The path towards hydrogen, ammonia, and electrofuels as maritime fuels

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HOPE - analyzing the potential role of marine hydrogen fuel cells solutions for regional shipping in the Nordic region

HOPE outlines and evaluates a concept design for a short sea shipping vessel using hydrogen and fuel cells for propulsion…

…including technical and cost aspects, barriers/drivers for and environmental impact of realization in the Nordics.

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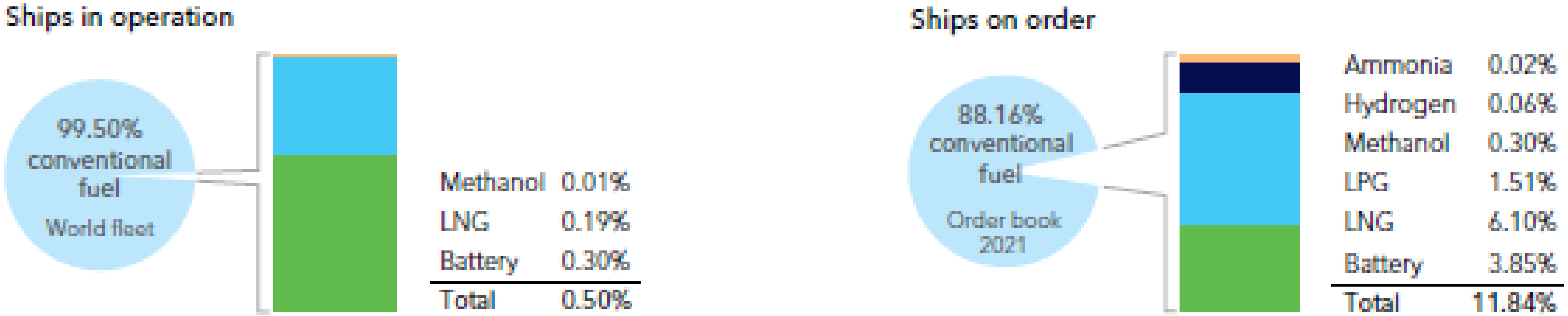
Funded by Nordic Energy Research, Danish EUDP, Business Finland, Swedish Transport Administration, Norwegian Research Council, Icelandic Research Center and in-kind from participating companies

Sweden: 5 % renewable marine fuels for domestic shipping in 2020

Uptake of alternative fuels for the world fleet as of June 2021 including ships in operation and on order [a]

Alternative fuel uptake (percentage of ships)



Key: Liquefied natural gas (LNG); liquefied petroleum gas (LPG)
a) Sources: IHSMarkit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry – AFI platform (afi.dnv.com)

DNV, 2021. DNV Energy Transition Outlook 2021 - Maritime forecast to 2050.

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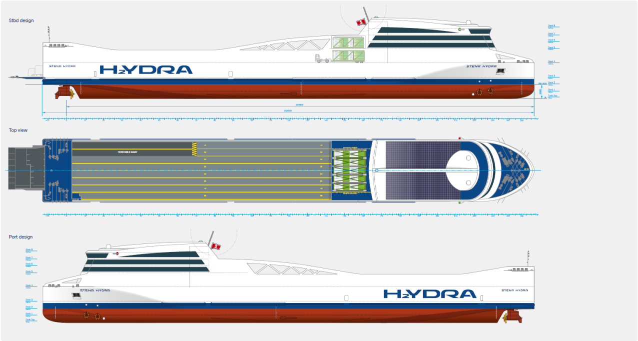
Overall conditions selected marine fuels

Fuel	Propulsion system	Technical maturity (fuel/propulsion)	Costs: fuel costs/investment cost (incl. propulsion, storage)	Fuel supply: existing/ potential	Safety
Electricity	Electric motor, battery	High/Medium	Low to high/Medium	High (limited supply ships)/High	Low risk
Methanol (bio or electrofuel)	Fuel cell	High/Medium	Low to high/High	Low/Medium to high	Low to medium
	ICE (internal combustion engine)	High/Medium	Medium to high/Low to medium	Low/Medium to high	Low to medium
Methane compressed (bio or electrofuel)	Fuel cell	High/Medium	Medium to high/High	Low/Medium to high	Low risk
	ICE	High/Medium	Medium to high /Low to medium	Low/Medium to high	Low risk
LBM (liquified methane, bio or electrofuel)	Fuel cell	High/Medium	Medium to high /High	Low/Medium to high	Low risk
	ICE	High/Medium	Medium to high / Low to medium	Low/Medium to high	Low risk
Green Hydrogen compressed	Fuel cell	Medium/Medium	High/High	Low/High	Larger risk
	ICE	Medium/Medium	High/Pot. Low tol high	Low/High	Larger risk
Green hydrogen liquified	Fuel cell	Medium/Medium	High/High	Low/High	Larger risk
	ICE	Medium/Medium	High/Pot. Low to high	Low/High	Larger risk
Green Ammonia	Fuel cell	Low/Medium	High/High	Low/High	Larger risk
	ICE	Low/Low	High/Pot. Low tol high	Low/High	Larger risk

Findings so far (1/3)

- From a global long-term perspective, hydrogen, in some form (liquified, compressed, ammonia or electrofuels), appears to be a cost-effective solution for reducing shipping's GHG emissions.
- Limited introduction of hydrogen and associated fuels in the short term. Some initiatives to introduce hydrogen for shipping, mainly in Norway.
- It seems possible from a technical perspective to use hydrogen for a regional RORO-ROPAX vessel, between the Nordic countries, even if electrification has advantages on certain routes.
- A concept design for the case study ship in HOPE is being developed incl. two different propulsion solutions (fuel cells and internal combustion engine) and two different storage possibilities (compressed and liquified hydrogen)

Which route and case vessel:
Gothenburg-Fredrikshavn, Ropax ship



Findings so far (2/3)

- Initial assessments indicate that hydrogen-based solutions for shipping is only cost-effective under some circumstances and minor extent. Does not seem to be the lowest cost option for regional shipping. Continued analysis will confirm this.
- There is a range of different barriers and drivers for the introduction of hydrogen in shipping. Companies face economic, organizational, behavioral, and technological barriers to adopt hydrogen technology
- Primarily economic barriers e.g. high costs, lack of infrastructure and green hydrogen supply, lack of regulations and standards, uncertainty and high risk.
- Supply of hydrogen? Even with significant plans for hydrogen production in the Nordics, uncertain how much hydrogen will be available for shipping. Relatively few of the Nordic projects for hydrogen and ammonia production clearly address the possible use in shipping.

Findings so far (3/3)

- Expansion of bunkering infrastructure for hydrogen in different forms is an extensive task.
- Guidelines and regulations are under development. Hydrogen based solutions must be tested in parallel.
- **Policies are crucial**. **Details in the policy design can be crucial for the prerequisites for different options not the least hydrogen solutions**.
- It is possible to substantially reduce the GHG emission/climate impact by introducing the assessed fuel-propulsion options by 2030 (2050 even more).
- For fuels such as ammonia and methane to have low climate impact, **policies that regulate CO_2 and other GHGs (CH_4 and N_2O) are needed**.
- Other environmental impacts also need to be assessed.

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Future marine fuel use: hydrogen, ammonia and/or electro-fuels?

Decarbonizing Nordic Transports – the Role of Different Alternative Transport Fuels

- Assessments of cost-effective alternative fuel options for aviation, shipping and road transport in an energy system context given carbon reduction requirements
- Open Nordic TIMES model: Cost minimizationc energy system model, Cover the national energy system in Sweden, Norway and Denmark
- Model satisfies defined modal demands for entire time horizon by deploying the technology mix with lowest costs while fulfilling CO_2 constraint (no net CO_2 emissions by 2050)
- Scenario cases: - Biomass/biofuel limitation

  - Carbon capture and storage (CCS)

  - High cost electric and fuel cell vehicles

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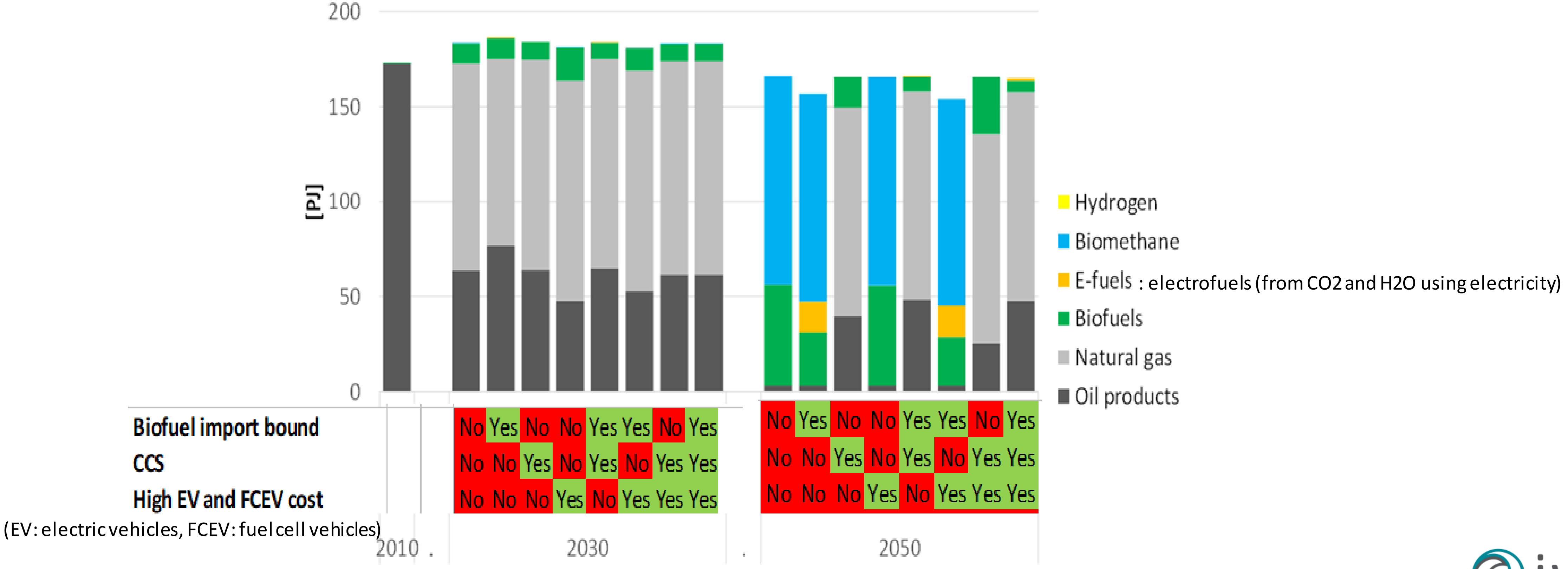
Fuel use in Scandinavian shipping sector in 2030 and 2050

No net CO2 emissions by 2050

Biofuels in all cases. No hydrogen. Electrofuels if no CCS and limited biomass



Hansson et al., 2021. Fuel choices for different transport modes when decarbonizing the Scandinavian energy system

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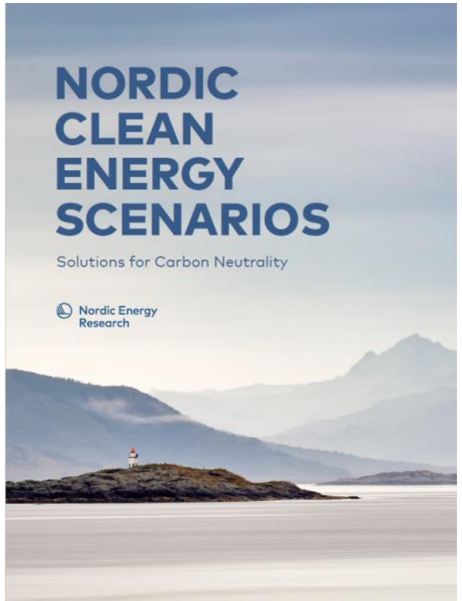
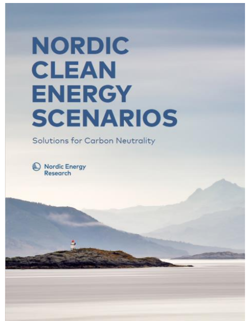
Nordic Clean Energy Scenarios

- Map potential long-term pathways to Nordic carbon neutrality using energy system modelling (Open Nordic Times model)

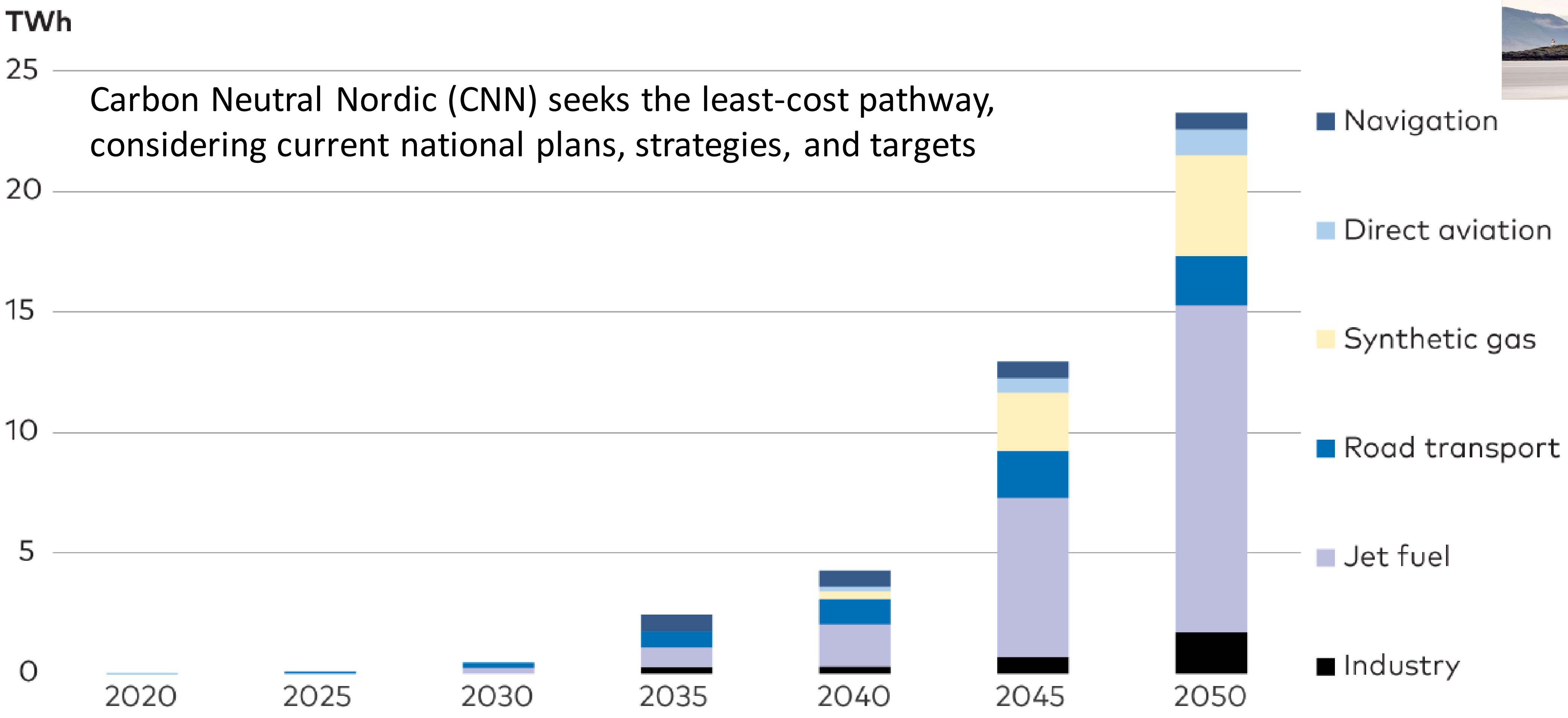


https://www.nordicenergy.org/project/nordic-clean-energy-scenarios-solutions-for-carbon-neutrality/

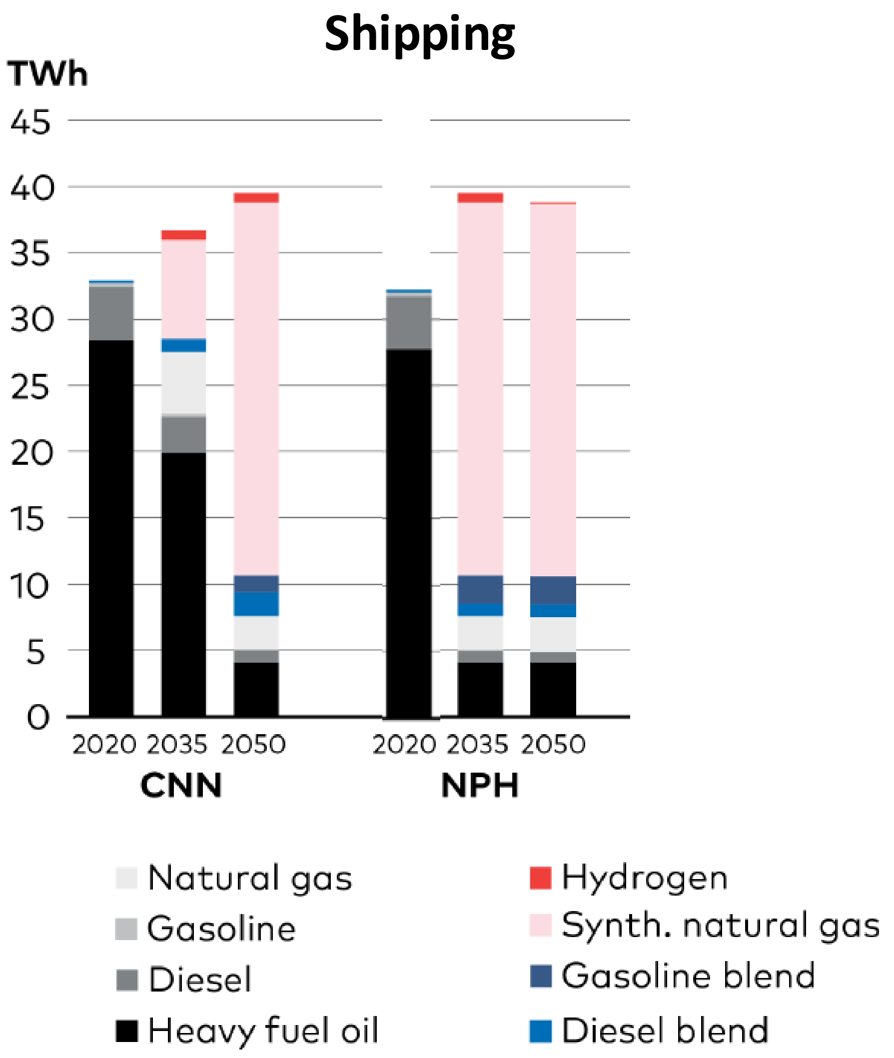
Hydrogen use in Nordic Clean Energy Scenarios 2020-50 by end-use



Carbon Neutral Nordic (CNN) seeks the least-cost pathway, considering current national plans, strategies, and targets

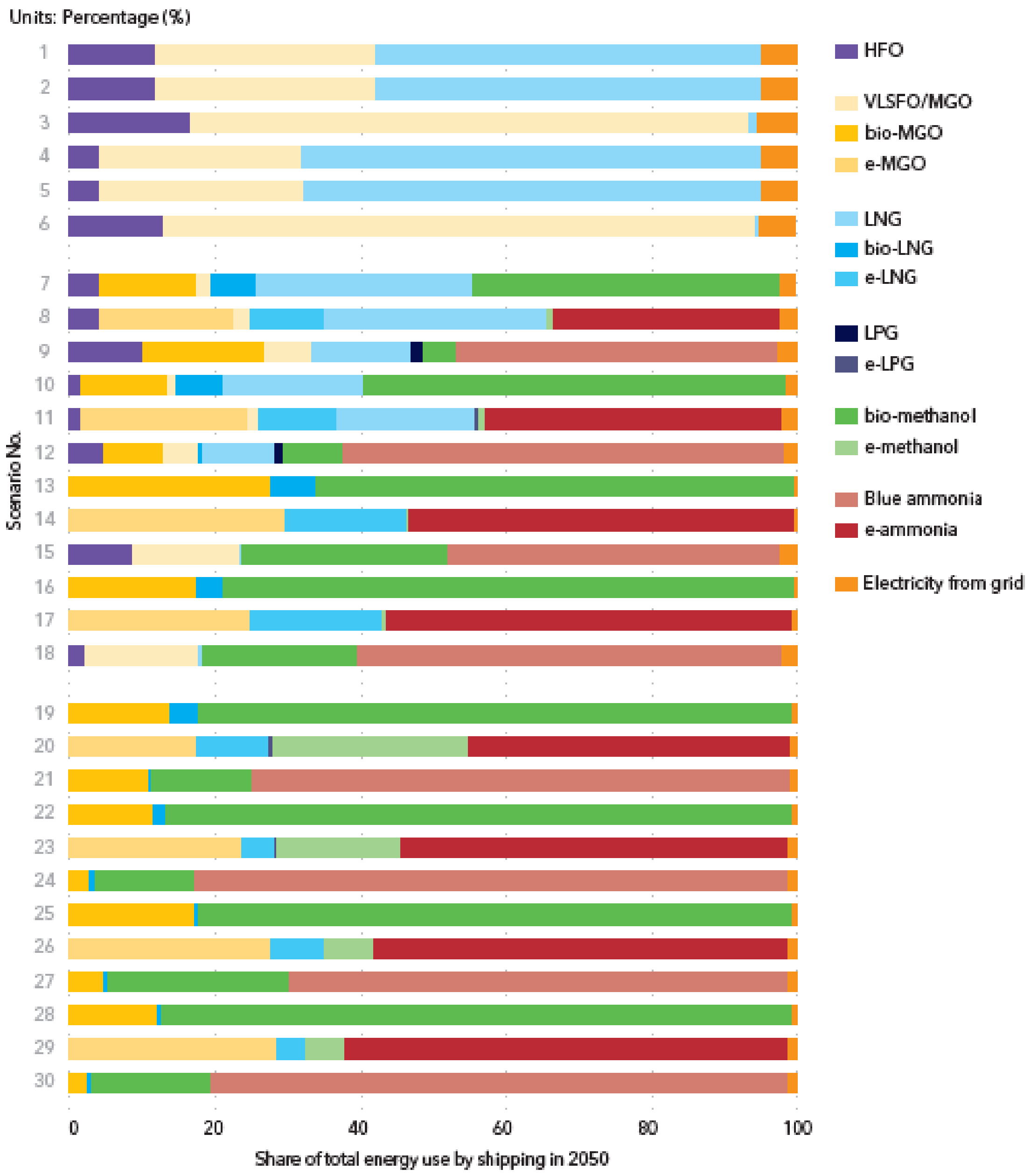


Cost-effective fuel choices in Nordic Clean Energy Scenarios 2020-2050 (fuel use)



Shipping: synthetic natural gas (methane) dominate in 2050. Synthetic fuels are based on hydrogen or bioenergy, sometimes combined with CCS

Share for various marine fuels of total shipping fuel use



DNV maritime scenarios 2020

Hydrogen: pure none international shipping

- Blue ammonia: 0-81% (16% average)
- Electro-ammonia: 0-61% (12% average)
- Electro-methanol: 0-27% (2% average)
- Bio-methanol: 0-87% (22% average)

DNV Hydrogen forecast to 2050:

- Forecast of most likely hydrogen future to 2050 includes e-methanol uptake in global shipping of 2% of shipping fuel mix in 2030, 10% in 2040 and 14% in 2050…
- …and ammonia uptake of 0.3% in 2030, 8% in 2040 and 35% in 2050.

DNV, 2021. DNV Energy Transition Outlook 2020 - Maritime forecast to 2050

Fuel EU Maritime (part of Fitfor55) impact assessment scenario

(% in EU)	2030	2050
Biofuels (likely mainly biodiesel)	6,2	47,8
Bio-LNG (LBM)	1,2	16,8
Liquid electrofuels	0	13,4
Gaseous electrofuels	0	4,9
Hydrogen	0	4,8
Ammonia	0	0,2
Methanol (mainly electro-methanol?)	0	0,1
Electricity (out of at port)	1,2 (1,2)	1,4 (1,0)
Total	**8,6**	**89,4**

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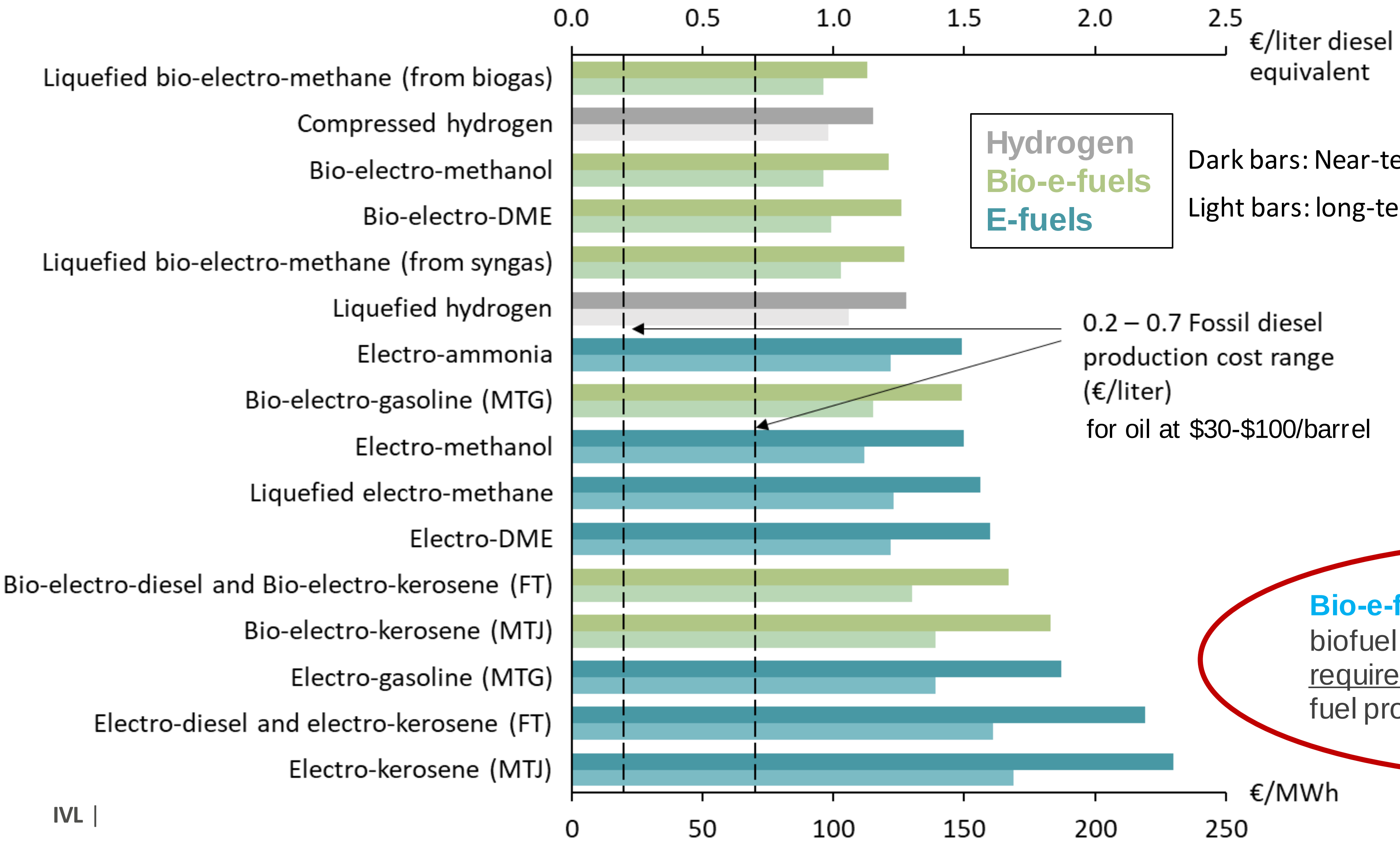
Future role of hydrogen and ammonia will depend on

- development of hydrogen-based solutions (cost, other emissions etc.)
- GHG emission performance
- expansion of low-carbon electricity generation
- availability of sustainable (marine) biofuels
- hydrogen demand in other sectors
- cost development of electrified options
- development of CCS and bio-CCS
- policies and their design

What about the possible cost for marine hydrogen based solutions?

Production costs for e-fuels, bio-e-fuels, and electrolytic hydrogen, based on literature review

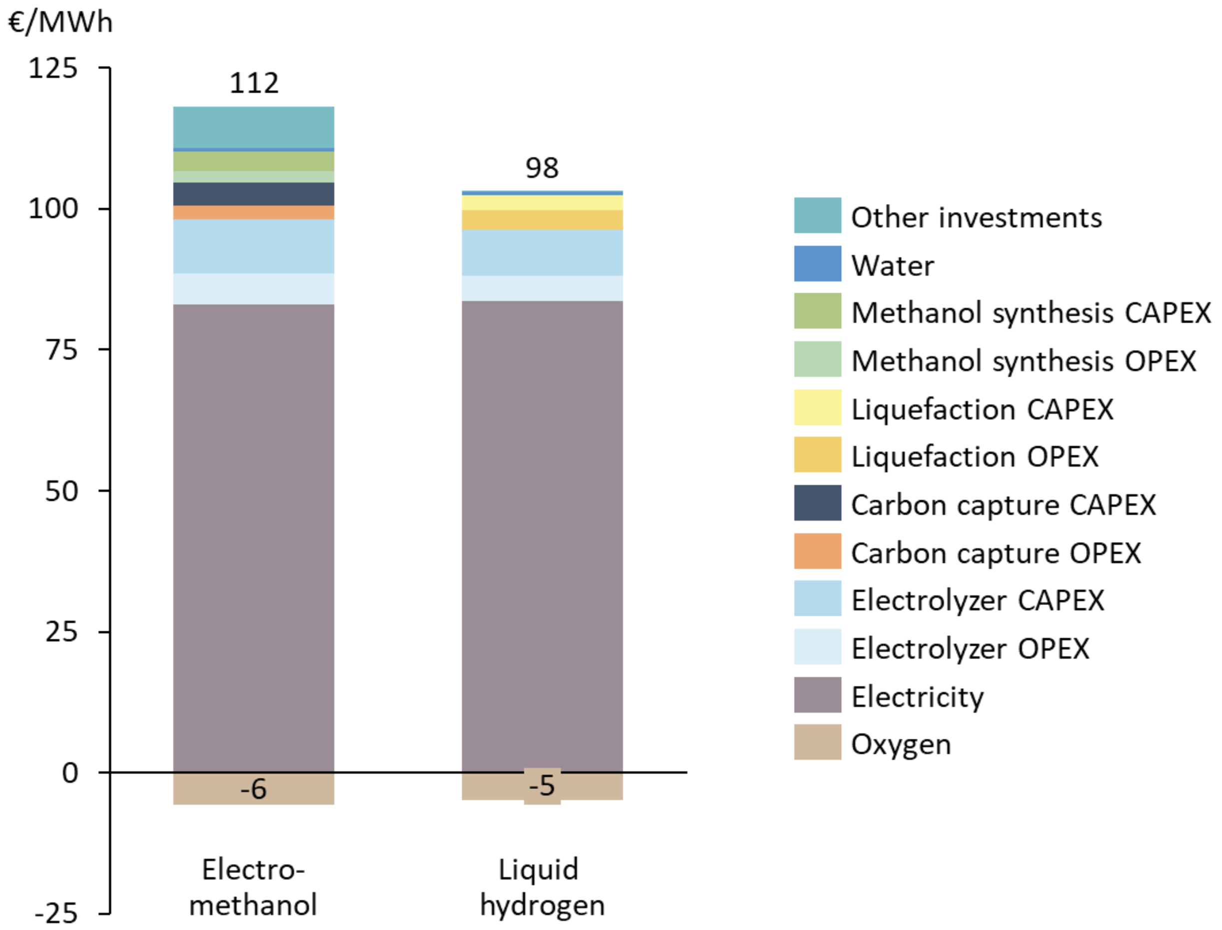


Notes: Costs for hydrogen storage and new fuel infrastructure, and revenue for oxygen are not included.

DME: dimethyl ether
MTG: methanol-to-gasoline
MTJ: methanol-to-jet
FT: Fischer-Tropsch

Bio-e-fuels: Formed by adding H_2 into a biofuel production facility. No carbon capture required. Production costs are spread over all fuel produced.

Production costs for electro-methanol and electrolytic hydrogen



Component costs using base values (long-term) from the literature review.

Costs for hydrogen storage and new fuel infrastructure are not included.

CAPEX: capital expenditures
OPEX: operational expenditures

E-fuel production costs are dominated by electricity costs, followed by electrolyzer costs. Incremental cost vs. liquefied hydrogen is relatively small.

Techno-economic comparison of marine fuel options

- Mobility cost (2030) incl. fuel production and distribution cost + propulsion cost
- Two type vessels: (i) Large ferry: main engine 11MW, 6 hours between ports, (ii) Container ship: main engine 55MW, 240 hours between ports
- Included options: Liquid hydrogen, ammonia, electrofuels (coal-based), combined bio- och electrofuels (all carbon in the biomass used for fuel)
- Internal combustion engines (ICE), fuel cells (FC) and battery-electric propulsion

Review of electrofuel feasibility - Prospects for road, ocean, and air transport. *Selma Brynolf, Julia Hansson, James E. Anderson, Iva Ridjan Skov, Timothy J. Wallington, Maria Grahn, Andrei David Korberg, Elin Malmgren and Maria Taljegård. Published in PRGE.*

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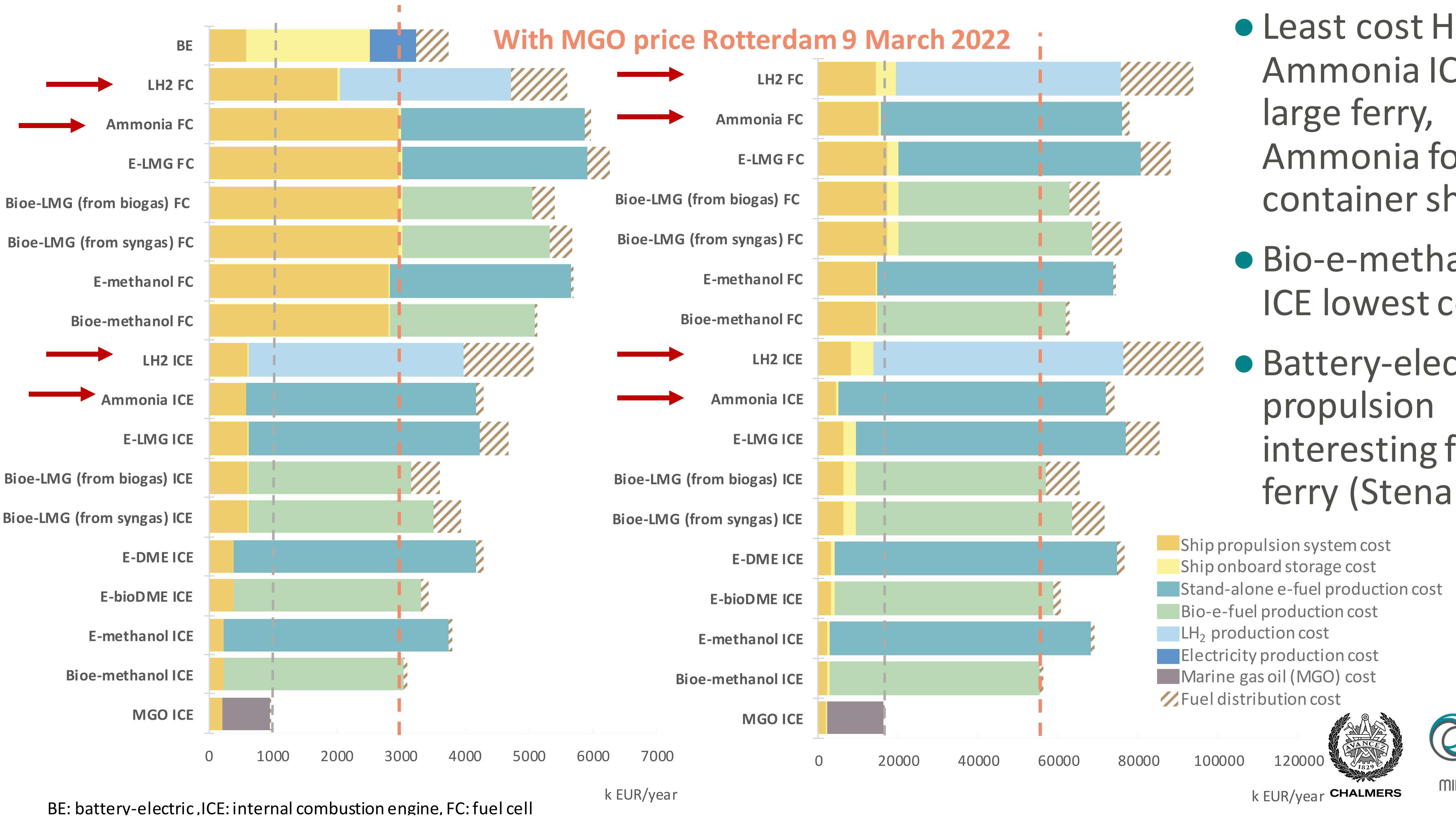
Large ferry   Container ship



- Least cost H2-NH3: Ammonia ICE for large ferry, Ammonia for container ship
- Bio-e-methanol in ICE lowest cost
- Battery-electric propulsion interesting for the ferry (Stena plan)

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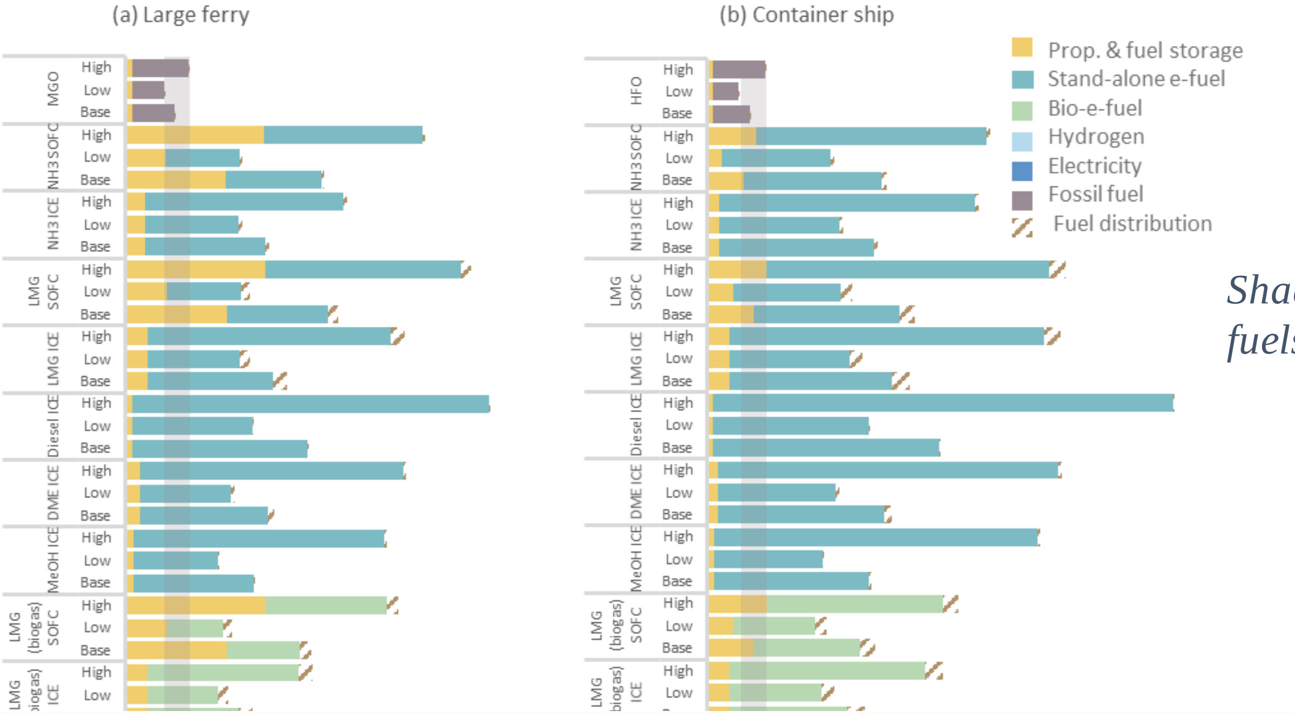
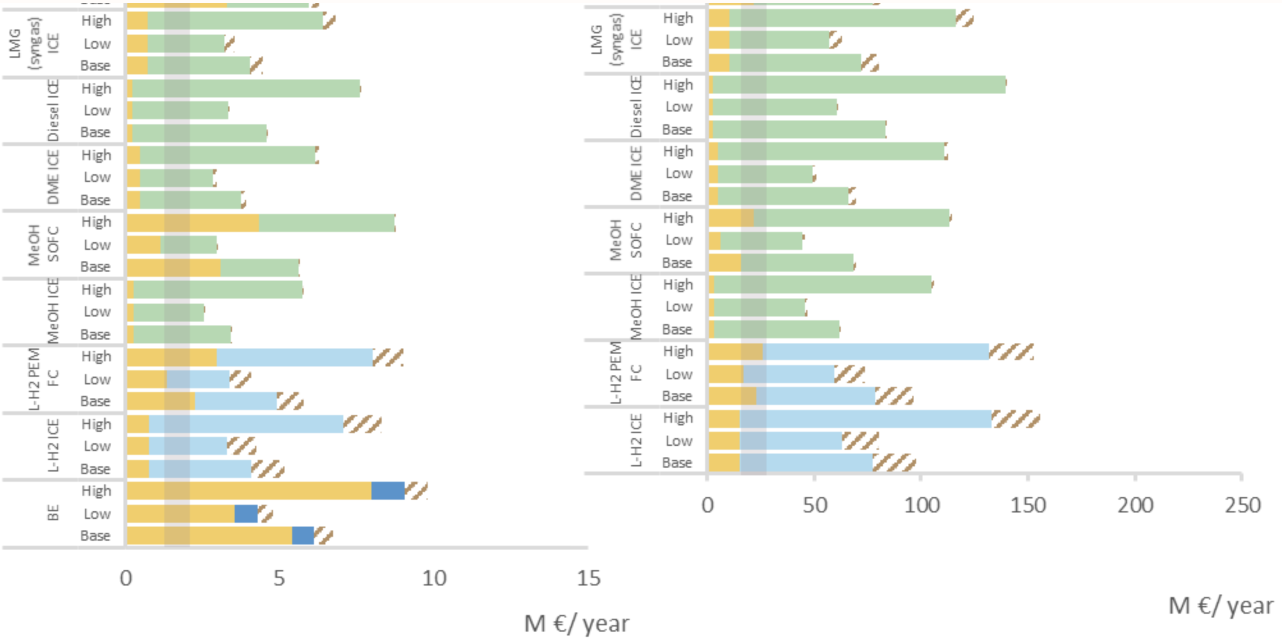
BE: battery-electric ,ICE: internal combustion engine, FC: fuel cell

Uncertainties in cost estimates: High, low and base case



Shaded areas depict conventional fossil fuels (marine gas oil, heavy fuel oil).

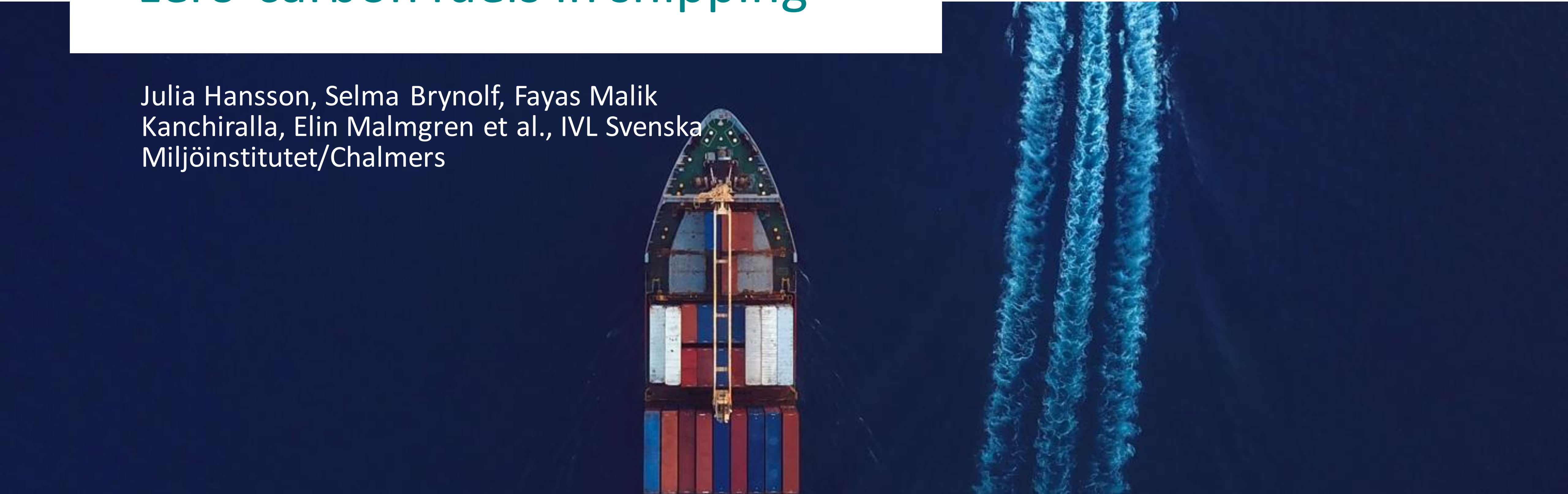
Considerably higher costs for e-fuels than fossil fuels (and biofuels) in ocean transport.



What about the GHG performance of marine hydrogen based solutions?

Nordic Council of Ministers

Nordic roadmap for introduction of sustainable zero-carbon fuels in shipping



Julia Hansson, Selma Brynolf, Fayas Malik Kanchiralla, Elin Malmgren et al., IVL Svenska Miljöinstitutet/Chalmers

Fuel Pathways considered

	Fossil fuel production pathways without carbon capture	Blue fuel production pathways	Green fuel production pathways		Main propulsion options considered[a]					Total # of combinations considered
		Steam reforming of natural gas with carbon capture and storage (NGccs-)	Biomass (bio-)	Nordic electricty mix (e-)	Four-stroke engines (4S ICE)	Two-stroke engines (4S ICE)	Proton-exchange membrane fuel cells (PEM FC)	Solid oxide fuel cells (SOFC)	Elec BE	
Ammonia (NH3)		Yes		Yes	Yes	Yes		Yes		6
Compressed hydrogen (CH2)		Yes		Yes	Yes	Yes	Yes			6
Liquid hydrogen (LH2)		Yes		Yes	Yes	Yes	Yes			6
Methanol (MeOH)			Yes	Yes	Yes	Yes		Yes		6
Liquid methane gas (LMG)				Yes	Yes	Yes		Yes		3
Electricty				Yes					Yes	1
Liquid natural gas (LNG)	As reference				Yes	Yes				2
Marine gas oil (MGO)	As reference				Yes	Yes				2

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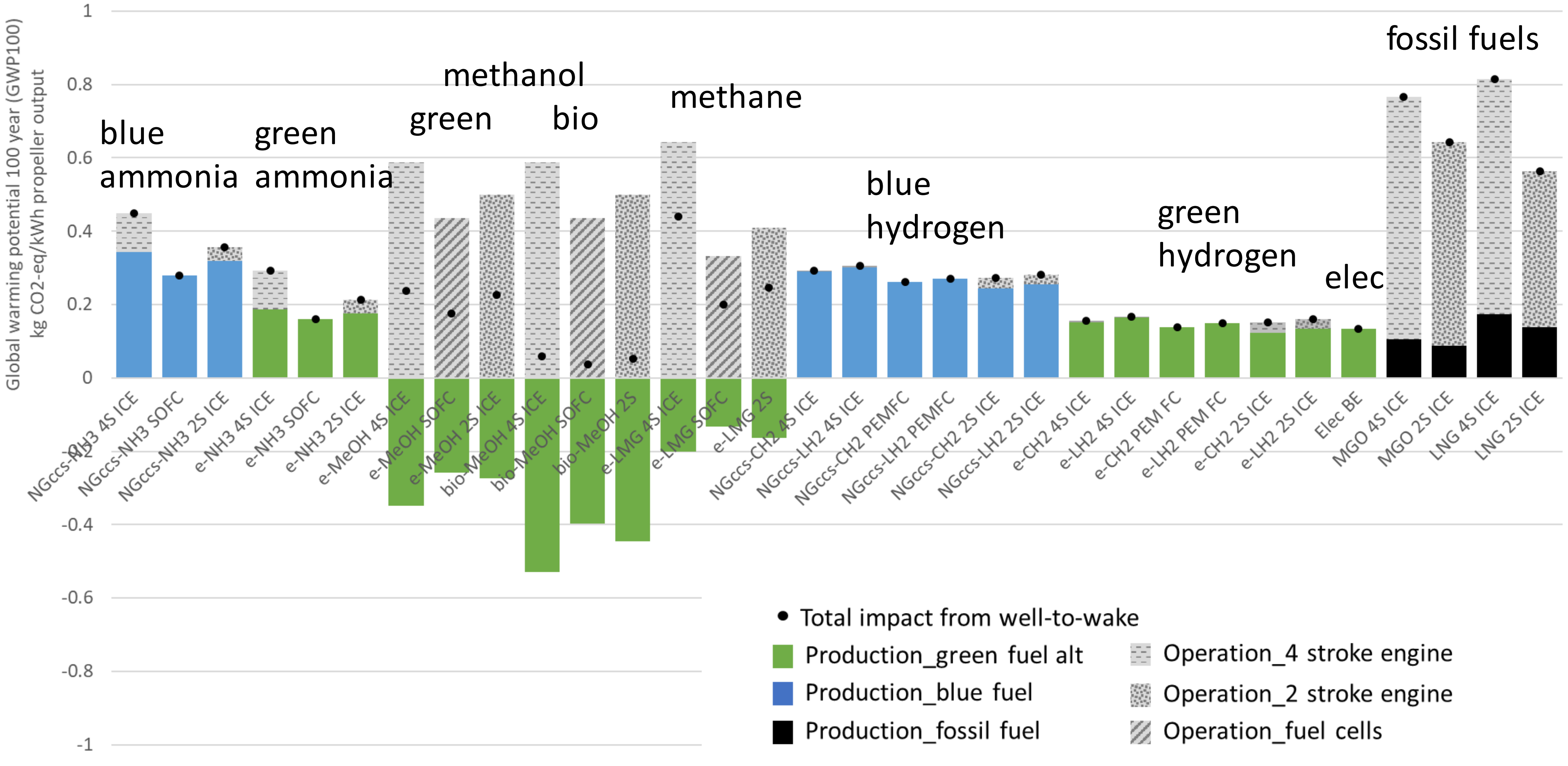
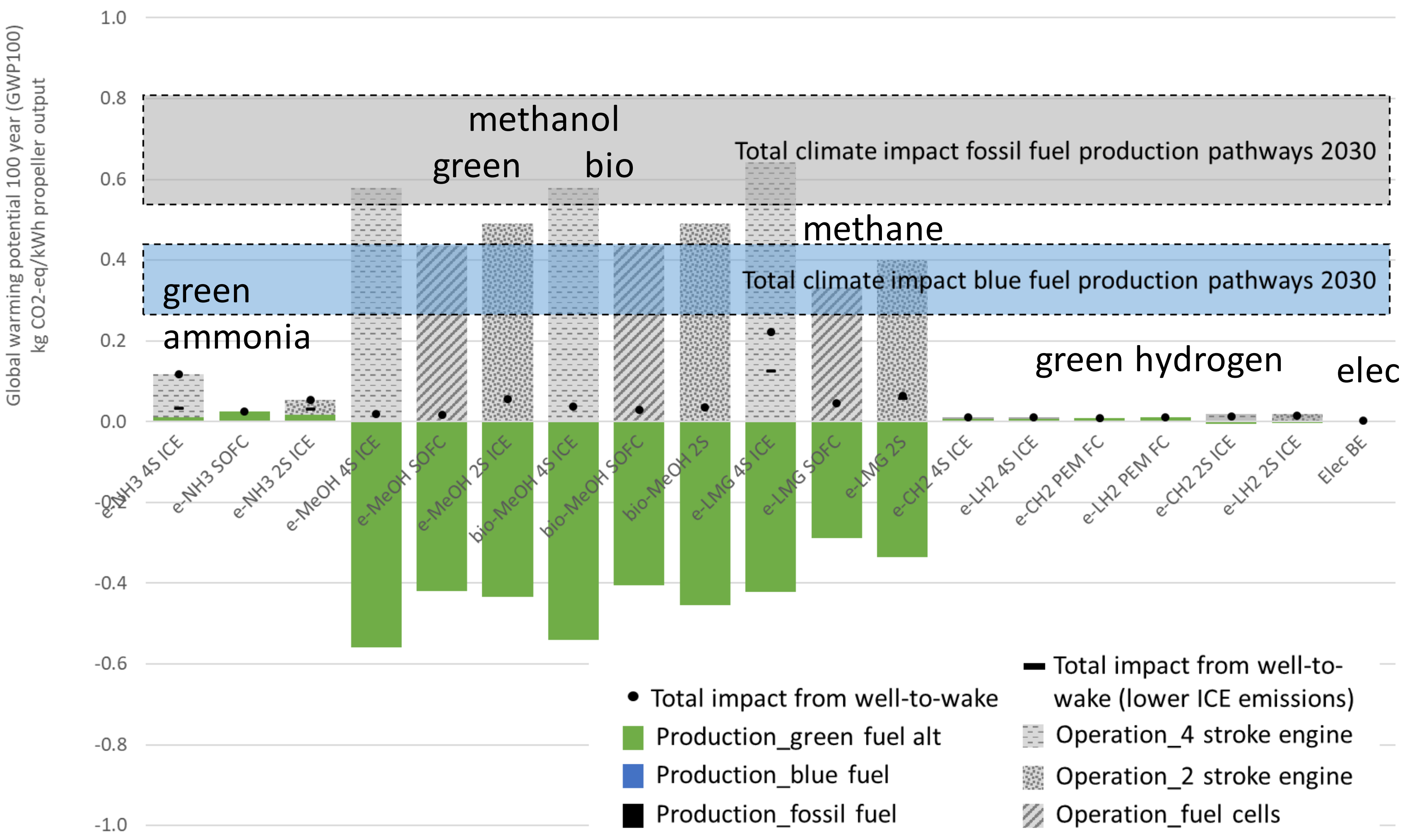
Estimated life cycle climate impact in 2030 (GWP100) WtW, Nordic electricity mix



Estimated life cycle climate impact in 2050 (GWP100), WtW, Nordic electricity mix



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Findings climate impact

- Possible to substantially reduce climate impact by introducing the assessed fuel-propulsion options by 2030 (2050 even more).
- Blue pathways have higher climate impacts than green pathways.
- 2030 perspective, the biomass-based methanol options lowest climate impact followed by battery electric option and the different green hydrogen options and green ammonia in fuel cells.
- Fuel cells lower climate impact compared to 2-stroke engine pathways, which is better than corresponding 4-stroke engine pathway.

Findings climate impact

- Several fuel and powertrain options under development (ammonia, hydrogen)-> their actual climate and environmental performance in 2030-2050 uncertain - lack of knowledge on emissions
- It is possible to reduce fuel related emissions of CH_4 and N_2O (ammonia and methane) but with a cost. These emissions need to be regulated too!
- Other environmental impacts also need to be assessed

Relevant literature

“Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping”, Kanchiralla, F.M., Brynolf, S., Malmgren E., Hansson, J., Grahn, M., *Environmental Science & Technology* 56 (17), 2022.

"**Review of electrofuel feasibility - Prospects for road, ocean and air transport**", Brynolf, S., Hansson, J., Anderson, J.E., M., Ridjan Skov, I., Wallington, T.J., Grahn, M., Korberg, A.D., Malmgren, E., Taljegard, M.J., accepted for publication in *Progress in Energy* (4) 042007, 2022.

"**Review of electrofuel feasibility - Cost and environmental impact**", Grahn, M., Malmgren, E., Korberg, A., Taljegard, M., Anderson, J., Brynolf, S., Hansson, J., Ridjan Skov, I., Wallington, T., *Progress in Energy* (4) 032010, 2022.

“**Life Cycle Assessment of Marine Fuels in the Nordic Region – Task 1C Roadmap for the introduction of sustainable zero-carbon fuels in the Nordic region**”, Brynolf, S., Hansson, J., , Kanchiralla, F.M., Malmgren E., Fridell, E., Report No.1-C/1/2022, *coming*.

“Studie på sjöfartsområdet - Styrmedel och scenarier för sjöfartens omställning”, Fridell, E., Hansson, J., Jivén, K., Styhre, L., Romson, Å., Parsmo, R.,, Nr U 6584, 2022.

“The Potential Role of Ammonia as Marine Fuel – Based on Energy Systems Modelling and Multi-Criteria Decision Analysis”, Hansson, J., Brynolf, S., Fridell, E., Lehtveer, M., *Sustainability* 12(8), 3265, 2020.

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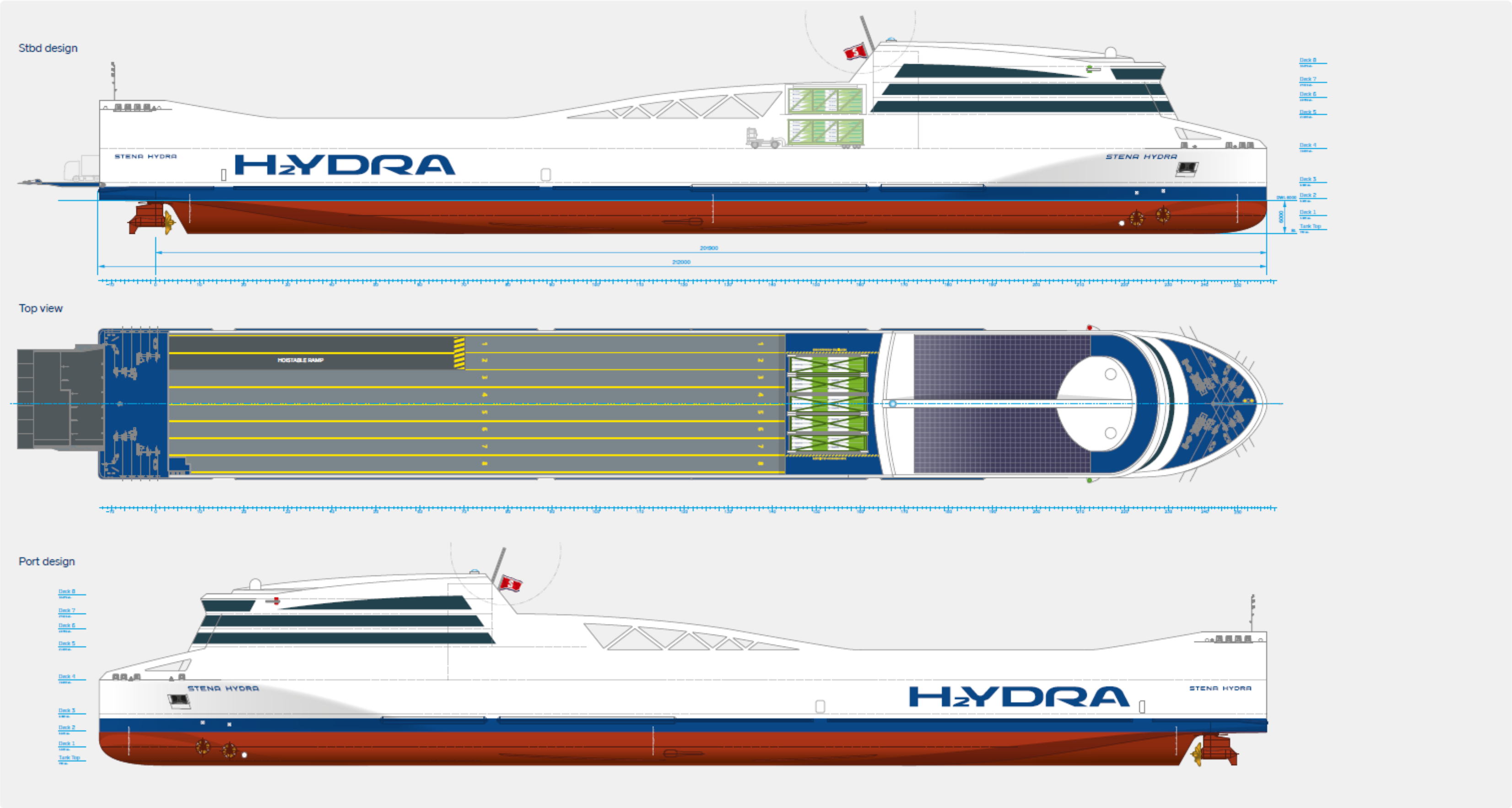

Thank you!

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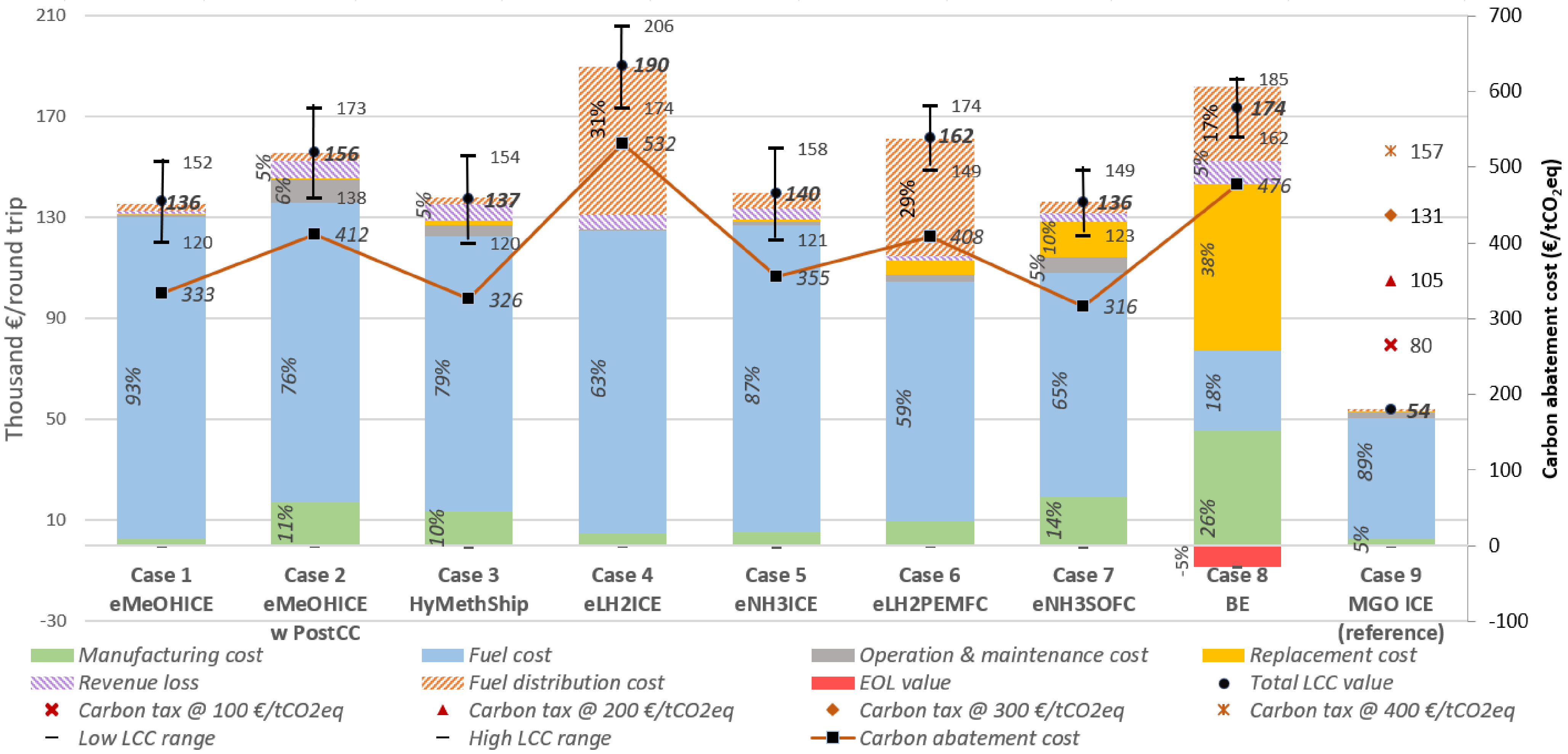
Economic assessment over ship fuel life cycle



"Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping", Kanchiralla, F.M., Brynolf, S., Malmgren E., Hansson, J., Grahn, M., *Environmental Science & Technology* 56 (17), 2022.