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TOWARDS NET-ZERO

INNOVATING FOR A CARBON-FREE FUTURE OF SHIPPING IN THE NORTH AND BALTIC SEA

October 2019

Project background

Christian Oldendorff – Initiator of Oldendorff Overseas Investment, co-owner of Reederei Nord and founder of Amplifier

Climate change is the biggest challenge of our generation. The shipping sector is one of the biggest contributors causing that change and has shown only very little innovation over the past decades. The time is now that industry leaders need to take action and find solutions to approach that challenge – not only to live up to their environmental and social duties, but also seize the economic potential of technological leadership in the space. Moving to zero-carbon shipping requires a rethinking of the entire shipping value chain, the development of innovative technologies and smart business models. Moreover, we need strong coalitions between ship owners, ship operators, fuel providers, ports and the public sector. This report is an attempt to align the shipping industry in the North and Baltic Sea region behind a joint vision of becoming a pioneer of sustainable shipping.

“The best way to predict the future is to create it.” – Peter Drucker

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Project background

This report is part of the initiative ‘Towards Net-Zero’ launched by Christian Oldendorff, the initiator of Oldendorff Overseas Investments, co-owner of Reederei Nord and founder of Amplifier.

The report was created by sus.lab, the Sustainability in Business Lab at ETH Zurich.

‘Towards Net-Zero’ aims at laying out a path towards zero-emission shipping in the North and Baltic Sea region by focusing mainly on zero-carbon fuels (i.e., hydrogen, ammonia and other hydrogen carriers as well as electrical propulsion/ batteries) and related technological innovations. The initiative is a call for action and an attempt to align key stakeholders incl. ship owners, ship operators, technology providers, fuel suppliers, investors, policy makers, consultants and academics behind a common vision for a more sustainable future of shipping.

Please note: This report is based on publicly available information as well as interviews with industry experts and innovators. Sources are provided on the individual pages. While interviewees endorse the general thrust of the arguments made in this report they may not agree with every finding or recommendation and they have not been asked to formally endorse the report.

This document represents a summary of the performed work – additional information and details are available in deep dive documents – available for download on www.towardsnetzero.com and www.suslab.ch

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Report summary

Globally, the shipping sector is responsible for about 3% of global GHG emissions – in order to meet the 1.5° C of the IPCC and reduce those emissions, technically feasible, commercially viable and safe solutions need to be identified. Some solutions are already readily available, such as operational efficiency measures (e.g., slow steaming, route optimization) and technical efficiency measures (e.g., improved hull designs, wind assistance). However, only alternative fuels, which are still pre-commercialization, allow for reducing emissions to zero.
Hydrogen and other hydrogen carriers (like ammonia) as well as the direct use of electrical power seem to provide the biggest potential (vs. hydrocarbon fuels from renewable energy) for a carbon-free future in shipping.
The North and Baltic Sea region has already positioned itself as an innovative powerhouse to push the development of the technologies required for these fuels. We believe, that the region could build on that position and become a pioneer of zero-carbon shipping, not only within the region, but also on a global level. We propose three focus areas to commence the journey:

Firstly, **deploy fully electric and diesel/ electric hybrids for selected maritime applications at scale** (new and as retrofits). Electric propulsion is already technically and economically feasible for many short-distance maritime applications. Fully electric short-distance ferries, for example, are deployable up to ~100nm under all sea conditions and depending on the route, are more profitable than diesel ferries already. Other attractive applications include fully electric short-distance utility vessels (e.g., tug boats, work boats, inland waterway cargo vessels) and hybrid medium-distance passenger vessels. Most ports are already in the process of upgrading their onshore power supply infrastructure, however, fast charging solutions are still not available at scale.

Secondly, **pilot hydrogen and ammonia propulsion systems for large freight ships**. About 90% of total global maritime emissions is caused by international trade and large freight ships, requiring energy carriers that allow for long-distance applications like hydrogen and ammonia. Both, hydrogen and ammonia can be produced through electrolysis from renewable electricity or through steam methane reforming (in combination with CCS) and could be supplied at scale within the next 10 years. Ammonia has a generally more mature supply chain. It is already produced at scale for the fertilizer industry and can be easily shipped over long distances. While sufficient ammonia production capacity to pilot ammonia vessels is available in the region already, the fuel can be produced outside the region in the longer term, leveraging low-cost renewable electricity capacities (e.g., in the Middle East). In order to transport hydrogen, liquefaction is required. Both, the technology and the capacity to liquify hydrogen, however, is still immature. To deploy ammonia and hydrogen on ship, storage remains technically challenging (i.e., safe handling of ammonia given its toxicity and handling of high pressures and/ or low temps of hydrogen). ICEs as well as dual-fuel ICEs for both, ammonia and hydrogen are expected to be commercially available within the next 3-5 years. Fuel cells would allow for even higher efficiencies and less emissions but still require 5-7 years to reach full commercial maturity. From an economic point of view, future fuel costs are difficult to predict but cost parity with MGO market prices seems possible for ammonia and hydrogen. The overall business case of ammonia and hydrogen shipping is not yet competitive with MGO, however, costs are expected to decline over time. For ammonia shipping, cost drivers are similar to MGO with higher cost for fuel and slightly higher space requirements. For liquid hydrogen, the main cost driver today is the price of fuel cells as well as for storage tanks. In the future, fuel cell costs are expected to decrease significantly and lower crew and maintenance costs could potentially compensate for higher engine costs (vs. MGO). The time is now to pilot these technologies and test ammonia and hydrogen on full scale vessels to fully understand open technological issues.

Thirdly, **develop new business models for zero-carbon fuels**. Fuel innovation needs to be accompanied by innovation in business and financing models. Examples of new business models include new bunkering solutions (like containerized batteries and energy packs as well as offshore hydrogen bunkering systems). The full potential of zero-carbon fuels could also be unleashed through remotely/ autonomously controlled ships enabled by *no maintenance engines* (i.e., fuel cells and batteries) resulting in reduced maintenance and crew costs – first design concepts exist already. Cross-value-chain collaborations (e.g., investment holding structures to share investment risks and long-term/ fixed-rate fuel contracts) could further reduce barriers to the deployment of zero-carbon shipping technologies.

Funding to make the transition happen is already available today: The EU ramped up innovation grants for the shipping sector in 2019 and EUR 40 billion is expected for climate-related innovation as part of the 'Horizon Europe' 2021-2027 program. Also national programs, venture capital funds, ship finance banks and opportunities to transfer costs to the end-customer can be leveraged to close the required investment gap. If zero emission shipping is indeed the political goal, then next to financial support regulators should provide further economic incentives to move away from fossil-based fuels. A carbon levy/ tax might be most effective and efficient, given the high abatement costs and the large number of emission sources of the sector.

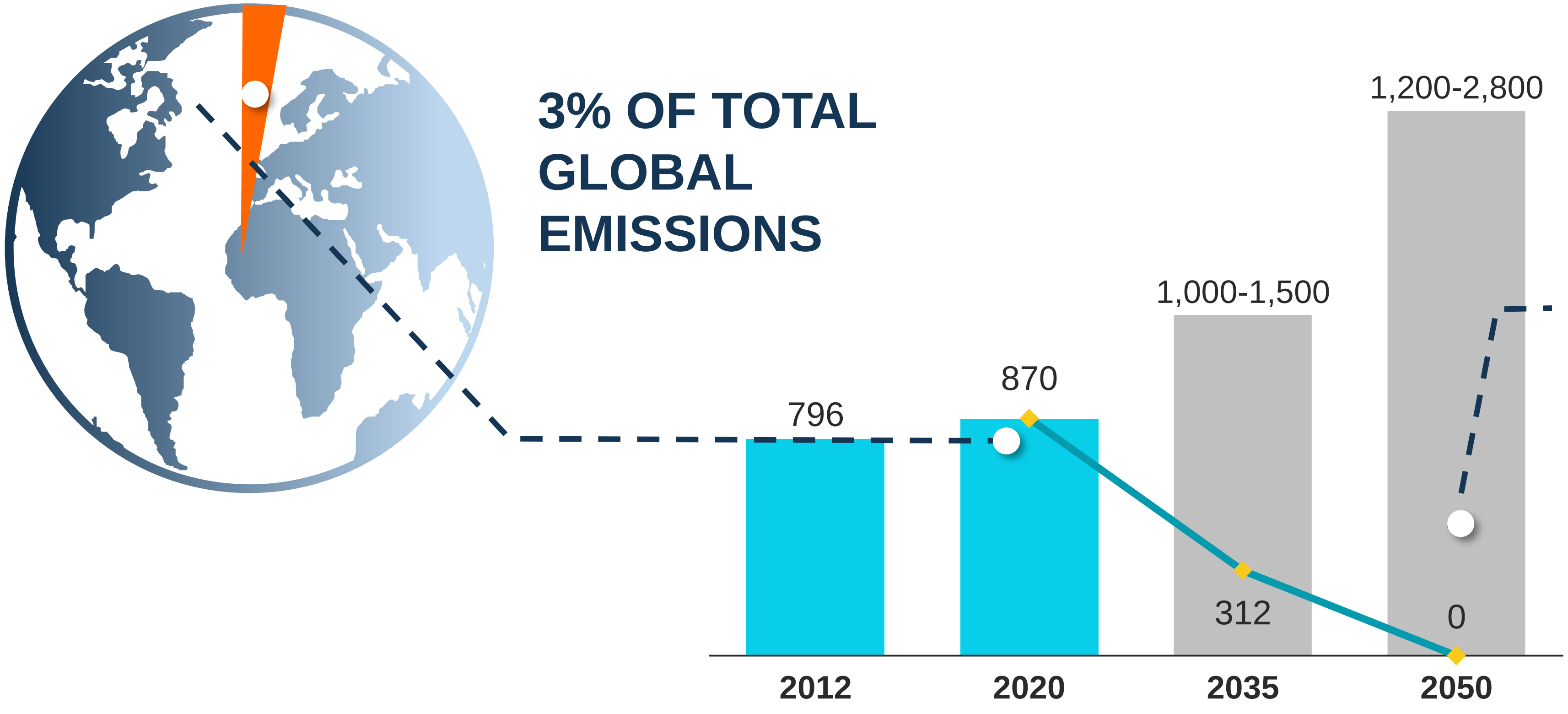
The transition to zero-emission fuels will certainly be a challenging journey, yet, with its strong ecosystem of relevant players across the value chain and supportive financial and regulatory institutions, the North and Baltic Sea region is perfectly positioned to pioneer zero-carbon shipping technologies.

Globally, the shipping sector is responsible for about 3% of global GHG emissions and current reduction targets are not in line with the IPCC's 1.5 degree scenario

Business as usual projected emissions vs. 1.5°C emission reduction requirement

Million tons of CO_2

Actual GHG emissions from shipping | Projected GHG emissions from shipping | IPCC 1.5°C pathway



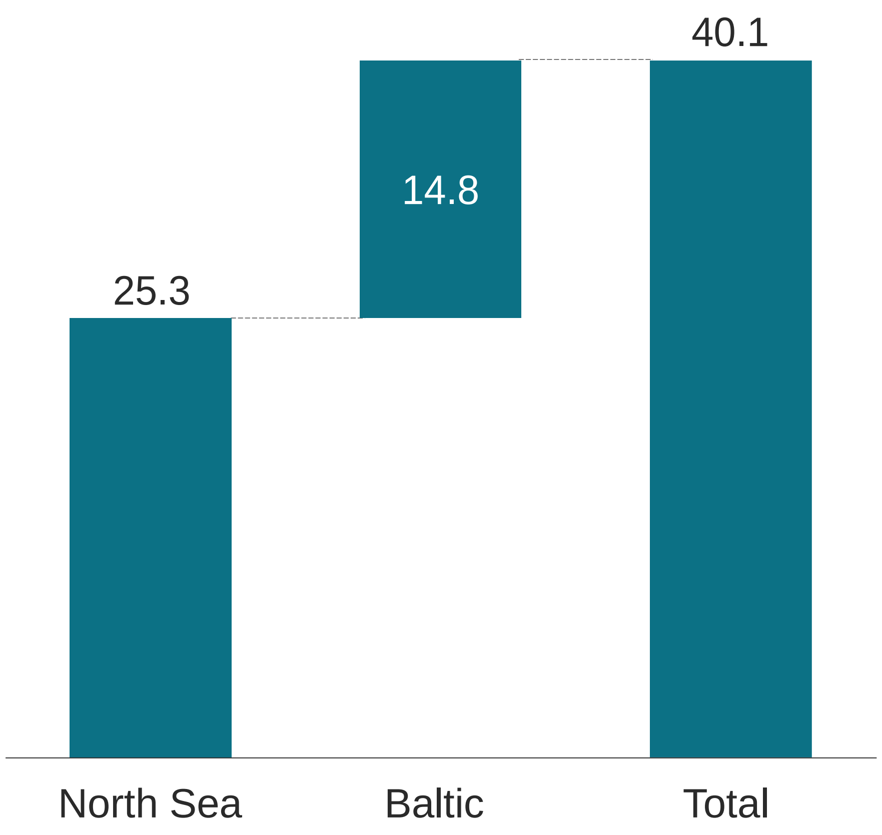
IMO INTERNATIONAL MARITIME ORGANIZATION

The IMO's Marine Environment Protection Committee adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision to reduce GHG emissions from international shipping by at least 50% by 2050 (compared to 2008) and phase them out as soon as possible in this century.

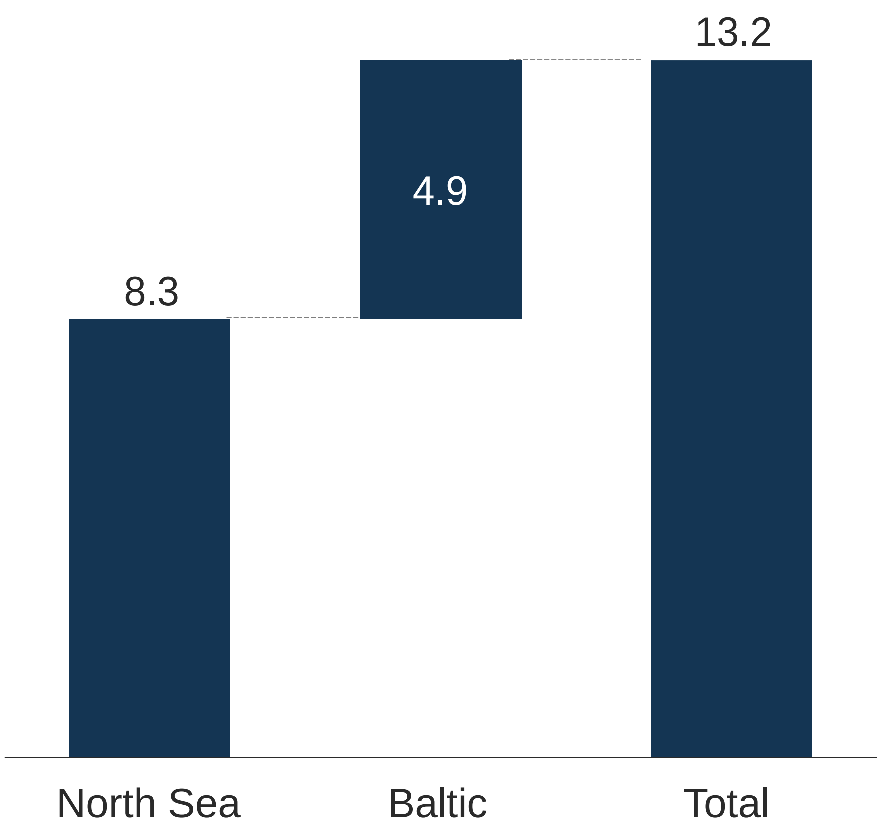
Source: IMO (2014): Third IMO GHG Study; Smith, T. W. P., Traut, M., Anderson K, Mcglade, C., Wrobel, P. (2015): CO2 Targets, Trajectories and Trends for International Shipping

The North and Baltic Sea region is responsible for ~5% of global CO2 emissions with ~40 Mt, based on fuel consumption of ~13 Mt of MGO-equivalent

CO2 emissions in the region
Mt per year



Fuel consumption in the region
MGO equivalent, Mt per year



The CO2 emission in the North and Baltic Sea region are ~40 Mt of CO2, equivalent to ~5% of the global 800 Mt

Source: Data provided by Finnish Meteorological Institute

Several international initiatives exist already with the goal to find technically feasible, commercially viable and safe solutions for zero emissions shipping

Global initiatives to reduce maritime emissions (exemplary)

Getting to Zero Coalition

GLOBAL MARITIME FORUM

The Getting to Zero Coalition is an alliance of 60+ companies within the maritime, energy, infrastructure and finance sectors, supported by key governments and IGOs, that is committed to getting commercially viable deep sea zero-emission vessels powered by zero-emission fuels into operation by 2030.

IMO INTERNATIONAL MARITIME ORGANIZATION

The IMO's Marine Environment Protection Committee adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision to reduce GHG emissions from international shipping by at least 50% by 2050 (compared to 2008) and phase them out as soon as possible in this century.

HOW DO WE GET TO ZERO?

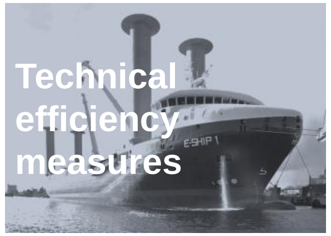
- **What are technically feasible, commercially viable, safe and fast routes towards zero-emission shipping?**
- **What can be done to effectively pioneer the transition towards zero emissions?**
- **How can the transition be financed?**

While a wide range of solutions to reduce GHG emissions in shipping exists, alternative fuels seem to be the only path to reach zero

Potentially most feasible (detail follows)

Measures to reduce GHG emissions

- Slow steaming
- Optimized route planning and weather routing
- Cold ironing/ on shore power supply
- More efficient port and cargo handling and logistics



- Improved hull designs and other ship design measures
- Frequent propeller polishing
- Air lubrication
- Alternative propulsion systems (e.g., wind assistance)
- Waste heat recovery

- Low-carbon fossil fuels
- Carbon-neutral bio fuels
- Carbon-neutral hydrocarbon fuels
- Zero-carbon fuels

Type	Description	Potential to reach zero-carbon
Low-carbon fossil fuels	Fossil fuels with a lower carbon footprint than conventional fossil fuels (e.g., LPG, LNG, Methanol)	Reduction by max. 20-30% vs. conventional fuels
Carbon-neutral bio-fuels	Fuels made from organic feedstock such as oils, sugars, or waste (e.g., Bio Diesel, Bio Methane, Bio Methanol)	Can be carbon-neutral, yet, scalability of production might be limited by resource and land requirements to produce biomass
Carbon-neutral hydrocarbon fuels	Synthetically produced (with the use of renewable energy and chemical compounds based on hydrogen and carbon (e.g., eDiesel, eMethane, eMethanol)	Can be carbon-neutral if produced with renewable energy and CO2 is captured
Zero-carbon fuels	Energy carriers that do not emit any CO2 to generate power (e.g., Hydrogen, Ammonia) or the direct use of electricity	Can be carbon-neutral if produced with renewable energy

Note: Carbon capture and storage not considered

Source: Faber et al., (2012): New Climate Institute (2019); Nordhaus (2013)

Zero-carbon fuels seem to offer a faster and most energy efficient route to transition compared to hydrocarbon fuels based on renewable electricity

	Feedstock supply	Fuel production	Fuel distribution	Fuel conversion (on ship)
Carbon-neutral hydrocarbon fuels from renewable electricity[1]	! Scarce for the next 10-20 years – in competition with all other sectors, in particular electrification	! Two additional process steps after hydrogen production ! Need for CO2-capture even in the distant future ! No large scale methane/ methanol synthesis available	+ Existing transportation and storage infrastructure can be used	! 95% of engines would have to be replaced for eMethane or eMethanol + Engines available
Zero-carbon fuels	+ Direct use of electricity is the most efficient wherever possible + For H2/ammonia two alternative paths with renewable electricity and natural gas (in combination with CCS)	+ One step process to hydrogen + Two step process to ammonia, which is available at industrial scale today	! No distribution infrastructure for hydrogen, very cost intensive storage ! Existing distribution for ammonia, bunkering facilities missing	! 100% of engines would have to be replaced ! Engines fully commercially available within 3-5 years only

Both transition paths require significant investments, however, zero-carbon fuels could offer a faster transition route as hydrogen (and other hydrogen-carriers) as they require less fuel production steps and can be produced from natural gas in combination with CCS.

1 Biofuels were excluded from the analysis due to concerns about food competition at scale. Future technology might be able to circumvent this issue, but is not currently ready for scale-up.

The North and Baltic Sea region has already positioned itself as an innovative powerhouse of the sector and could drive change on a global level

Fuel suppliers & ports	▪ 'Northern Lights' project to produce carbon-neutral hydrogen at scale (SMR + CCS) from 2023 ▪ Port of Hamburg to install the worlds largest electrolyzer to produce green hydrogen ▪ Yara invests in green ammonia in Netherlands and Australia
Ship designers & equipment providers	▪ Multiple designs for zero-emission vessels available ▪ MAN develops ammonia fueled engine to be commercially available by 2022 ▪ CMB develops mono-fuel and dual-fuel hydrogen engines
Ship owners & operators	▪ High interest in assessing available solutions for low and zero-emission shipping ▪ Variety of demonstration projects ongoing across Europe
End customers	▪ Maersk and DHL pledged net-zero by 2050 ▪ 60+ companies, incl. Maersk, Unilever, EuroNav and others joined the 'Getting to Zero' Coalition
Financial institutions	▪ EUR 40bn for climate innovation over 5 years from EU alone ▪ Multiple national financing schemes esp. in Scandinavian countries ▪ Launch of the Poseidon Principles (global framework for responsible ship finance)
Governments	▪ Multiple national initiatives launched, e.g., Clean Maritime Plan in the UK and the Green Shipping Program in Norway

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We found three main areas to focus on for driving the transition towards zero-carbon shipping

1

Deploy fully electric and diesel/ electric hybrids for selected maritime applications at scale – new and as retrofits

2

Pilot hydrogen and ammonia propulsion systems for large freight ships

3

Develop new business models for zero-carbon shipping

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1 Electric propulsion is already technically and economically feasible for many short-distance maritime applications

Fully electric short-distance ferries

- Deployable up to ~100nm under all sea conditions
- Depending on the route, most fully electric ferries are more profitable than diesel ferries already
- Most ports are upgrading their onshore power supply (OPS) infrastructure, however, fast charging solutions are still rare

Fully electric short-distance utility vessels

- Tug and work boats as well as inland waterway cargo vessels are suitable for fully-electric propulsion
- Potentially lower OPEX vs. conventional systems due to reduced maintenance and fuel costs

Hybrid medium-distance passenger vessels

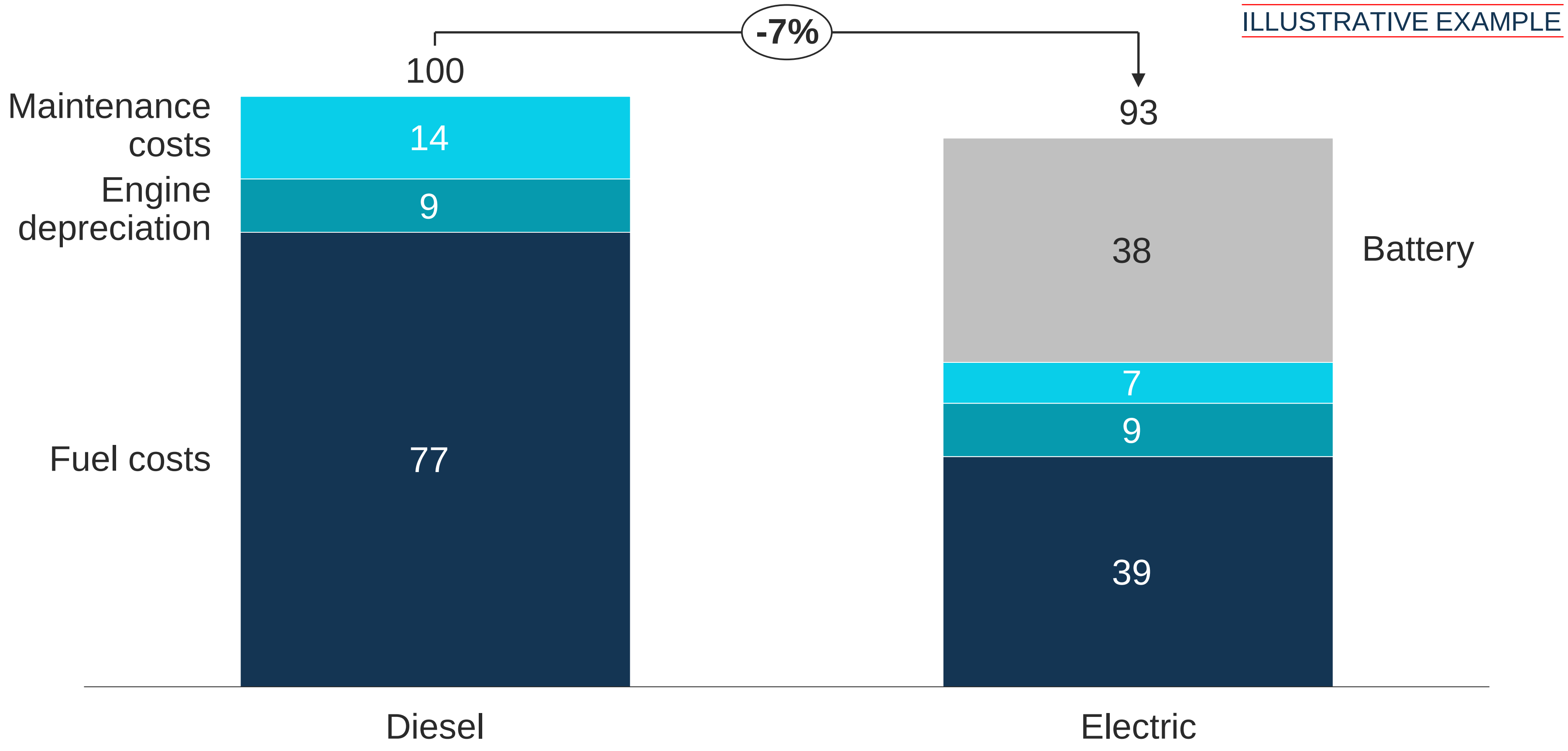
- Hybrid systems allow for longer distance and more flexibility
- Simple retrofitting of existing vessels as most vessels use diesel-electric transmission systems already
- Potentially lower OPEX vs. conventional systems due to reduced maintenance and fuel costs and increased engine efficiency

Sources: Images from gCaptain, Portliner, Colorline

1 For battery/ electric vessels, the upfront investment is the main cost driver and can be compensated by low electricity cost

CASE EXAMPLE: 30 passenger shuttle vessel, diesel vs. electric

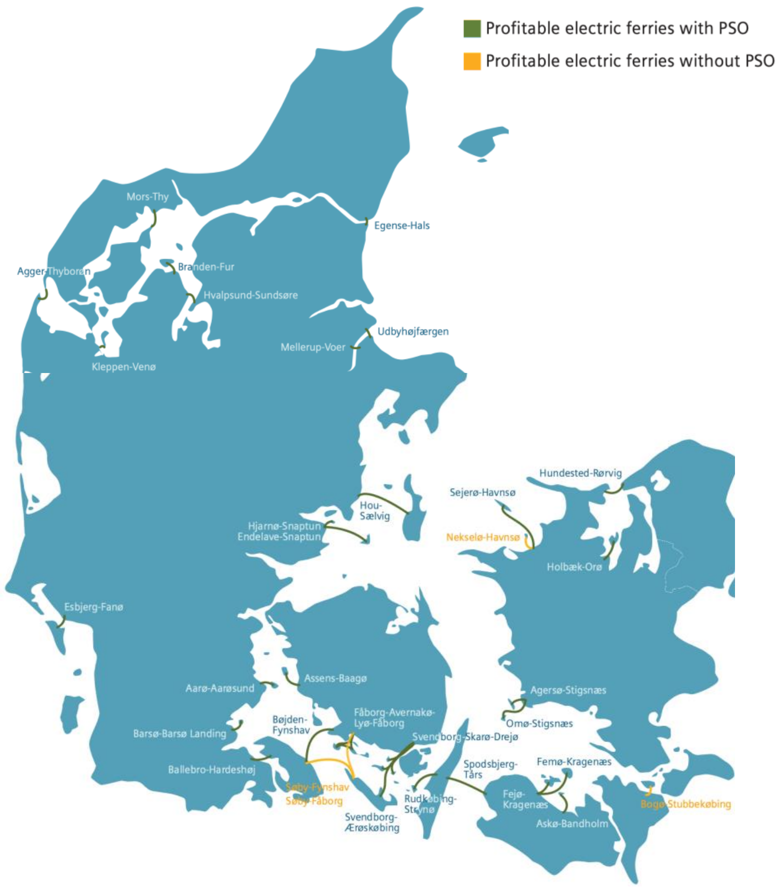
Annual fully-loaded cost distribution, in percent



- **For shorter distances, battery vessels are more economic than diesel vessels today already**
- **High cost of batteries can be compensated by lower electricity vs. fossil fuel cost (depending on fuel and electricity prices) and lower maintenance costs**

Sources: Transport Transformation (2018)

1 Depending on the region, electric ferries would already be more profitable than comparable diesel vessels on most journeys – Example Denmark



- Replacing Denmark's 52 costal diesel ferries on 42 domestic routes with fully electric ferries could result in annual savings of EUR 11 mio
- Case will become more attractive in the future due to pending phase out of electricity levy and historically low diesel price
- Required investment of EUR 56 mio for:
  - New batteries
  - Expanding the existing electricity grid locally to the port mooring
  - Lighter materials
  - Batteries

A study for Denmark's ferry transport by Siemens suggests:

- **7 out of 10 fully electric ferries are more profitable than diesel ferries**
- **Replacing Denmark's costal diesel could save 50,000t of CO2 p.a.**
- **Average payback is 5.5 years**

Source: Siemens: Electrification of Denmark`s Ferry Fleet

1 Most ports are upgrading their onshore power supply infrastructure; however, fast charging solutions are still rare

- Many ports in the North and Baltic Sea installed **onshore power supply (OPS)** already, allowing vessels in berth to access the local grid
- **OPS allows to:**
  1. **Switch off the on-board auxiliary power**, thus minimizing in port pollution (including noise pollution)
  2. **Re-charge the on-board batteries** of fully electric and hybrid vessels
- Article 4 of the 2014 **EU** directive on the deployment of alternative fuels infrastructure states that **members shall install OPS before the end of 2025**, unless there is no demand or if costs are disproportionate to benefits – including environmental benefits
- Despite the roll-out of OPS in the region, **fast charging solutions are still required to reduce the charging time of vessels** with on-board batteries

Source: Directive 2014/94/EU of the European Parliament and of the Council (October 2014)

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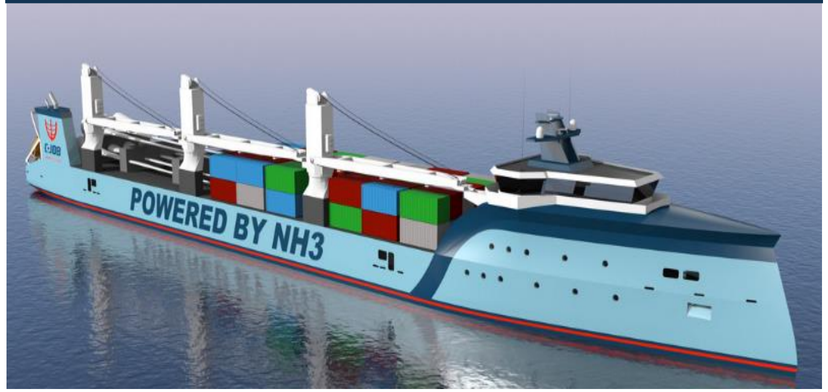
2 Both hydrogen and ammonia need be tested on full scale vessels – both combustion engines and fuel cell demonstration projects are needed

Medium-distance hydrogen vessels

- Hydrogen allows for more autonomy than battery/ electric
- Fuel cells are already available and MW size systems are ready for testing, costs are expected to come down, driven by automotive
- Combustion engines are under development and expected to be fully commercial within 5 years
- Liquid hydrogen is limited in range due to space constraints and investments in tanks

Deep-sea ammonia vessels



- Ammonia is currently the only viable option for deep sea zero-emission fuels
- From a supply chain perspective, ammonia also has the potential to provide a *faster route to decarbonization* than hydrogen
- No public ammonia pilots were found, but designs are available and combustion engines are under development
- Existing ammonia tankers could be a first case for piloting

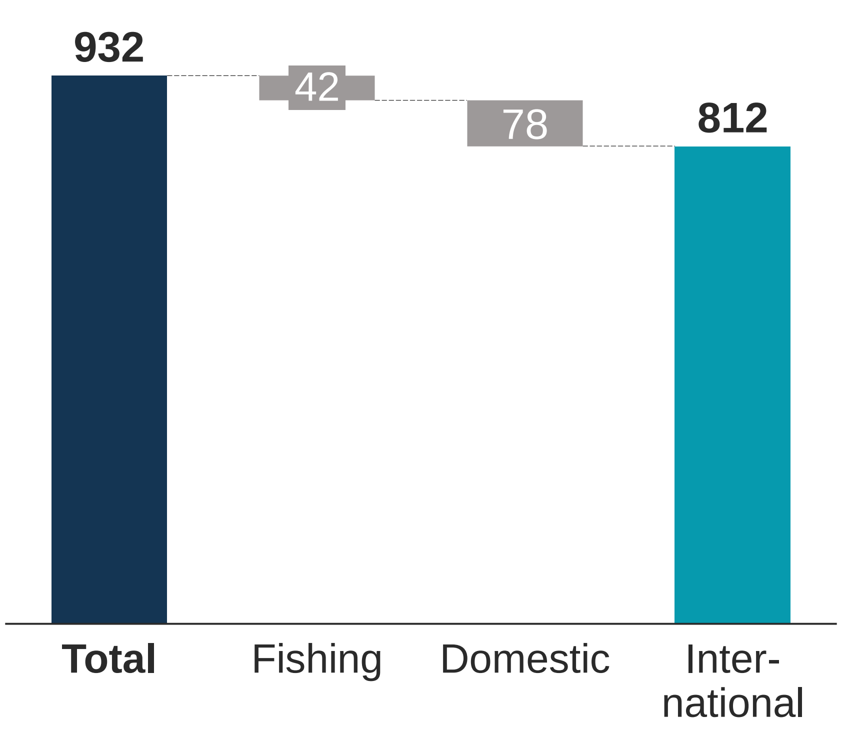
Sources: Images from Havyard, Niels de Vries, c-job

Open issues for commercial testing

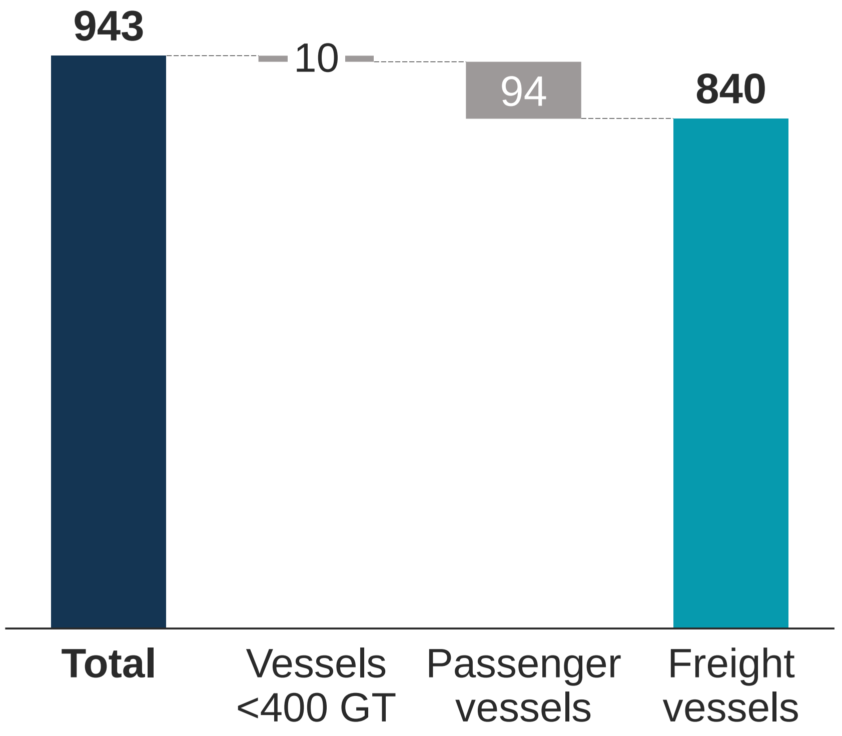
- **Demonstrate safe handling of fuels** (e.g., toxicity for ammonia, very low temperatures for hydrogen)
- **Fully understand pros and cons** of fuel cells vs. ICE
- **Fully understand losses** in handling hydrogen along the supply chain
- **Develop procedures and certifications**
- **Signal market demand** to the rest of the value chain
- **Get started on the cost reduction curve** beyond first of a kind (e.g., engineering, components)

2 About 90% of total global maritime emissions are caused by international trade and freight ships

Global shipping CO_2 emissions by journey type
Mt of CO_2 (2015)



Global shipping CO_2 emissions by vessel type
Mt of CO_2 (2007)



87% of shipping emissions stem from international trade and 90% percent from large freight vessels (>400 GT)

Source: ICCT (2013-2015): Greenhouse Gas Emissions From Global Shipping; WMU Journal of Maritime Affairs (2009)

2 For deep-sea shipping, from a technical and supply perspective, ammonia has potential to provide a faster route to decarbonization than hydrogen

	Fuel production	Fuel distribution/ storage	Ships and engines
Ammonia	+ Two **alternative paths** with renewable electricity and natural gas (in combination with CCS) + Production **available at scale** already	+ **Transported at scale** on the sea **already** ! **No bunkering** facilities yet	+ **Dual fuel ICEs** fully commercial **within 5 years** ! **Solid oxide fuel cells** expected **in 5-10 years** – PEM need reformers ! Additional **safety measures against toxicity required**
Hydrogen	+ Two **alternative paths** with renewable electricity and natural gas (in combination with CCS) ! Liquefaction **not implemented at scale**	! **No distribution infrastructure**, very cost intensive storage ! **Bunkering facilities not yet commercial** + Sector can benefit from **hydrogen trend in road/ rail transport**	+ **Dual fuel ICEs** fully commercial **within 5 years** + **Fuel cells** expected **in 5-10 years** – benefit from fuel cell development in automotive

- **Both, ammonia and hydrogen could provide valid solutions to decarbonize selected maritime applications at scale within the next 10 years**
- **Ammonia has a generally more mature supply chain, incl. e.g., components**
- **Ammonia and hydrogen ships are not cost-competitive with MGO equivalents, but costs are expected to decrease over time – especially ammonia vessels could provide a competitive business case**

2 In the North and Baltic Sea, the replacement of fossil fuels with zero-emission fuels would correspond to ~4% of global hydrogen or ~20% of global ammonia production

Technology	Current fuel consumption[1]		Corresponding hydrogen demand[3]		Corresponding ammonia demand[4]
North Sea	**8.3 Mt** *Energy Density = 41.4 GJ/ton[1]*	▶	**2.9 Mt**	or	**18.5 Mt**
Baltic Sea	**4.9 Mt** *Energy Density = 42.72 GJ/ton[2]*	▶	**1.7 Mt**	or	**11.0 Mt**
Total	**13.2 Mt**	▶	**4.6 Mt**	or	**29.5 Mt**
Total share of current global market			**~4%**	or	**~21%**

1 Calculated for 50% HFO and 50% MGO
2 Calculated for 88% MGO, 0.1% LNG and remaining HFO and MDO
3 Energy density = 120 GJ/ton
4 Energy density = 18.6 GJ/ton
Source: Data provided by Finnish Meteorological Institute

2 Several green ammonia projects are under development or at pilot stage in the region (and globally)

Pioneering organization	Project description
Yara Sluiskil plant in the Netherlands	▪ Capacity: 1.5Mt/year ▪ Recycles hydrogen, which is a waste-product of Dow's nearby ethylene cracker plant ▪ Reduction of CO_2-intensity of about 10kt/year and decrease in energy consumption of 0.15 PJ/year
OCP pilot plant in Germany and Morocco	▪ Announced plans to develop Green Hydrogen and Green Ammonia as sustainable raw materials for use in fertilizer production ▪ Builds pilot plants in both Germany (already under construction) and Morocco (foreseen) ▪ Considers the establishment of an African Institute for Solar Ammonia
Siemens in the UK	▪ Capacity: 11tons/year ▪ Green Ammonia demonstration project at the Rutherford Appleton Laboratory in Oxfordshire, England for GBP 1.5 mio ▪ Involved in further pilot projects and offers commercially proven electrolysis technology
Yara Pilbara plant in Western Australia	▪ Capacity: 0.85Mt/year ▪ Green ammonia demonstration project to integrate green hydrogen into an existing Ammonia plant ▪ Renewable electricity of 100+ MW (i.e., 200ha solar array required) ▪ First demonstration of 100% carbon-neutral ammonia production at scale

Source: Company websites

2 Large scale projects for green hydrogen are starting, e.g., the Port of Hamburg and the Port of Rotterdam pioneer on-site zero-carbon hydrogen production

Pioneering organization	Project description
Port of Hamburg	▪ The port of Hamburg plans a 100MW electrolyzer to produce H2 from excess renewable electricity produced offshore (decision expected by end of 2019) ▪ H2 production is estimated at 2tons/hr according to Siemens ▪ The motivation for the project is to create energy storage by using hydrogen as an energy carrier ▪ The electrolyser will be the first of its capacity globally (existing electrolysers have a maximum capacity of 10MW) and will be build in modular form allowing for future expansion
Port of Rotterdam	▪ H-vision is a collaboration between 16 parties[1] mainly from the port of Rotterdam industrial area to explore large-scale production and application of blue H2 ▪ The project is a clear solution to decarbonize high-temperature heat and power generation, and transition towards an H2 economy ultimately based on green H2 ▪ The positive results of the feasibility study provides Rotterdam with a new opportunity to develop itself into a major hub for the production, uptake and trading of hydrogen

1 Deltalinqs, TNO, Air Liquide, BP, EBN, Engie, Equinor, Gasunie, GasTerra, Linde, OCI N.V., the Port of Rotterdam Authority, Shell, TAQA, Uniper and Royal Vopak

Source: Company websites of Port of Hamburg, Sunfire, Port of Rotterdam

2 The “Northern Lights” project could make production of “blue hydrogen” and ammonia from natural gas with CCS reality within the next years

equinor Shell TOTAL

Equinor, Shell and Total have signed MoU with 7 European companies[1] to develop CCS value chains supported by the Norwegian State

Technology description

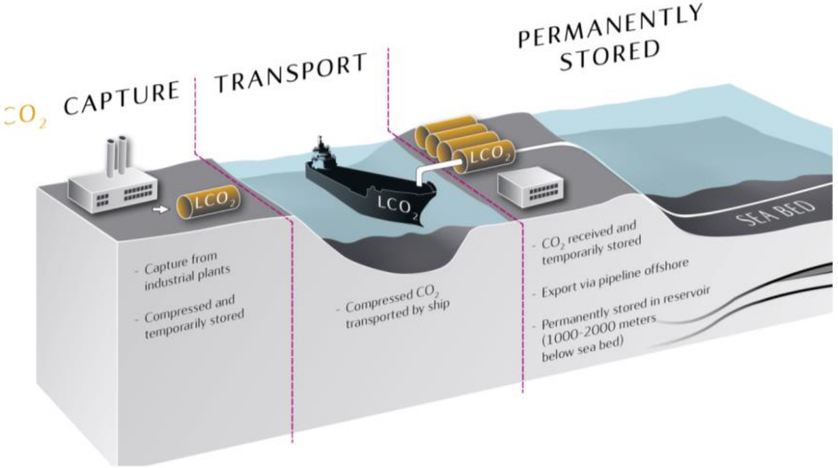
- The ‘Northern Lights’ project includes **transport, reception and permanent storage of CO2** in the North Sea
- **Equinor's CCS method is a proven process** as the company has been re-injecting recovered CO2 into the ground for decades

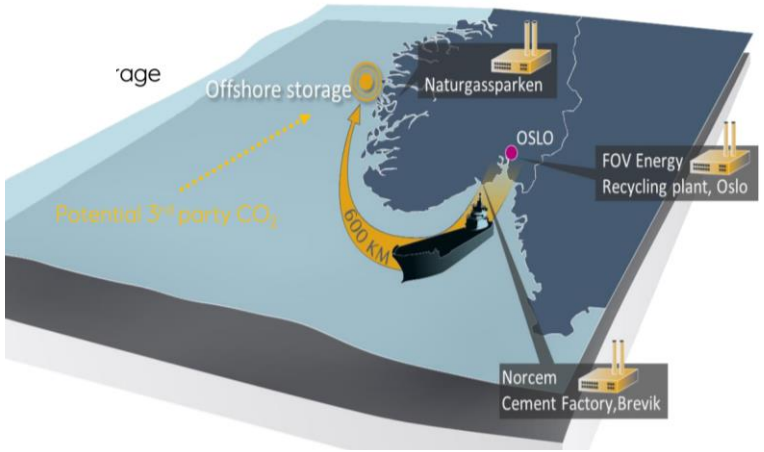
Economic implications

- Currently **no hydrogen costs available** from ‘Northern Lights’
- A detailed design study with similar scope for Northern England (H21) arrived at **EUR 1,080-1,800 per ton of hydrogen** or **EUR 206-307 per ton of ammonia**

Next develop-ment steps

- At the **end of 2019**, a confirmation well for CO2 storage is to be drilled in the Johansen formation to study the reservoir’s suitability and capacity





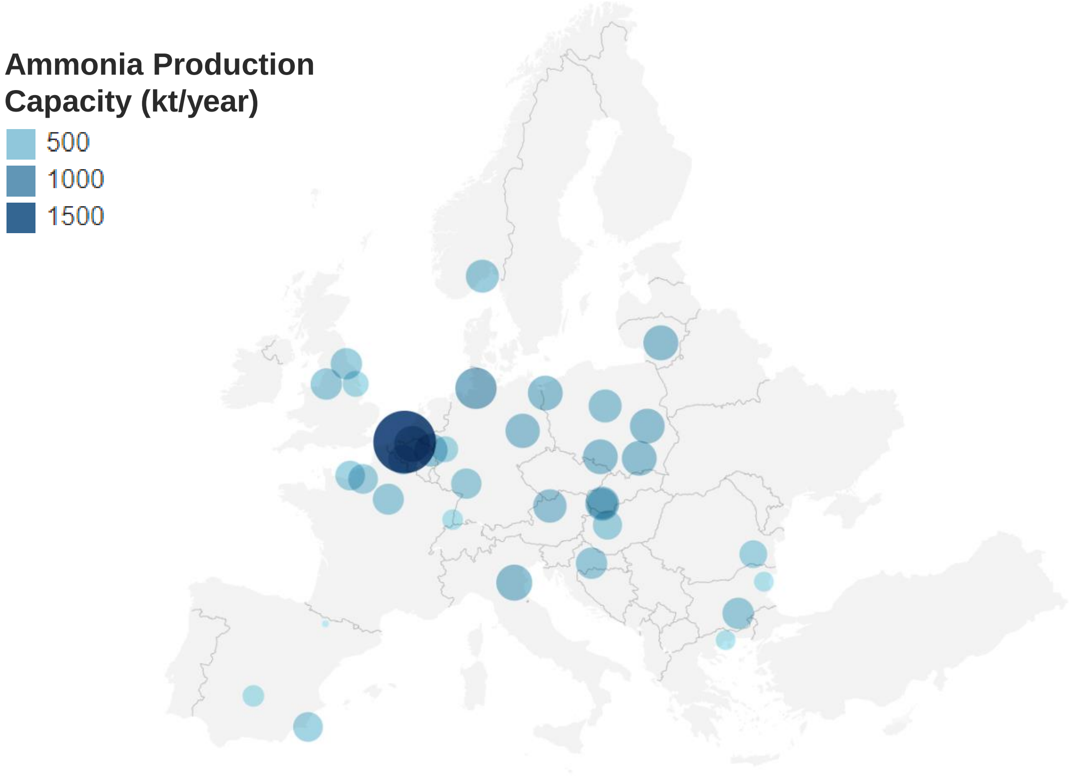
1 Air Liquide, Arcelor Mittal, Ervia, Fortum Oyj, HeidelbergCement AG, Preem, and Stockholm Exergi

Source: Press research and interviews, H21 North of England, 2018, Images Goassnova, Northern lights

2 For the piloting phase, fossil based ammonia and hydrogen are available in the region

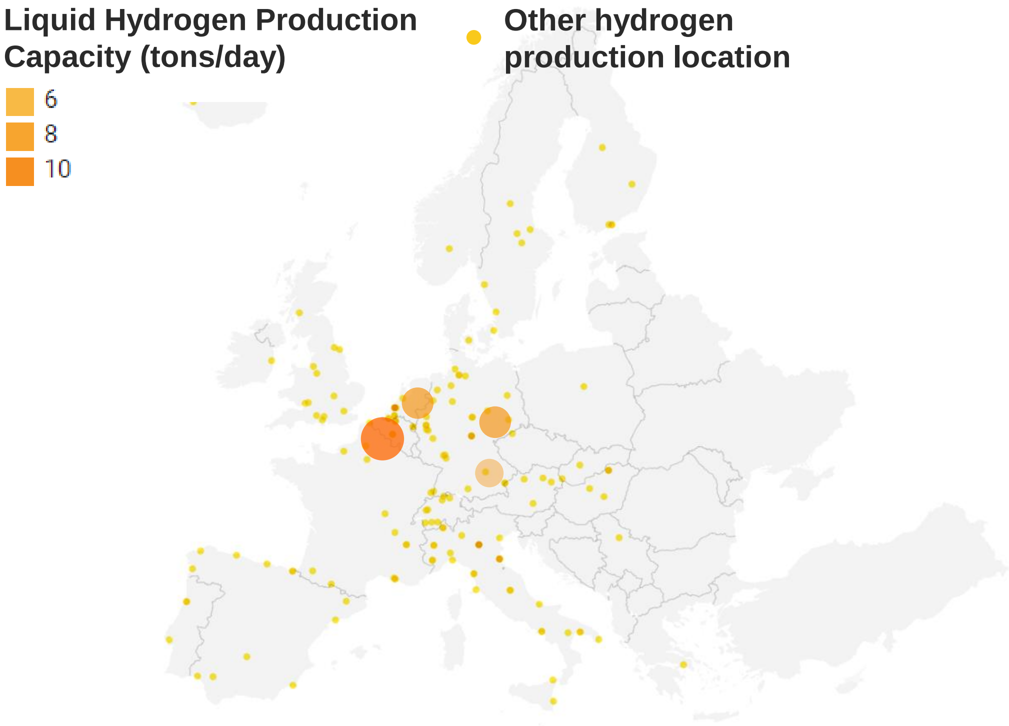
Ammonia production capacity in Europe

The production capacity of active ammonia plants is ~18 Mt/year



Hydrogen production in Europe

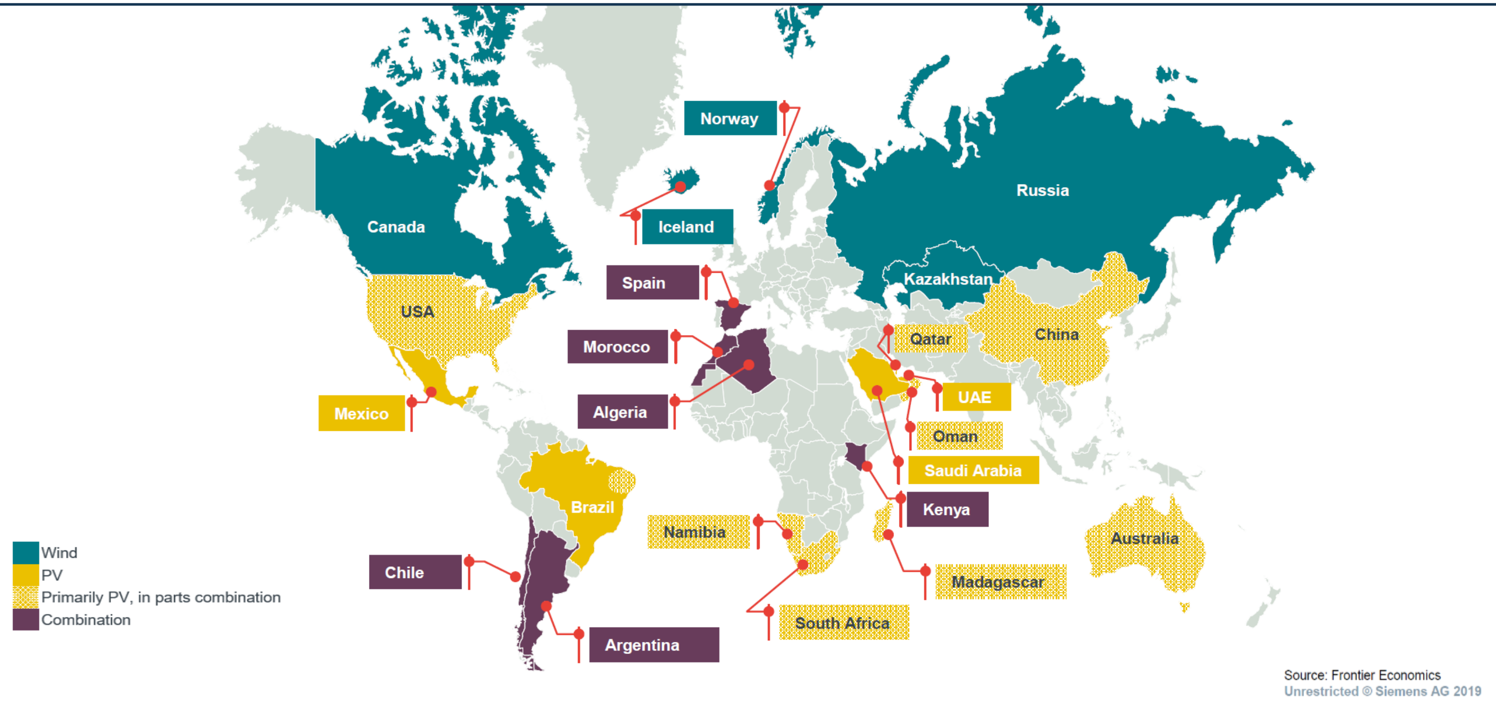
Liquid hydrogen production capacity is ~26 tons/day, ~9,500 tons/year (7% of world production) and multiple sites exist around the Baltic/ North Sea



Source: Europe Merchant Hydrogen Plant, h2tools, 2015; Ammonia Production in Europe, Fertilizers Europe

2 In the medium term, ammonia and hydrogen could be produced outside of Europe as renewable electricity is available at e.g., EURct ~2 per kWh for solar in the Middle East vs. e.g., EURct ~4 per kWh in Germany

Potential for fuel generation from renewable electricity[1]



The quoted prices are for intermittent energy, which drives cost for H2 due to high CAPEX in electrolyzers. Baseload electricity has higher rates.

1 Source: Florian Bergen: Electricity-based fuels as a link between the electricity and transport sectors; Siemens AG; ETIP Wind Workshop
2 Source: IRENA (2018): Renewable Power Generation Costs in 2018
3 Source: GCC (2019); IRENA: Renewable Energy Market Analysis
4 Source: Bloomberg New Energy Finance
5 Source: Fraunhofer ISE (March 2018): Levelized Cost of Electricity

Cheapest sources produce at EURct ~2 per kWh

- Record low prices for new installations of solar PV in Dubai, Mexico, Peru, Chile, Abu Dhabi and Saudi Arabia with USDct ~3 per kWh (EURct ~2.7)[2]
- Cheapest recorded: Sakaka, Saudi Arabia, USDct ~2.34 (EURct ~2.1)[3]
- Onshore wind is now as cheap as USDct ~2.7 per kWh (EURct ~2.4) in India and Texas, without subsidy[4]
- For comparison: LCOE of electricity in Germany today for utility scale PV is EURct 3.7-6.8 per kWh, and EURct 4-8.2 per kWh for onshore wind (without VAT)[4]

2 Transport and storage of ammonia and hydrogen remain challenging due to relatively low energy densities for H2 and potential safety concerns for ammonia

	Energy density by fuel, GJ/m3	Volume increase vs. MGO
MGO/ MDO	37	1.0
Liquid Methane	23	1.6
Methanol	16	2.3
Ammonia	13	2.9
Hydrogen (liquified)	9	4.3
LOHC	7	5.4
Hydrogen (compressed)	5	7.7
Electrical power/ battery	1	64

	Volume requirements	Safety concerns	Technological maturity
Ammonia	+ / ! NH3 requires 3x the storage space of MGO/ MDO	! NH3 is toxic if inhaled and very toxic to aquatic life with long lasting effects	+ Storage technology readily available (similar to LPG)
Hydrogen (liquified, LOHC, compressed)	! Low volumetric energy density of H2 compared to MGO/ MDO results in 4-8x more storage space	! H2 requires high pressure of ~800 bar or very low temperature down to -253 degrees	! Storage technology not yet available at large commercial scale

Source: Niels de Vries (2019): Safe and effective application of ammonia as a marine fuel; Mission Possible (2019); Hydrogenious

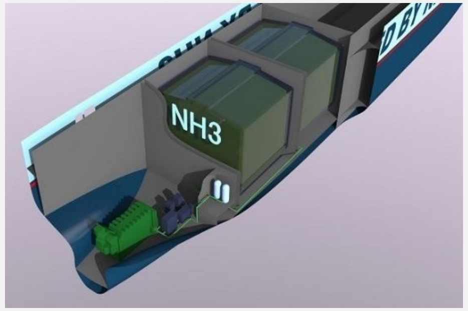
2 While ammonia can conveniently be stored in liquid form, toxicity needs to be addressed by specific safety measures

Ammonia hazards vs. other energy carriers

Energy carrier	Key hazards			
Ammonia	Acute toxic	Corrosive	Environmental	Gas under pressure
Hydrogen	Flame	Gas under pressure		
LNG	Flame	Gas under pressure		
Diesel	Flame	Acute toxic	Health hazard	

Potential safety measures to mitigate risks

- Safety systems to prevent ammonia release at tank refill
- Safe design of the tank to withstand collision (e.g., external frames, level indicators, gas alarms)
- High-pressure alarms on evaporators to protect down flow system
- Temperature controls on reformers
- Ammonia sensors at absorbers
- Gas alarms on the ICE and fuel cell system
- Crew trainings on how to handle ammonia



- Ammonia is less flammable than other fuels, and can be easily stored at -33.4°C and at 1 bar.
- However, ammonia is more hazardous to human health than other energy carriers and requires additional safety measures
- Safe handling and storage of ammonia has been developed in the fertilizer industry, however, ammonia is not currently permitted to be used as marine fuel by the ICG Code
- MAN is working on getting ammonia accepted by receiving “approval from a flag state, likely Norway, to use ammonia as a marine fuel,” – expected to be completed by 2019

Source: Ammonia energy.org; GHS: Safety Data Sheets for NH3, Hydrogen, LNG and Diesel; DTU: Safety Assessment of Ammonia as a Transport Fuel, image, c-job

2 Ammonia is transported at scale on sea already and transport can be flexibly scaled using LPG tankers

Storage conditions for ammonia transporta-tion

- Ammonia can be stored and transported as a liquid under various conditions:
  - Fully pressurized: 10 bar at 20°C
  - Fully refrigerated: -33°C at 1 bar
  - Semi pressurized/refrigerated
- LPG requires similar storage conditions to ammonia, thus LPG tankers are fully capable of transporting ammonia.

LPG tanker capacity

- Globally, about 120 LPG tankers are in service today with 22 additions announced for 2018-2022
- Part of the global fleet can be repurposed to transport ammonia from locations with cheap production to the North and Baltic sea area

EXAMPLE

YARA received its order of 5 new LPG tankers in 2016, which are used as ammonia carriers. The company transports ammonia from numerous countries on dozens of barges ranging in loading capacity from 4,000 - 25,500 tons of ammonia. Ammonia has been transported by sea for decades in vessels with a capacity up to 60,000 tons.

Source: Technavio: Global LPG Tanker Market 2019-2023; F. Laeisz

2 For hydrogen, transport and bunkering is not available yet, but first designs for liquefied hydrogen combined transport and bunkering vessels exist

mossmaritime equinor Wilhelmsen DNV·GL

Moss Maritime, Equinor, Wilhelmsen and DNV GL have developed a design for a liquefied hydrogen (LH2) bunker vessel

Technology description

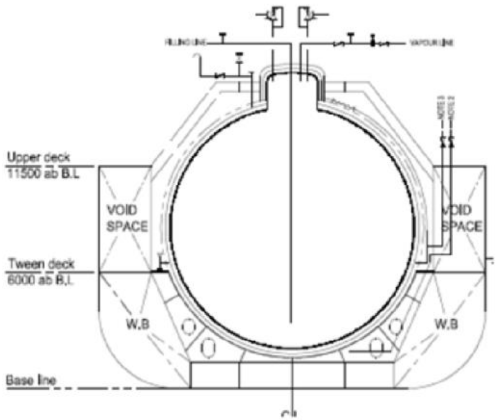
- Cargo: **500 tons LH2**
- Function: **provide transport**, e.g., from the North Sea to the Mediterranean **and bunkering services** to merchant/ cruise ships
- Built on design of a LNG ship
- No consumption of own cargo (was not part of scope)
- Conclusion: **Equipment can all be sourced**, LH2 is manageable in a safe way

Economic implications

- **Initial cost 3-4x of a similar LNG ship** – driven by tanks and "first of a kind" effect with suppliers e.g., coming from space industry
- **Cost expected to come down quickly and substantially** if regulatory environment signals that development costs for equipment can be recuperated over large volume

Next development steps

- E.g., explore if a similar or even smaller design could be used as **floating bunkering vessel in the North and Baltic Sea Sea**

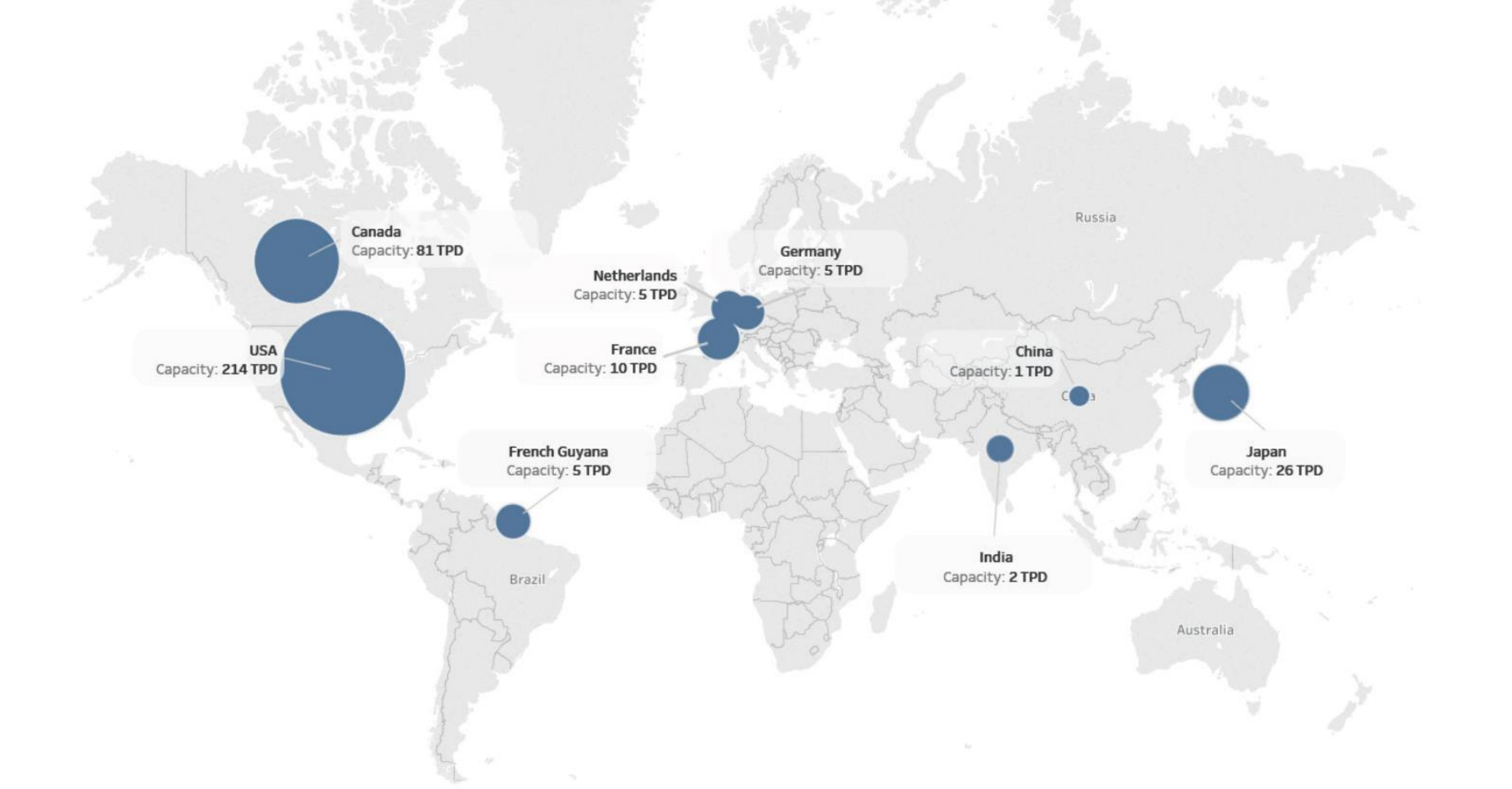


Source: Press, industry interview

2 Liquefaction capacity (esp. in Europe) is low with capacity increases planned over the next years

Global liquid hydrogen production

Tons of liquid hydrogen produced per day today



Source: NCE Maritime Cleantech; Norwegian future value chains for liquid hydrogen

A total ~350 tons/day of liquid hydrogen is produced today (or 130 kt/year) corresponding to about ~0.1% of total hydrogen production

- Most of the current liquefaction takes place on the American continent with production capacity expected to increase, as Air Liquide, Air Products and Praxair have announced plans to build plants with a combined production of an additional 90 tons/day
- In Europe, there are currently three production plants for liquid hydrogen in operation with a total capacity of roughly 25 tons/day with Germany expecting to increase production by another 10 tons/day as of 2021

2 For bunkering, only few priority ports in the North and Baltic Sea region require infrastructure upgrades as route patterns suggest

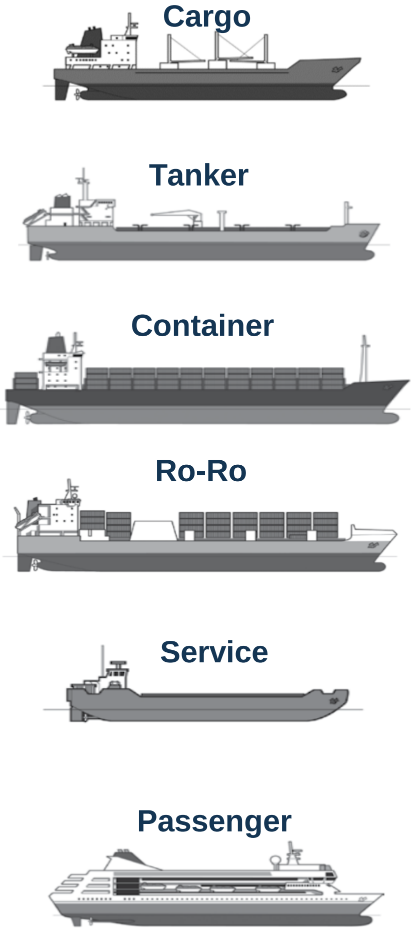
Vessel type

Freight vessels

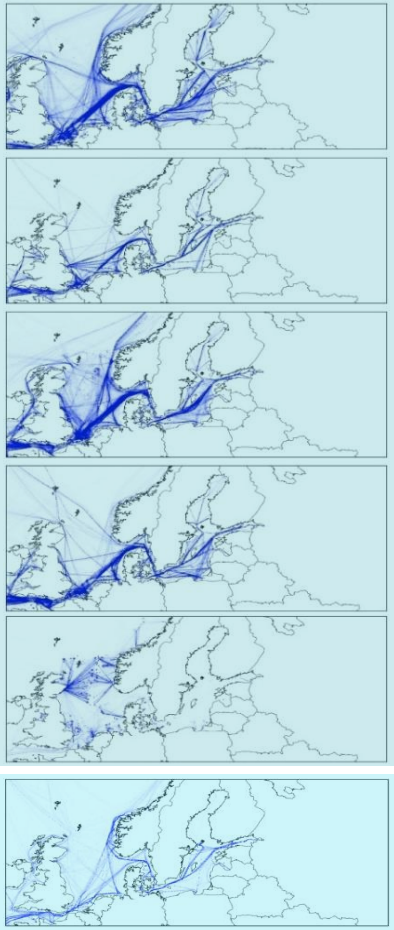
- Cargo
- Tanker
- Container
- Ro-Ro
- Service

Passenger vessels

- Passenger



Route pattern



Major ports

North Sea	Baltic Sea
▪ London, UK ▪ Tees & Hartlepool, UK ▪ Stavanger, NO ▪ Antwerp, BE ▪ Zeebrugge, BE ▪ Esbjerg, DK	▪ Ust-Luga, RU ▪ Primorsk, RU ▪ Kilpilahti, FI ▪ Klaipeda, LT ▪ Gdansk, PL ▪ Gdynia, PL ▪ Szczecin, PL ▪ Helsingborg, SE
▪ Grimsby & Immingham, UK ▪ Forth, UK ▪ Oslo, NO ▪ Rotterdam, NL ▪ Amsterdam, NL ▪ Hamburg, DE	▪ St. Petersburg, RU ▪ Riga, LV ▪ Rostock, DE ▪ Lübeck, DE ▪ Göteborg, SE
▪ Peterhead, UK ▪ Dover, UK ▪ Kristiansand, NO ▪ Hirtshals, DK ▪ Ostend, BE	▪ Tallin, EE ▪ Swinoujscie, PL ▪ Puttgarden, DE ▪ Holmsund, SE ▪ Trelleborg, SE ▪ Ystad, SE ▪ Stockholm, SE ▪ Vaasa, FL ▪ Helsinki, FL

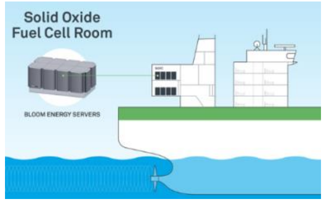
Source: Data provided by Dr. Jukka-Pekka Jalkanen, Finnish Meteorological Institute

2 Combustion engines for both ammonia and hydrogen are close to commercialization already

	Ammonia dual fuel engine, 2020/21	**H2 medium speed engine, 2020**
Technology description	▪ Ammonia dual-fuel engine based on existing liquid gas injection engine with an efficiency targeted of 50% ▪ Uses MGO in low load range up to 10%, then any mix between NH3 and MGO possible ▪ System will be applicable to full range of engines and can be retrofitted to 3,000 existing (dual-fuel) ▪ Similar system has been on market for methanol since 2013 and for LPG since 2018 	▪ Hydrogen medium speed engine (also available as dual-fuel engine) with wide usage range, e.g., marine main engine for tugboats, ferries and barges as well as marine auxiliary engines for all sea-going ships ▪ Power range between 0.8 and 2.8 MW and are available in 6, 8, 12 and 16 cylinder configurations ▪ Won its first order for its design of a hydrogen powered crew transfer vessel until end of 2020 ▪ CMB and Japan-based TFC work together to build world's first passenger ferry powered by a dual fuel hydrogen-diesel internal combustion main engine – I vessel expected to be delivered in 2021 
Economic implications	▪ Dual-fuel is 25% more expensive than normal HFO ▪ Tank size will double compared to LPG	▪ TBD
Time to commercial	▪ Launch in 1-2 years ▪ Fully commercial with certification processes for safety/ class notation in ~5 years	▪ Launch in 2020

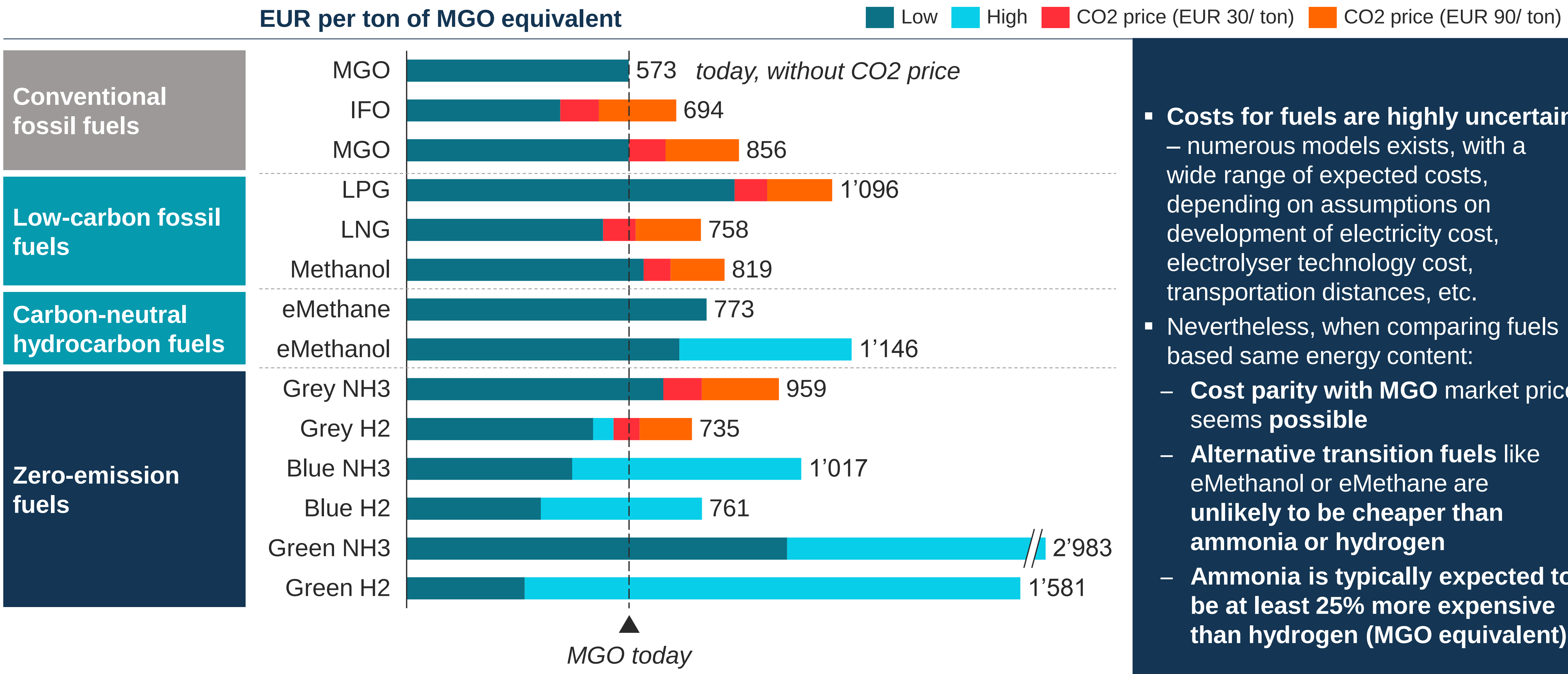
Source: MAN public material and interview; Industry websites; CMB website

2 Fuel cells would allow for higher efficiencies and could be ready for commercial deployment as soon as 2023

	Solid oxide FC (SOFC) for ammonia	PEM FC for hydrogen
Technology description	▪ Can use a wide range of fuels (ammonia, LNG, methanol, diesel, hydrogen) ▪ High temperature (600-700°C), high tolerance for impurities ▪ No NOx emissions, i.e., no need for SCR 	▪ Can use hydrogen only, other fuels need to be reformed 
Economic implications	▪ 60% electrical efficiency, up to 85% with heat recovery ▪ Reduction of maintenance vs. ICE ▪ Future cost expectation: EUR ~850 /kW	▪ 50-60% electrical efficiency ▪ Reduction of maintenance vs. ICE ▪ Currently EUR ~1,800 /kW - cost expected to drop up to a factor 10 over the coming years, driven by mass market in mobility/ residential
Time to commercial	Likely several years away, e.g.,: ▪ Japanese IHI with Kyoto university demonstrated 1 kW from a direct ammonia SOFC in early 2018 ▪ Joint venture established between SHI and Bloom Energy (provider of stationary SOFCs) in Sept 2019 for natural gas fuel cells for shipping	Within the next 3 years, e.g.,: ▪ ABB/ Ballard joint development for marine – 1-3 MW will be pilotable by 2020, 3-5 MW can be commercial from 2023

Source: Press releases and homepages, US Department of Energy (2017): Hydrogen and Fuel Cells Program Record, interviews

2 The costs of ammonia and hydrogen are highly uncertain, but cost parity with MGO market price seems possible

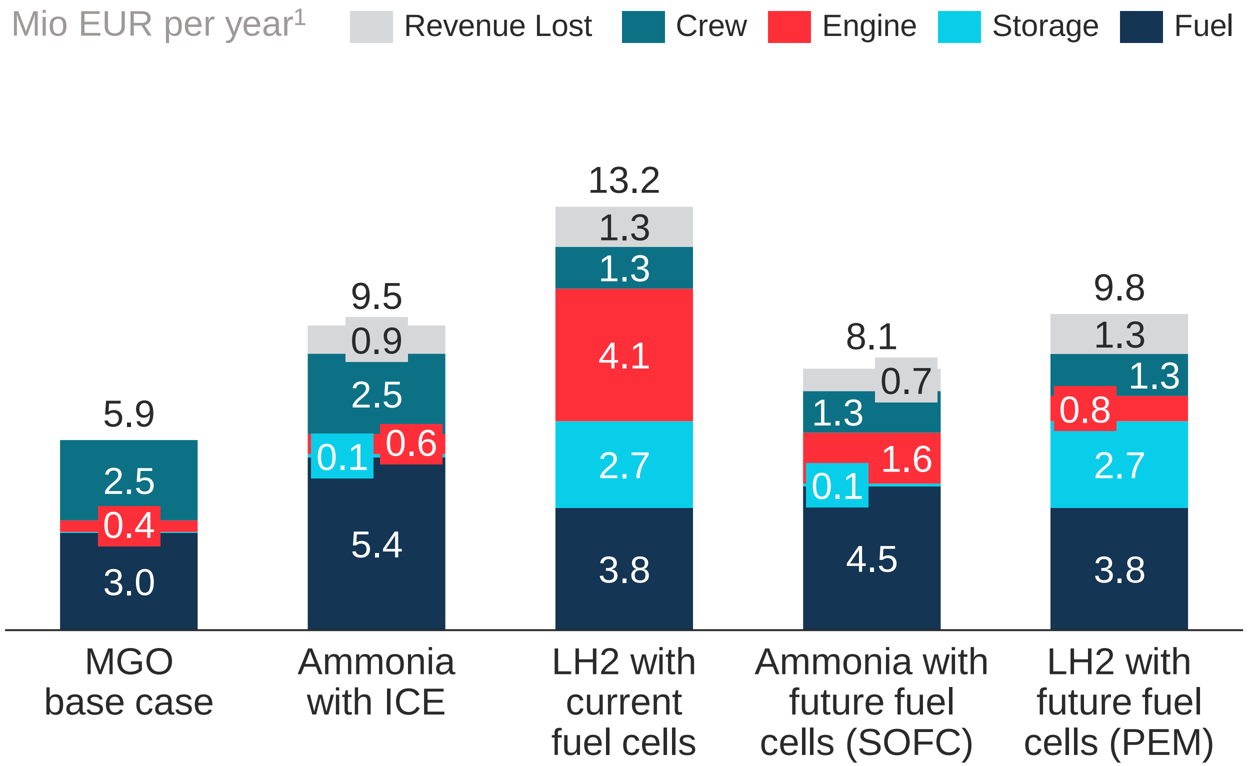


Note: For a detailed list and sources, see deep dive document available from www.towardsnetzero.com/ or www.sus.lab.ch

- **Costs for fuels are highly uncertain** – numerous models exists, with a wide range of expected costs, depending on assumptions on development of electricity cost, electrolyser technology cost, transportation distances, etc.
- Nevertheless, when comparing fuels based same energy content:
  - **Cost parity with MGO** market price seems **possible**
  - **Alternative transition fuels** like eMethanol or eMethane are **unlikely to be cheaper than ammonia or hydrogen**
  - **Ammonia is typically expected to be at least 25% more expensive than hydrogen (MGO equivalent)**

2 The business case of ammonia and hydrogen shipping is not yet competitive with MGO, however, costs are expected to decline over time

- Case for long distance container vessel with ~12,000 km range[2]
- Today, we assume ICEs for ammonia and fuel cells for hydrogen
- In the future, we assume fuel cells for both at lower cost and higher efficiency (fuel and storage cost were not adjusted)



- For ammonia, cost drivers are similar to MGO with higher cost for fuel and slightly higher space requirements
- For liquid hydrogen, the main cost driver today is the price of fuel cells as well as for storage tanks (in long distance case)
- Fuel cells are expected to reduce crew requirements for maintenance – in the future, this could potentially compensate for higher engine costs
- Fuel cell costs are expected to come down over the coming years and lifetime increases are expected

1 Linear depreciation and cost of capital at 7%;
2 Assumptions: Ship: Capacity 1'380 TEU, main engine: 14'280 kW, consumption: 21.3 tons HFO at 16 knots, lifetime 30years, days in operation: 250 days per year;
NH3 at 453 EUR/ ton, H2 at 2300 EUR/ ton, NH3 tank: 3 EUR/kWh, LH2 tank 5.3 EUR/kWh, ICE 425 EUR/KW, PEM for H2 today: 1780 EUR/KW (10 years lifetime), PEM for H2 future: 425 EUR/KW (15 years lifetime), SOFC for ammonia future: 850 EUR/KW (15 years lifetime); Payload: 555 EUR/ton/a & 202 EUR/m3/a;

Sources: Own calculations, based on "Comparison of ship fuels and propulsion systems", Hydrogen Europe and Ludwig Bölkow Systemtechnik (2019)

2 For hydrogen, commercial ships are already being realized – for ammonia no concrete vessel projects were found

Hydrogen vessel pilots

- For short distances, **hydrogen ferries are already in development**, e.g., the 2-days-range hydrogen ferry Golden Gate Zero Emissions Marine, or the Hjelmeland Ferry (expected in 2021)
- **Cruise ships offer and economically interesting pathway to demonstrate the potential of hydrogen** as fuel and engine are a relatively small cost component and can be passed on to passengers – case studies include the FreeCO2ast, NO (expected 2021-22) and an RCC Icon Class Ship for Royal Caribbean (expected 2025)

Hydrogen ships need to be tested for larger vessels to fully understand the potential of the fuel – cruise ships could offer an economically interesting case for first floating pilots

Ammonia vessel pilots

- **No ammonia pilot projects were found** (on a vessel level)
- An **ammonia tanker ship** powered by it`s own cargo (ammonia) **has been designed**, but **has not been piloted yet**
- Main **obstacle is** constituted by the **use of toxic substances** as a fuel under the IGC Code – discussions in progress

The use of ammonia as a fuel needs to be tested on a full scale to fully understand the open issues including save fuel handling – existing ammonia tankers could be a first case (similar to the demonstration of LNG fuelled ships)

Source: Golden Gate Zero Emissions Marine,FuelCellsWorks, Norled, FuelCellsWorks, Maritime Executive, WorldMaritimeNews, c-job, Ammonia Energy, Safety4Sea

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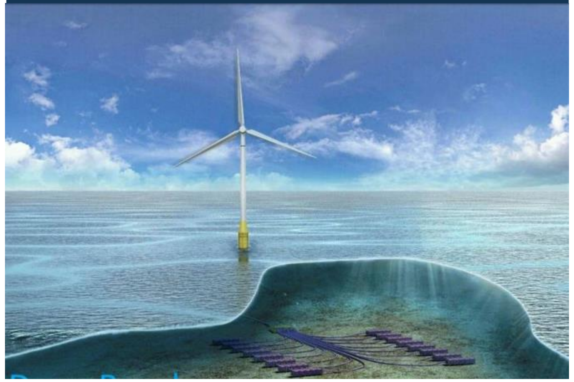
3 Fuel innovation needs to be accompanied by innovation in business models

Innovation examples

Containerized energy

- Containerized batteries and/ or energy packs (i.e., zero-carbon fuel fuel cells and tanks) allow to adapt to lowest cost fuels, allow for retrofitting, can keep capital costs for tanks down and increase bunkering efficiency

Off-shore hydrogen bunkering



- Offshore bunkering systems for hydrogen could help to overcome energy density issues while using wind energy and deep-sea water pressure to produce and store hydrogen at low costs

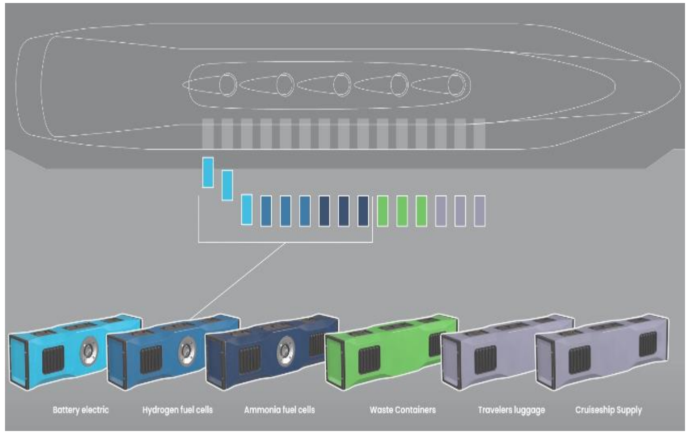
Autonomous freight shipping

- Remote controlled ships are enabled by "no maintenance engines", i.e., fuel cells and batteries and have the potential to reduce crew costs

Cross-value-chain collaborations

- In the ramp-up phase, costs for zero-carbon shipping can be (partially) taken on by end-customers through certificates
- Long-term/ fixed-rate fuel contracts combined with regulatory incentives could reduce tech and fuel price uncertainty

3 Containerized energy could increase bunkering speed and increases fuel flexibility of vessels

Solution		Example	
Containerized batteries	▪ Major drawbacks of fully electric/ battery ships incl. long charging times and reduced range flexibility (most fully electric ships only operate in-between fixed point connections) ▪ Containerized batteries could significantly speed up charging processes and allow for increased route flexibility	Port Liner proposes vanadium redox flow batteries housed in a container (E-Powerbox) that is recharged by exchanging liquid electrolyte or the entire unit	
		ABB, Corvus, EST Floattech, Kongsber/ Rolls and others offer batteries and control equipment in a single shipping container that can be installed on any vessel	
Containerized energy packs – fuel cells and fuel tanks	▪ Other zero-carbon fuels (e.g., hydrogen or ammonia) also face challenges regarding bunkering speed/ complexity and range ▪ Containerized energy packs (i.e., fuel cells and fuel tanks) could solve these problems ▪ Energy packs lined up at port allowing for a quick exchange ▪ Energy packs allow for more flexibility in energy supply mix according to local port infrastructure and vessel mission needs	*No known concepts of the kind available to date*	

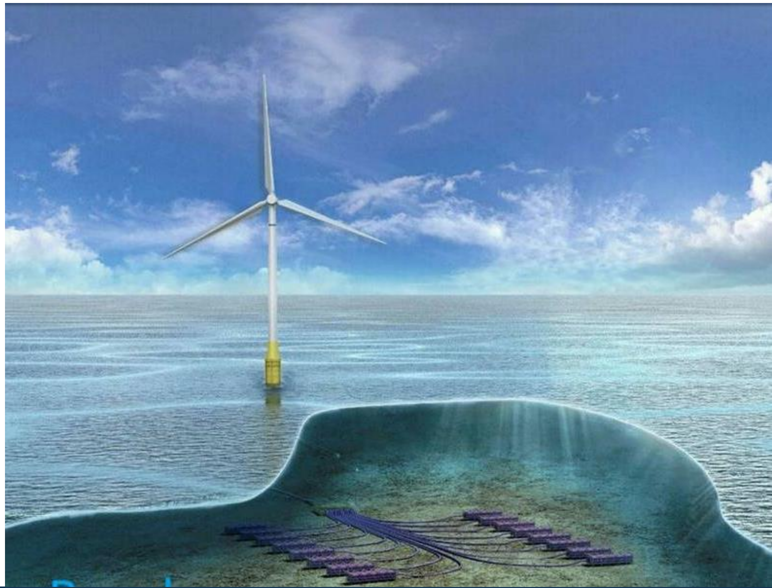
Source: Port Liner webpage, ABB webpage

3 Offshore bunkering systems for hydrogen could help to overcome energy density issues – EXAMPLE: Deep Purple

- **Hydrogen requires 4-8 times more space on-ship vs. MGO due to its lower volume energy density**
- **Better voyage planning could help to reduce tank space and minimize opportunity costs due to lost cargo space**
- **Off-shore bunkering solutions like the Deep Purple project could further solve hydrogen bunkering and storage issues**

- 'Deep Purple' is a multi-company[1] project aiming at converting power from offshore wind to hydrogen and storing it on the seabed
- Turbine-level electrolysis is used to feed seabed hydrogen tanks, where output from offshore wind farms can be stored
- The hydrogen could be re-electrified to provide a clean source of power for offshore oil and gas platforms or used directly for hydrogen ships
- The project timeline envisages a large-scale onshore wind pilot from 2021, with a full-scale demonstrator running off Norway by 2025

TechnipFMC
subsea valley™
SOGN OG FJORDANE ENERGI
MARITIM FORENING SOGN OG FJORDANE
SINTEF
HYON



1 TechnipFMC, SINTEF, Subsea Valley, Maritim Forening Sogn, HYON and Fjordane

Source: Recharge News: 'Deep Purple' seabed hydrogen storage for offshore wind plan

3 Autonomous shipping provides multiple benefits to the shipping industry, yet, major challenges need to be resolved

Benefits

- Direct economic benefits to ship operators through **crew and fuel cost reductions** (less maintenance and increased operational efficiency); indirect benefits include more efficient use of on-board space
- **Reduced human errors** (75%-96% of all accidents are human-related)
- On a network level, **improved optimization of operation and processes**
- **New business opportunities** especially regarding data-related services
- Increased on-board **safety**

Challenges

- Improvements in **sensor technology, high-resolution ranging data and instrumentation accuracy** through heavy R&D
- **Legal framework** that governs the use of autonomous ships needs to be developed, esp. for international shipping
- **Reliability of on-board mechanical and electrical machinery** is vital, since no immediate repairs are possible

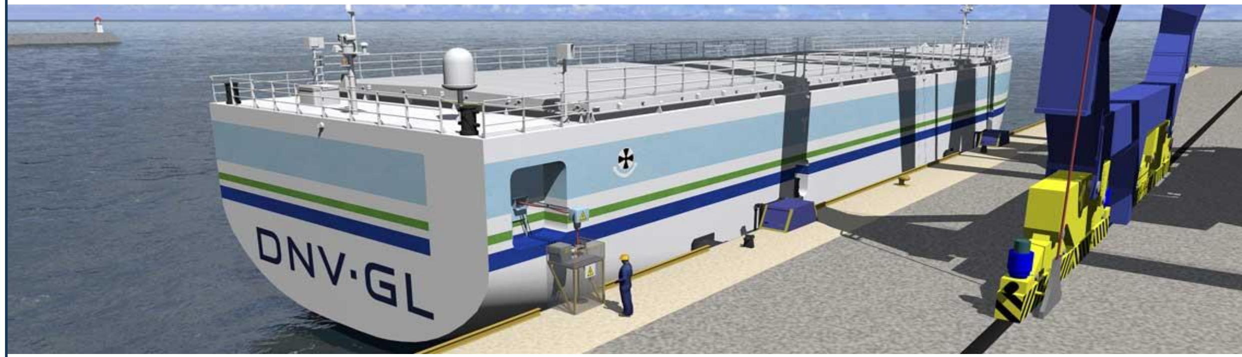
Source: DNV GL: Remote and Autonomous Ships: AAWA (2016)

Economic benefits are believed to be **highest on deep-sea freight vessels** transporting low-value cargo

Nevertheless, **first uses** in commercial shipping (piloting and then operational use) are expected in **regional short-sea shipping** for special applications

Segments that could see the first applications of autonomous vessels incl. **ferries, offshore supply vessels operating in coastal areas and small cargo vessels used for short-sea shipping**

ReVolt – The unmanned, zero-emission, short-sea vessel



ReVolt is a 60m long, fully battery powered and autonomous vessel concept for the short-sea segment. Compared to a conventional diesel-run vessel, ReVolt has annual savings > USD 1 mio due to increased load capacity and low O&M cost.

3 Cross-value-chain collaborations could help to overcome key barriers for the deployment of zero-carbon shipping technologies

	Ship owner	Ship operator	Fuel supplier	Potential solutions (not exhaustive)
High technology uncertainty and development costs	Needs to invest in technology development, while operators have little incentive to share costs	No incentive to pay for development of zero-carbon technologies without regulatory push as such technologies might increase operating expenses	Needs to invest in technology development, while operators have little incentive to carry parts of the costs	**Investment holding structures** bringing together public investors and impact-focused private investors to provide financing and reduce technology investment risk for ship owners Pushing of (partial) costs for zero-carbon shipping (incl. technology development and fuel costs) to end-customer through **"zero-emission shipping"** certificates
Fuel price uncertainty	Owners' asset value depends on ability to offer least cost fuel option, which highly depends on future fuel prices	Full cost exposure to fuel prices, hence, prefer least cost fuel option and low fuel price fluctuations (high uncertainty for zero-carbon fuels)	High uncertainty regarding future demand for zero-carbon fuels increases risk when investing in relevant infrastructure	**Long-term/ fixed-rate fuel contracts**, e.g., based on power/ fuel purchasing agreements from renewables in combination with regulatory incentives

Source: Collaborative consortium for sustainable shipping

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Funding is available for demonstration projects and to bridge the gap for fuel costs

Public funding

- The EU ramped up innovation grants for the shipping sector in 2019; **EUR 40 bn are expected for climate-related innovation** as part of the 'Horizon Europe' 2021-2027 program and many national programs exist
- **EIB and EIF have different financing schemes** to fund projects, incl. e.g., **EUR 350 mio** for guarantees, **EUR 100 mio** in blended grants/ debt financing and loans

Venture capital

- **Specialized VC funds for shipping** emerged in recent years, mostly focusing on digital innovation

Banks

- **100 bn USD in ship financing** are subject to the 'Poseidon principles' – signed by 11 lending banks

End-customers (certificates)

In the "ramp-up phase" there is potential for making end customers pay via green shipping certificates

- 70% of customers are willing to pay a **price premium of up to 5% for green products** and the market for voluntary mechanisms **grew from** ~6Mt in 2010 to >40Mt in 2017
- The **cost of shipping is <0.1% of end customer prices**
- Lantmännen/ Yara launched a first project for a carbon free food chain

Note: For a detailed list and sources, see deep dive document available from www.towardsnetzero.com

Market based measures (MBMs) could provide the right economic incentives to reduce emissions, however, a tailored approach is required

MBMs could provide the right incentives for the shipping industry to reduce GHG emissions

Operator/ charterer

Carbon price signal from the MBM creates incentive to buy/charter more efficient ships

Ship owner

Competition among ship owners for charterer business creates incentive to invest in more fuel efficient ships

Ship builder

Demand from ship owners for efficient ships drives increased investment in climate friendly shipping technology including research and development

However, shipping (as well as other hard-to-abate sectors) requires a tailored approach as abatement costs are higher than existing carbon prices

European ETS price vs. indicative supply-side abatement costs of hard-to-abate sectors

Source: DNV GL (2019); Markets Insider (2019); Energy Transition Commission (2019); New Climate Institute (2019); World Bank Group (2018); Ecofys (2018)

Two major types of MBMs exist with a carbon levy/ tax potentially best suited for shipping

Potentially best suited for shipping

	Carbon levy/ tax	Emission trading scheme (ETS) for shipping
Description	A designated payment matched to emissions reporting could be paid directly to the IMO, or integrated into the berthing fee structure that shipping companies pay to port authorities.	Emission allowances are distributed freely among participants or sold. Scarcity of available allowances creates a carbon price.
Effective-ness	+ Provides **high degree of price certainty** and is therefore, most likely to incentivize ship operators to take operational measures and ship owners/ investors to invest in technical measures + Needs **lower price levels** than e.g., ETS for the same impact due to lack of price volatility and uncertainty	+ **Provides high degree of certainty** regarding overall emissions cap ! Uncertainty of future price levels leading to **unpredictable responses in terms of investing into technological changes**
Transaction costs and adminis-trative burden	! **Medium** – All ships must be monitored; no trading of allowances or purchase of offset credits	! **High** – All ships must be monitored to determine individual GHG emissions; shipping companies must participate in the carbon market with small shipping companies that emit relatively little GHG emissions incurring relatively high transaction costs

- **Carbon levy/ tax might be most effective and most efficient** in delivering economic incentives to reduce GHG emissions
- **ETS** for shipping is not recommended because it is…
  - **… limited in terms of effectiveness** as ETSs fail to provide transparency on future carbon prices
  - **… limited in terms of efficiency** as ETSs come along with high transaction costs and a low overall economic efficiency given that a shipping-specific ETS needs to be set up to account for the relatively high abatement costs of the sector vs. other sectors
- Given the nature of the industry, **MBMs need to be implemented internationally** to avoid carbon leakage

Source: New Climate Institute (2019), interviews

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Let's build the 'Silicon Valley of zero-emission technologies' in shipping

Petrissa Eckle – Executive Director sus.lab, ETH Zurich

The transition to zero-emission fuels will certainly be a challenging journey. Essentially it requires building entirely new value chains from fuel supply to new shipping engines as well as the supporting financing and business models – all within the coming 10-15 years.

There are many uncertainties on technology performance and costs, on the pace at which infrastructure can be developed, on future carbon prices and on *which technology will make it*. At the same time there is great opportunity, not only to radically improve the environmental footprint of shipping, but also economically. The North and Baltic Sea region has the potential to become the 'Silicon Valley of zero-emission technologies' for the shipping sector, taking technology leadership, regionally and globally. Therefore, the region is perfectly positioned, with a strong ecosystem of all relevant players across the value chain, organizations and individuals willing and capable to take on the challenge and supportive financial institutions and regulators.

"The future depends on what we do in the present."- Mahatma Gandhi

This report was prepared by sus.lab at ETH Zurich

Sus.lab is an initiative of SusTec, the chair for Sustainability and Technology at ETH Zurich

Dr. Petrissa Eckle

Executive Director of sus.lab

Petrissa‘s deep passion for building a more sustainable future led her from a PhD in Physics to a Post Doc in Sustainability to 5 years in management consulting at McKinsey & Company, where she helped clients navigate the energy transition, embrace big data/ analytics and build innovation centers. As leader of sus.lab, she is excited to use her experience to work with an equally passionate team to accelerate progress towards a sustainable future.

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Alex focuses on clean-tech innovation and systemic change for a more sustainable economy, both as a project manager at sus.lab and as an independent consultant. He is also an investor in early-stage clean-tech startups. Previously he spent 4 years as a management consultant at McKinsey & Company, where he worked primarily in electrical power, advanced electronics and industrial manufacturing sectors across Europe and Sub-Saharan Africa.

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Christina Nakhle

Project Manager at sus.lab

Christina completed an MBA in Energy Management at TU Berlin, preceded by a Bachelors in Civil Engineering at the American University of Beirut. In her work experience she focused on energy efficient buildings and policies to decarbonize the building stock; in addition to scouting and evaluation of sustainable construction materials. Her master thesis focused on the impacts of the privatization of the electricity sector.

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We warmly thank the many experts in industry and academia for sharing their thoughts and insights

Glossary

AFC	Alkaline fuel cell
CAPEX	Capital expenses
CCS	Carbon capture and storage
CGH2	Compressed gas hydrogen
CH4	Methane/ natural gas
CO	Carbon monoxide
CO2	Carbon dioxide
DCS	Data collection system
DMFC	Direct methanol fuel cell
D.O.D.	Depth of discharge
eq	Equivalent
ETS	Emission trading system
EU	European Union
FC	Fuel cell
GHG	Greenhouse gas
GJ	Giga Joule
Gt	Gigatons
GW	Gigawatt
GWh	Gigawatt hour
H2	Hydrogen
HFO	Heavy fuel oil
HT-PEMFC	High temperature PEM fuel cell
ICE	Internal combustion engine
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IGC	International gas carrier code for construction and equipment of ships carrying liquefied gases in bulk
IGF	International code for safety of ships using gases or other low-flashpoint fuels
IGO	Intergovernmental organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kWh	Kilowatt hour
LH2	liquefied hydrogen
LNG	Liquid natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquid petroleum gas
MARPOL	Protocol of maritime pollution
MBM	Market-based measures
MCFC	Molten carbonate fuel cell
MDO	Marine diesel oil
MGO	Marine gas oil
MoU	Memorandum of understanding
MRV	Monitoring, reporting, verification
Mt	Megatons
MW	Megawatt
MWh	Megawatt hour
NH3	Ammonia
nm	Nautical miles
NMC	Lithium-nickel-manganese-cobalt
NOx	Nitrogen oxide
OPEX	Operational expenses
OPS	Onshore power supply
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
R&D	Research and development
SMR	Steam methane reforming
SOFC	Solid oxide fuel cell
SOx	Sulphur oxide
TW	Terawatt
TWh	Terawatt hour

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