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

Dr. Tue Johannessen
January 30th, 2020
Recap (I) from the morning presentation: All the way in 2050

Our challenge for going #AllTheWay:
A transition from annual consumption of approx. 10 million tons of fossil fuel to net-zero operations

Present in
130+
Countries

Revenues\(^1\) of
39,019
USD million

Profits\(^1\)
220
USD million

~70,000 employees
~750 vessels
~70 terminals

https://youtu.be/2XBO_ZULmAk
Recap (II): Getting to zero requires new fuel pathways

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”.

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

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

24 October 2019
Sustainability

LR and Maersk joint study finds that to develop zero carbon ready ships, shipowners must invest for fuel flexibility, and follow the need for policy interventions and fundamental changes to incentives scheme for shipping.
For various fuel pathways:
A holistic view on the entire energy value chain is needed

Note: Solely for illustration purposes

Cost driver
Low/medium TRL
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 (H₂) → methanol synthesis via ‘green’ CO₂.
- 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?
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”

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
**Power-to-X:**

**From low to high power**
**From high to low raw material input**

<table>
<thead>
<tr>
<th>Quantity / quality of bio raw material</th>
<th>Renewable power input</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional biofuel:</strong> Bio-based raw material with limited power input needed</td>
<td></td>
</tr>
<tr>
<td><strong>Bio-to-oil (biomass/waste):</strong> Pyrolysis/gasification, HTL, ... and some renewable power (water -&gt; H₂) for fuel upgrade</td>
<td></td>
</tr>
<tr>
<td><strong>Biogas: Convert bio-CH₄ to MeOH:</strong> Renewable power to help convert biomethane to MeOH</td>
<td></td>
</tr>
<tr>
<td><strong>Biogas: Methane &amp; CO₂ to MeOH:</strong> Renewable power (water -&gt; H₂) to upgrade the CH₄ &amp; CO₂ to MeOH</td>
<td></td>
</tr>
<tr>
<td><strong>(Bio-)CO₂ to MeOH:</strong> CO₂–CC from biomass combustion / bio-gas CO₂; renewable power (water -&gt; H₂) to upgrade the CO₂</td>
<td></td>
</tr>
<tr>
<td><strong>“Air” to methanol:</strong> Green electricity, Direct Air Capture (CO₂) and water (electrolysis)</td>
<td></td>
</tr>
<tr>
<td><strong>Green ammonium:</strong> Green electricity, air (N₂) and water (electrolysis)</td>
<td></td>
</tr>
<tr>
<td><strong>Green hydrogen:</strong> Green electricity and water (electrolysis)</td>
<td></td>
</tr>
</tbody>
</table>

Decoupled from biomass market
Zero CO₂ release; no CO₂ input

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

(*) 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

Power2Ammonia
Production of ammonia synthesis gas in an SOEC core
- 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: NH₃ as SOEC Fuel
  - WP4: Design of Demo and Full Scale NH₃ plant
  - WP5: Project management and Dissemination
- Partners:
  - Vestas
  - EUDP
  - Sintex Denmark

CH₂ + CO₂ + 3H₂O + El → 2CH₄ + H₂O + 2O₂

<table>
<thead>
<tr>
<th></th>
<th>CH₂</th>
<th>CO₂</th>
<th>H₂</th>
<th>N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ [%]</td>
<td>42</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product gas</td>
<td>97.69</td>
<td>0.00</td>
<td>0.95</td>
<td>1.36</td>
</tr>
</tbody>
</table>

€10.7 million from the Danish Energy Agency’s funds for energy storage

Biogas upgrade with green H₂: Biomethane

Power2Gas
Biogas upgrade using H₂ from SOEC

Biogas (60% CH₄ and 40% CO₂) upgraded to Substitute Natural Gas (SNG) via SOEC and methanation of CO₂ in biogas

CH₄ + CO₂ + 3H₂O + El → 2CH₄ + H₂O + 2O₂

www.nextgenroadfuels.eu
The high-level view: Fuel conversion “Lego” bricks

Blue/Green fuel synthesis

- Green E
- H₂
- H₂O
- Biomass

Green E → H₂ → eFuel1 → H₂-Carrier(s) → Fuel-to-power conversion → eFuel2 → H₂-Carrier(s)

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

EATS: Exhaust After-Treatment Solution
Hybridization is likely to be an important “link” between new fuels and energy efficiency improvements.

**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 CO₂
Reduction of CO₂ emissions
Cost reductions

**”Tomorrow”**: Reduced consumption of a costly future fuel
Reduction of CO₂ emissions
Cost reductions
The high-level view: Fuel production “Lego” bricks

Blue/Green fuel synthesis

H₂-Carrier(s)

H₂

Green E

H₂O

Biomass

H₂-Carrier(s)

eFuel1 ?
eFuel2 ?

Fuel-to-power conversion

Additive

Main Engine

Aux engine

Hybridization / generator

Safety

Monitoring & compliance

Integration & controls

Power @ shaft

EATS: Exhaust After-Treatment Solution

Example: P2X:

Hydrogen production is an “always needed” first step.

Electrolysis (CAPEX & OPEX): key cost drivers

Renewable power is a bottleneck

Electrolysis (CAPEX & OPEX): key cost drivers

Renewable energy is a bottleneck

Cycle for hydrogen carrier

MeOH, DME, e/bioLNG: “C”

Ammonia: “N”
Total efficiency: A function of choice of fuel, selection of components and clever integration.

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

When we combust fossil fuels, we create highly disordered (diluted) CO₂ in the Earth’s atmosphere: 410 ppm CO₂ in 4,200,000,000 km³ air

If we need to go carbon negative (tipping point?), we have to capture CO₂ 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 CO₂ (& low Nox)
  \[ 2 \text{NH}_3 + 1\frac{1}{2} \text{O}_2 \rightarrow 2 \text{N}_2 + 3 \text{H}_2\text{O} \]
- and NH₃ made it again from hydrogen and access to nitrogen:
  \[ \text{N}_2 + 3\text{H}_2 \rightarrow 2 \text{NH}_3 \]
- “N” Round-trip: 78% of atmosphere is N₂ - not 410 ppm (0.041%)
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 CO₂ 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 N₂ than CO₂.
- Beneficial for PFP (Power-to-Fuel-to-Power) for NH₃.

Future outlook:
Solid Oxide Electrolyzers (green H₂) can exceed 90% efficiency in power-to-H₂.
Ammonia conversion in Solid Oxide Fuel Cells can exceed 60% efficiency.
Combined green ammonia fuel path holds potential to get close to 50% PFP

### Table 2

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Separation [a]</th>
<th>CO₂ transport [b]</th>
<th>PFPflue[c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>methane</td>
<td>0.037</td>
<td>0.006</td>
<td>31%</td>
</tr>
<tr>
<td>MeOH</td>
<td>0.043</td>
<td>0.007</td>
<td>32%</td>
</tr>
<tr>
<td>DME</td>
<td>0.045</td>
<td>0.007</td>
<td>28%</td>
</tr>
<tr>
<td>ammonia</td>
<td>0.008</td>
<td>–</td>
<td>35%</td>
</tr>
</tbody>
</table>

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

Data from: [https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5089635/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5089635/)
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 N₂O)
  - On-board fuel storage/management system / safety
  - Solid Oxide Fuel Cell for aux. “engine”?

- **Regulation:**
  - Quality of new fuel
  - CO₂ verification “stamp”
  - Safety – bunker fuel and vessel approvals

(*) Not complete list
Synergies between bio-fuels and Power-to-X: Mitigate the potential limitation of bio-carbon

Pilot fuel: Conventional liquid bio-fuels (2-10%)  
Bio-to-oil (biomass/waste): Pyrolysis, HTL, … and some renewable power (water → H₂) for fuel upgrade

Main fuel: Low flash-point “eFuels” (NH₃, CH₃OH, bio-CH₄)  
- Biogas: Upgrade CO₂ to MeOH: Renewable power (water → H₂) to upgrade the CO₂-fraction of biogas to methanol
- Biogas: Methane & CO₂ to MeOH: Renewable power (water → H₂) to upgrade the CH₄ & CO₂ to MeOH
- Bio-CO₂ to MeOH: CD₂→CC from biomass combustion; renewable power (water → H₂) to upgrade the CO₂
- “Air” to methanol: Green hydrogen for ammonia synthesis
  - Green ammonia: Green electricity, air (N₂) and water (electrolysis)
  - Green hydrogen: Green electricity and water (electrolysis)

Decoupled from biomass market  
Zero CO₂ release; no CO₂ input

The general concern about the availability of biofuels for transportation, aviation and shipping can be mitigated if shipping only needs the pilot fuel.
When will cost of renewable power become “low enough”?
How do we make it through a transition period with reduced CO₂ impact?
Input for discussion: LNG as a bridge-fuel towards IMO 2050 for the industry in general?

Prospects for Energy and Maritime Transport in the Nordic Region / T. Johannessen; 26/2-2020

A temporary LNG era would still have massive CO₂ emissions

Alternatives?

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

Source: DNV-GL 2050 scenario
NG as energy source for fuel transition with central CO₂ “control”: NG → hydrogen & CCS → Blue ammonia?

Blue NH₃: The area “covers” 4500 million ton CO₂

Cost of centralized CO₂ capture (solve it now): ~ 50 $/ton CO₂ (probably less)

Cost of Direct Air Capture (solve the problem “later”): ~ 130 $/ton CO₂ (likely more)

Magnitude of upfront CO₂ “value”: 360 billion $
A successful transition phase through strong technical solutions, high efficiency and customer demand for green solutions.

Transition period: Cost of new fuels vs. customer demand

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

ECO Delivery – Now there is choice

New fuels for net-zero operation

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.

First commercially viable carbon-neutral vessel in operation

High efficiency

Maersk to pilot a battery system to improve power production

All efficiency improvements help to reduce consumption of ANY fuel

Growing market demand?

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.

First commercially viable carbon-neutral vessel in operation

High efficiency

Maersk to pilot a battery system to improve power production

All efficiency improvements help to reduce consumption of ANY fuel

Growing market demand?
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