Prospects for Energy and Maritime Transport in the Nordic Region

Power-to-X and energy carriers for future carbon-neutral shipping

Dr. Tue Johannessen

January 30th, 2020

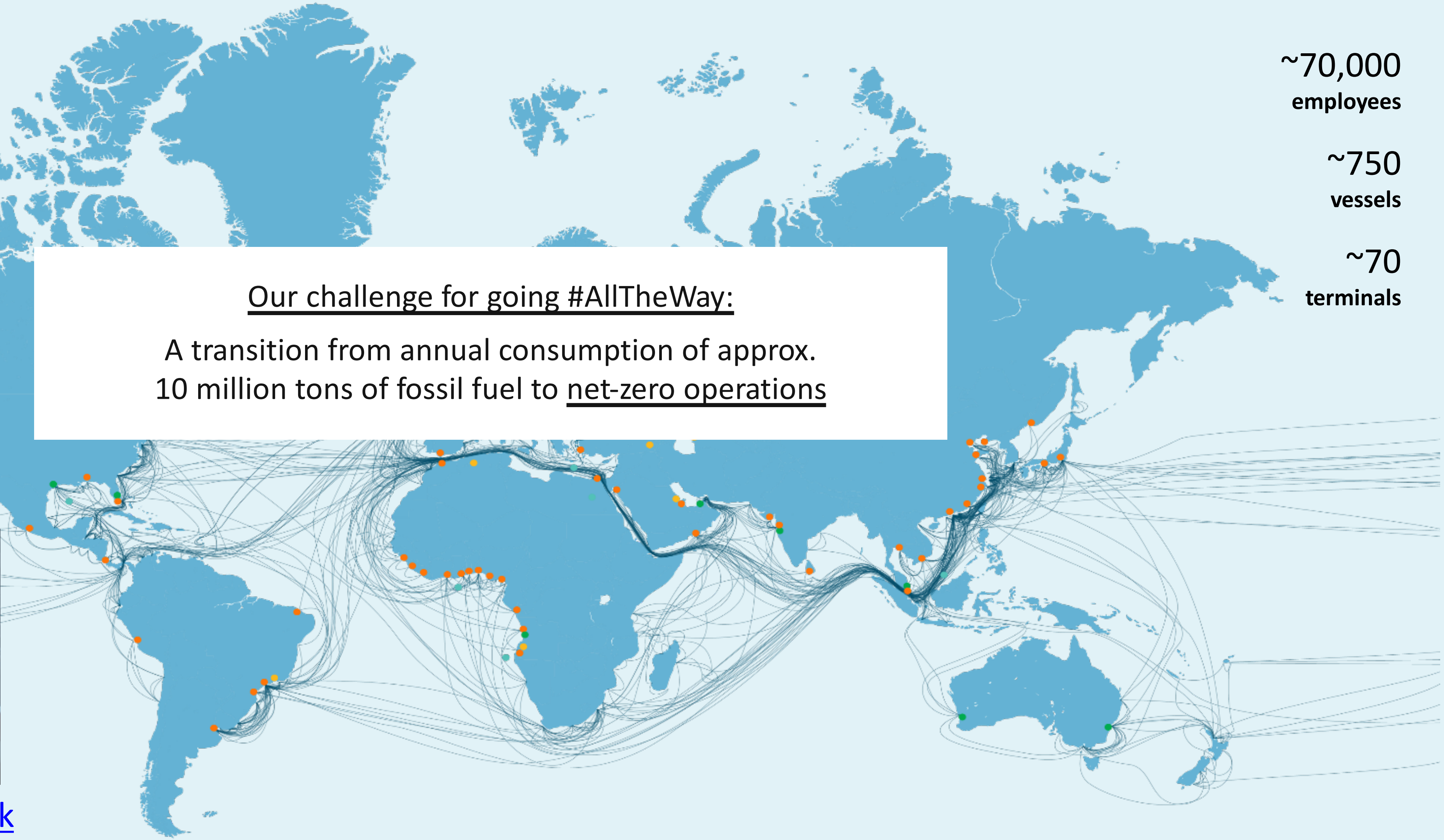
#AllTheWay

Recap (I) from the morning presentation: All the way in 2050

Present in
130+
Countries

Revenues[1] of
39,019
USD million

Profits[1]
220
USD million



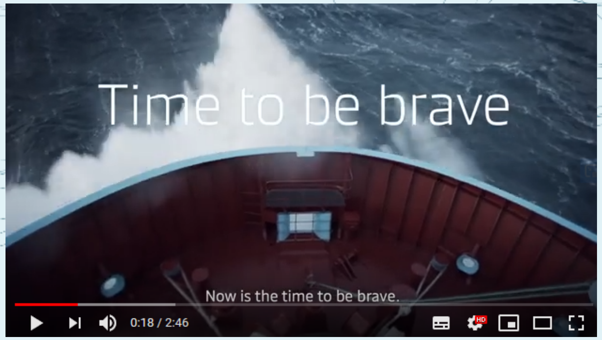
Our challenge for going #AllTheWay:

A transition from annual consumption of approx. 10 million tons of fossil fuel to net-zero operations

~70,000
employees

~750
vessels

~70
terminals



https://youtu.be/2XBO_ZULmAk

1. FY 2018

Recap (II): Getting to zero requires new fuel pathways

MAERSK QUOTE BOOK MANAGE TRACK

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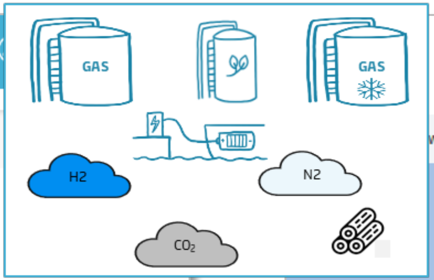
Press releases

Alcohol, Biomethane and Ammonia are the best-positioned fuels to reach zero net emissions

24 October 2019

Sustainability



Sectors Solutions Services Insights Innovation News

ws → New study indicates that achieving net zero is an 'OPEX not a CAPEX challenge'.

New study indicates that achieving net zero is an 'OPEX not a CAPEX challenge'.

24 Oct 2019 SUSTAINABILITY MARINE & SHIPPING

LR and Maersk joint study finds that to develop zero carbon ready ships, shipowners must invest for fuel flexibility and points to the need for policy interventions and fundamental changes to incentives scheme for shipping.

Maersk quotes:

- *"The main challenge is not at sea but on land,"*
- *"Technology changes inside the vessels are minor when compared to the massive innovative solutions and fuel transformation that must be found to produce and distribute sustainable energy sources on a global scale".*

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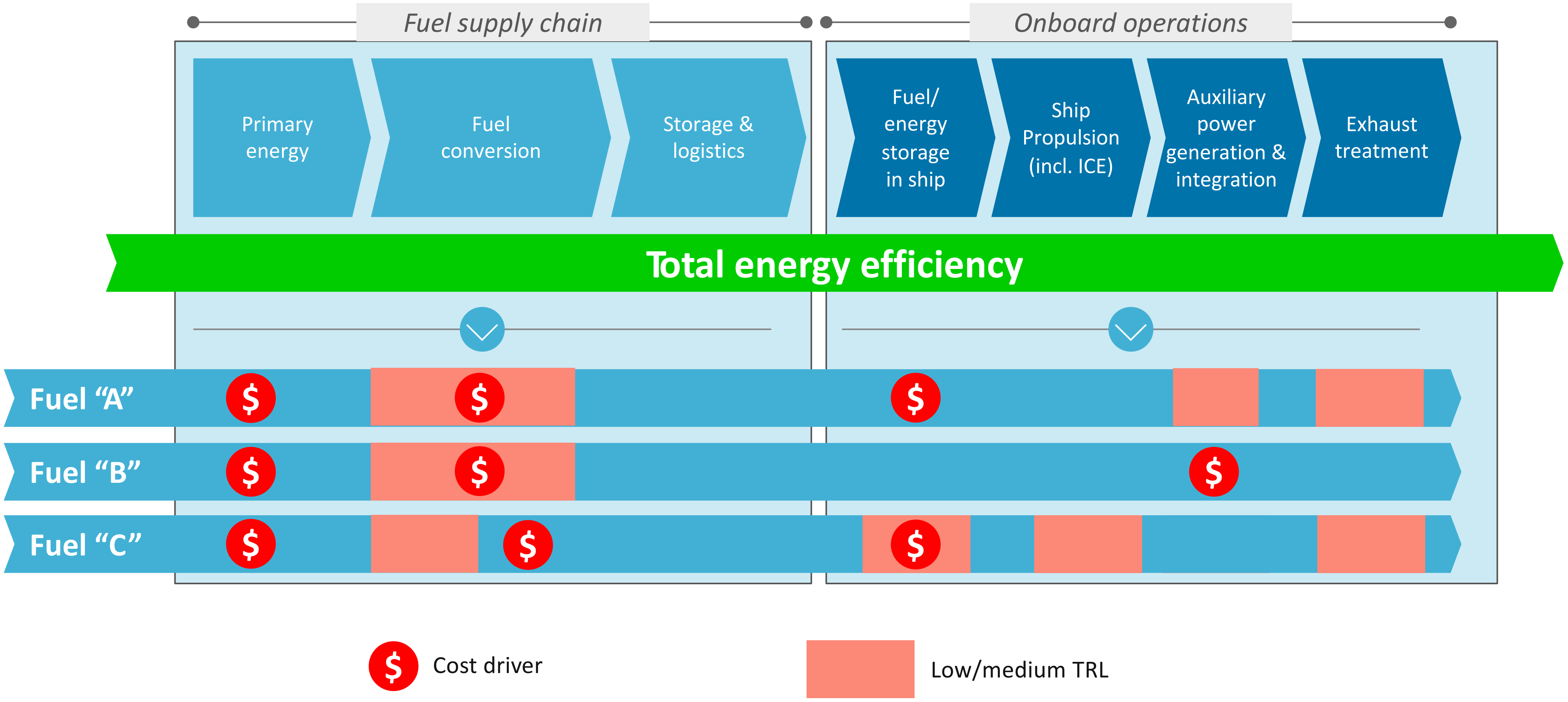
For various fuel pathways:
A holistic view on the entire energy value chain is needed



Note: Solely for illustration purposes

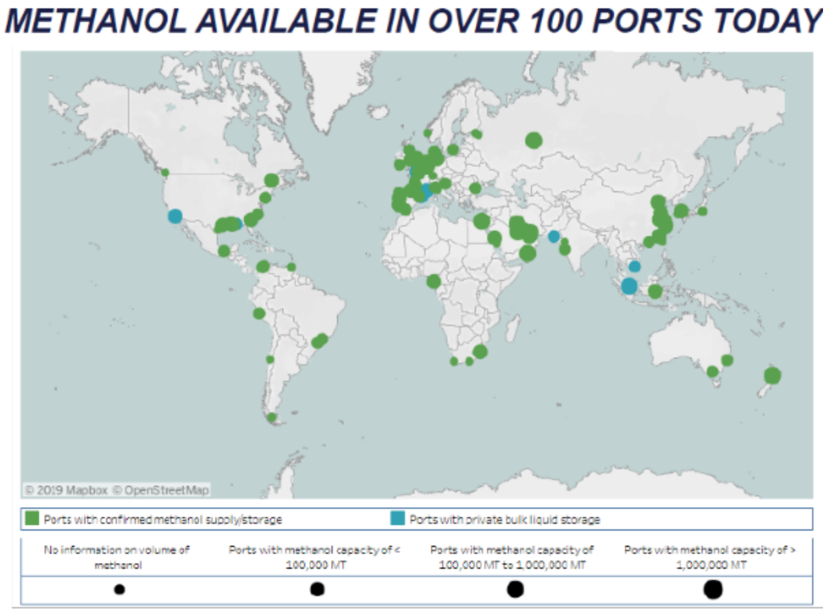
Volume: What would it mean if it was **methanol**?

It can be made from renewable resources: Green electricity, water and “green” carbon.

- Renewable electricity → electrolysis of water to make hydrogen (H_2) → methanol synthesis via ‘green’ CO_2.
- Main bottlenecks: Low-cost electricity / Scale & cost of electrolyzers. Bio-carbon availability?

Already a mature market, mainly for chemical industry, but…

- Current global market: approx. 120 million tons/year
- Maersk would need: approx. 20 million tons of methanol pr. year to replace our current use of HFO
- Some key questions:
  - How much could be made?
  - Who will be fighting for it?



https://public.tableau.com/profile/quantzig#!/vizhome/MethanolAvailabilityDataTopGlobalMaritimePorts/MethanolFuelAvailabilityatPorts

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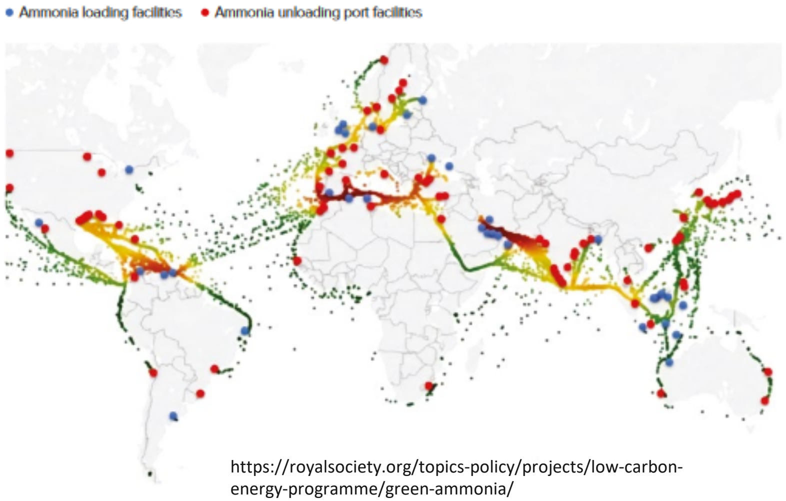
Volume: What would it mean if it was **ammonia**?

It can be made from renewable resources:
Green electricity, air and water.

- Renewable electricity → electrolysis of water to make hydrogen (H_2) → ammonia synthesis via HB process.
- Main bottleneck: **Low-cost electricity / Scale & cost of electrolyzers**
- Alternative intermediate option: LNG → hydrogen via SME and CCS → "Blue ammonia"

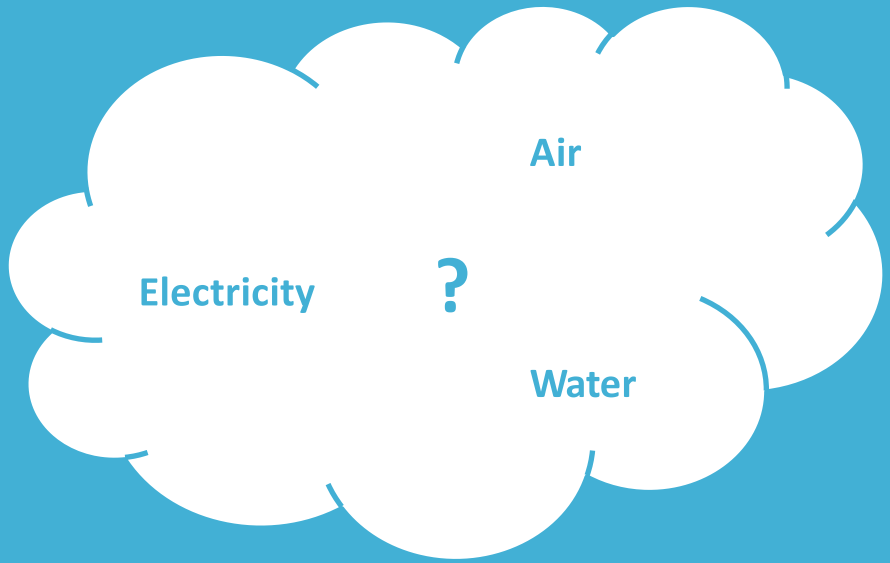


https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

Ammonia market is mature; mainly for fertilizer industry, but…

- **Current global ammonia market:** 180 million ton NH_3/year (20 million ton NH_3/year in free trading shipped globally)
- **Maersk would need:** 20 million ton NH_3/year to replace 10 million ton HFO/year.
- Same key questions are relevant

How to define Power-2-X: “Raw” power vs. raw materials



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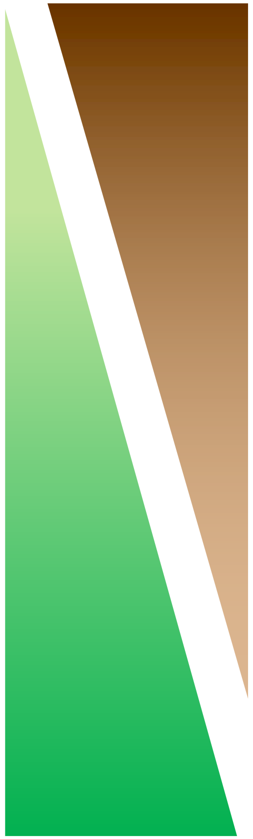
Power-to-X: From low to high power
From high to low raw material input(*)

Note: Biocrude & MeOH can be further refined/upgraded to other syn-fuels or products

Quantity / quality of bio raw material



Renewable power input

Conventional biofuel: Bio-based raw material with limited power input needed

Bio-to-oil (biomass/waste): Pyrolysis/gasification, HTL, … and some renewable power (water -> H_2) for fuel upgrade

Biogas: Convert bio-CH_4 to MeOH: Renewable power to help convert biomethane to MeOH

Biogas: Methane & CO_2 to MeOH: Renewable power (water -> H_2) to upgrade the CH_4 & CO_2 to MeOH

(Bio-)CO_2 to MeOH: CO_2–CC from biomass combustion / bio-gas CO_2; renewable power (water -> H_2) to upgrade the CO_2

"Air" to methanol: Green electricity, Direct Air Capture (CO_2) and water (electrolysis)

Green ammonia: Green electricity, air (N_2) and water (electrolysis)

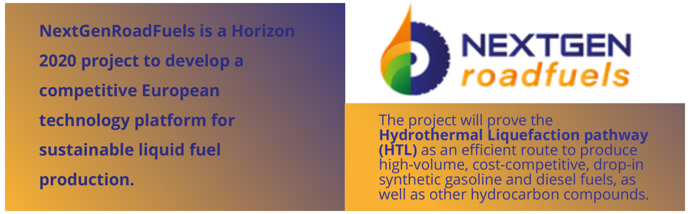
Green hydrogen: Green electricity and water (electrolysis)

} Decoupled from biomass market
Zero CO_2 release; no CO_2 input

(*) For illustration purpose; exact placement and fraction or absolute amount of renewable power not based on numbers

"Raw" power vs. raw materials: Examples of developments

HTL progresses: H2020



www.nextgenroadfuels.eu

€10,7 million from the Danish Energy Agency's funds for energy storage

Together with a series of partners, GreenLab will create the world's first largescale facility for production of green hydrogen and methanol

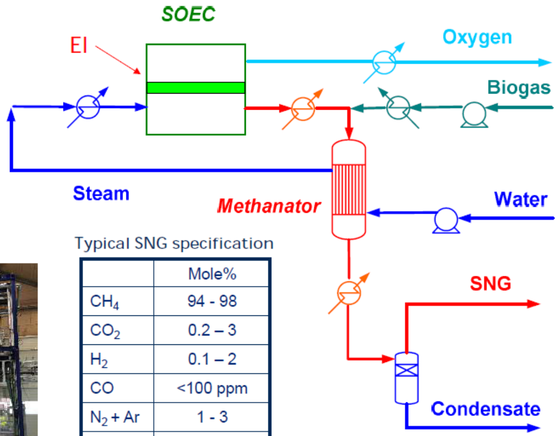
Biogas upgrade with green H_2: Biomethane

Power2Gas
Biogas upgrade using H_2 from SOEC

Biogas (60% CH_4 and 40% CO_2) upgraded to Substitute Natural Gas (SNG) via SOEC and methanation of CO_2 in biogas

$$CH_4 + CO_2 + 3H_2O + El \rightarrow 2CH_4 + H_2O + 2O_2$$

	CH_4	CO_2	N_2	H_2
Inlet (cleaned biogas)	56	43	1	0
Product gas	**97.69**	0.00	0.95	1.36

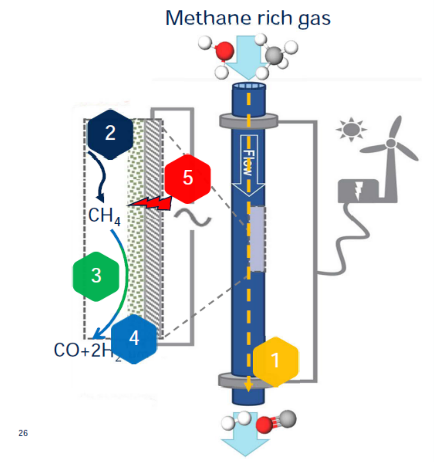


Typical SNG specification

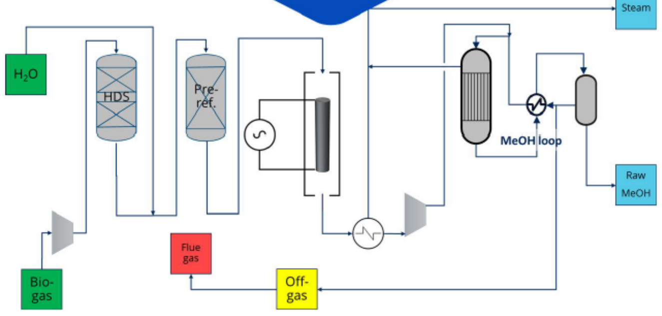
	Mole%
CH_4	94 - 98
CO_2	0.2 – 3
H_2	0.1 – 2
CO	<100 ppm
N_2 + Ar	1 - 3
HHV, KJ/Nm^3	37,000 - 40,000

10 HALDOR TOPSOE

Biogas upgrade with green H_2 and eSMR: Bio-CH_4 & CO_2 → MeOH



Project sum: 8.5 mio €



Sintex, Aarhus University, Energinet, PlanEnergi, Blue World Technologies, Aalborg Universitet, DTU, HALDOR TOPSOE

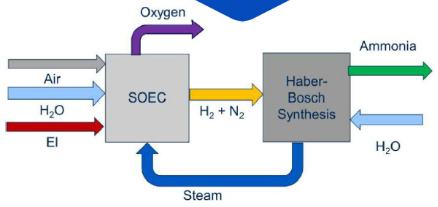
Power 2 Ammonia

Power2Ammonia
Production of ammonia synthesis gas in an SOEC core

Project sum: 3.5 mio €

- EUDP funding obtained December 2018
- Project January 2019 to March 2022
- Work packages
  - WP1: Design and construction of SOEC unit
  - WP2: SOEC Plant Operation
  - WP3: NH_3 as SOEC Fuel
  - WP4: Design of Demo and Full Scale NH_3 plant
  - WP5: Project management and Dissemination
- Partners:

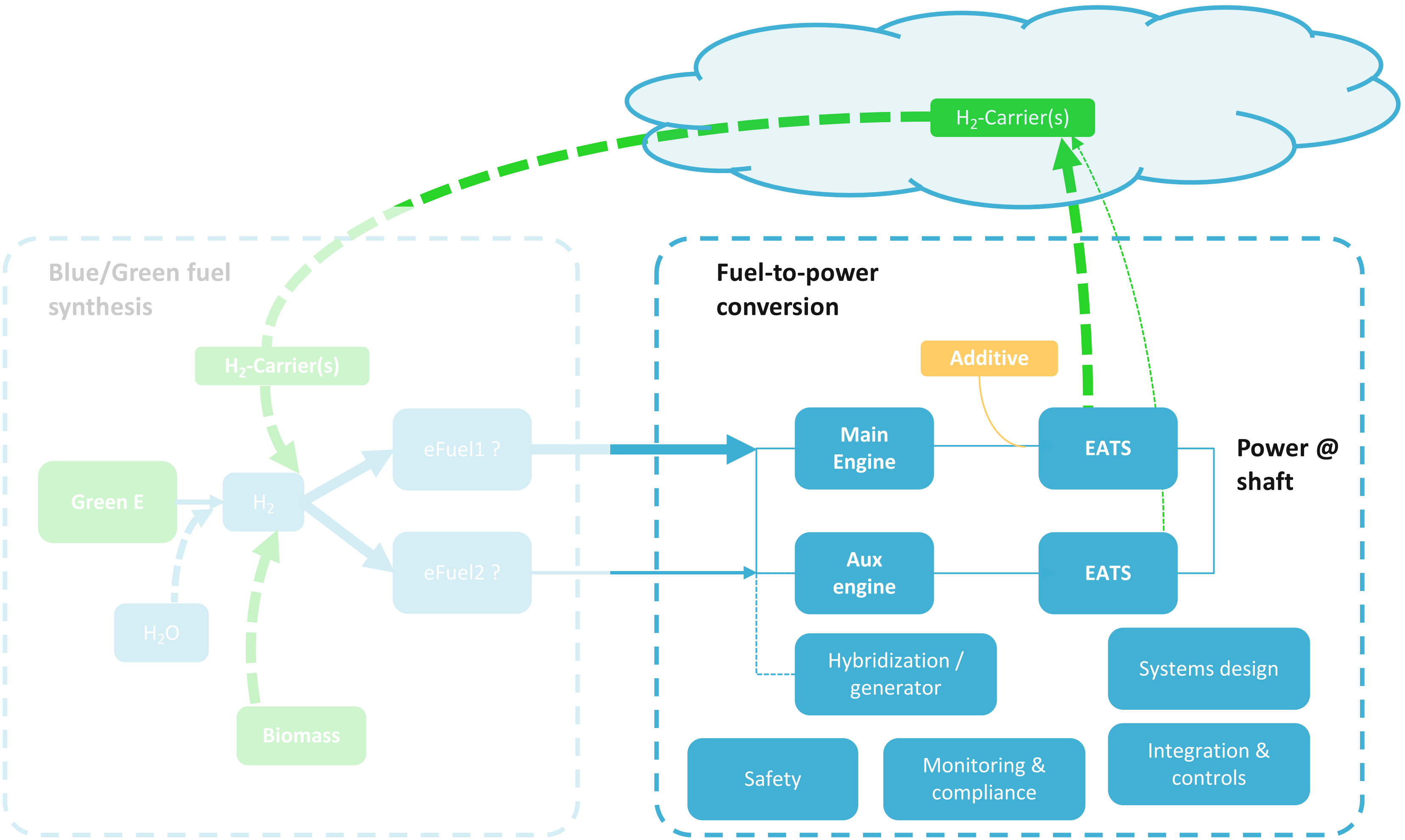
Aarhus Universitet, DTU, Vestas, Ørsted, equinor, Energinet.dk



SOEC concept to be demonstrated in EUDP project "SOC4NH3"
- 50 kW SOEC (8 stacks)

18 HALDOR TOPSOE

The high-level view: Fuel conversion "Lego" bricks



EATS: Exhaust After-Treatment Solution

Main engine: **ICE** or Fuel Cell ?

Aux. Engine: ICE or **Fuel Cell** ?

Fuel: One or "several" pr. vessel ?

After-treatment:

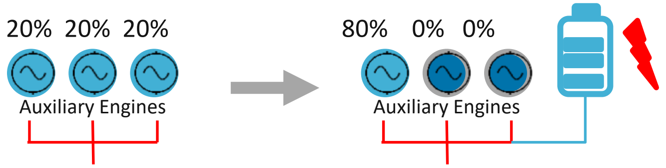
- NOx ? SOx ?, PM/PN?, SCR?, Filter?
- Additives

Power management variants:
Hybridization/battery/generator ?

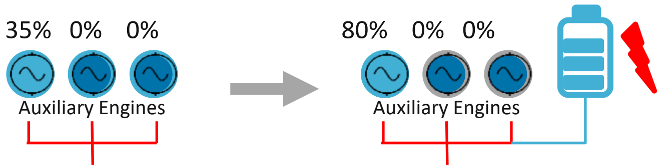
Safety

Hybridization is likely to be an important "link" between new fuels and energy efficiency improvements

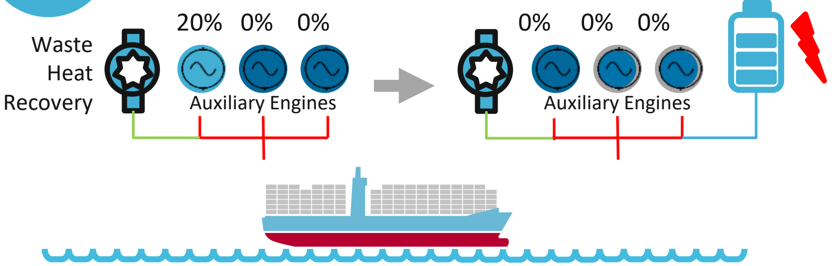
1 Spinning Reserve



2 Power Optimization



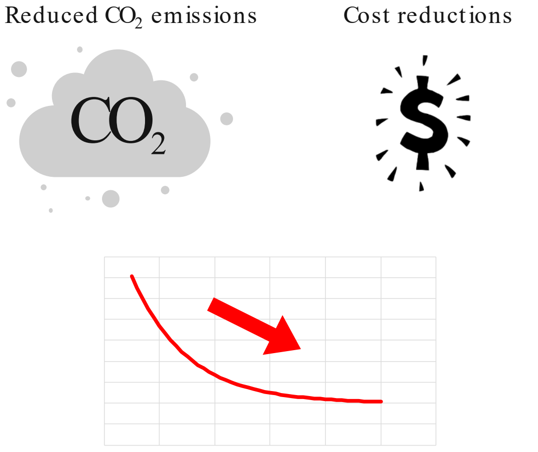
3 Waste Heat Recovery



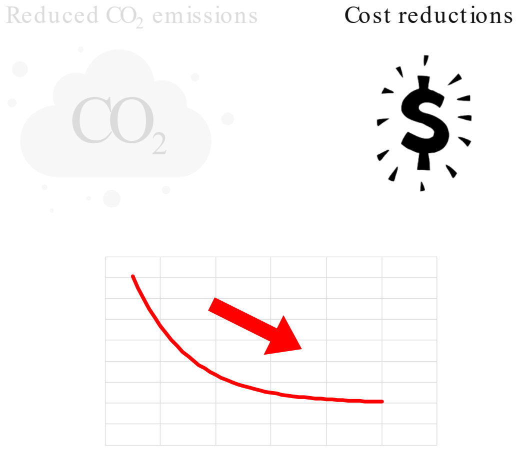
Hybridization: Growing impact when new power-generation solutions & new fuels will be implemented

- Dimensioning of e.g. fuel cell systems is critical (higher cost/kW)
- Response time of gen-sets: (ICE vs. PEM vs. SOFC)

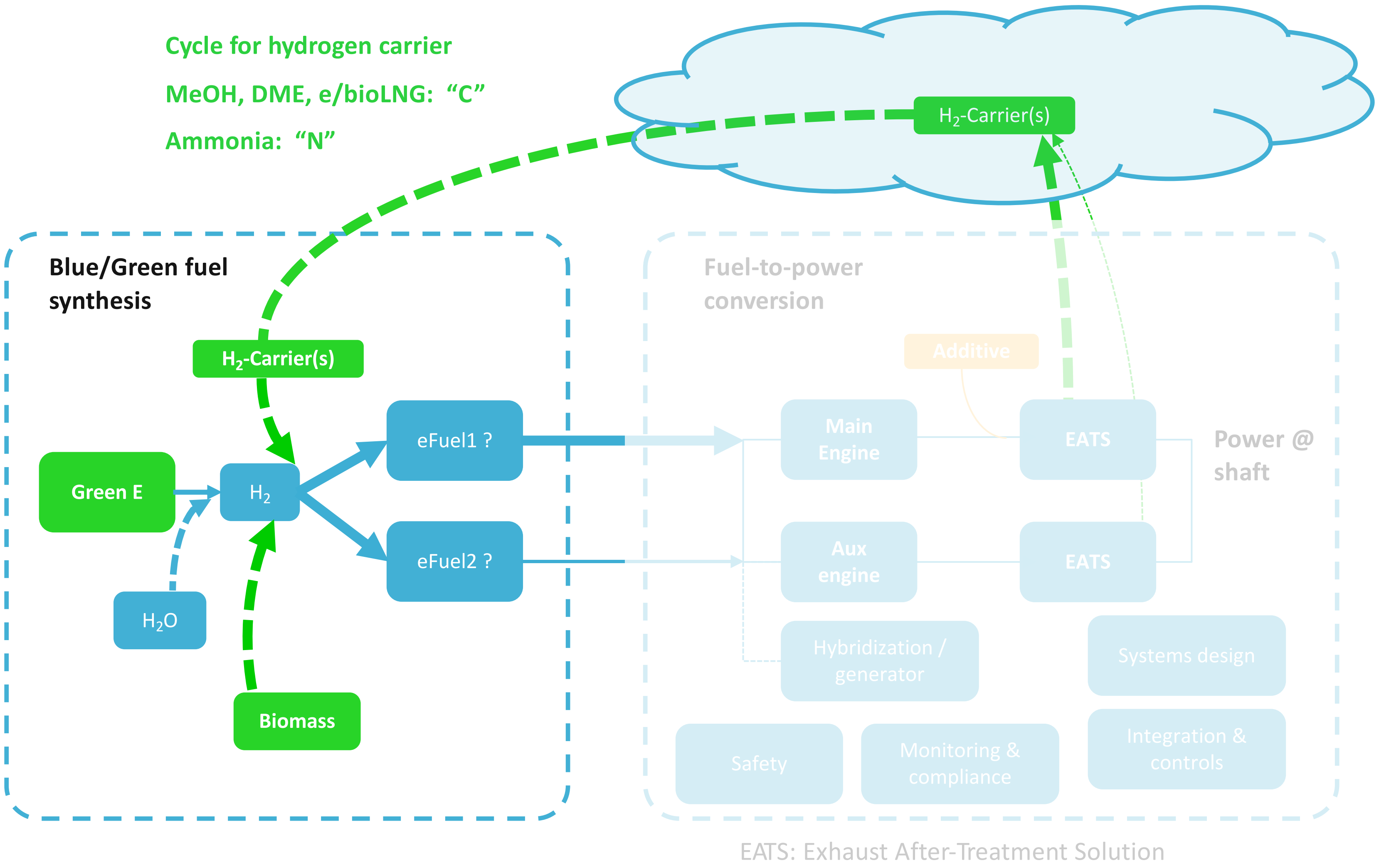
Today: Less CO_2



"**Tomorrow**"
Reduced consumption of a costly future fuel



The high-level view:
Fuel production “Lego” bricks



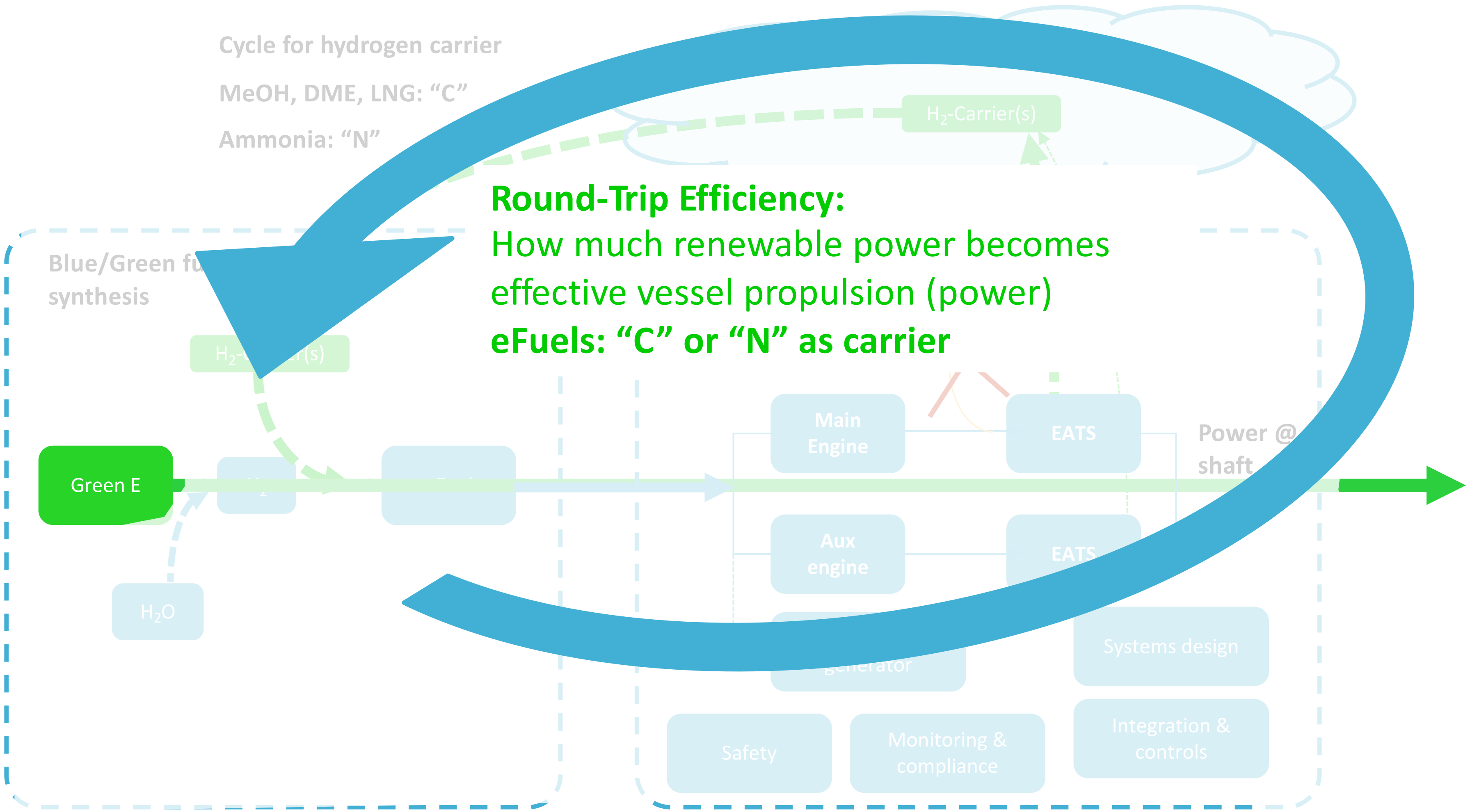
Example: P2X:

Hydrogen production is an “always needed” first step.

Electrolysis (CAPEX & OPEX): key cost drivers

Renewable power is a bottleneck

Total efficiency: A function of choice of fuel, selection of components and clever integration.



Round-Trip Efficiency:
How much renewable power becomes effective vessel propulsion (power)
eFuels: "C" or "N" as carrier

Power-to-Fuel-to-Power / Round-Trip Efficiency is a key factor.

Maximize kWh propulsion per kWh green E (or green raw materials)

…and why is ammonia interesting as hydrogen carrier ? A 'hint' from old-school thermodynamics

Entropy

$$\Delta_{mix} S = -nR(x_1 \ln x_1 + x_2 \ln x_2)\,.$$
$$\Delta_{mix} G = -T \Delta_{mix} S$$

can be seen as a measure of the molecular disorder, or randomness, of a system.

- When we combust fossil fuels, we create highly disordered (diluted) CO_2 in the Earth's atmosphere:
  410 ppm CO_2 in 4,200,000,000 km^3 air

- **If we need to go carbon negative (tipping point?), we have to capture CO_2 again.**
  Not easy. Fighting entropy !

- **The ammonia molecule:**
  - Does not contain carbon atoms. Hydrogen "sits" on a nitrogen atom
  - Ideal ammonia combustion: No release of CO_2 (& low Nox) — $2\ NH_3 + 1½\ O_2 \rightarrow 2\ N_2 + 3\ H_2O$
  - and NH_3 made it again from hydrogen and access to nitrogen: — $N_2 + 3H_2 \rightarrow 2\ NH_3$
  - "N" Round-trip: 78% of atmosphere is N_2 - not 410 ppm (0.041%)

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The "dilution impact " for carbon-based eFuels vs. PFP

Where is carbon captured from ? "Thin air" or concentrated flue gas

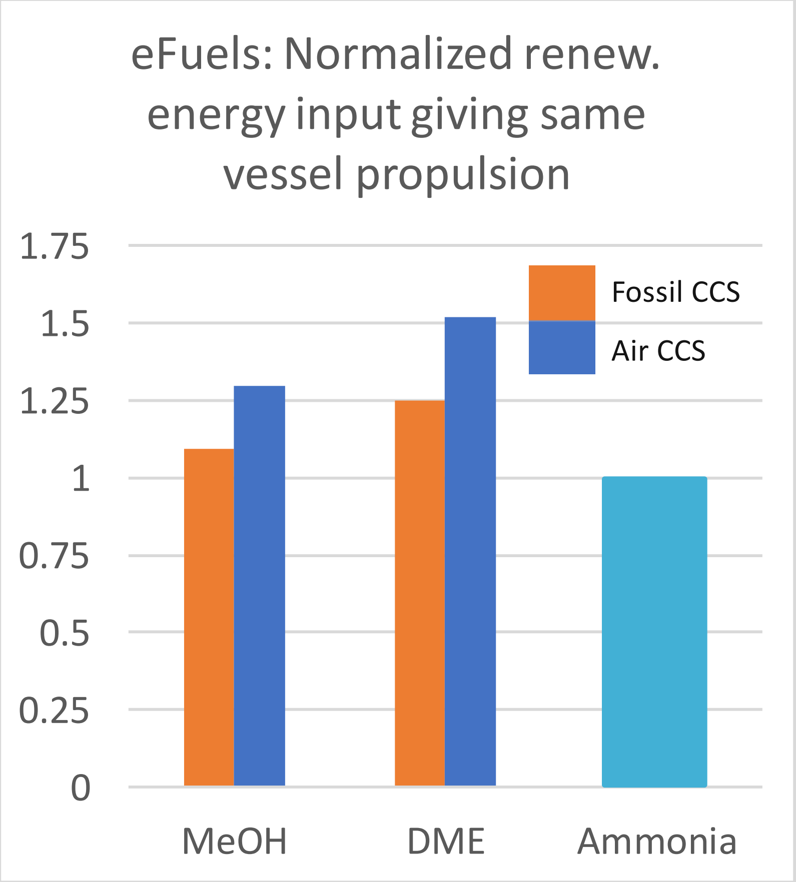
- It is easier to capture CO_2 from a concentrated source (biomass combustion or bio-gas) than from 410 ppm in air (DAC).
- Nitrogen is 78% of air. Almost 2000 times less air to "manage" than DAC. Easier to get N_2 than CO_2.
- Beneficial for **PFP** (**P**ower-to-**F**uel-to-**P**ower) for NH_3.

Future outlook:

Solid Oxide Electrolyzers (green H_2) can exceed 90% efficiency in power-to-H_2.

Ammonia conversion in Solid Oxide Fuel Cells can exceed 60% efficiency.

Combined green ammonia fuel path holds potential to get close to 50% PFP



Note: "Back-of-the-envelope" calculation. Not peer-reviewed graph.
Based on data from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5089635/

Table 2

PFP^{flue} indices of the seven assessed alternative fuels.

Fuel	Separation[a]	CO_2 transport[b]	PFP^{flue}[c]	
methane	0.037	0.006	31 %	27 %
MeOH	0.043	0.007	32 %	27 %
DME	0.045	0.007	28 %	23 %
ammonia	0.008	–	35 %	35 %

CO_2 from flue gas (capture from fossil or biomass combustion 'outlet')

CO_2 from air

Data from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5089635/

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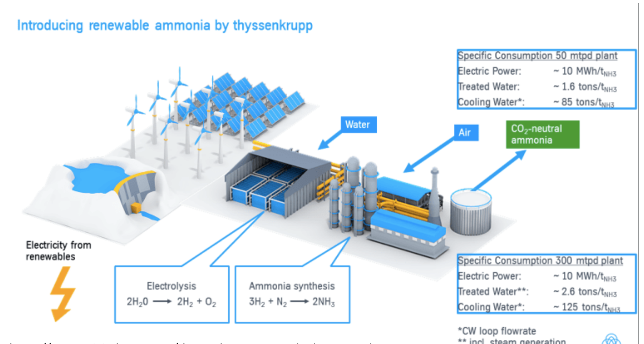
The transition ?

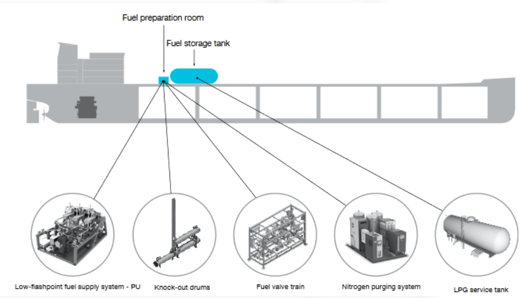
New fuel roadmaps do however have challenges – full feasibility must be clarified for each

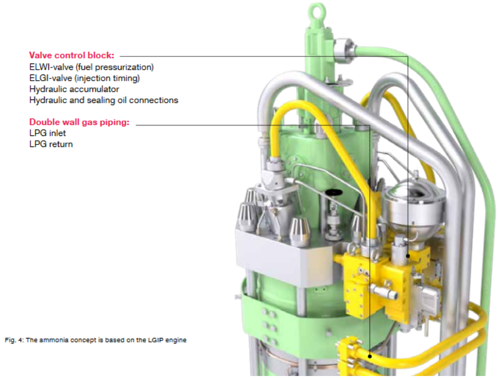
- Fuel production & supply
  - How to ensure manufacturing and supply in large scale
  - Projected cost and global availability as bunker fuel
  - Understanding of "interference" or synergies with other markets
- Technology
  - New fuel proven in marine engines (2/4 stroke)
  - Aftertreatment (NOx, SOx, PM and N_2O)
  - On-board fuel storage/management system / safety
  - Solid Oxide Fuel Cell for aux. "engine" ?
- Regulation:
  - Quality of new fuel
  - CO_2 verification "stamp"
  - Safety – bunker fuel and vessel approvals

(*) Not complete list



https://ammoniaindustry.com/thyssenkrupps-green-hydrogen-and-renewable-ammonia-value-chain/






https://vigor.net/projects/harvest

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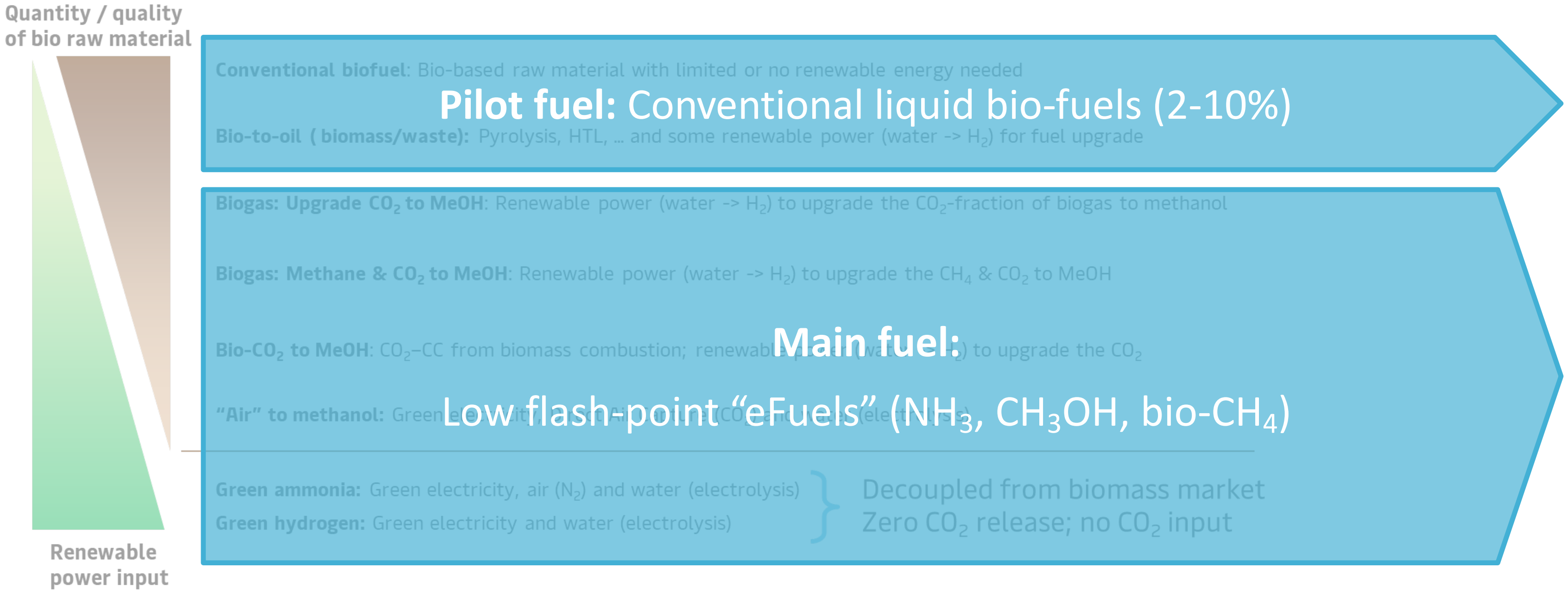
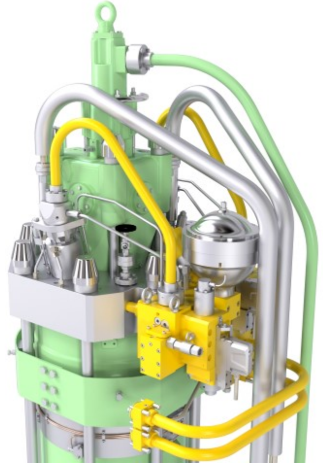
Synergies between bio-fuels and Power-to-X: Mitigate the potential limitation of bio-carbon

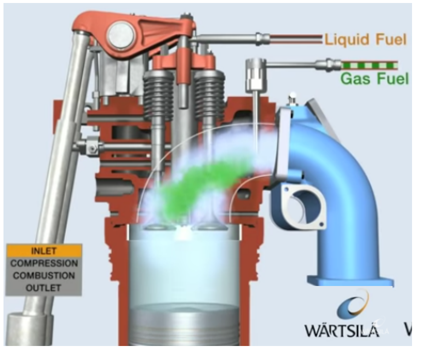


Example of Duel-Fuel engines:

MAN & Wärtsilä



https://corporate.man-es.com/press-media/news-overview/details/2018/09/03/man-energy-solutions-unveils-me-lgip-dual-fuel-lpg-engine



https://www.youtube.com/watch?v=6mifHJ3MkfE

The general concern about the availability of biofuels for transportation, aviation and shipping can be mitigated if shipping only needs the pilot fuel.

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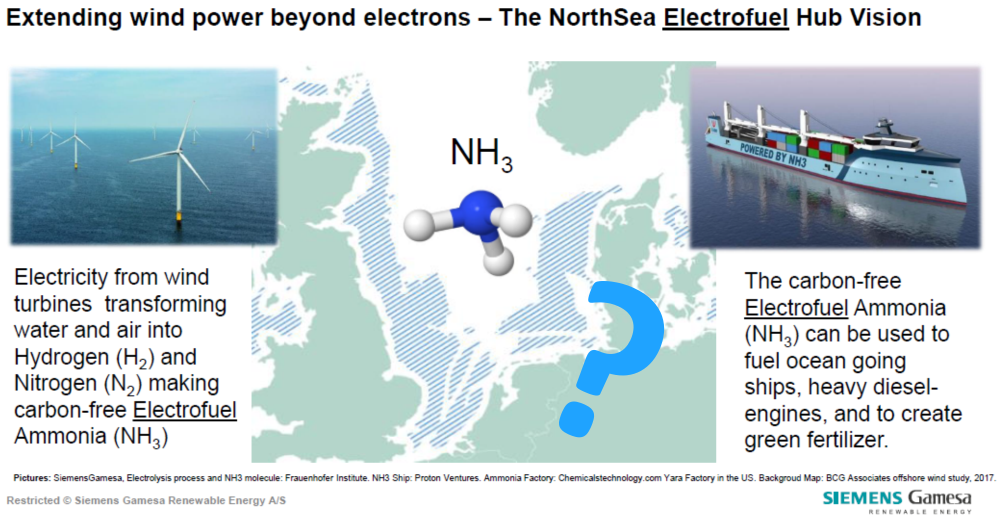
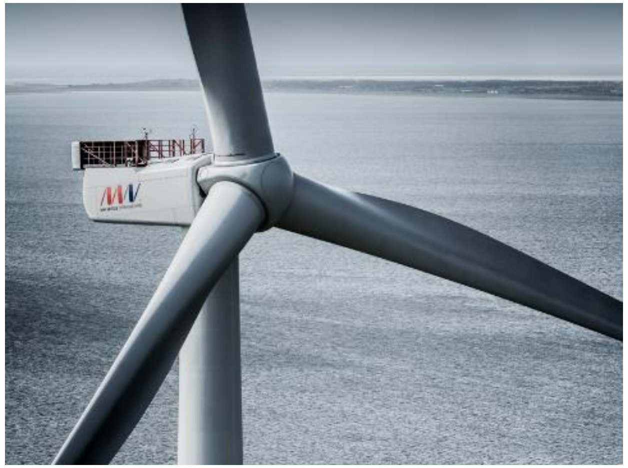
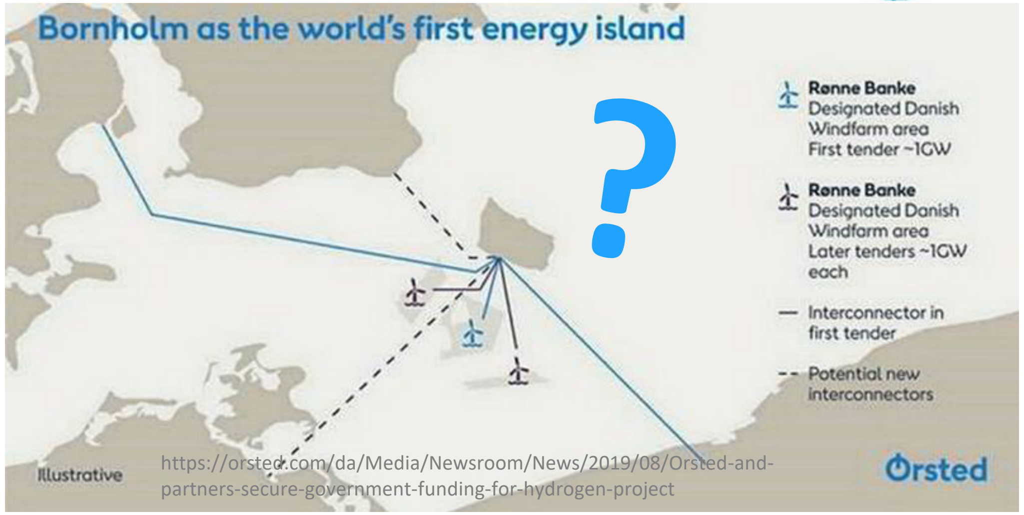
When will cost of renewable power become “low enough” ?
How do we make it through a transition period with reduced CO_2 impact ?







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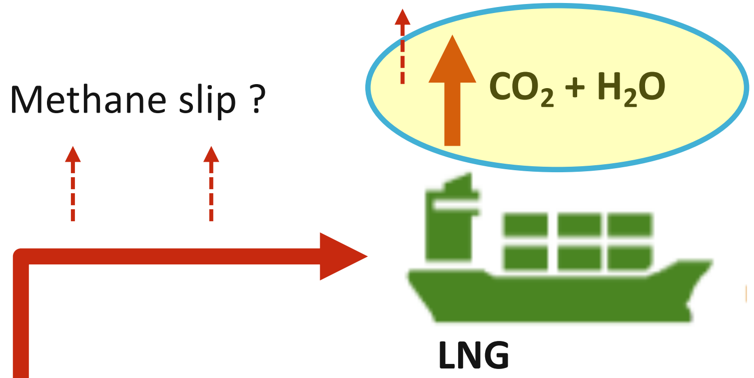
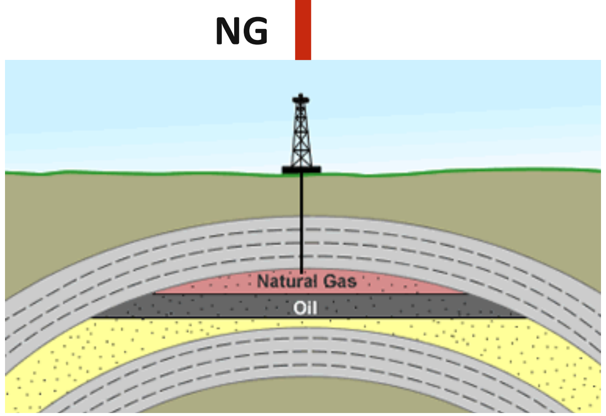
Input for discussion:
LNG as a bridge-fuel towards IMO 2050 for the industry in general ?

Input for the panel debate



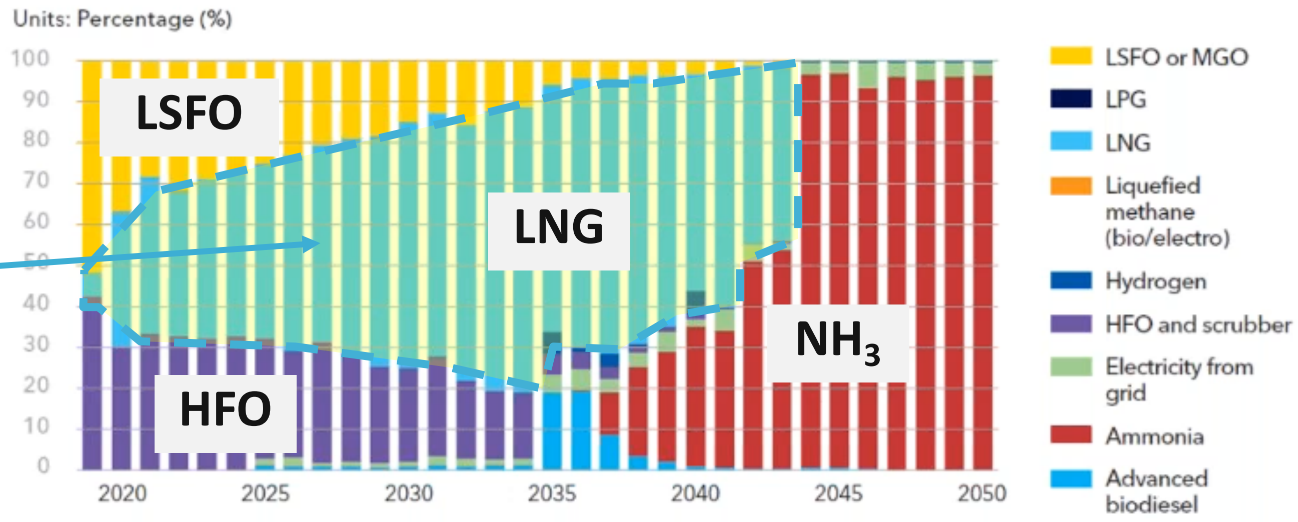


A temporary LNG era would still have massive CO_2 emissions

Alternatives ? ?

Source: DNV-GL 2050 scenario

If main focus is on **design requirements**, the shift in fuel and fuel-converter technology on newbuildings is very abrupt



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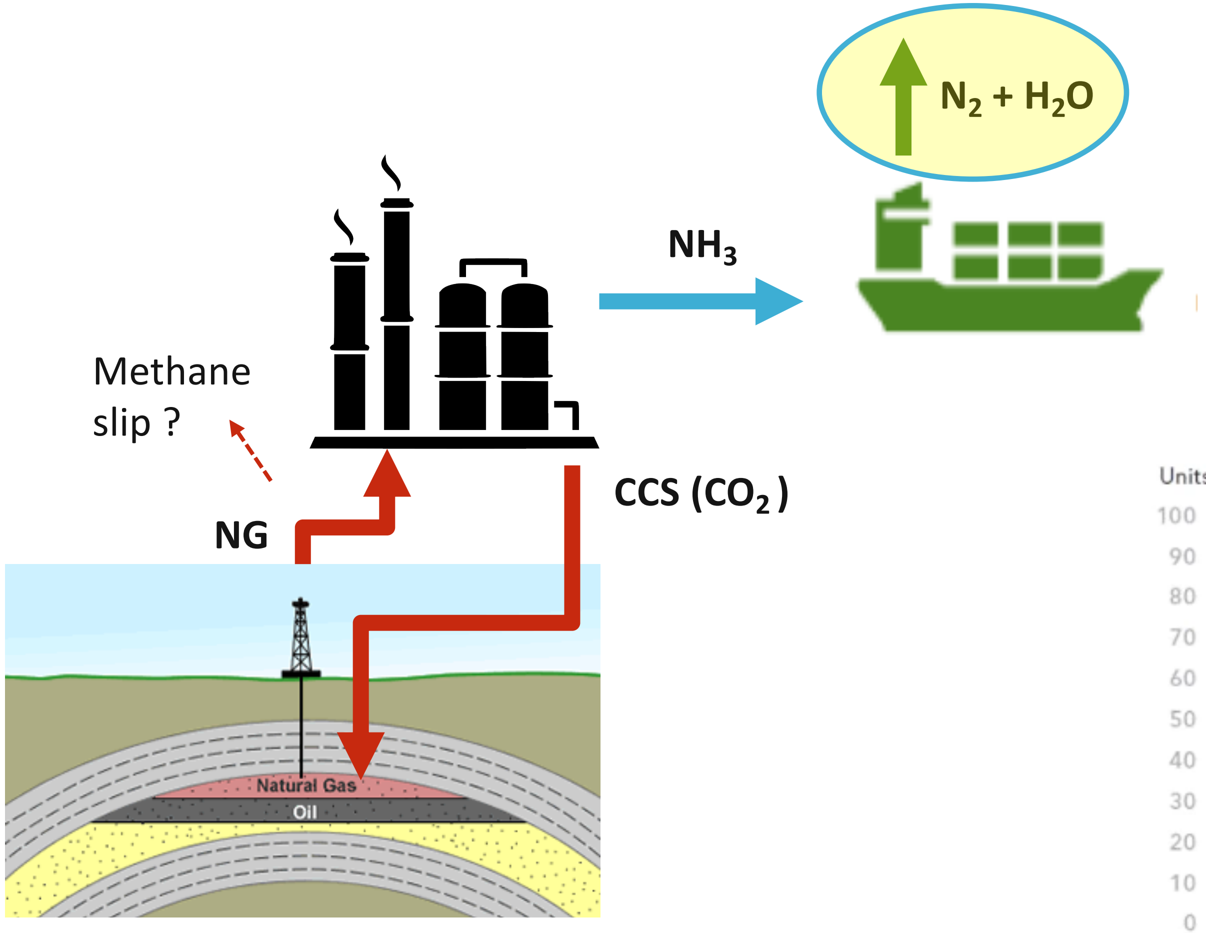
NG as energy source for fuel transition with central CO_2 "control": NG → hydrogen & CCS → Blue ammonia ?

Input for the panel debate

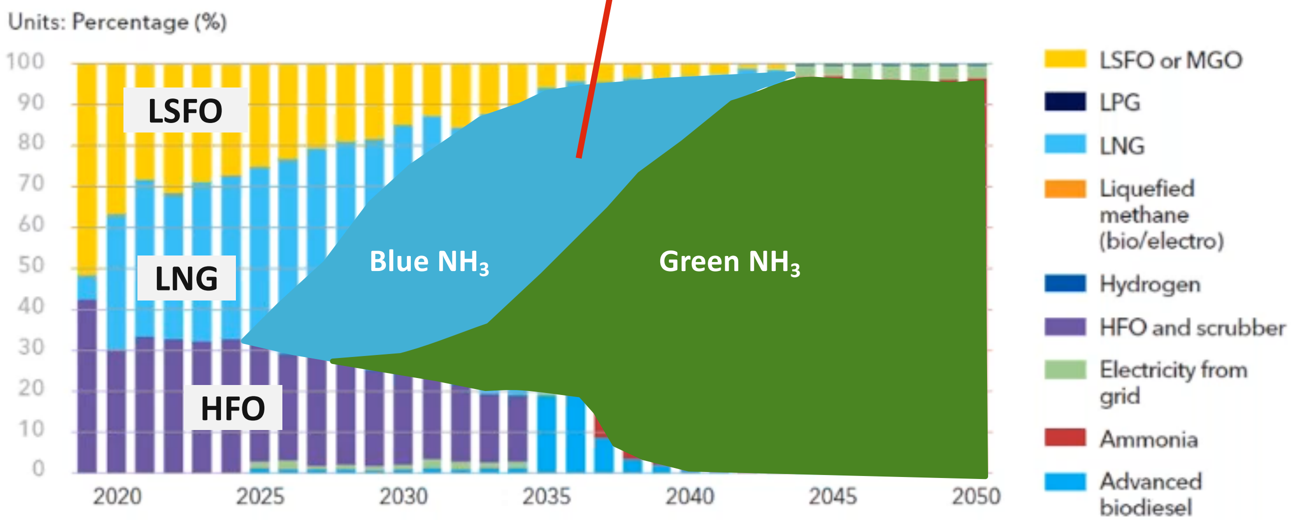


Blue NH_3 : The area "covers" 4500 million ton CO_2

Cost of centralized CO_2 capture (solve it now):
~ **50 \$/ton CO_2** (probably less)

Cost of Direct Air Capture (solve the problem "later"):
~ **130 \$/ton CO_2** (likely more)

Magnitude of upfront CO_2 "value": **360 billion \$**



Further benefit of accelerated NH_3: Reduce the cost impact of a two-step infrastructure change

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A successful transition phase through strong **technical solutions, high efficiency** and **customer demand** for green solutions.

Diverging

Converging

Ideation

Engaging with ecosystem & stakeholders

Decision Point

Analysis on safety, availability, supply, cost etc.

Design

Contract

Build

2019

2023

2027

2028

2030

First **commercially viable** carbon-neutral vessel in **operation**

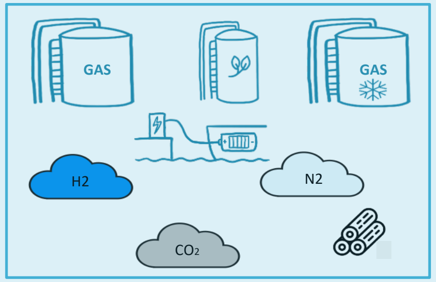
ECO Delivery – Now there is choice

Transition period: Cost of new fuels vs. customer demand

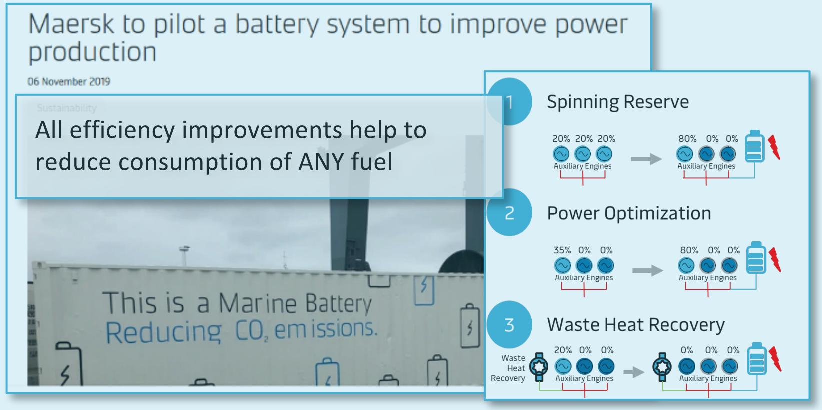
Premium rates for C-neutral shipping:
Helpful in a fuel transition period.
Growing market demand?

Narrow in on a few technologies to focus efforts toward the goal of having the first commercially viable carbon-neutral vessels in operation by 2030

New fuels for net-zero operation



High efficiency



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Thank you for the opportunity to share some thoughts…

Going carbon-neutral #AllTheWay has strong focus at Maersk

We are many colleagues working hand-in-hand across the organization and with our partners:

Future solutions / Technical innovation / Machinery

Tue Johannessen, Future solutions

tue.johannessen@maersk.com

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