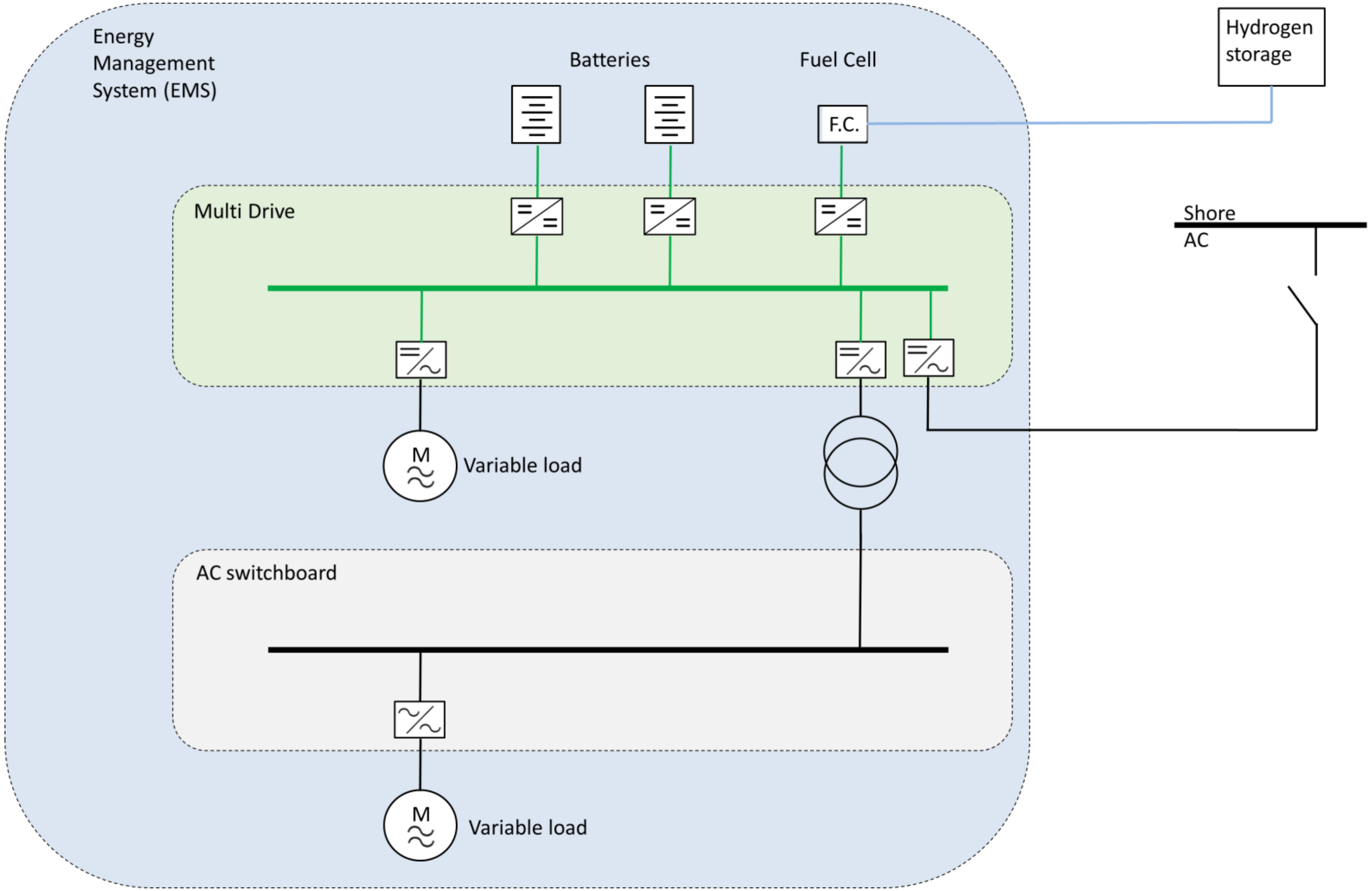
HySeas III: First Steps: Small-Scale Testing (Norway)

Objective: implement in practice a small energy/power system using fuel cells/batteries and loads



Source: Kongsberg

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HySeas III: First Steps: Small-Scale Testing (Norway)

Source: Kongsberg

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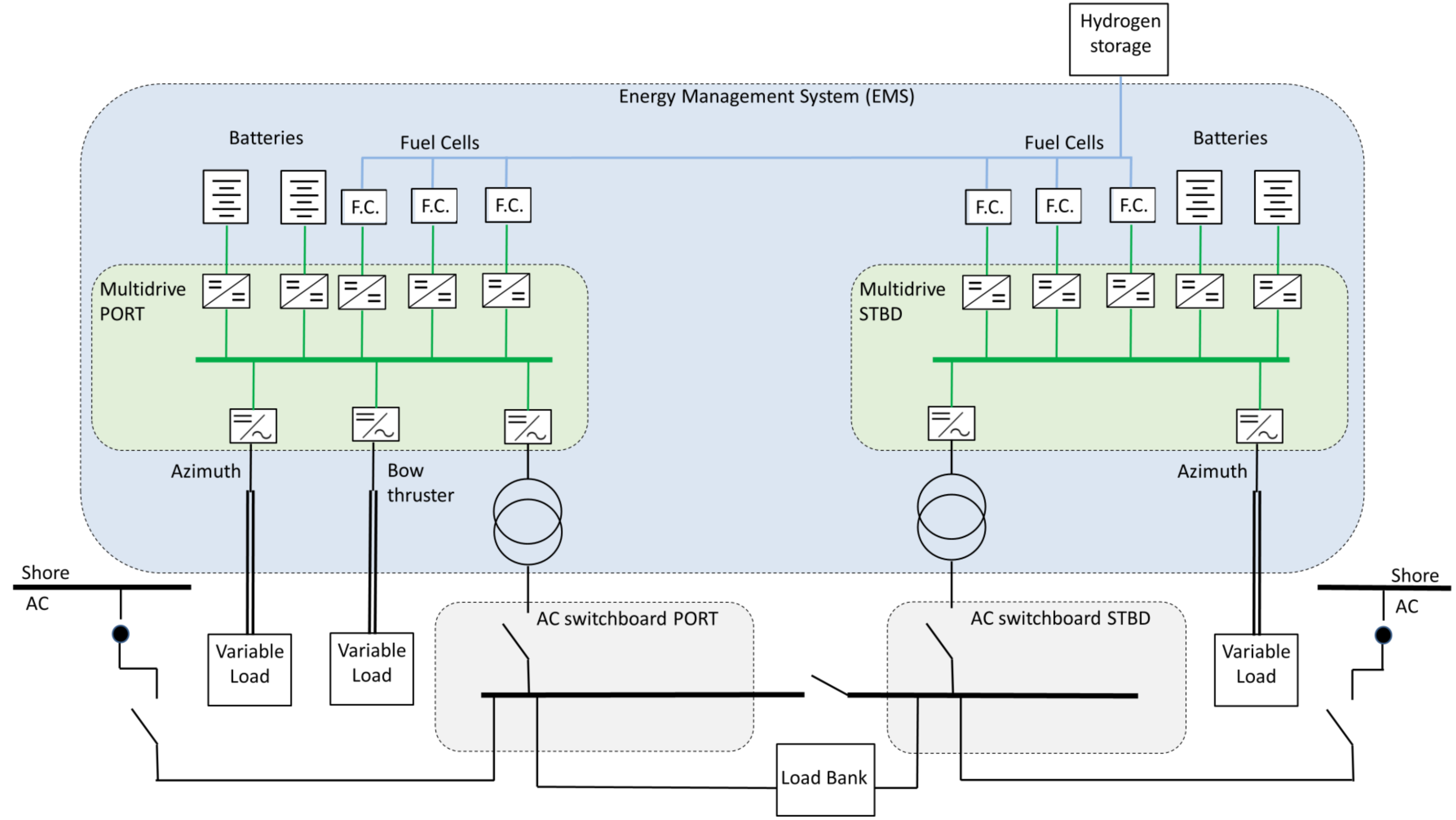
HySeas III: Next Steps: Full Size Testing in Norway

Objective: testing full size system on land



Source: Kongsberg

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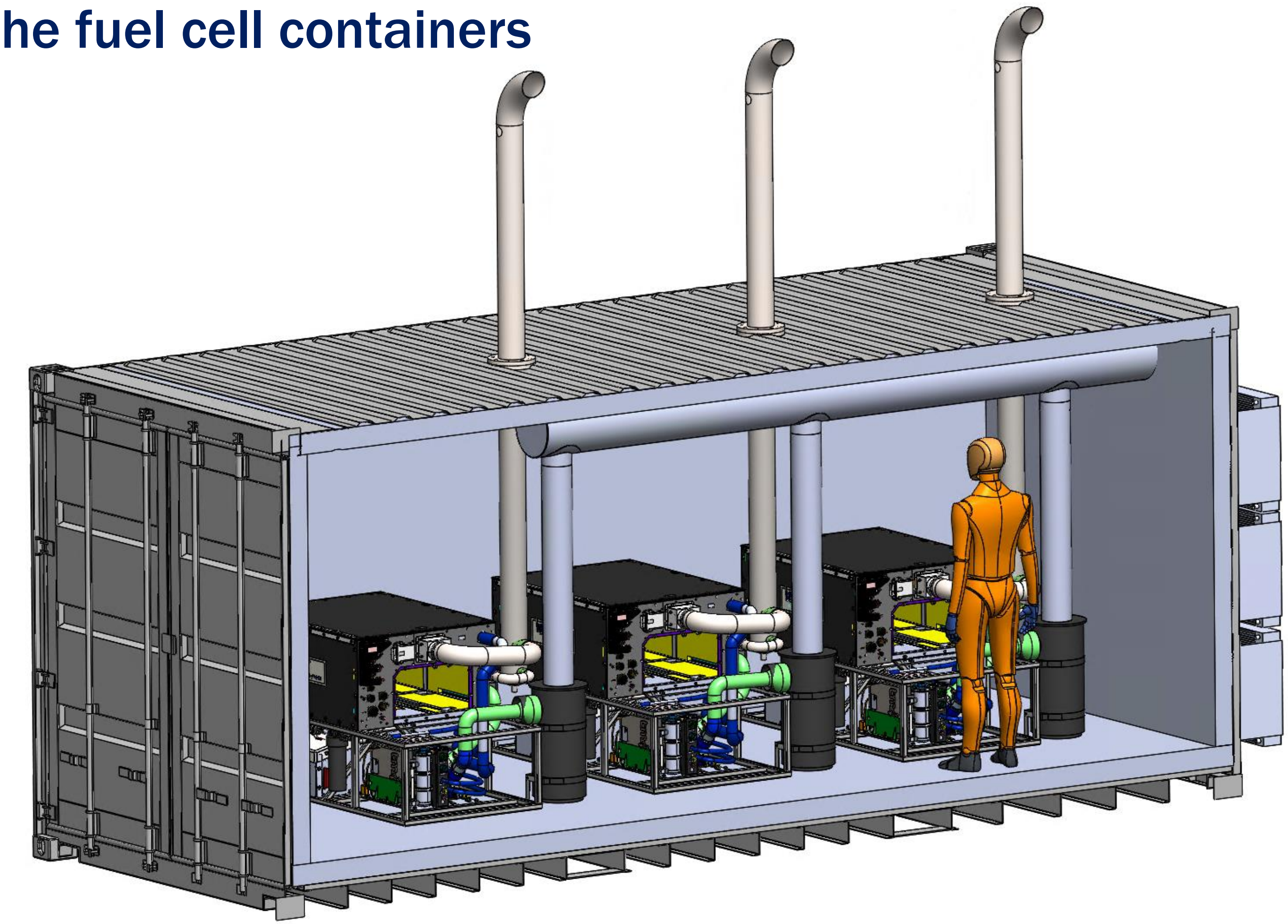
HySeas III: Next Steps: Full Size Testing

Detail of one of the fuel cell containers



Source: Ballard Power Systems

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HySeas III: Next Steps: Full Size Testing

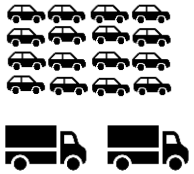
Compressed Hydrogen storage

Fuel Cells

DC Li Ion Batteries

Powering:
- 6 x 100kW Ballard Fuel cells
- Li Ion Battery Systems
- ~1000kg Hydrogen stored

Capacity Requirement:
- 120 passengers
- 18 cars
- 2 Heavy Goods Vehicles



Preliminary Dimensions
- 39.9m LOA
- 10m Beam
- 4m Depth Approx.
- Landing craft style hull

Source: Ferguson Marine

Route:
- Kirkwall-Shapinsay
- 4 nautical miles
- 25 minutes
- Lifeline Service

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HySeas III: Compressed Hydrogen Bunkering

- Hydrogen temperature rises significantly during the refilling due to the Joule-Thomson effect, which produces increase of temperature for hydrogen expansion at room temperature
- Temperature rise leads to: exceeding safety temperature of the tank but also lower hydrogen density (so lower mass refilled)
- All fuelling parameters all have influence on the temperature rise, the three most important of which: initial pressure, filling rate, initial hydrogen temperature
- Bunkering compromise: fastest and fullest fuelling but with little heating and limited flowrate
- A standard exists for light duty vehicles (under 10kg) SAE J2601, but there is no standard for refilling around 250kg of H_2 – need to start from scratch to define the refuelling protocol
- Battery charging

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HySeas III: Compressed Hydrogen Bunkering

ORKNEY ISLANDS COUNCIL
Ferry Services

Shapinsay

Effective from 23 November 2020 until 1 May 2021

(Abbreviations on page 2).

Mon.	**Shapinsay.** D. 07:30 (a).	**Kirkwall.** D. 08:15 (a).	**Shapinsay.** D. 09:00 (a).	**Kirkwall.** D. 09:45.	**Shapinsay.** D. 10:30.	**Kirkwall.** D. 11:30.	**Shapinsay.** D. 13:30.	**Kirkwall.** D. 14:15.	**Shapinsay.** D. 15:15.
Kirkwall. D. 16:00.	**Shapinsay.** D. 16:45.	**Kirkwall.** D. 17:30.	**Shapinsay.** A. 17:55.						
Tue.	**Shapinsay.** D. 07:30 (b).	**Kirkwall.** D. 08:15 (b).	**Shapinsay.** D. 09:00 (b).	**Kirkwall.** D. 09:45.	**Shapinsay.** D. 10:30.	**Kirkwall.** D. 11:30.	**Shapinsay.** D. 13:30.	**Kirkwall.** D. 14:15.	**Shapinsay.** D. 15:15.
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Wed.	**Shapinsay.** D. 07:30 (b).	**Kirkwall.** D. 08:15 (b).	**Shapinsay.** D. 09:00 (b).	**Kirkwall.** D. 09:45.	**Shapinsay.** D. 10:30.	**Kirkwall.** D. 11:30.	**Shapinsay.** D. 13:30.	**Kirkwall.** D. 14:15.	**Shapinsay.** D. 15:15.
Kirkwall. D. 16:00.	**Shapinsay.** D. 16:45.	**Kirkwall.** D. 17:30.	**Shapinsay.** A. 17:55.						
Thu.	**Shapinsay.** D. 07:30 (b).	**Kirkwall.** D. 08:15 (b).	**Shapinsay.** D. 09:00 (b).	**Kirkwall.** D. 09:45.	**Shapinsay.** D. 10:30.	**Kirkwall.** D. 11:30.	**Shapinsay.** D. 13:30.	**Kirkwall.** D. 14:15.	**Shapinsay.** D. 15:15.
Kirkwall. D. 16:00.	**Shapinsay.** D. 16:45.	**Kirkwall.** D. 17:30.	**Shapinsay.** A. 17:55.						
Fri.	**Shapinsay.** D. 07:30 (b).	**Kirkwall.** D. 08:15 (b).	**Shapinsay.** D. 09:00 (b).	**Kirkwall.** D. 09:45.	**Shapinsay.** D. 10:30.	**Kirkwall.** D. 11:30.	**Shapinsay.** D. 13:30.	**Kirkwall.** D. 14:15.	**Shapinsay.** D. 15:15.
Kirkwall. D. 16:00.	**Shapinsay.** D. 16:45.	**Kirkwall.** D. 17:30.	**Shapinsay.** A. 17:55.						
Sat.	**Shapinsay.** D. 09:00 (b).	**Kirkwall.** D. 09:45.	**Shapinsay.** D. 10:30.	**Kirkwall.** D. 11:30.	**Shapinsay.** D. 13:30.	**Kirkwall.** D. 14:15.	**Shapinsay.** A. 15:15 (a).	**Kirkwall.** D. 16:00 (a).	**Shapinsay.** D. 16:45 (a).
Kirkwall. D. 17:30 (a).	**Shapinsay.** A. 17:55.								
Sun.	**Shapinsay.** D. 10:30 (a).	**Kirkwall.** D. 11:30 (a).	**Shapinsay.** D. 13:30 (a).	**Kirkwall.** D. 14:15 (a).	**Shapinsay.** A. 14:40.				

Bunkering possibility at noon

Bunkering possibility: End of the journey

Source: Okney Island Council- Orkney Ferries

Available at: http://www.orkneyferries.co.uk/pdfs/acctimetables/winterspring/shapinsay_winterspring.pdf

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HySeas III: Compressed Hydrogen Bunkering

Complexity of different alternatives:

	T ambient	0°C	-20°C	-40°C
1 dispenser	- complex			
2 dispensers				
3 dispensers				+ complex

Complexity in terms of :

- architecture : if have several dispensers and a precooling unit
- operation : more dispensers = more connections to do

→ If more complex, more expensive and more risks

- Kirkwall: feasible but most complex case, to be avoided
- Shapinsay: better cases, can do the simplest case (1 dispenser, ambient temperature)

Source: McPhy

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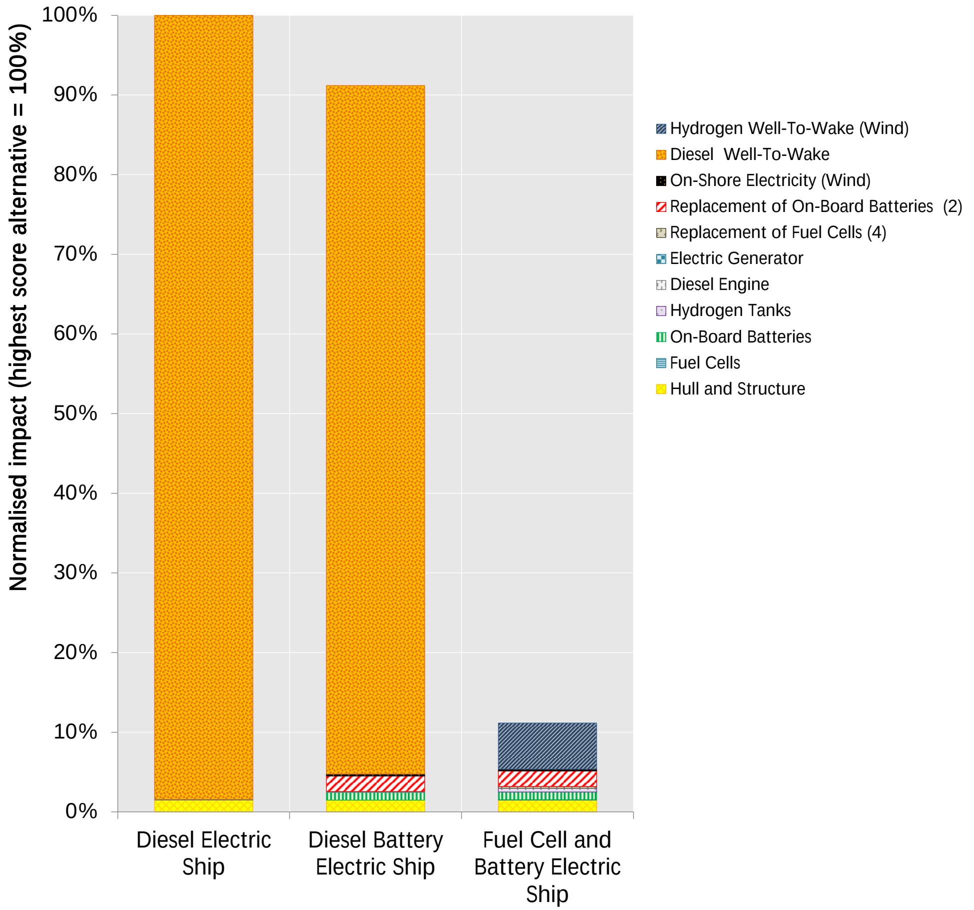
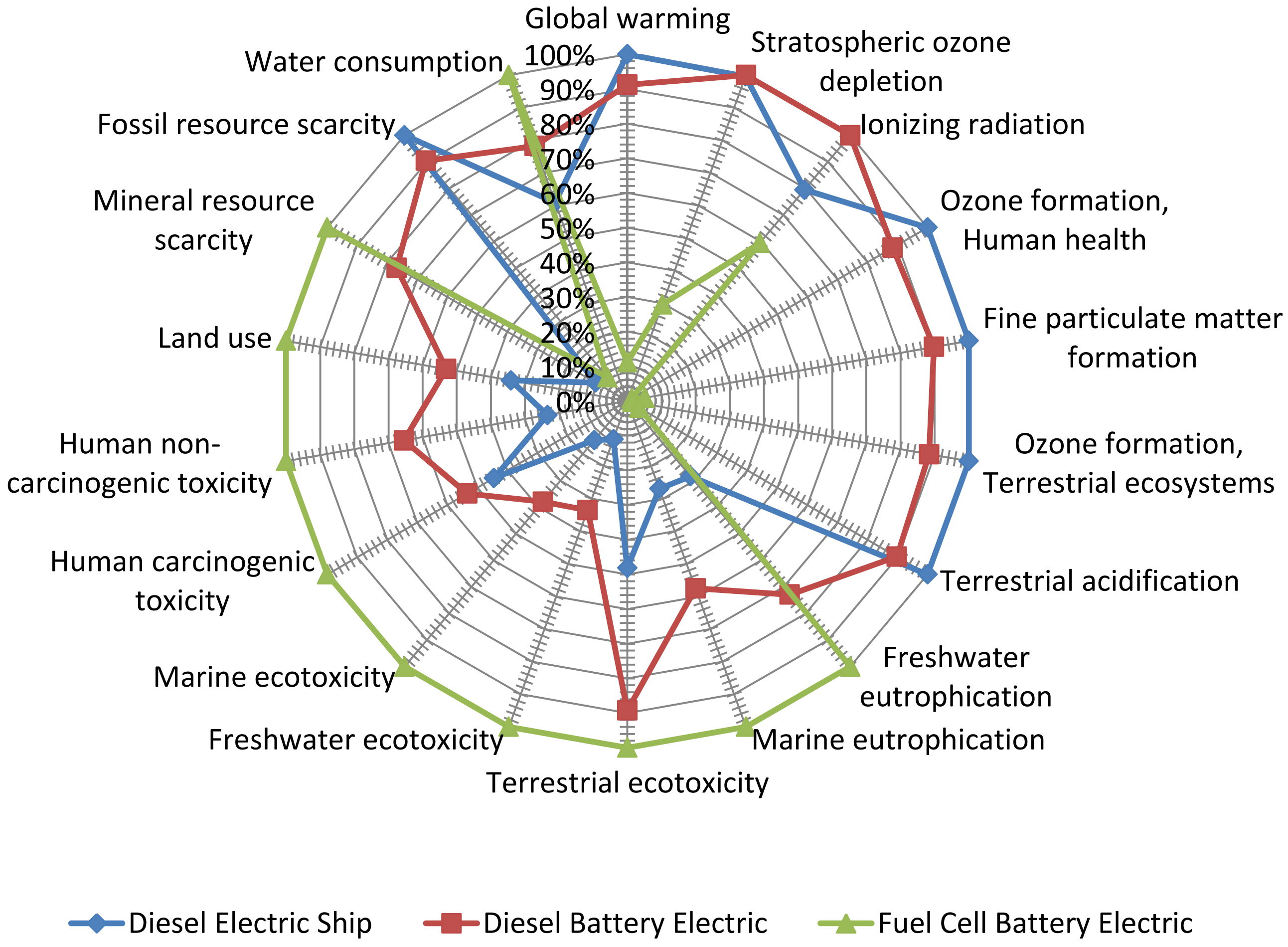
HySeas III: Environmental Assessment

Contribution of Equipment and Fuel to the Global Warming Potential (Normalised to the highest impatc)



Gomez Trillos, J. C., et al. (2019). Chapter 2: Life Cycle Assessment of a Hydrogen and Fuel Cell RoPax Ferry Prototype. Progress in Life Cycle Assessment 2019. S. Albrecht, M. Fischer, P. Leistner and L. Schebek, Springer Nature Switzerland.

Comparison of Impact Assessment Results of Different Ship Propulsion Alternatives



Deutsches Zentrum für Luft und Raumfahrt (2020). "Wasserstoff als ein Fundament der Energiewende - Teil 2: Sektorenkopplung und Wasserstoff: Zwei Seiten der gleichen Medaille.„ Available at: https://www.dlr.de/content/de/dossiers/2020/wasserstoff.html

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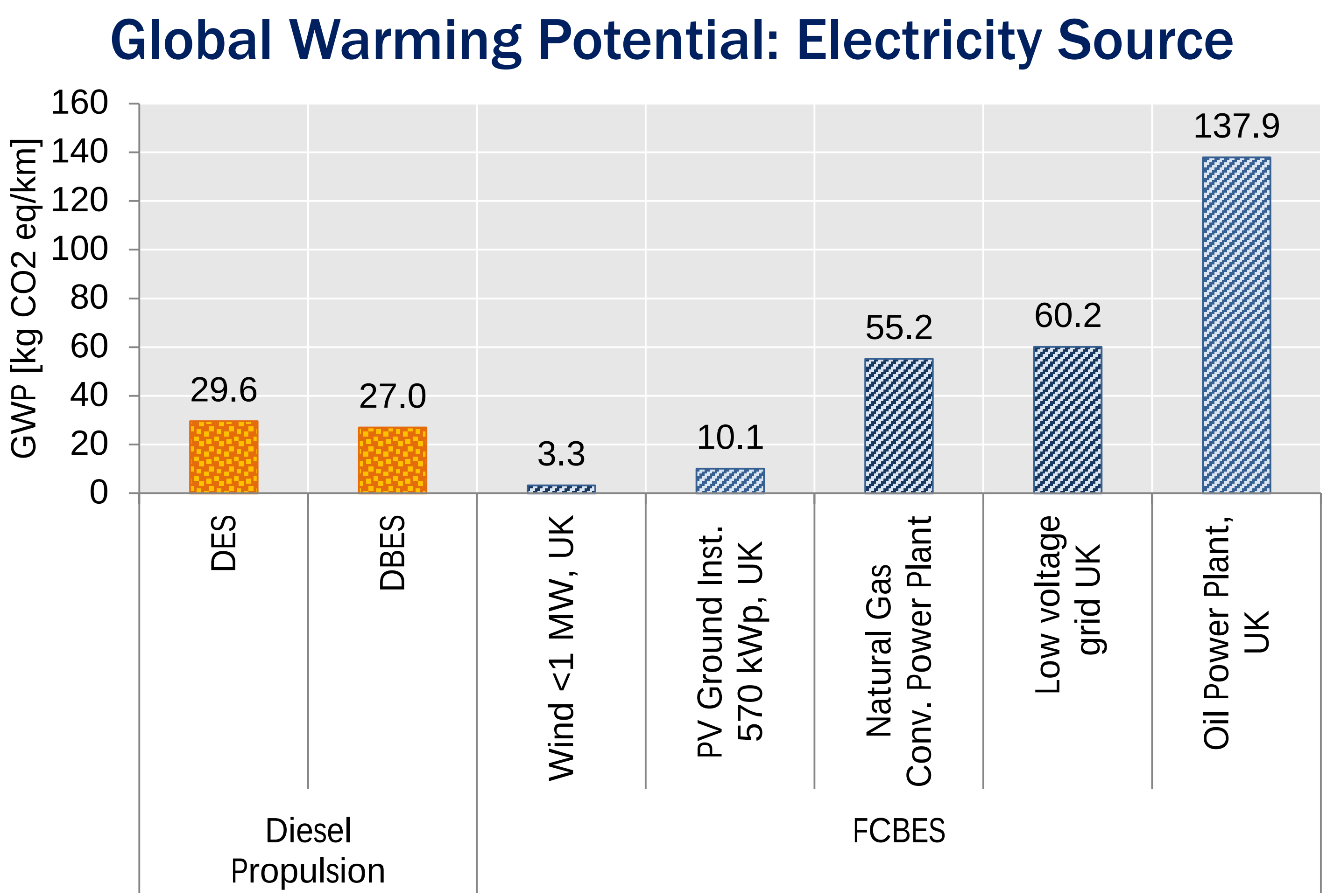
HySeas III: Environmental Assessment



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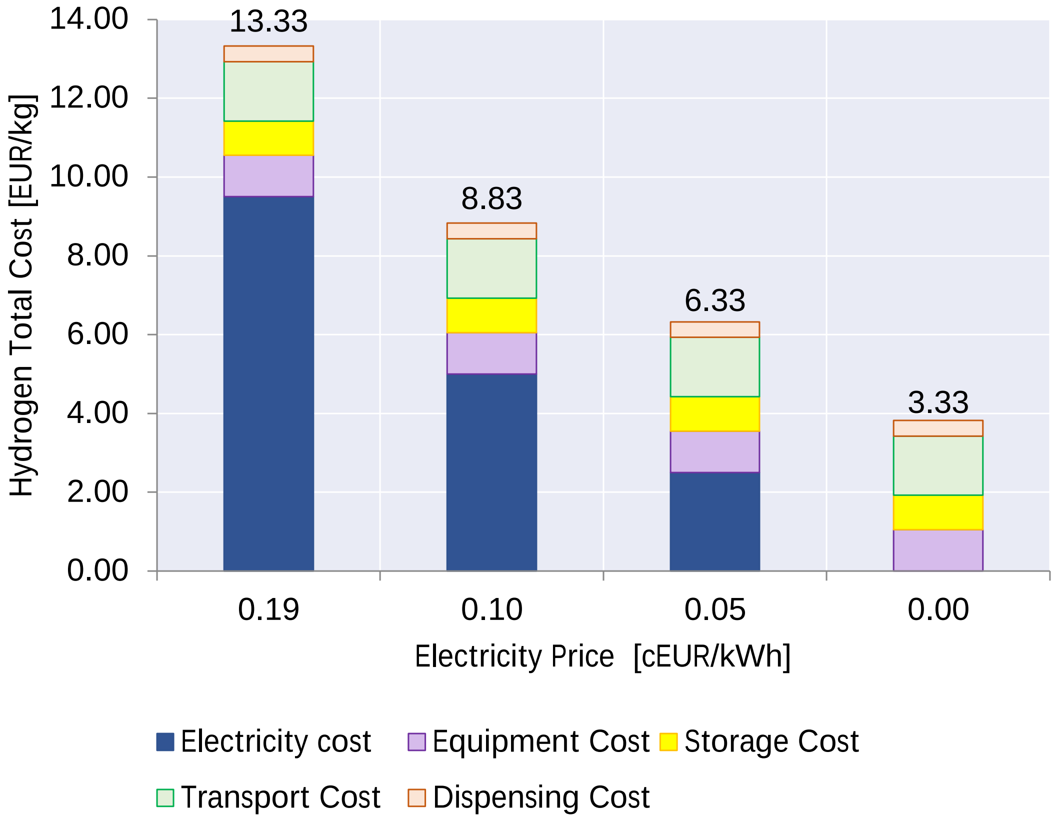
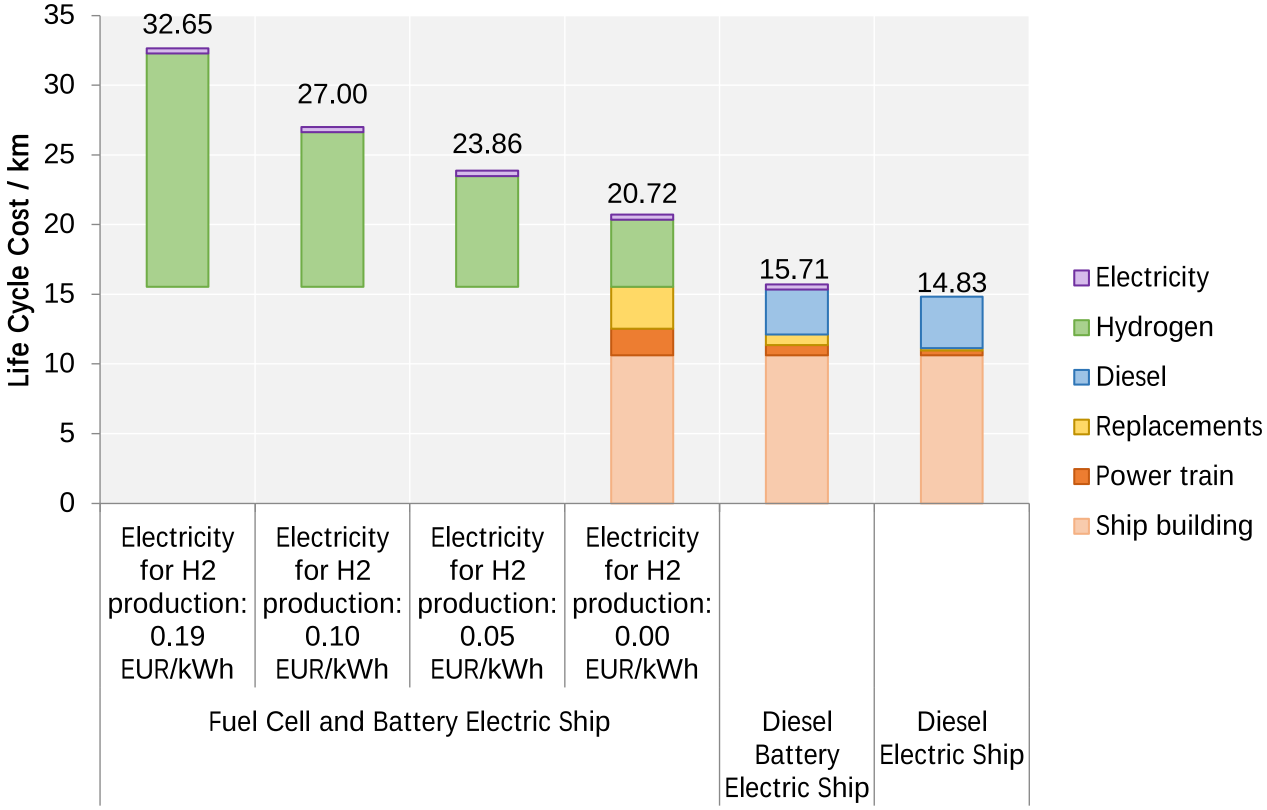
HySeas III: Economic Assessment



Gomez Trillos, J. C., et al. (2020) In press.

Assumptions: EUR to USD: 1.1; Electrolyser 900USD/kW; Electricity consumption 50kWh/kg H_2; Capacity factor of wind in Orkney: 62%; Lifetime: 25 years; OPEX: 3% CAPEX/year; Compressed storage in trailers as currently in Orkney; Transport with trucks as currently in Orkney;



Gomez Trillos, J. C., et al. (2020) In press.

Own calculations assuming a hydrogen price of 3.83 EUR/kg H2, Marine Diesel price 0.73 EUR/kg, electricity price of 0.10 EUR/kWh (Orkney), ship building price:9.2 MEUR, battery price 550 EUR/kWh, Fuel cell price: 1500 EUR/kW heavy duty, hydrogen storage price of 15 EUR/kWhH2. Fuel Cell and Battery Electric Ship fuel consumption: 54840 kg/year + 164225 kWh/year. Diesel Battery Electric Ship: 194593 kg diesel/year. Diesel Electric Ship: 221579 kWh/year.

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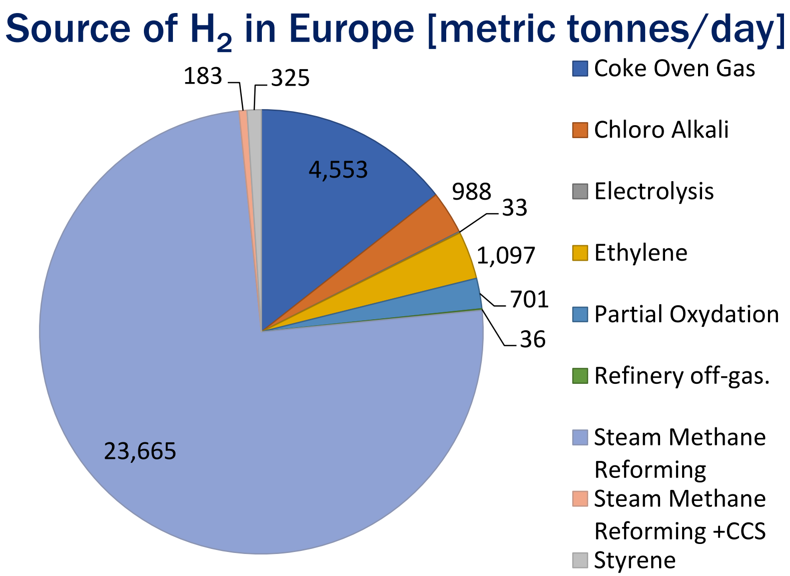
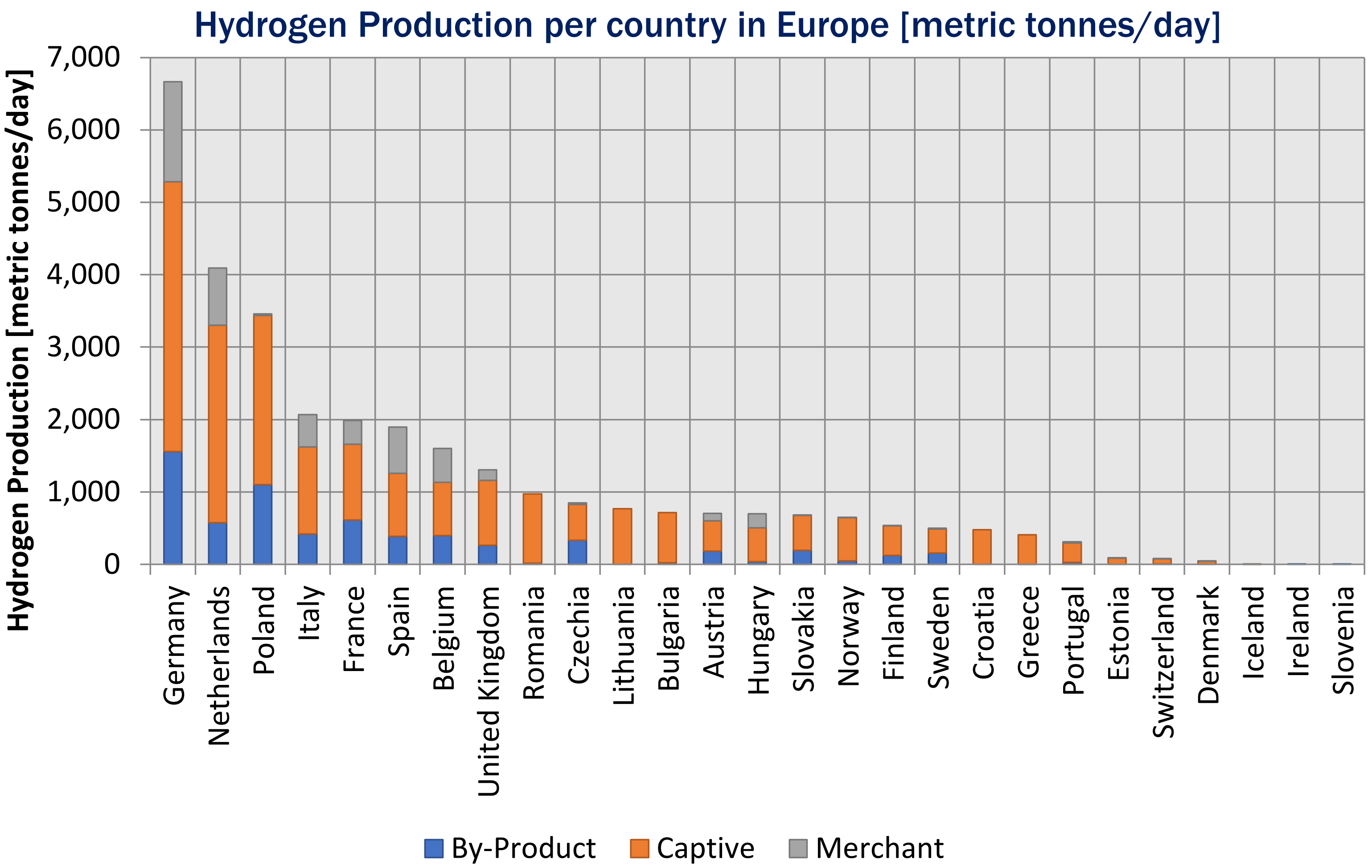
Hydrogen Availability in Europe: Industrial Plants

- **Merchant: sold as product**
- **Captive: internal use**
- **By-product: recovered**
- **Global H_2 demand: 70 MMT+40MMT mixed***

***MMT: Million metric tonnes**





Source: Fuel Cells & Hydrogen Observatory; Available at: https://www.fchobservatory.eu/sites/default/files/reports/Chapter_2_Hydrogen_Molecule_Market_070920.pdf

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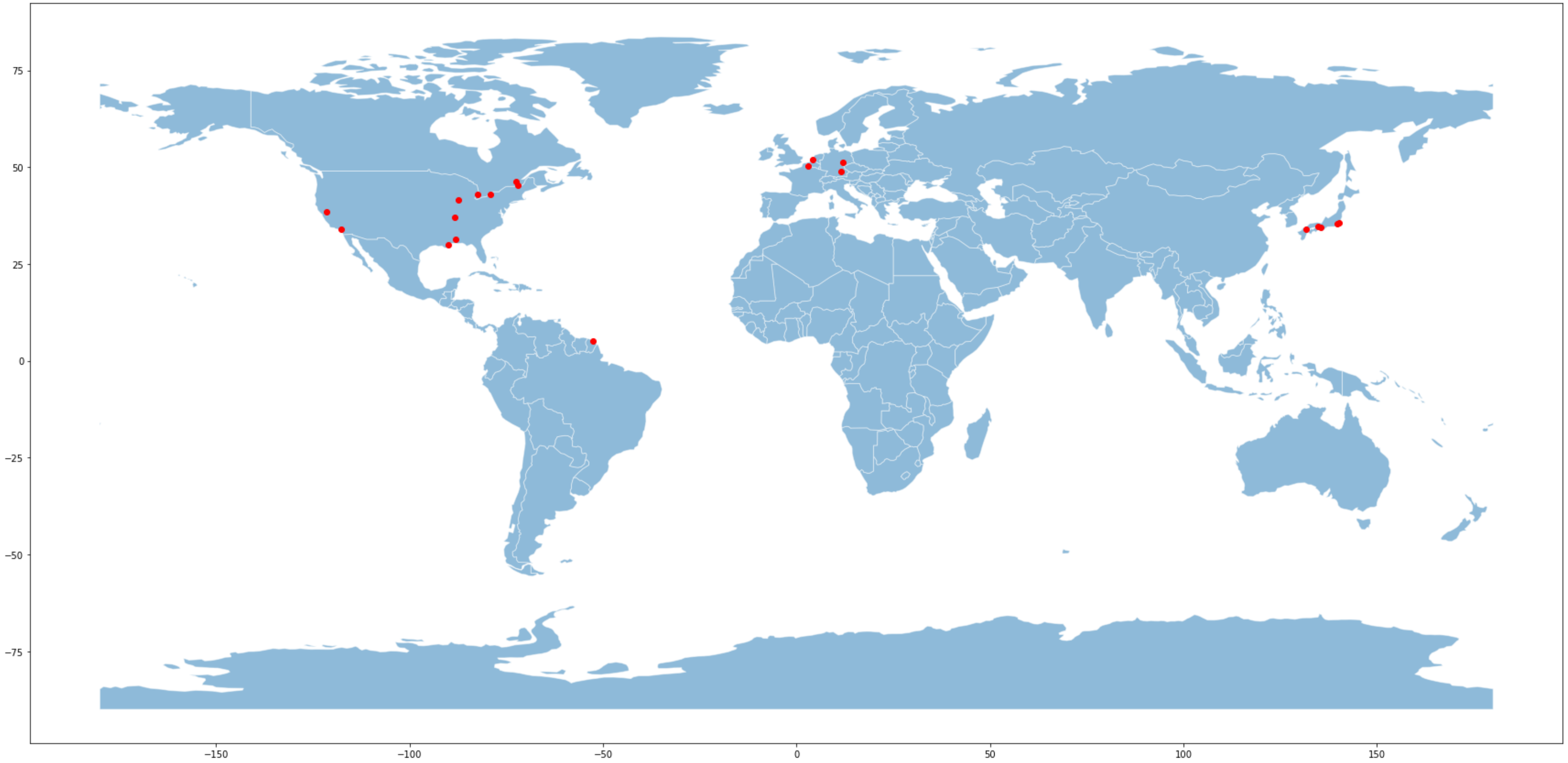
Hydrogen Availability: Liquid Hydrogen

It also depends on the physical state of hydrogen...

Country	Output kg/day
USA	209,167
Canada	51,461
Japan	35,607
France	10,500
Germany	10,100
Netherlands	5,400
Guiana	2,500
Australia	0,25*

*Port of Hastings: https://hydrogenenergysupplychain.com/port-of-hastings/



Own plot/Data source: https://h2tools.org/hyarc/hydrogen-production

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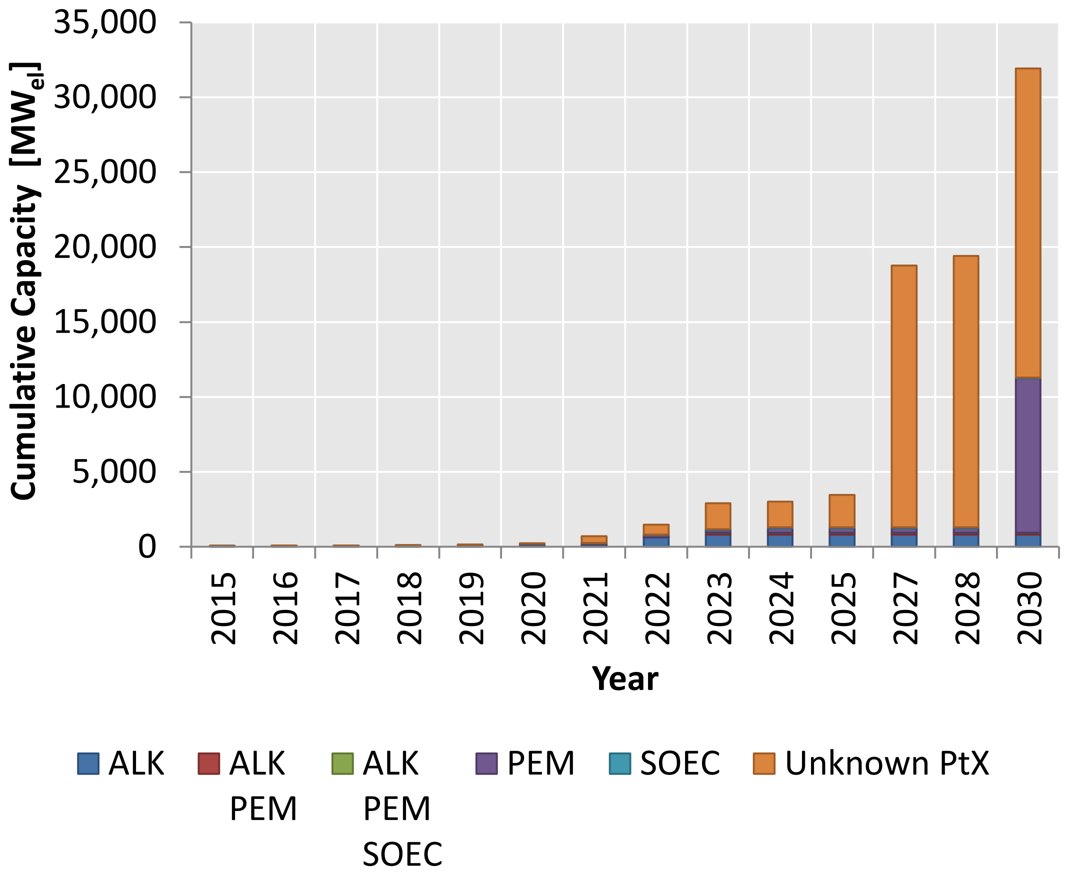
Hydrogen Electrolysis Additions and Cost

H_2 Electrolysis Expected Cumulative Capacity in Europe [Mw_{el}]



Source of data: https://www.iea.org/reports/hydrogen

Prospects for Electrolysis CAPEX reduction: experience rates of electrolysis: 18±6%

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Conclusions

- HySeas III is upscaling a solution for hydrogen and fuel cells powered ships
- Bunkering of compressed hydrogen has challenges due to the properties of hydrogen (Joule-Thomson effect), leading to longer bunkering times or the need of hydrogen precooling
- The use of hydrogen produced with renewable energies allows the reduction of global waming potential effects of the energy supply for ships
- In terms of costs, hydrogen production via electrolysis is highly dependent on the electricity price and has an important influence in the life cycle cost of the ship
- Physical state of hydrogen also matters: there are only 4 plants producing liquid hydrogen in Europe
- There will be important additions of electrolysis capacity in the next years

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Thank you!

Juan Camilo Gómez Trillos

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More about Hydrogen Cost/Price

Source	Production cost EUR/kg	Retail Price EUR/kg	Year	Compressed/Liquid	Electrolysis/SMR	Note
FCH-JU (2017)	4-5	-	2025	Compressed	Unknown	
Hinicio(2015)	5-7	-	2030	Compressed	Unknown	
E4 Tech(2014)	2.2-5.0	-	2014	Compressed	Electrolysis	
E4 Tech(2014)	2.5	-	2014	Compressed	Gas Reformation	
US DOE*(2012)	1.5-1.9	-	2020	Compressed	Gas Reformation	
Idealhy(2013)	1.72	-	N.A.	Liquid	Electrolysis	
Kawasaki(2018)	2	-	Estimation current project plans	Liquid	Coal gasification	
ZEP(2017)	2-4	-	2019	Compressed	Gas Reformation	
ZEP(2017)	4.8		2019	Compressed	Electrolysis	
ZEP(2017)	3	-	2045	Compressed	Electrolysis/Gas reformation	
Shell(2017)	1.5-4	-	2017	Compressed	Gas Reformation	
Shell(2017)	1.8-3.0	-	Projected Market price	Compressed	Gas Reformation	
Shell(2017)	6-8		2017	Compressed	Electrolysis	
Shell(2017)	4	-	Projected Market price	Compressed	Electrolysis	
IRENA(2018)	4.4-5.3	-	2018	Compressed	Electrolysis	
IRENA(2018)	-	11.5-14.5	2018	Compressed	Electrolysis	
IRENA(2018)	0.9-2.6	-	2025	Compressed	Electrolysis	
IRENA(2018)	-	4.4-6.1	2025	Compressed	Electrolysis	
GCSP(2019)	2.7-2.8	-	2019	Compressed	Electrolysis	
GCSP(2019)	3	-	2019	Liquid	Unknown	
DNV-GL(2019)	2-5	.	2030	Compressed	Electrolysis	
DNV-GL(2019)	1-1.6		2030	Compressed	Gas Reformation	
Greensight	-	7.1	2019	Liquid	Gas Reformation	
Greensight	-	11	2020	Compressed	Electrolysis	
Greensight		7.5	2023	Compressed	Electrolysis	

Source of data:

NCE Maritime CleanTech (2019). "Norwegian future value chains for liquid hydrogen." Report. URL: https://maritimecleantech. no/wp-content/uploads/2016/11/Report-liquid-hydrogen. pdf.

The Future of Hydrogen (2019). IEA. Available at: https://www.iea.org/reports/the-future-of-hydrogen

Glenk, G. and S. Reichelstein (2019). "Economics of converting renewable power to hydrogen." Nature Energy **4**(3): 216-222.

European Commission (2020). A hydrogen strategy for a climate-neutral Europe.

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More about Hydrogen Cost/Price

Source	Production cost EUR/kg	Retail Price EUR/kg	Year	Compressed/Liquid	Electrolysis/SMR	Note
Klebanoff & Pratt(2016)	-	5.2-6.5	2016	Liquid	Unknown	
Glenk & Reichelstein(2019)	3.23	-	2015	Compressed	Electrolysis	Germany
Glenk & Reichelstein(2019)	2.55	-	2015	Compressed	Electrolysis	Texas
Glenk & Reichelstein(2019)	1.92	-	2030	Compressed	Electrolysis	Germany
Glenk & Reichelstein(2019)	2.29	-	2030	Compressed	Electrolysis	Texas
EIA(2019)	1.5-2.1		near-long term	-	Gas Reformation	Australia
EIA(2019)	1.6-2.4		near-long term		Gas Reformation	Chile
EIA(2019)	1.7-2.3		near-long term		Gas Reformation	China
EIA(2019)	1.7-2.4		near-long term		Gas Reformation	Europe
EIA(2019)	1.8-2.4		near-long term		Gas Reformation	India
EIA(2019)	2.2-2.7		near-long term		Gas Reformation	Japan
EIA(2019)	1.1-1.6		near-long term		Gas Reformation	Middle Eas
EIA(2019)	1.4-2.0		near-long term		Gas Reformation	North Afric
EIA(2019)	1.2-1.8		near-long term		Gas Reformation	nited State
EIA(2019)	2.0-4.3		near-long term		Electrolysis	Australia
EIA(2019)	1.5-2.7		near-long term		Electrolysis	Chile
EIA(2019)	1.5-2.1		near-long term		Electrolysis	China
EIA(2019)	2.8-3.7		near-long term		Electrolysis	Europe
EIA(2019)	1.5-2.5		near-long term		Electrolysis	India
EIA(2019)	3.7-5.6		near-long term		Electrolysis	Japan
EIA(2019)	1.5-3.8		near-long term		Electrolysis	Middle Eas
EIA(2019)	1.5-2.9		near-long term		Electrolysis	North Afric
EIA(2019)	2.0-3.3		near-long term		Electrolysis	nited State
EU Commission (2020)	1.8-2.3		2030		Gas refomation + CCU	Europe
EU Commission (2020)	1.0-2.2		2030		Electricity from Renewables	Europe

Source of data:

NCE Maritime CleanTech (2019). "Norwegian future value chains for liquid hydrogen." Report. URL: https://maritimecleantech. no/wp-content/uploads/2016/11/Report-liquid-hydrogen. pdf.

The Future of Hydrogen (2019). IEA. Available at: https://www.iea.org/reports/the-future-of-hydrogen

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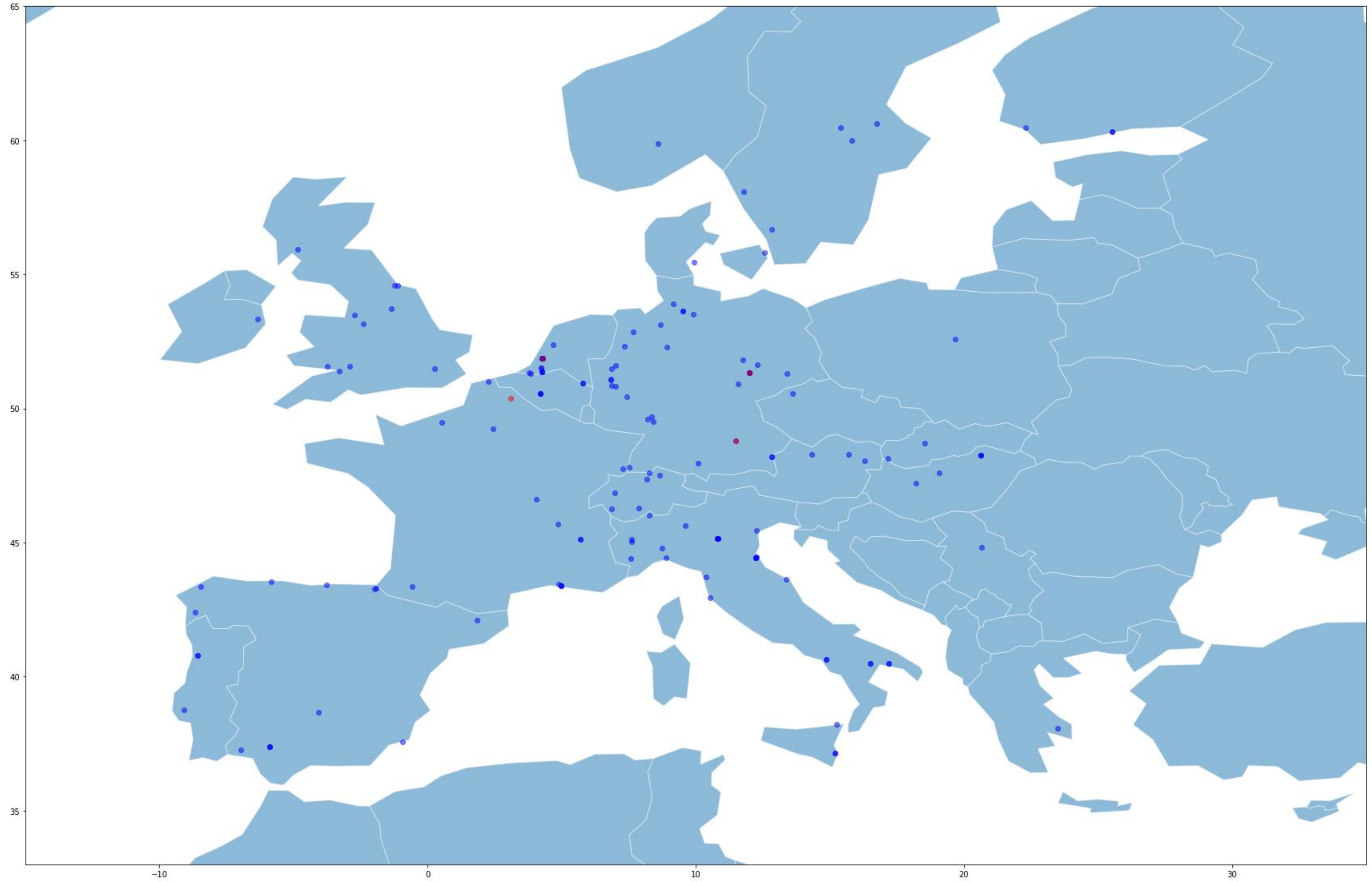
Hydrogen Production Sites in Europe



Own plot/Data source: https://h2tools.org/hyarc/hydrogen-production

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research and innovation programme under grant
agreement no: 769417

HySeasIII

HySeas III: Hydrogen Environment

HySeas III benefits from work done on other projects in Orkney:

- Hydrogen infrastructure from Surf n Turf and BIG HIT – includes specially designed hydrogen tube trailers tested and approved for transport of hydrogen on ferries, consideration of hydrogen safety on land based infrastructure
- HyDime – conversion of a small auxiliary genset on a ferry to run on a hydrogen mix – includes safety certification and crew training, HAZIDs and HAZOPs

Source: https://www.bighit.eu/about

Funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement no: 769417

HySeas III: Training

- Orkney Islands Council has worked with Orkney College to provide ship specific materials for development of training – teaching notes, visual aids
- Currently includes hydrogen safety awareness and continuity training for bunkering connections, and also additional instruction for hydrogen over LNG developed with UK MCA
- Training comes under the IGF Code, but the ISM Code also requires operating company to assure adequately qualified and familiarised crew
- Competence assurance cannot be achieved with familiarisation on another vessel
- No full IGF compliant course for now, but MCA can “recognise” what Orkney are doing

CHAPTER 8
OPERATIONAL AND TRAINING REQUIREMENTS
8.1 Operational requirement
8.1.1 The whole operational crew of a gas-fuelled cargo and a passenger ship should have necessary training in gas-related safety, operation and maintenance prior to the commencement
of work on board.
MSC 86/26/Add.1

8.2.1 *Training in general*
The training on gas-fuelled ships is divided into the following categories:
.1 category A: Basic training for the basic safety crew;
.2 category B: Supplementary training for deck officers; and
.3 category C: Supplementary training for engineer officers.

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