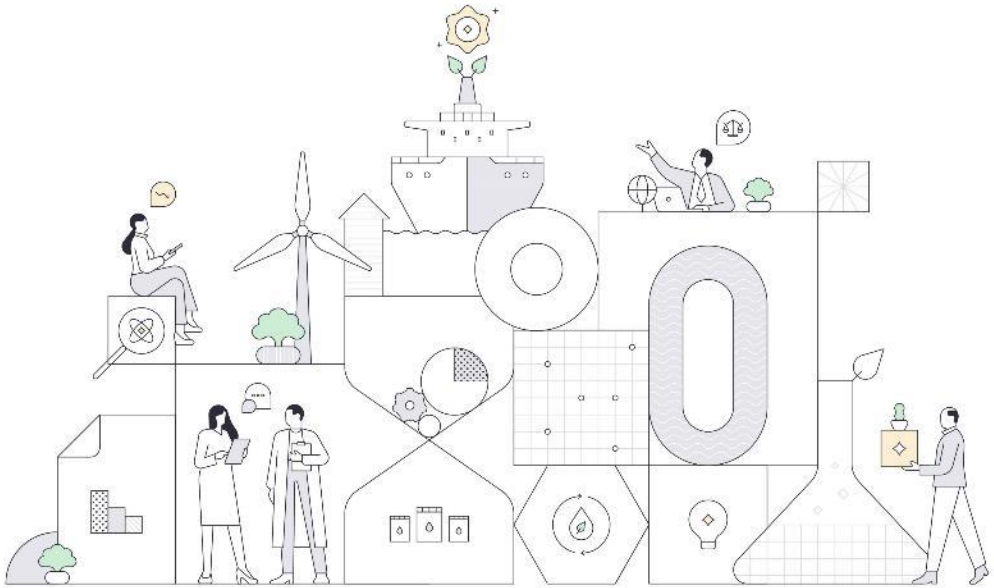


Power-2-X and energy carriers for carbon-neutral shipping

Dr. Tue Johannessen,
Head of Maritime Application & Viability
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

The key messages

- **Maritime Decarbonization**: Understanding the scale of the challenge for a global fleet of ~ 70,000 ships using 250 million ton of fossil fuels per year

- **Power-to-X-to-Power** (it is not just P2X): Technology developments to facilitate and accelerate an end-to-end transition

- **Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping** – an initiative to catalyze the transition

Situational assessment and targets

Decoupled growth and emissions by efficiency but only temporary

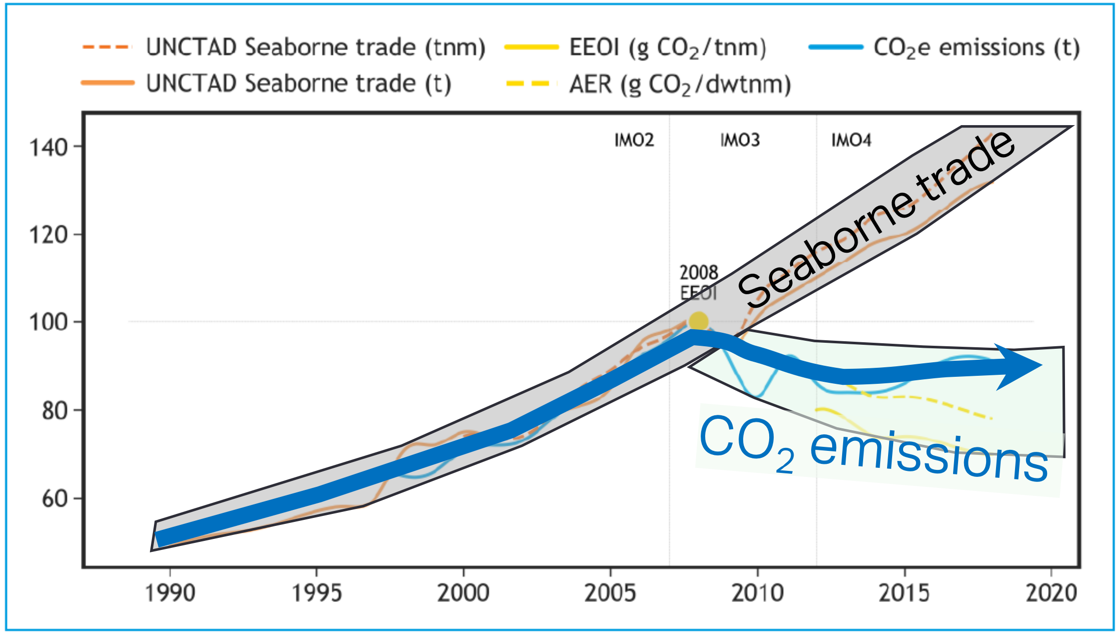
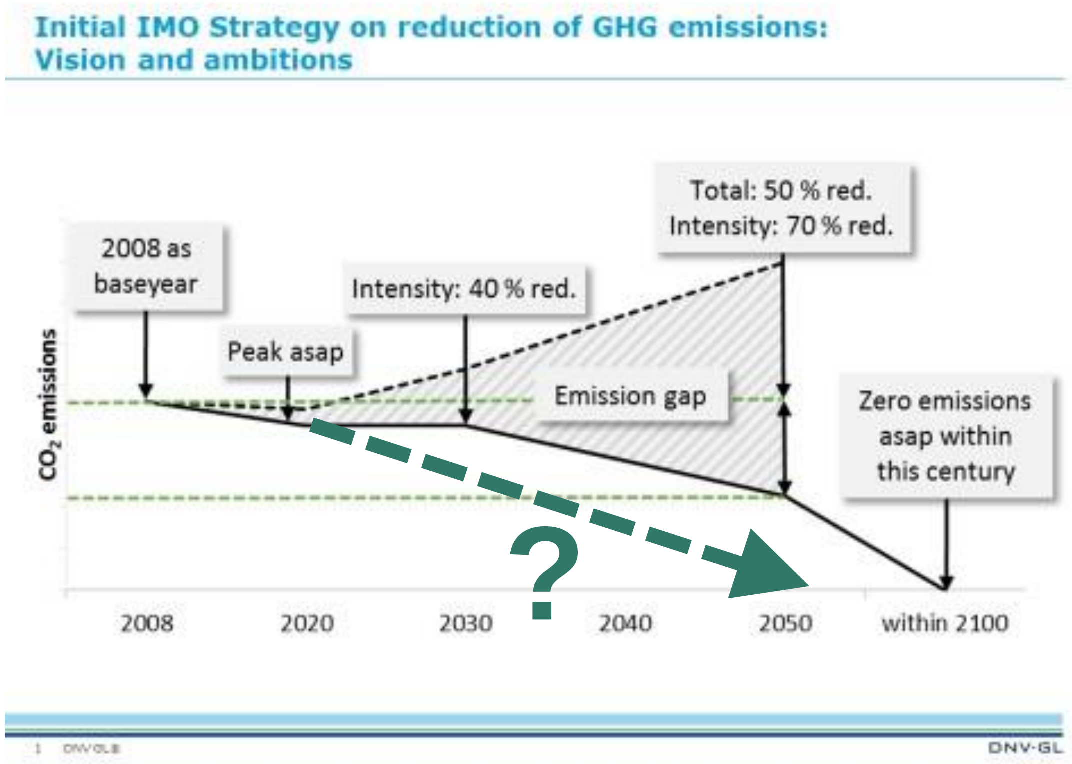


Figure 2 – International shipping emissions and trade metrics, indexed in 2008, for the period 1990-2018, according to the voyage-based allocation[2] of international emissions[3]

Source: Fourth IMO GHG Study 2020 – Final report

Systemic changes and massive investments needed to decarbonize beyond efficiency



Source: DNVGL

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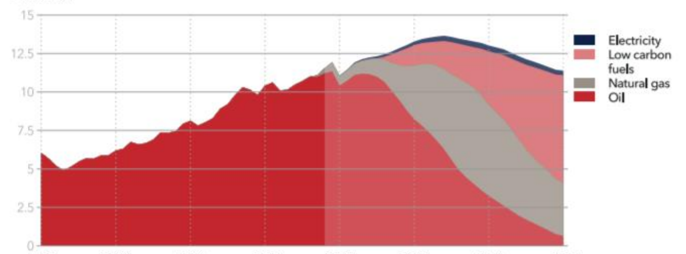
Many industry projections – clarity of transformation path(s) needed

DNV GL Energy Transition Outlook

60% Low carbon fuels / 30% LNG / 10% Fuel Oil

FIGURE 1.10

World maritime subsector energy demand by carrier



Natural gas includes LNG and LPG. Biomass includes advanced biodiesel and LBG.
Historical data source: IEA WEB (2019)

ABS sustainability Outlook

40% Fuel Oil / 10% LNG / 35% Ammonia+ H2 /

7% Biofuels / 7% Methanol

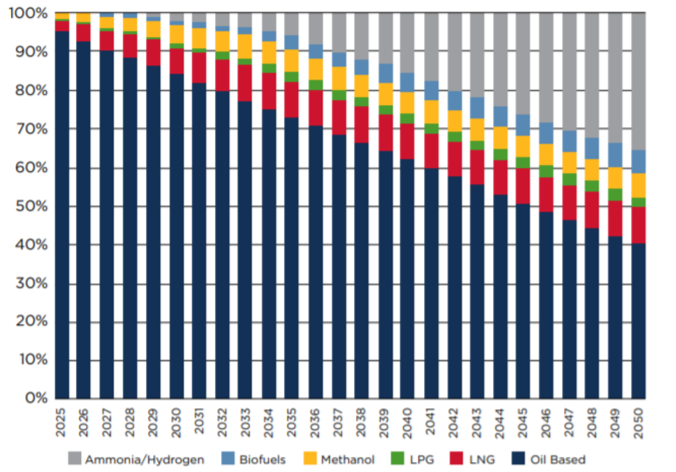


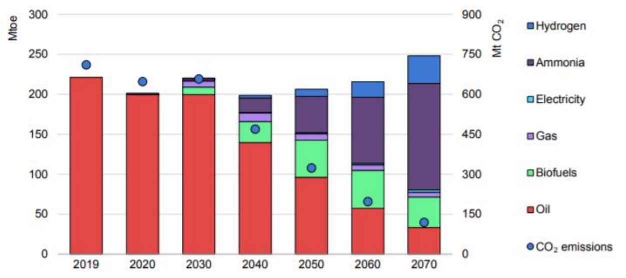
Figure 24: Projected marine fuel use to 2050

IEA

50% Fuel Oil / 25% Ammonia + H2 / 20% Biofuels

(Total consumption 210 MTOE)

Figure 5.11 Global energy consumption and CO_2 emissions in international shipping in the Sustainable Development Scenario, 2019-70



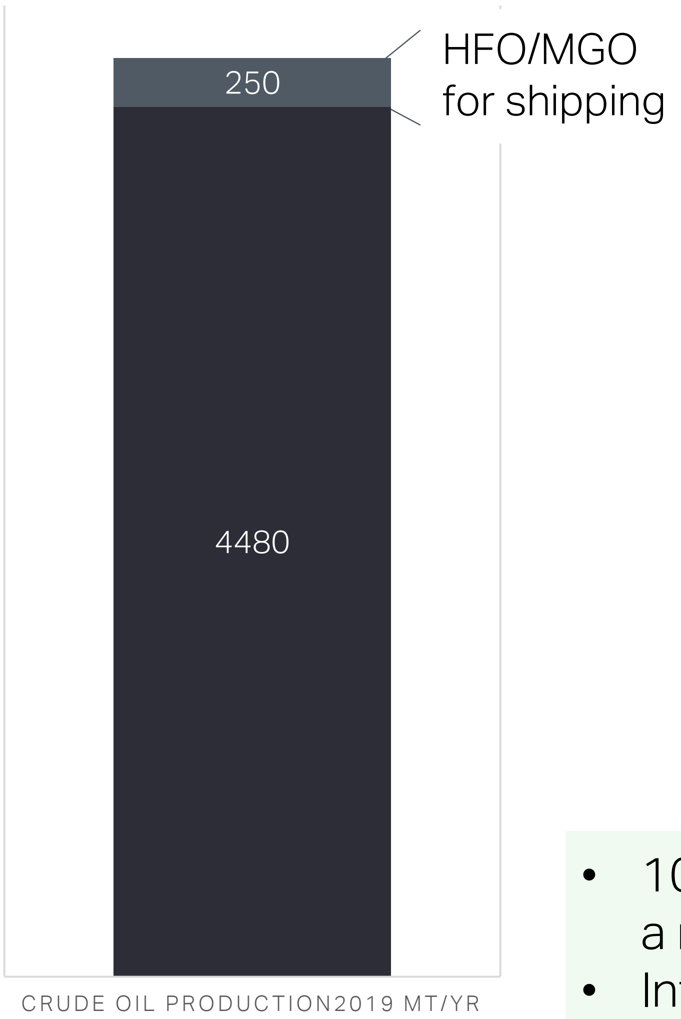
Notes: Efficiency improvements more than offset activity growth in the 2030s and 2040s, but by 2050 activity demand growth overwhelms efficiency improvements, leading to increases in final energy demand. The category biofuels includes biomethane and is considered to be carbon neutral.

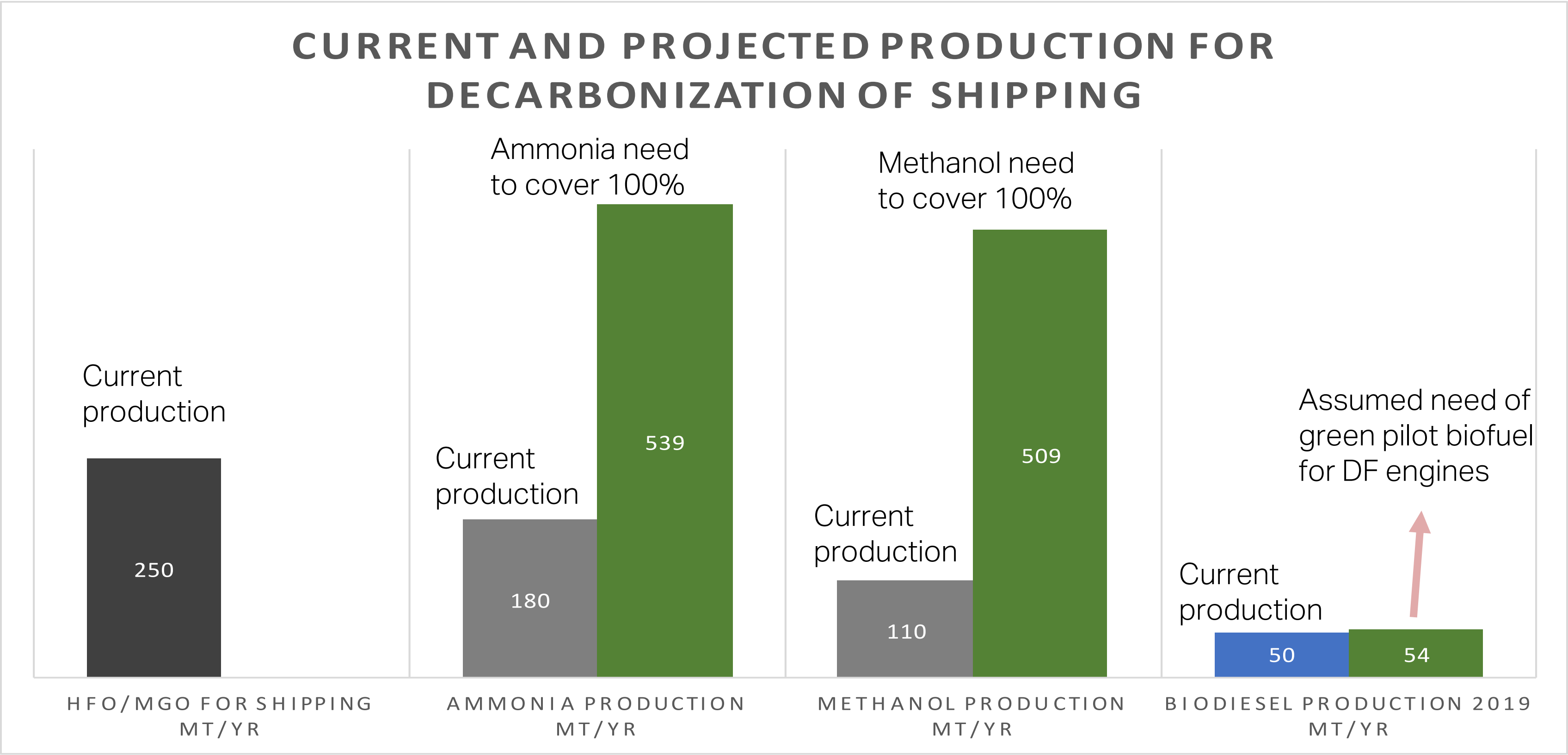
Emissions from international shipping fall by more than four-fifths between 2019 and 2070 in the Sustainable Development Scenario, mainly due to switching to biofuels and hydrogen-based fuels.

<u>Some noticeable differences:</u>

- Share of Fossil fuel oil in 2050 – transition speed
- Share of LNG
- Tank-to-wake vs. full LCA
- No methanol in IEA projection
- Biofuel impact differ significantly

The scale of the challenge to replace HFO

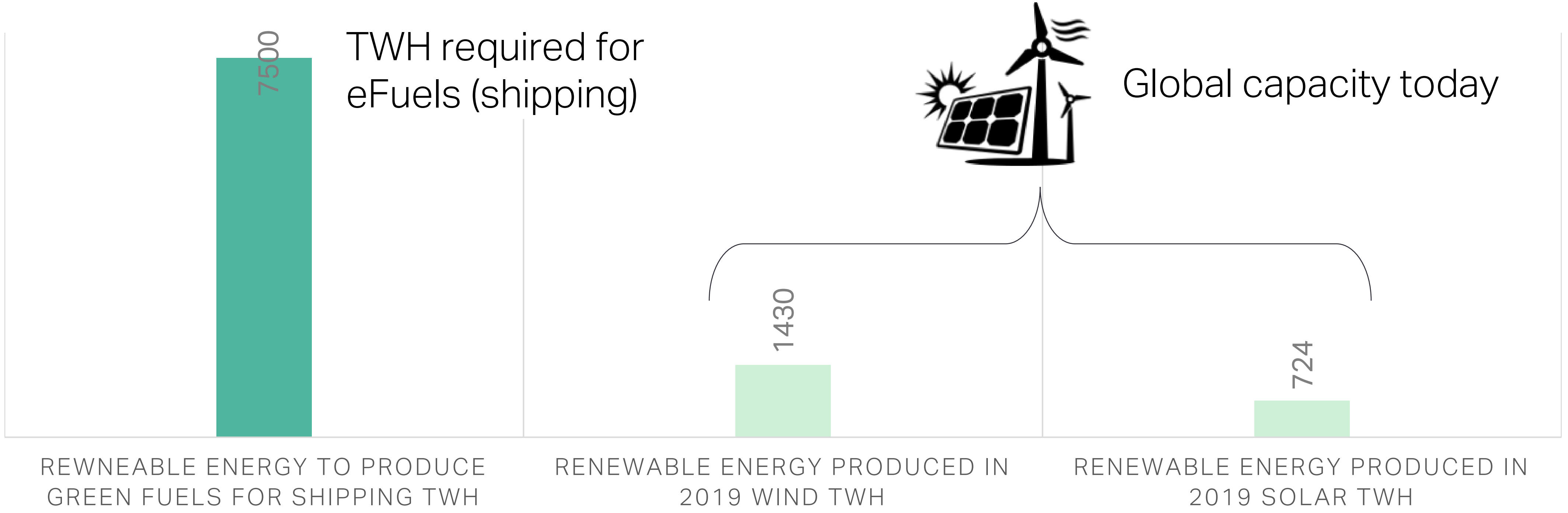




- 100% HFO-replacement by green ammonia or methanol requires a major increase in global production capacity.
- Infrastructure to manage supply & bunkering requires massive scaleup and transformation (oil-tanker → "X"-tanker)

Power-to-X = indirect electrification:

The pace of transition is linked to growth in renewable energy production



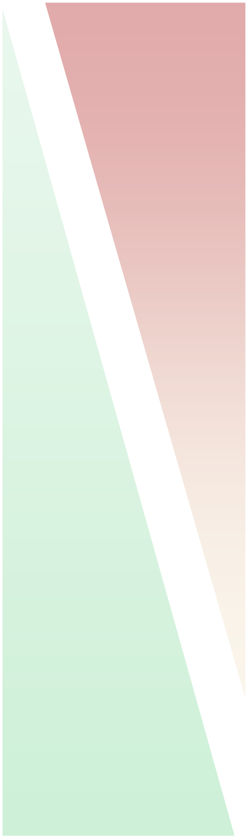
A significant increase of renewable energy is required to produce the green fuels of the future to replace the HFO/MGO for shipping. **Compared to current worldwide wind/solar energy production, a 3-4 time increase is needed**, just to cover shipping decarbonization. Much more additional renewable energy will be needed for decarbonization of other sectors => **Very important to maximize energy efficiencies along the value chain.**

Power-to-X:

From low to high power content
From high to low raw material input(*)

Illustrative

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

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Power-to-X:

From low to high power content
From high to low raw material input(*)

Illustrative

We do not need "one silver bullet"
– we need a lot from several viable paths

Quantity / quality of bio raw material

Renewable power input

Conventional liquid fuels; normal flashpoint
→ long-term pilot fuels for dual fuel engines

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

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

Needed as net-zero pilot fuel (3-10%) in 2-stroke engines

Low flashpoint / cryogenic carbon-based

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)

Zero-carbon gaseous fuels (low flashpoint/cryogenic)

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

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

The new Center for Zero Carbon Shipping: Facts

Founded in **2020** with initial base funding of **DKK 400mn** by A.P. Møller Foundation

Located in **Copenhagen: a central team** with a **global** outreach

Registered as a **not-for-profit commercial foundation with a charitable purpose.** Self owned entity.

Neutral and open platform for collaboration across the value chain, with an anticipated **growing partnership base**

Established by seven founding partners from across the ship-powering supply chain, with commitment to contribute resources

ABS MAERSK MITSUBISHI HEAVY INDUSTRIES, LTD. SIEMENS Cargill MAN Energy Solutions NYK LINE

Our Guiding Principles

- We are independent and neutral, aiming for objectivity through transparency, facts and scientific methods
- We are open-minded to and unbiased about new ideas
- We enable and inspire leadership for the industry
- We believe in partnering and collaboration
- We are tenacious due to our sense of urgency
- We build confidence and trust
- We show the world it is possible – and *how*

We will accelerate the development of solutions and drive transformation towards Zero Carbon Shipping

TECHNICAL SOLUTIONS FOR DECARBONIZATION

- Create **overview and comparison** of possible future solutions using consistent frameworks, data and methods
- Develop **end-to-end systems demonstrating feasibility** of decarbonizing shipping segments, identifying critical **gaps** (technology, commercial, financial, environmental, safety, regulatory)
- **Accelerate** the maturation of 'Front Runners' by creating focus, attracting resources and engaging in development of critical components in the most feasible systems

GLOBAL TRANSITION NARRATIVE

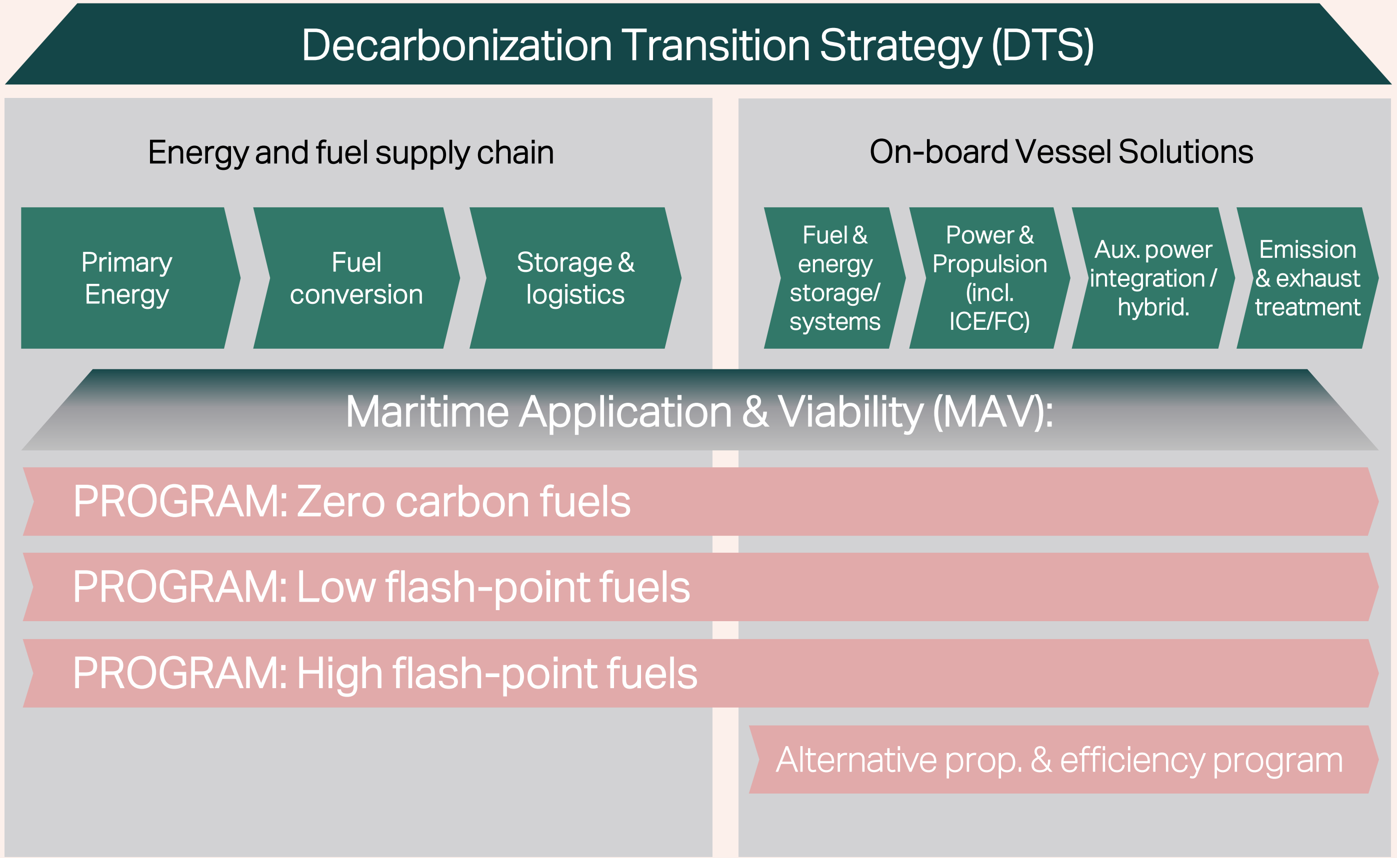
- Create the **narrative** of the shipping sector transformation **pathway** in the global picture
- Engage in **regulatory** developments
- Leverage **partnerships and available funds** for sharing risk in maturation and demonstration projects
- Support development and realization of **commercial and financial opportunities**
- Create **transparency** of life-cycle carbon efficiency of investments, systems and operations

Center R&D Strategy

R&D for Transformation

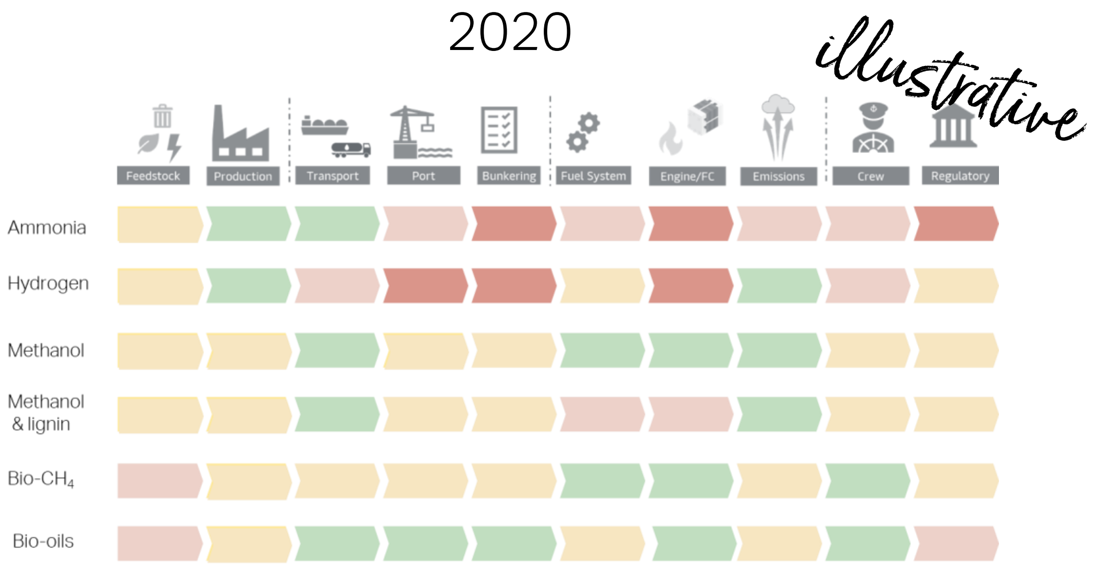
Objective:
Create clarity in future pathways and confidence to accelerate required developments and investments.

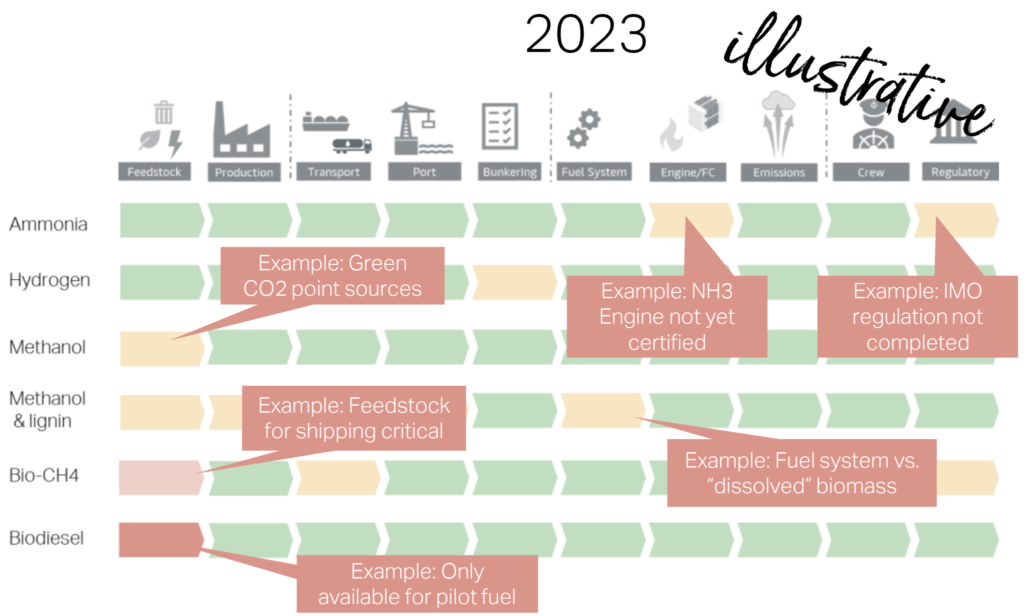
How:
Structured R&D programs on energy/technical systems (MAV) closely integrated with regulatory, financial and commercial opportunities (DTS)



We apply a structured approach to technical- and commercial feasibility assessments

The Center will create overviews and be involved in a portfolio of R&D- and demonstration projects to de-risk pathways with development needs for each vessel segment.





TRL and/or MRL	(Major) challenges remaining	Solution identified. Needs validation	Mature & proven

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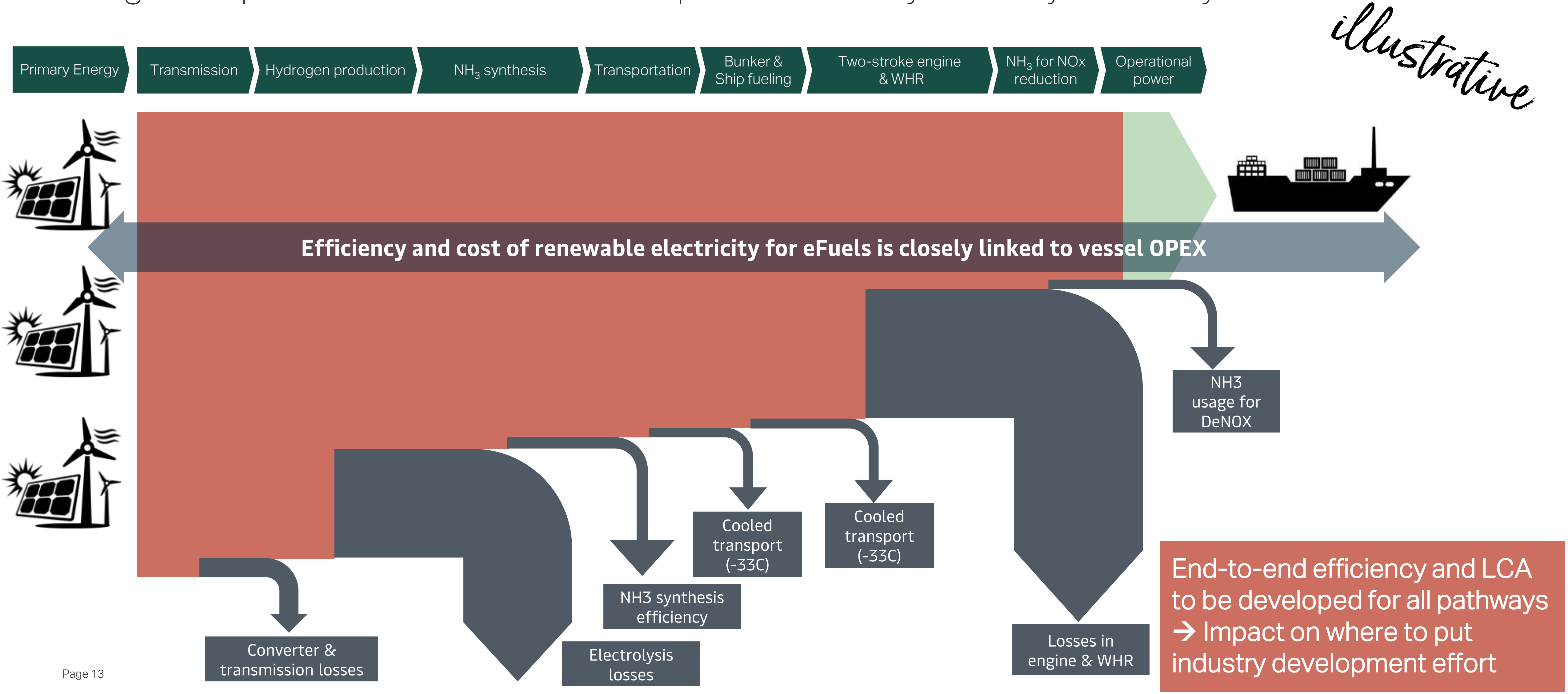
Top-down overview to facilitate R&D focus

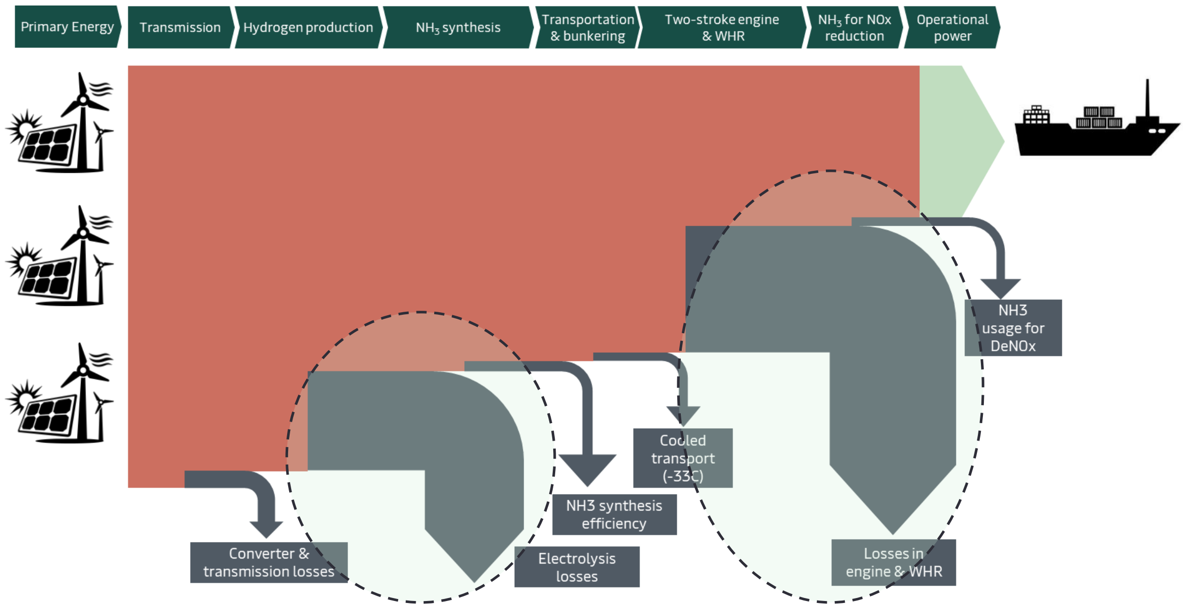
Marginal impact: Cost, decarbonization potential, life-cycle-analysis, safety, TRL



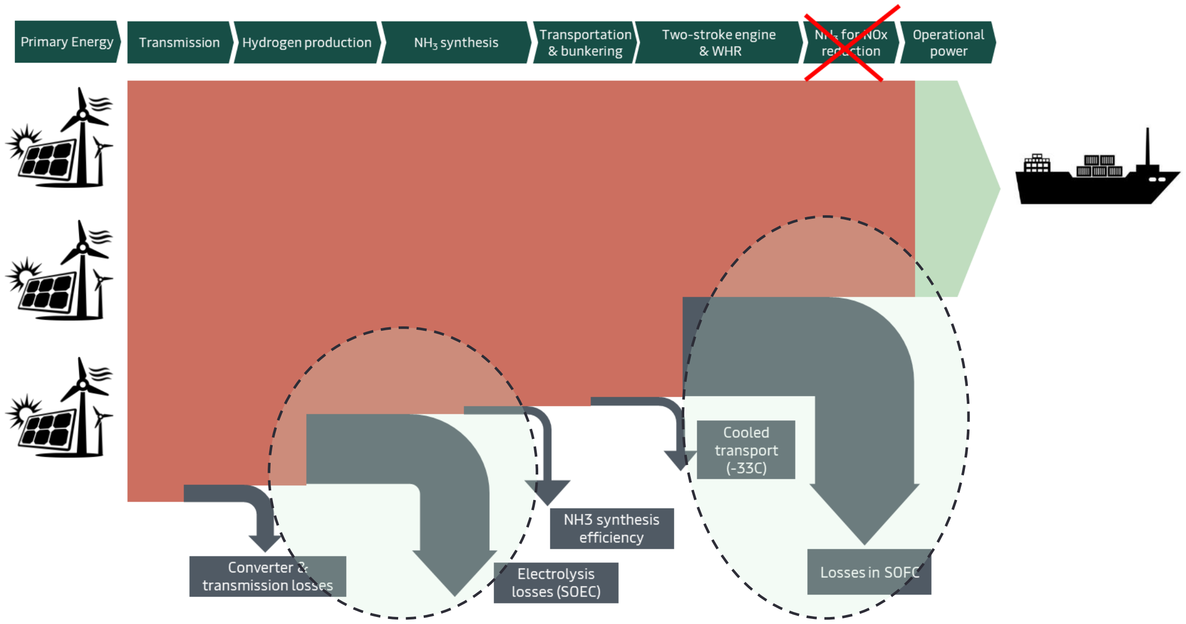
For same Power-to-X-to-Power path:

Individual links in the chain contribute to major end-to-end impact opportunity.

Low-temperature electrolyzer and ICE



High-temperature electrolyzer and SOFC



illustrative

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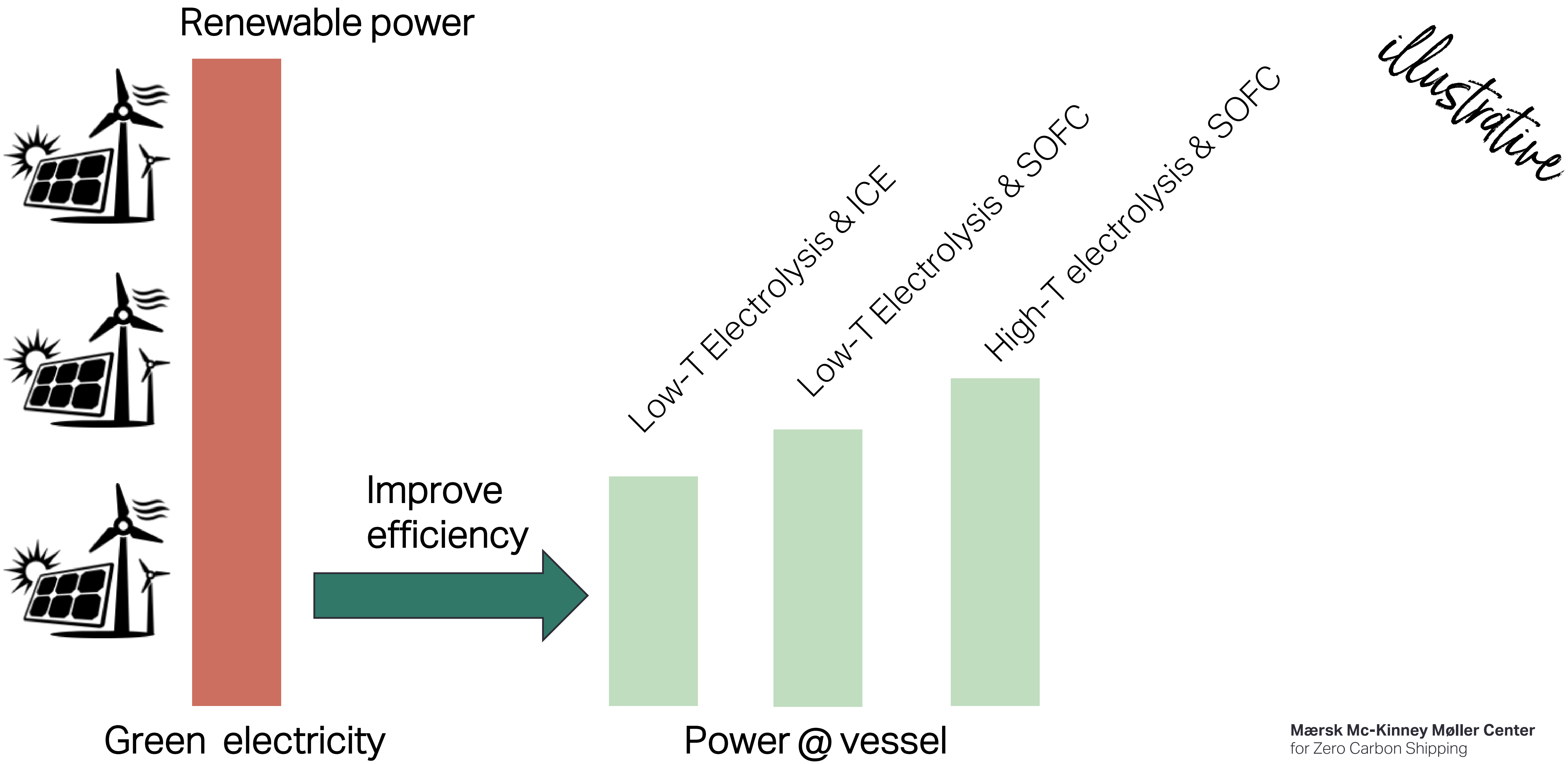
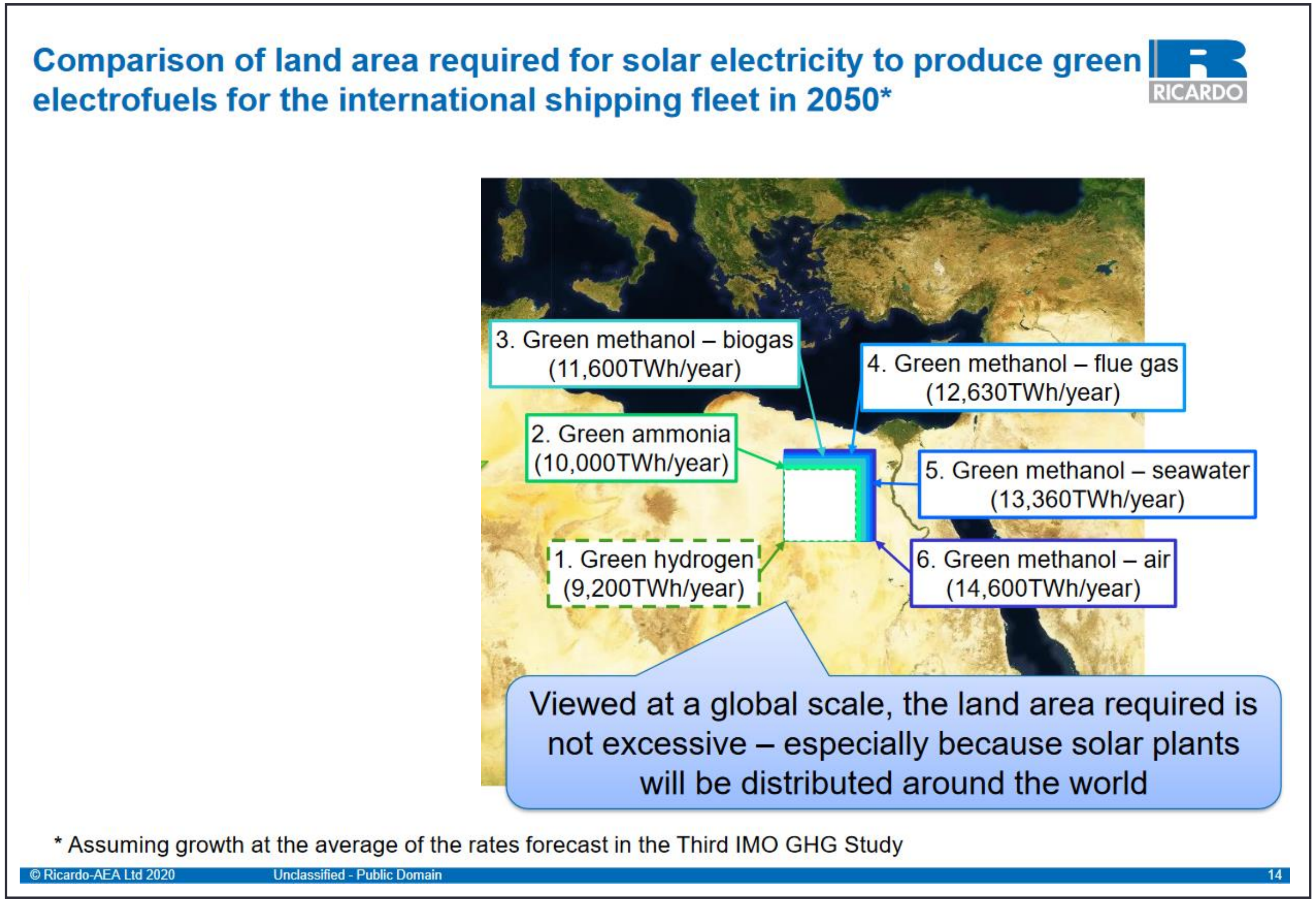
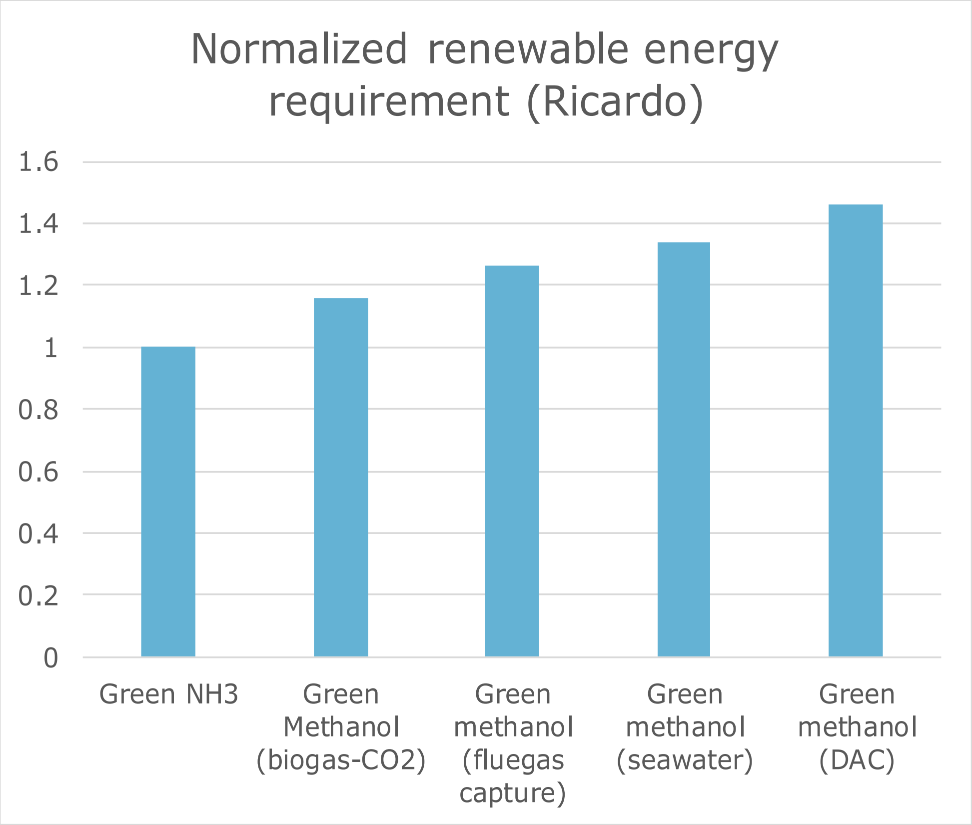
With future technology "bricks", we could approach 45% RTE(*)



Choice of X? Estimation from Ricardo on eFuels for shipping by 2050

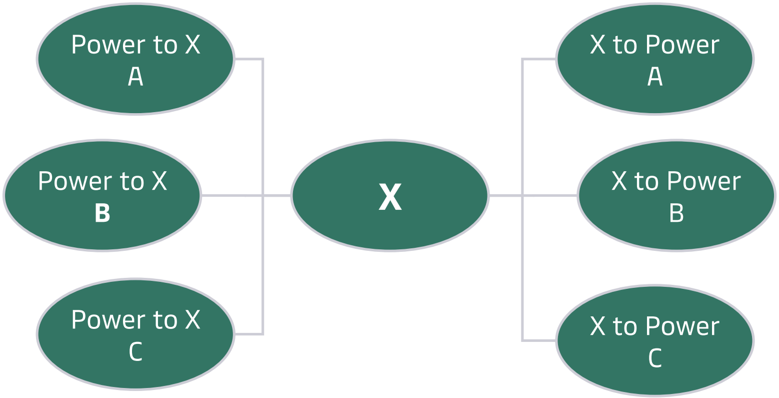


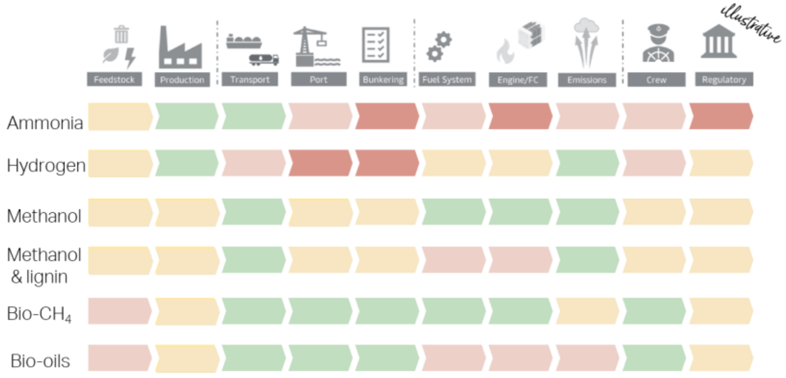


- Cost of CO_2 (= energy for capture) is critical for the methanol pathway
- Co-location of H2 and biogenic CO_2 ?
- Long-distance transport of 'hydrogen energy' is more feasible as ammonia(*)

(*) https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

Systemic overview needed





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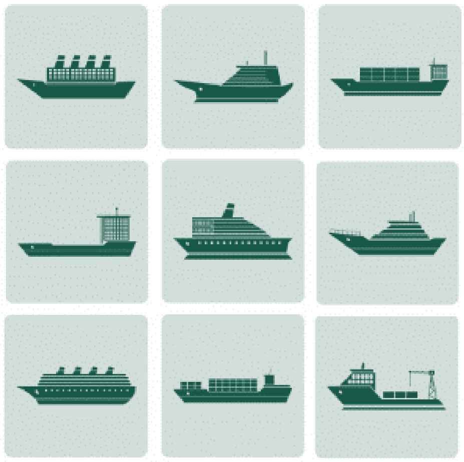

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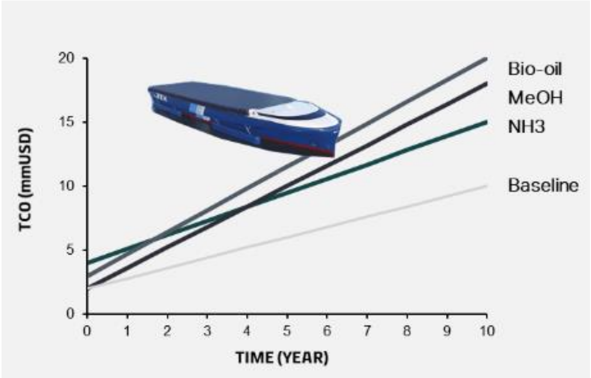

Generating a clear understanding of the pathways and transition roadmaps

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End-to-end efficiency – our obligation to search & find …

The technologies and pathways enabled and applied have a massive impact on the total required scale of renewable energy production for shipping.

Example of global impact:
A 10% improvement in "wind-to-wake" efficiency can reduce by ~20,000 the number of 10 MW off-shore wind turbines for maritime P2X