OVERVIEW ON PTX OPTIONS STUDIED IN NCE AND THEIR GLOBAL POTENTIAL BASED ON HYBRID PV-WIND POWER PLANTS

Mahdi Fasihi, Dmitrii Bogdanov and Christian Breyer

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Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants

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Agenda

- Motivation
- Methodology and Data
- Results (Annual Basis Model)
- Results (Hourly Model)
- Summary
Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants

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Motivation

- Natural gas, LNG and diesel
  - increasing demand
  - diminishing resources
  - emissions

- Methanol (MeOH)
  - increasing demand
  - feedstock for chemical industry
  - alternative fuel

- Dimethyl ether (DME)
  - an attractive substitute for diesel
  - high cetane number
  - soot-free combustion

- Ammonia
  - fossil based feedstock for chemicals and fertilizer for food production
  - 1% of total global GHG emissions

- Liquefied hydrogen (LH₂)
  - Potential fuel for marine sector

- Fossil-based fuels, global warming, COP21 and national targets
  - to keep global temperatures "well below" 2°C above pre-industrial times
  - "endeavor to limit" them even more, to 1.5°C
  - emissions under a sustainable level

- RE available, but energy system transformation is challenging
  - fluctuating RE and energy storage
  - 100% direct electrification impossible
    - mobility sector
    - chemicals

Natural gas, LNG and diesel:
- Increasing demand
- Diminishing resources
- Emissions

Methanol (MeOH):
- Increasing demand
- Feedstock for chemical industry
- Alternative fuel

Dimethyl ether (DME):
- An attractive substitute for diesel
- High cetane number
- Soot-free combustion

Ammonia:
- Fossil based feedstock for chemicals and fertilizer for food production
- 1% of total global GHG emissions

Liquefied hydrogen (LH₂):
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Fossil-based fuels, global warming, COP21 and national targets:
- To keep global temperatures "well below" 2°C above pre-industrial times
- "Endeavor to limit" them even more, to 1.5°C
- Emissions under a sustainable level

RE available, but energy system transformation is challenging:
- Fluctuating RE and energy storage
- 100% direct electrification impossible
  - Mobility sector
  - Chemicals

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Motivation: RE-fuels

- Fossil-based fuels can be generated synthetically from sustainable sources of carbon and electricity
  - PtG, PtMeOH and PtDME, emerging technologies
  - PtNH3, LNG and Gas-to-Liquids in commercial phase
  - Power-to-Liquids technology ready for market

- RE-fuels and chemicals
  - non-diminishing resources
  - costs stable or declining
  - no costs for harmful emissions (CO₂, etc.)
  - drop in fuels for available infrastructure
  - energy storage
  - a step towards fuel security

- Sites with excellent solar and wind energy can be used to power PtX systems.

- Cost and generation potential in 2030?
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Methodology
RE-PtG-LNG Value Chain

Key insights:
- Substitution of the fossil hydrocarbon value chain by a RE basis
- Utilisation of downstream fossil infrastructure
- Integrated heating system
- Water recycling

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Results
PtG-LNG Value Chain Energy Flow & Mass Balance

Power-to-Gas--LNG (2030)

- PtG eff.: 64%
- LNG value chain eff.: 90%
- Overall efficiency: 57%

- Oxygen available for potential market

Almost all water demand supplied by DAC & methanation

87% of energy demand supplied by excess heat

Oxygen available for potential market

- RE [kWh]
- H2 [kWh]
- Water [kg]
- CO2 [kg]
- HT Heat [kWh]
- O2 [kg]
- LNG [kWh]
- SNG [kWh]
- LT Heat [kWh]
- Seawater [kg]
- Water Loss [kg]
- Heat [kWh]
- Heat Loss [kWh]
- Carbon loss [kg]
- Extra Heat [kWh]

*LT: low temperature  *HT: high temperature  *WS: water storage  *SWRO: Sea Water Reverse Osmosis

- Heat Exchanger
  - Heat: 170 kWh
  - Heat Loss: 24 kWh
  - Extra Heat: 6 kWh

- Electrolysis
  - RE: 26 kWh
  - RE: 974 kWh
  - Seawater 13 kg
  - SWRO 6 kg

- CO2 DAC
  - CO2: 113 kg
  - Heat: 170 kWh
  - Heat Loss: 78 kWh
  - O2: 165 kg
  - Water Loss: 4 kg

- Methanation
  - 93 kg
  - 91 kg
  - SNG: 638 kWh

- Liquefaction
  - LNG: 583 kWh
  - Shipping
  - LNG: 581 kWh
  - Regasification
  - SNG: 573 kWh

Almost all water demand supplied by DAC & methanation

87% of energy demand supplied by excess heat

Oxygen available for potential market
Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants

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Results
PtG-GtL Energy Flow & Mass Balance

- PtG eff.: 64%
- GtL eff.: 59%
- Overall efficiency: 38%

- Oxygen available for GtL plant and potential market
- High temperature heat from FT plant available for market

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Key insights:
- Substitution of the fossil hydrocarbon value chain by a RE basis
- Utilisation of downstream fossil infrastructure
- Integrated heating system
- Water recycling

Methodology
RE-PtL Value Chain

- Dashed lines represent fluctuating flows
- Continuous lines represent steady flows

Diesel; 60%
Jet fuel/kerosene; 25%
Naphtha; 15%

1 barrel of PtL products (vol%)

Naphtha: 15%
Jet fuel/kerosene: 25%
Diesel: 60%

H₂
Results

PtL Energy Flow & Mass Balance

- PtH2 eff.: 84%
- H2tL eff.: 65%
- Overall efficiency: 53%
- Oxygen available for potential market
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Methodology
RE-PtMeOH/DME Value Chain

- Dashed lines represent fluctuating flows
- Continuous lines represent steady flows

Key insights:
- Substitution of the fossil-based chemicals value chain by a RE basis
- Integrated heating system
- Two electricity storage options

With CO₂ and hydrogen storage, synthetic plant (SP) works on baseload
In the shortage of RE, the baseload electricity demand by SP could be supplied by batteries or a PtG-GtP unit
Results
PtMeOH/DME Energy Flow & Mass Balance

- Electrolyser is the main electricity consumer
- PtH₂ eff.: 84% (HHV)
- PtMeOH overall efficiency eff.: 52.5% (LHV)
- PtDME overall efficiency eff.: 54.3% (LHV)
- Oxygen available for sale on respective O₂ markets
- Heat pump decreases direct electricity consumption
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**Methodology**

**RE-PtNH₃ Value Chain**

Key insights:
- Substitution of fossil-based ammonia value chain by a RE basis
- ASU and ammonia synthesis plants are coupled and run on baseload
- Two storage options for hydrogen (cavern & buffer)
- Batteries before and after transmission line
- PtG-GtP as a second option for maintaining partial baseload electricity demand (not in the figure)

Ammonia synthesis net reaction:
\[ \text{N}_2 + 3\text{H}_2 \rightarrow \text{NH}_3 + \text{heat} \]

- Dashed lines represent fluctuating flows
- Continuous lines represent steady flows

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Results
PtNH₃ Energy Flow & Mass Balance

- Electrolyser is the main electricity consumer
- PtH₂ eff.: 84% (HHV)
- PtNH₃ overall eff.: 65.5% (HHV)
- Oxygen available for sale on respective O₂ markets
- Excess utilisable heat available from electrolyser and synthesis plant

RE: Renewable Electricity  LT: low temperature  SWRO: Sea Water Reverse Osmosis
Results
PtLH₂ Energy Flow & Mass Balance (Preliminary Study)

- H₂ liquefaction decreases the volume by 788 times.

- Plant's size has a great impact on capex. Sizing exponents for liquid hydrogen plants range from 0.6-0.7.

- Hydrogen compression is an initial step in H₂ liquefaction. Thus availability of high pressure hydrogen would decrease the energy demand and capex of liquefaction process. For comparison, hydrogen compression needs 10 times more energy than methane compression.

- According to PRAXAIR, for hydrogen liquefaction, it is possible to reduce from today's energy usage of 10 kWh/kg\textsubscript{LH₂} to around 5 kWh/kg\textsubscript{LH₂}. This would also halve the compressors and motors in the plant, which will also lead to cheaper plants.

- For an energy AND cost optimised case, 6 kWh/kg\textsubscript{H₂} electricity demand for hydrogen liquefaction has been projected (Cardella 2017), which is used in our model.
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- Summary
1) Patagonia as the case study
   - Equal installed capacities of PV single-axis tracking and Wind
   - 7200 annual cumulative FLh with 10% critical overlap: 6480 net FLh
   - All PtX plants at coast
   - No storage option or transmission line cost included
   - Synthesis units (except PtG) run on baseload

2) Japan as the target market for RE-LNG
   - Regasification Plant
   - Patagonia – Japan marine distance: 17,500 km

3) EU as the target market for RE-diesel and RE-chemicals
   - Patagonia – Rotterdam marine distance: 13,500 km
Results

Cost of Power-to-Fuel/Chemical Options

- SNG and PtG-GtL are the cheapest and the most expensive synthetic fuel, respectively.
- The production cost of RE-diesel, RE-methanol and RE-DME are close to each other, however the fuel-parity (cost competitiveness) depends on their respective market price and CO₂ emission cost.
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Hourly Basis Model

- Optimised configuration of PV (fixed tilted and single-axis tracking), wind power, storage options (battery, PtG-GtP, and gas (H₂, CO₂ and SNG) storage), electricity transmission lines and PtX plants facilities (electrolyser, CO₂ DAC, desalination and synthesis plants), based on an hourly potential of solar and wind in a 0.45° × 0.45° spatial resolution for the least cost fuel or feedstock production.

- The datasets for solar irradiation components and wind speed are provided from NASA and reprocessed by DLR. Feed-in time series of wind power plants are calculated for standard 3 MW wind turbines (E-101) with hub height conditions of 150 meters.

![Weighed average PV and Wind hourly generation profile for Iran](image)
Results

Full load hours

- sites with cumulative FLh higher than 3000 have been taken into account as they have the lowest LCOE
- PV single-axis tracking provides 200-600 higher FLh than PV fixed-tilted
- wind FLh are much higher than PV FLh due to 24h harvesting
- Patagonia, Somalia and Tibet have the highest cumulative FLh globally
Results
Levelised Cost of Electricity (LCOE)

- sites of high FLh of PV or Wind plants have the lowest LCOE
- LCOE of PV single-axis tracking is about 4-5 €/MWh cheaper than LCOE of PV fixed tilted, and even more relevant more FLh (20-30%) on a least cost basis
- Atacama Desert reaches PV LCOE of close to 15-17 €/MWh
- Patagonia reaches wind LCOE of close to 19-20 €/MWh
Results
LCOE for Cost-optimised PtX Systems

• optimal combination of PV and Wind for hybrid PV-Wind plants to achieve an optimal combination of LCOE and FLh for downstream PtX plants

• No fixed tilted PV would be installed, while PV-Wind ratio is even in most regions

• top sites in the world may reach hybrid PV-Wind LCOE of 17-20 €/MWh

• Long distance power lines may be too expensive for harvesting electricity far away from the cost

• top sites in the world are usually located at coast and can deliver electricity to PtX plants at costs of about 25-30 €/MWh
Results
The share of PV and batteries from 2030 to 2040

- in Africa, the installed capacity of batteries would be up to 60% of installed capacity of hybrid PV-wind plant by 2040.
- strong increasing relevance of battery technology from 2030 to 2040
Results

Sources of Additional LCOE

- distance to coast and consequently electricity transmission cost are determinative factors which can block a fuel export case
- for long distances to the coast with a high share of PV, such as Tibet, more battery installations, balance the system for a lower electricity transmission cost
- excess electricity due to overlap and curtailments (to optimise the capacity of transmission lines and PtX plants)
Results

Levelised Cost of Fuels (LCOF)

- LCOF as a function of LCOE and FLh of plants’ components
- In 2030, top sites in the world reach LCOF of 70 – 80 €/MWh (0.68 - 0.77 €/l for diesel and 27.4 - 31.3 USD/MMBtu for SNG)
- LNG value chain adds 15-20 €/MWh to delivered SNG cost
- Regions not so far from coast are generally a better place due to lower electricity transmission cost
Results
Levelised Cost of Fuels (LCOF)

- Patagonia, Somalia, Western Sahara and the coasts of Australia and Brazil produce the cheapest methanol within the range of 400-600 €/tonne.
- DME production cost is about 200-300 €/tonne more expensive for each site, depending on the corresponding LCOE.
- The difference in ammonia production cost at coast and remote areas is smaller than the methanol case, due to lower transmission line cost assumption.
Results
Optimised PtX Production Potential

- maximum 10% of the land allowed to be used for PV and Wind each
- global diesel demand in 2030 would be about 20,000 TWh\text{diesel}, and for that generation of 33,000 TWh\text{liquid fuels} is required. Thus, global diesel demand can be met at costs less than 93 €/MWh\text{diesel} (0.87 €/l\text{diesel})
- potential of about 50,000 TWh\text{SNG} for cost less than 100 €/MWh\text{fuel} (39.1 USD/MMBtu) in 2030
- With today’s prices, large scale production of SNG or SLF would not be cost competitive with conventional fuels even in the best scenario, in 2030.

LNG price in Japan: 102% of Brent crude oil price.
(Regasification cost included)

Diesel cost in EU: 119% of Brent crude oil price
Results

Optimised PtX Production Potential

- The generation potential is much more than the demand.
- RE-ammonia is likely to reach the market prices faster. However, RE-methanol is not also off the chart.
- Profit from oxygen or emission cost for conventional products could tighten the gap between conventional and RE-feedstock prices.

![Graphs showing industrial cost curves for RE-MeOH/DME in 2030 and wholesale ammonia prices and Brent oil.](image-url)
Results
Case study – the Maghreb region & Finland

RE-Synthetic Fuels (SF) production cost curve in the Maghreb region countries and Finland for cost year 2030

Ratio of PV to hybrid PV-Wind plant installed capacity for PIK, for cost year 2030

Ratio of PV to hybrid PV-Wind plant installed capacity for PIK, for cost year 2040
Ongoing Projects

- Master’s thesis on Direct Air Capture (DAC)
  - literature review and techno-economic analysis

- Bachelor’s thesis on H₂, N₂ and CO₂ storage (cavern, buffer) and compressor
  - literature review
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Publications

Journals


Conferences

- Fasihi M., Bogdanov D., Breyer Ch., 2015. Economics of global gas-to-liquids (GtL) fuels trading based on hybrid PV-Wind power plants, ISES Solar World Congress 2015, Daegu, Korea, November 8-12; http://bit.ly/2huFJIV
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Summary

- The idea is to use hybrid PV-Wind electricity to produce synthetic fuels or chemicals in the best sites in the world for export.

- RE-fuels are a non-diminishing fossil CO$_2$ free fuels, which will enable both fuel security and environmental compatibility.

- LNG downstream value chain is needed for delivering RE-SNG to far-off regions.

- With PtL, refinery products downstream value chain can be used.

- Methanol is one of the most widely used chemicals in industry with a growing potential as a fuel

- With no carbon-carbon bonds and high ecetane number, RE-DME could be a potential carbon neutral soot-free substitution for diesel

- CO$_2$ emission cost and by-products of the synthetic plants (O$_2$ & heat) can play a significant role in some regional cases to reach fuel parity

- Ammonia is the most likely studied feedstock to become cost competitive first, followed by methanol.
NEO-CARBON Energy project is one of the Tekes strategy research openings and the project is carried out in cooperation with Technical Research Centre of Finland VTT Ltd, Lappeenranta University of Technology (LUT) and University of Turku, Finland Futures Research Centre.

Thanks for your attention!
Key References


Further reading on power-to-water/ desalination

Backup
### Supplementary Material

#### key specifications in 2030

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<th>device</th>
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### Supplementary Material

**key specifications in 2030**

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<th>device</th>
<th>unit</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Methanation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capex</td>
<td>€/kW(_{SNG})</td>
<td>234</td>
</tr>
<tr>
<td>Opex fix</td>
<td>% of capex p.a.</td>
<td>4</td>
</tr>
<tr>
<td>Opex var</td>
<td>€/MWh(_{SNG})</td>
<td>0.0015</td>
</tr>
<tr>
<td>lifetime</td>
<td>year</td>
<td>30</td>
</tr>
<tr>
<td>eff.</td>
<td>%</td>
<td>77.8</td>
</tr>
</tbody>
</table>

| **Electrical Compression Heat Pump** | | |
| Capex                         | €/kWth        | 590  |
| Opex fix                      | % of capex p.a.| 0.34 |
| Opex_var                      | €/kWth        | 0.0017|
| lifetime                      | year          | 25   |
| COP                           | -             | 3    |
| **Hydrogen Storage**          | unit          | H\(_2\) cavern | H\(_2\) buffer |
| Capex (net, HHV)              | €/kWh\(_{H_2}\) | 0.3 | 12.7 |
| Opex fix                      | % of capex p.a.| 3   | 2    |
| lifetime                      | year          | 30  | 30   |
| Cycle eff.                    | %             | 100 | 100  |
| E/P ratio                     | -             | 369 | 12   |
| Self discharge                | %/h           | 0   | 0    |
Results
Hourly Basis Analysis: LCOE

- sites of high FLh of PV or Wind plants have the lowest LCOE
- LCOE of PV single-axis tracking is about 4 €/MWh cheaper than LCOE of PV fixed tilted, and even more relevant more FLh (20-30%) on a least cost basis
- In 2030, Atacama Desert reaches PV LCOE of close to 15-17 €/MWh and Patagonia reaches wind LCOE of close to 19-20 €/MWh
- sharper cost reduction for PV than for wind electricity from 2030 to 2040
Results
LCOE for cost-optimised PtX systems

- optimal combination of PV and Wind for hybrid PV-Wind plants to achieve an optimal combination of LCOE and FLh for downstream PtX plants
- share of PV increases significantly from 2030 to 2040 and will become the dominating technology in the Americas, Africa, Asia and Oceania, finally in almost all regions within 45°N/S around the equator
- top sites in the world reach hybrid PV-Wind LCOE of 17 - 20 €/MWh in 2030 and 13 – 16 €/MWh in 2040
- top sites in the world can deliver electricity to coast at a cost of about 30 €/MWh in 2030 and 25 €/MWh in 2040
- the extra cost is due to power transmission line and batteries cost, efficiency loss and excess electricity curtailments
- electricity generation and transmission for PtL system follows similar pattern, with small differences
Results
Levelised Cost of Fuels (LCOF)

- LCOF as a function of LCOE and FLh of plants’ components
- in 2030, top sites in the world reach LCOF of 70 – 80 €/MWh (0.68 - 0.77 €/l for diesel and 27.4 - 31.3 USD/MMBtu for SNG)
- in 2040, top sites in the world reach LCOF of 65 – 70 €/MWh (0.60 - 0.68 €/l for diesel and 25.4 – 27.4 USD/MMBtu for SNG)
- LNG value chain adds 15-20 €/MWh to delivered SNG cost
- regions not so far from coast are generally a better place due to lower electricity transmission cost
- more regions with attractive production cost in 2040