DTU

Marie Münster, Professor in energy system analysis
DTU Management
Nordic Energy, Nuuk 5/10 2022

# Innovation Needs for Sustainable Maritime Fuels

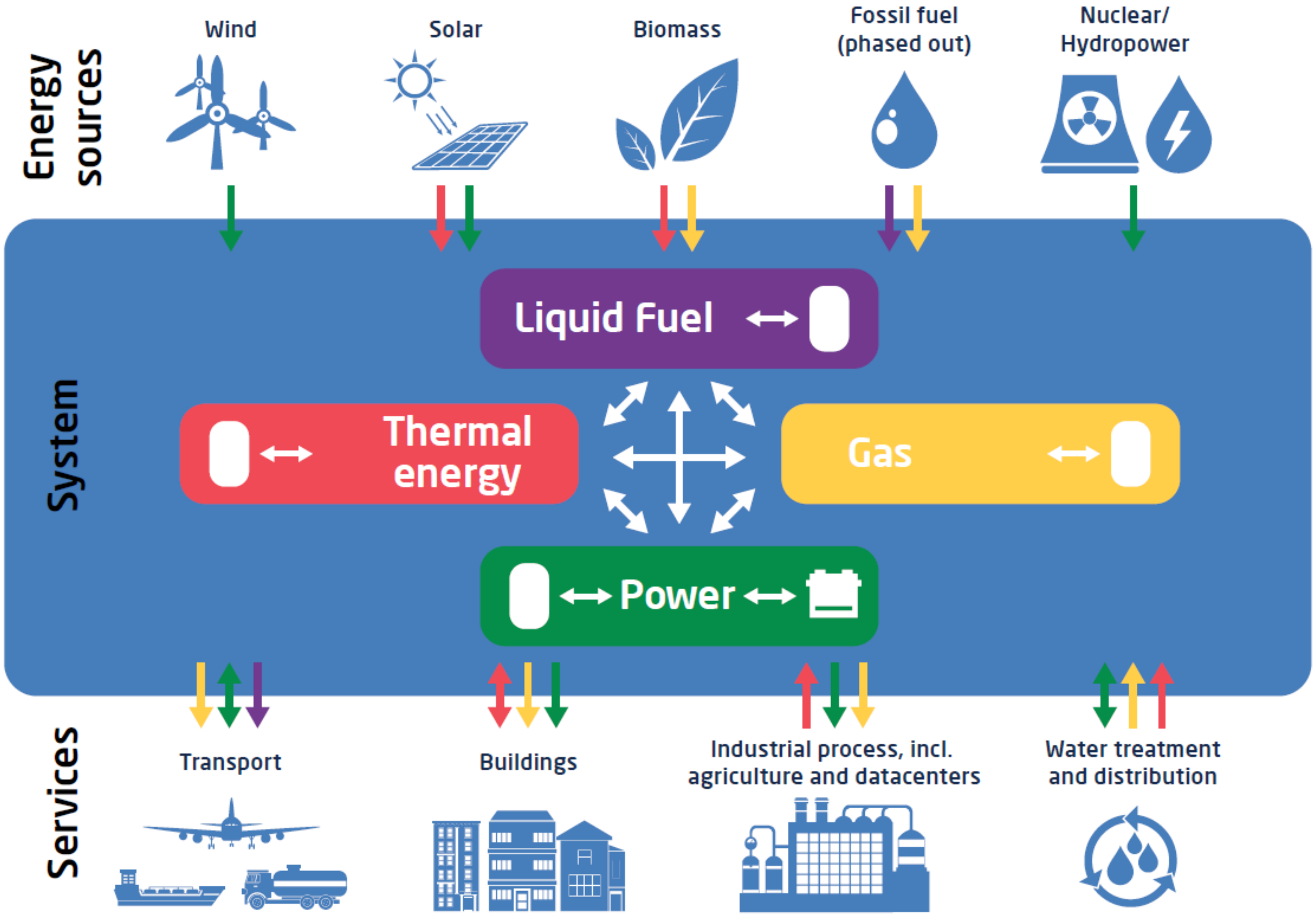
# Smart energy systems and sector coupling

**Power to other sectors**

- Direct and indirect electrification

**Others to power sector**

- Flexibility and storage




[UK Summary of DTU Sector Development report about Smart Energy Systems](). July 2020

# MarE-fuel

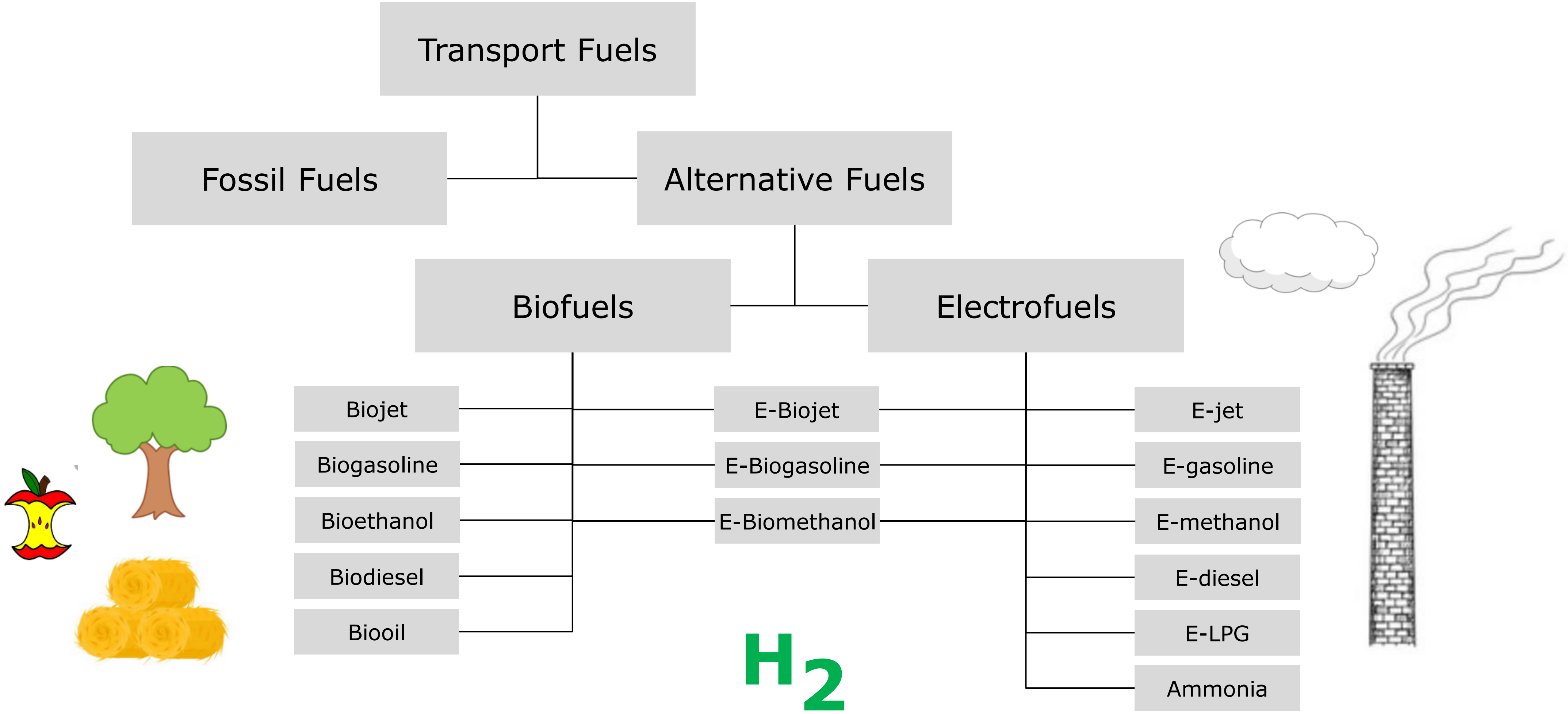
## Electro-fuels for long-range maritime transport

- Scope;
  - **Identify the most promising fuels and their synthesis routes for future sustainable shipping**
  - **Compare candidate fuels with respect to energy efficiency, emissions and cost to the operator**

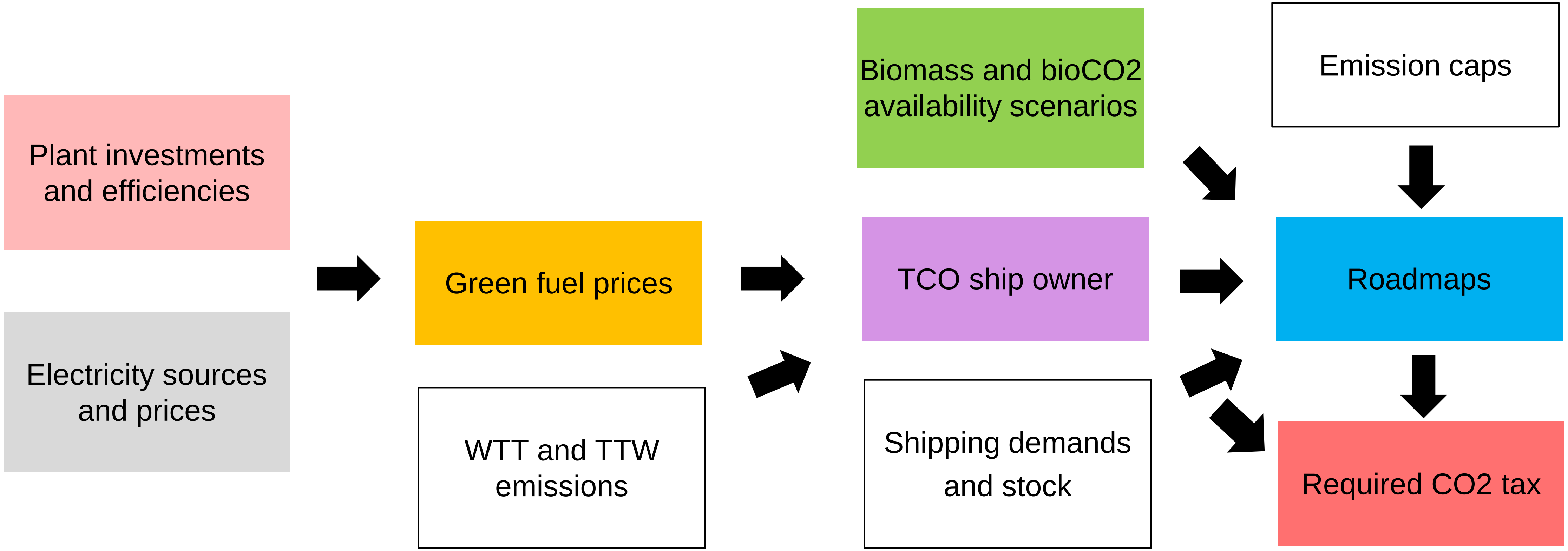
- Partners
  - » DTU Management, DTU Energy, DTU Mechanical Engineering
  - » Maersk Line A/S
  - » OMT, Odense Maritime Technology
  - » DFDS
  - » Copenhagen Economics and Torben A. Sørensen

https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# Fuel production



# Roadmaps for green fuels - an appetizer

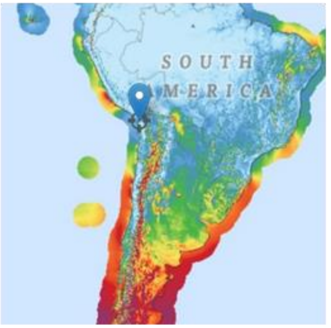


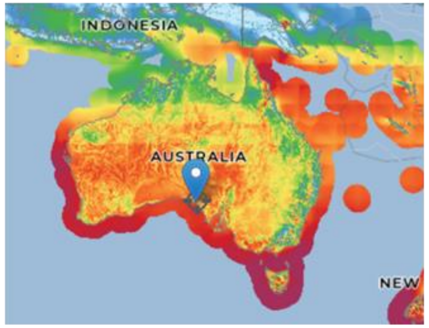

https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

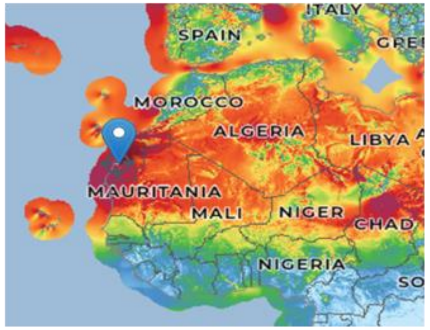
# Where ? 4 representatives weather profiles are tested

| | North Chile (Arica) | South Australia (Ceduna) | North Europe (Esbjerg) | North West Africa (Dakhla) |
|---|---|---|---|---|
| | LOW wind<br>EXTREMELY HIGH sun | HIGH wind<br>HIGH sun | VERY HIGH wind<br>LOW sun | VERY HIGH wind<br>VERY HIGH sun |

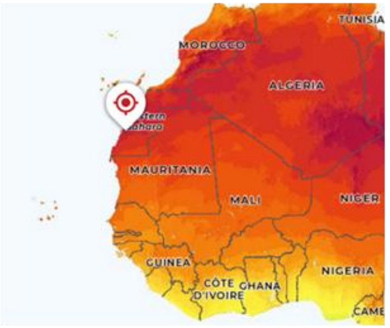
**Wind ressource**





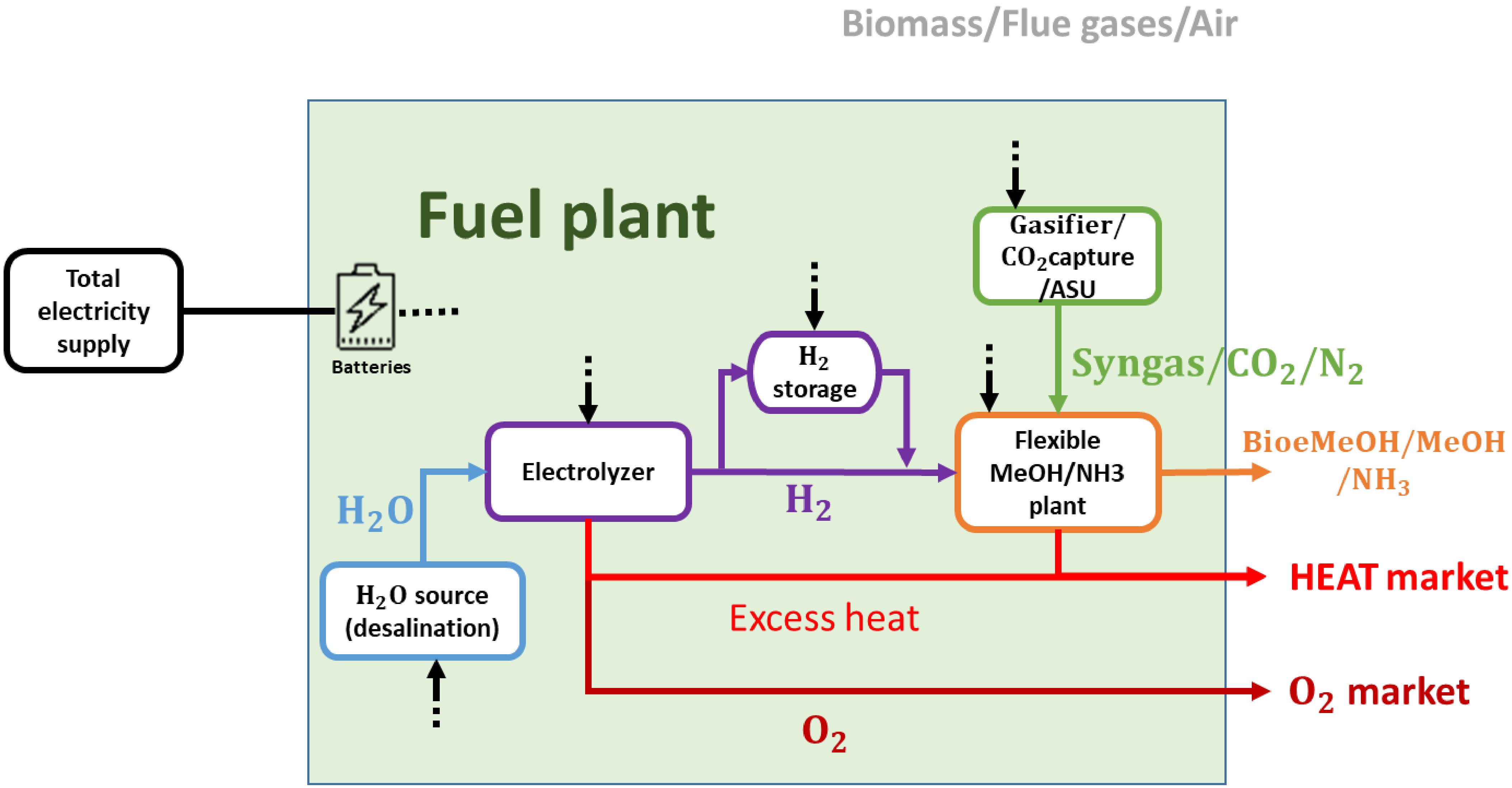



**Solar ressource**



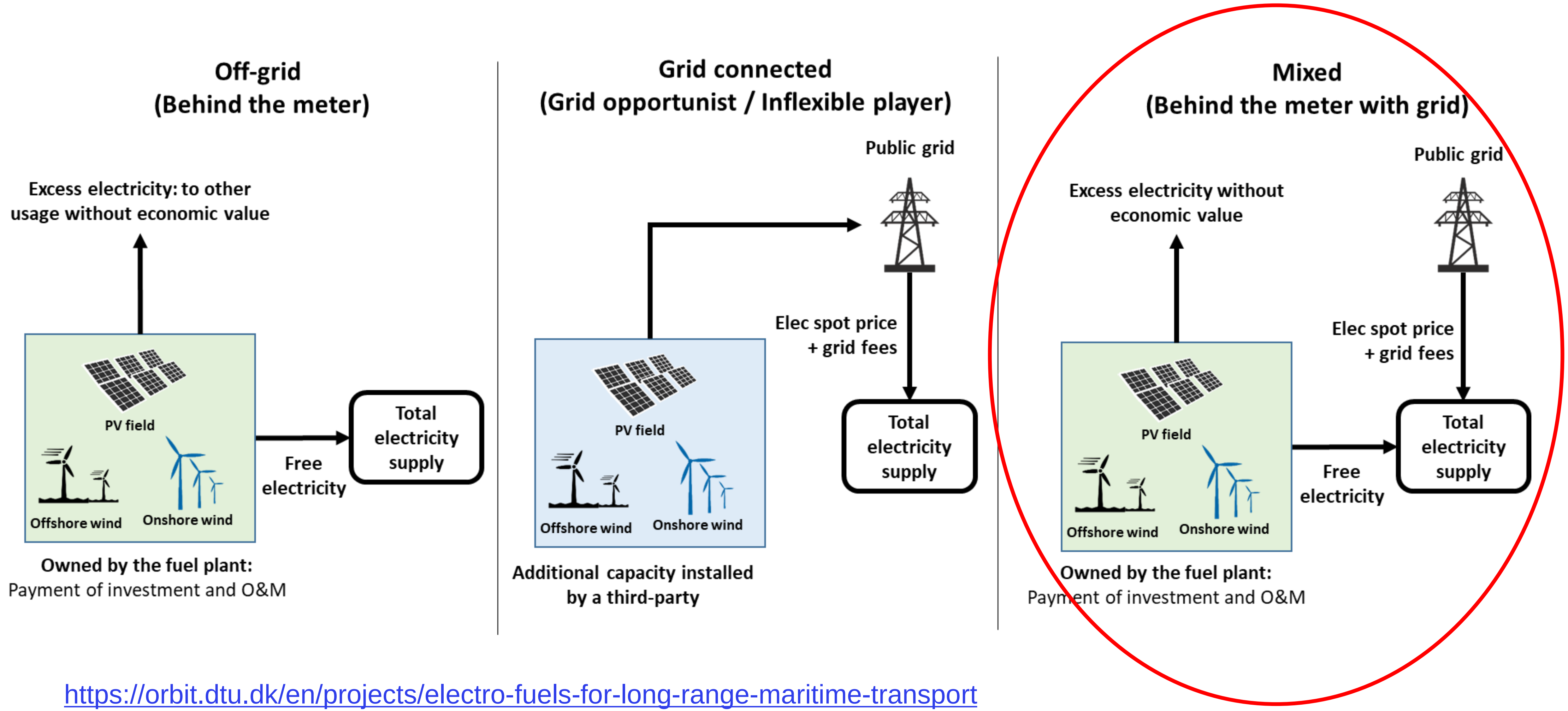

https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# Fuel plant system



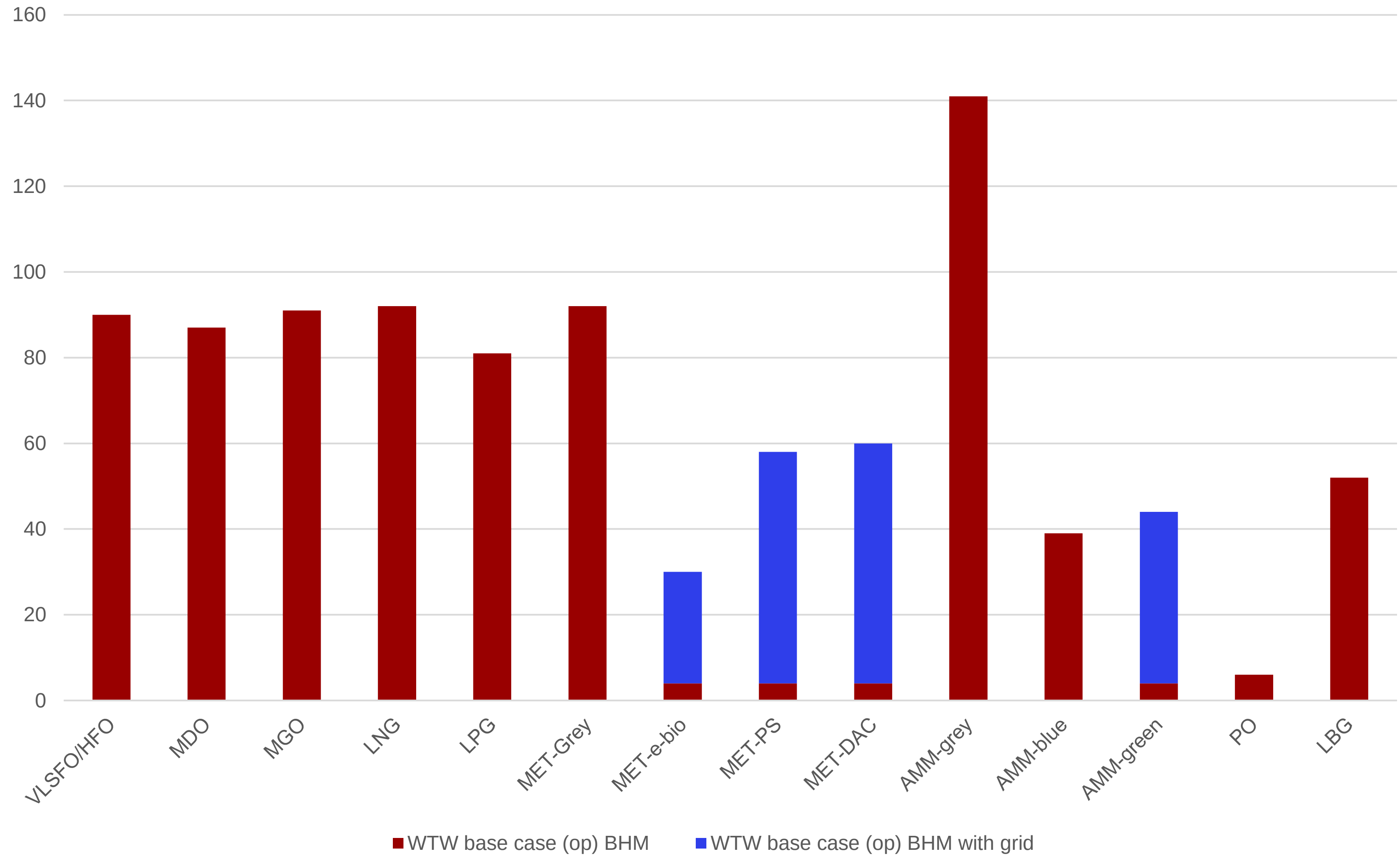

https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# How ? 4 differents power supply configurations are tested



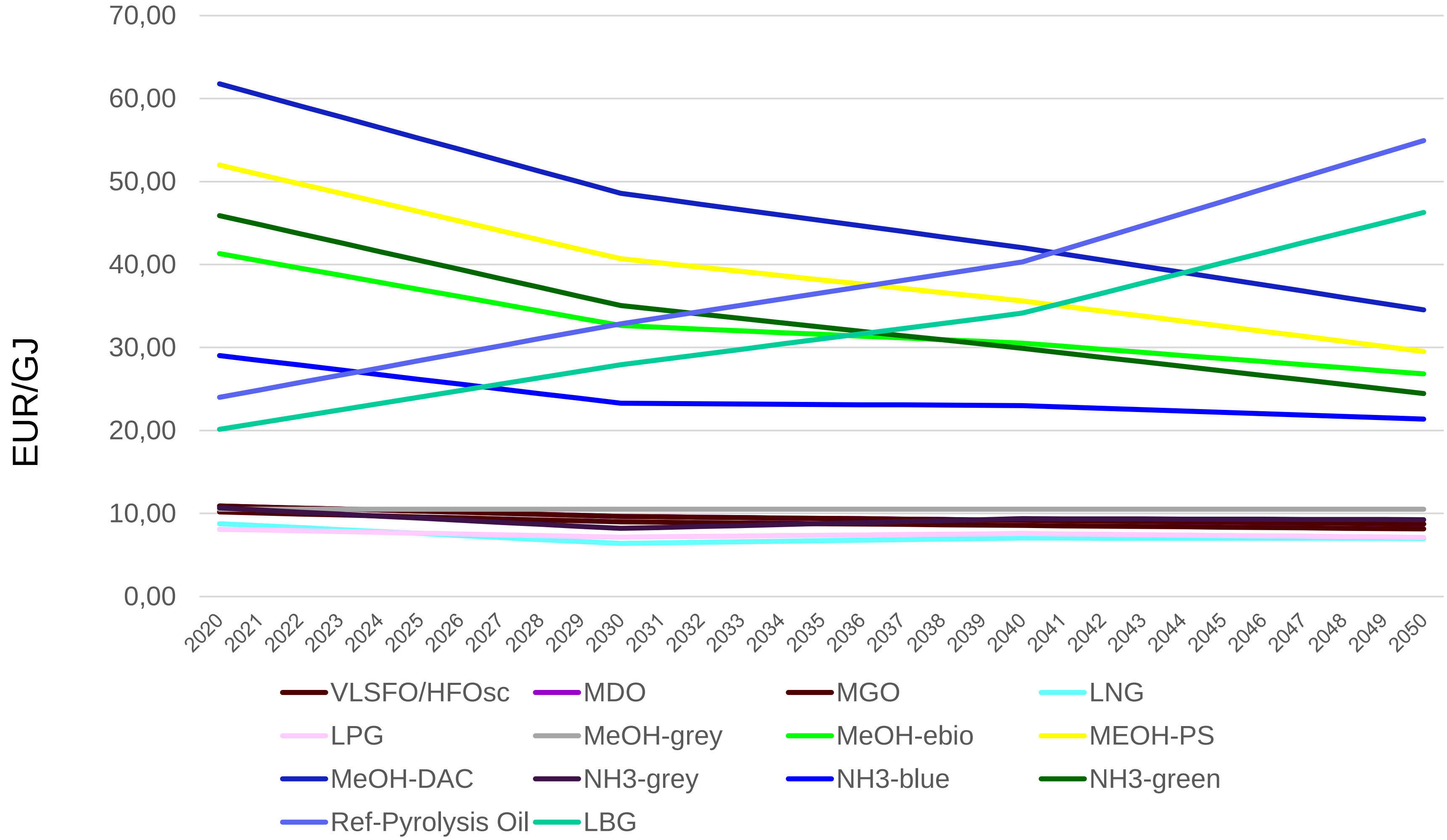

https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# GHG emissions w/wo grid 2020 (kg $CO_{2e}$/GJ)




https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# Fuel prices

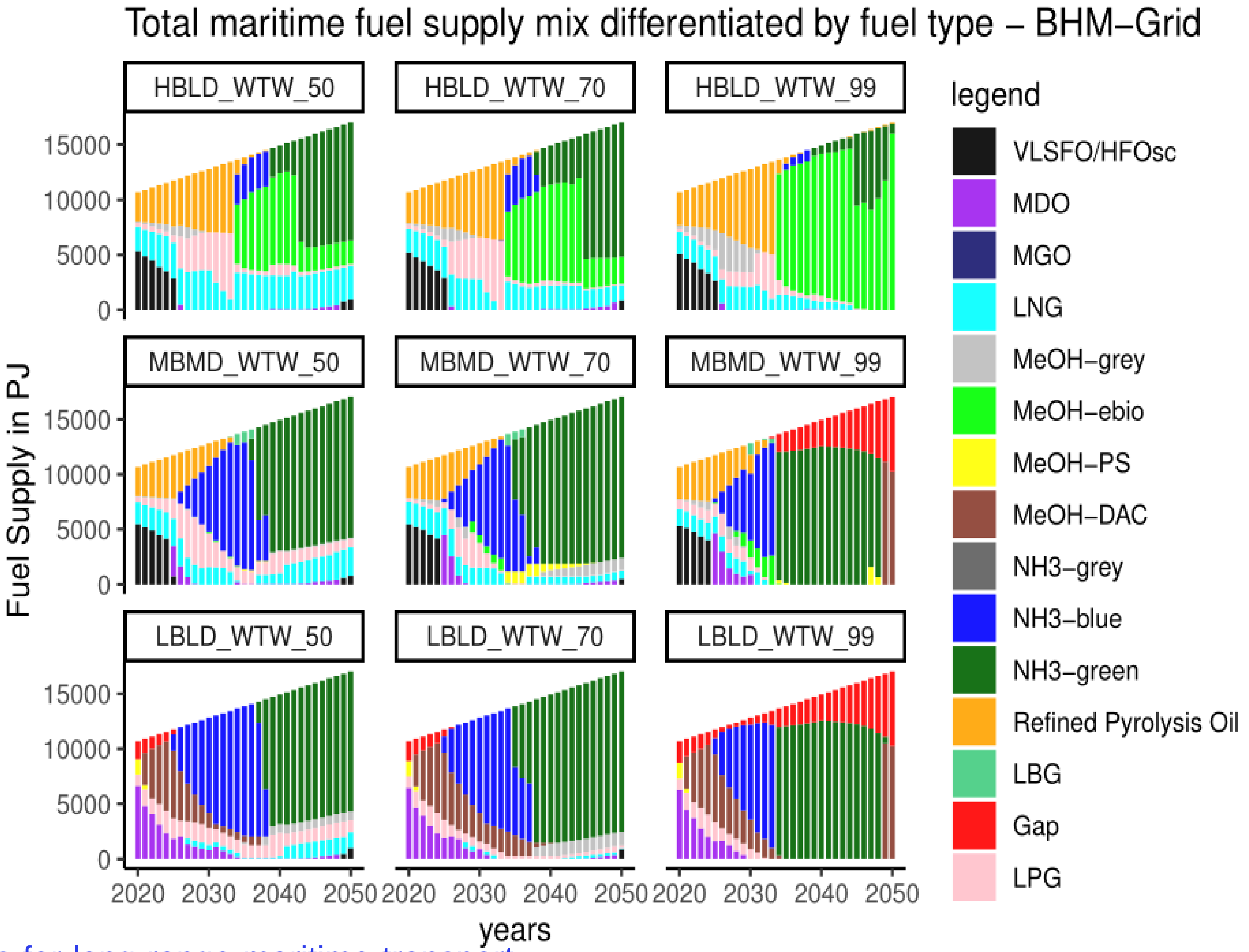



(Early 2021 natural gas price forecast)

https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# Behind-The-Meter(BHM) with grid

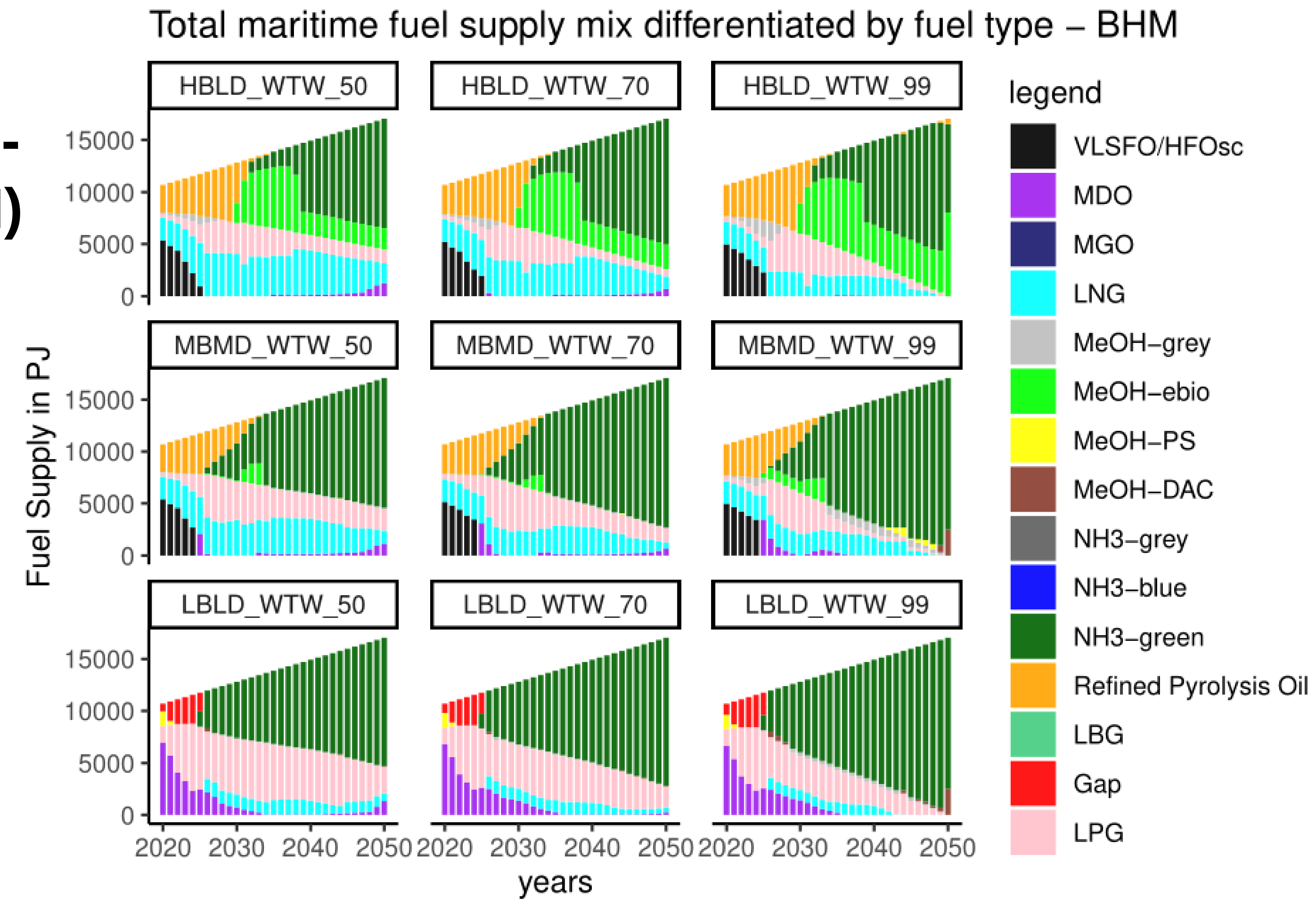
| Electricity from grid | | | |
|---|---|---|---|
| | 2020 | 2030 | 2050 |
| NH3 | 19% | 48% | 54% |
| Bio-e-MeOH | 18% | 51% | 53% |




https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

**No Ramping Constraint**

# Behind-The-Meter (BHM)




https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

# Conclusion

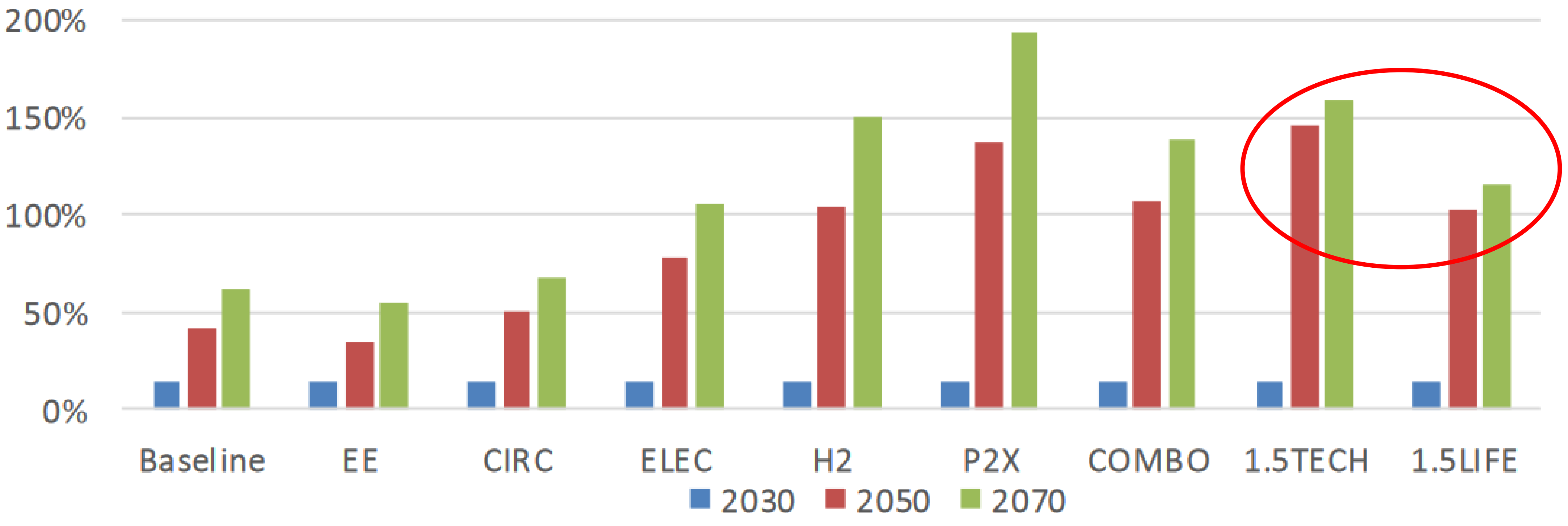
- The cheapest production is with mixed own production and grid consumption - due to avoided storages and/or oversizing of production units
- This leaves issues with emissions related to grid electricity production
- When off-grid, there is high value of a **high capacity factor** from own power production from wind and solar
- Incomes from sales of by-products (e.g. O2 and heat) may contribute to competitiveness
- Biofuels might be cheaper at first, but ammonia may become cheaper in the longer term
- Using black electricity for "green" fuels must be avoided.

# Upscaling requirements

- **Wind turbines** (or solar cells) : 10 – 25 times current annual installation rate.
- **Chemical synthesis**: 1.5 to 4.5 times the 2020 production rate.
- **Electrolysis**: more than by a factor of 1000 (or in other words 4000 years at current build up rate)
  - Today only ~0,3 GW is currently in operation and the annual build up rate is ca. 0,2 GW/year.

# Potential electricity demand increases

**Figure 22: Increase in gross electricity generation compared to 2015**

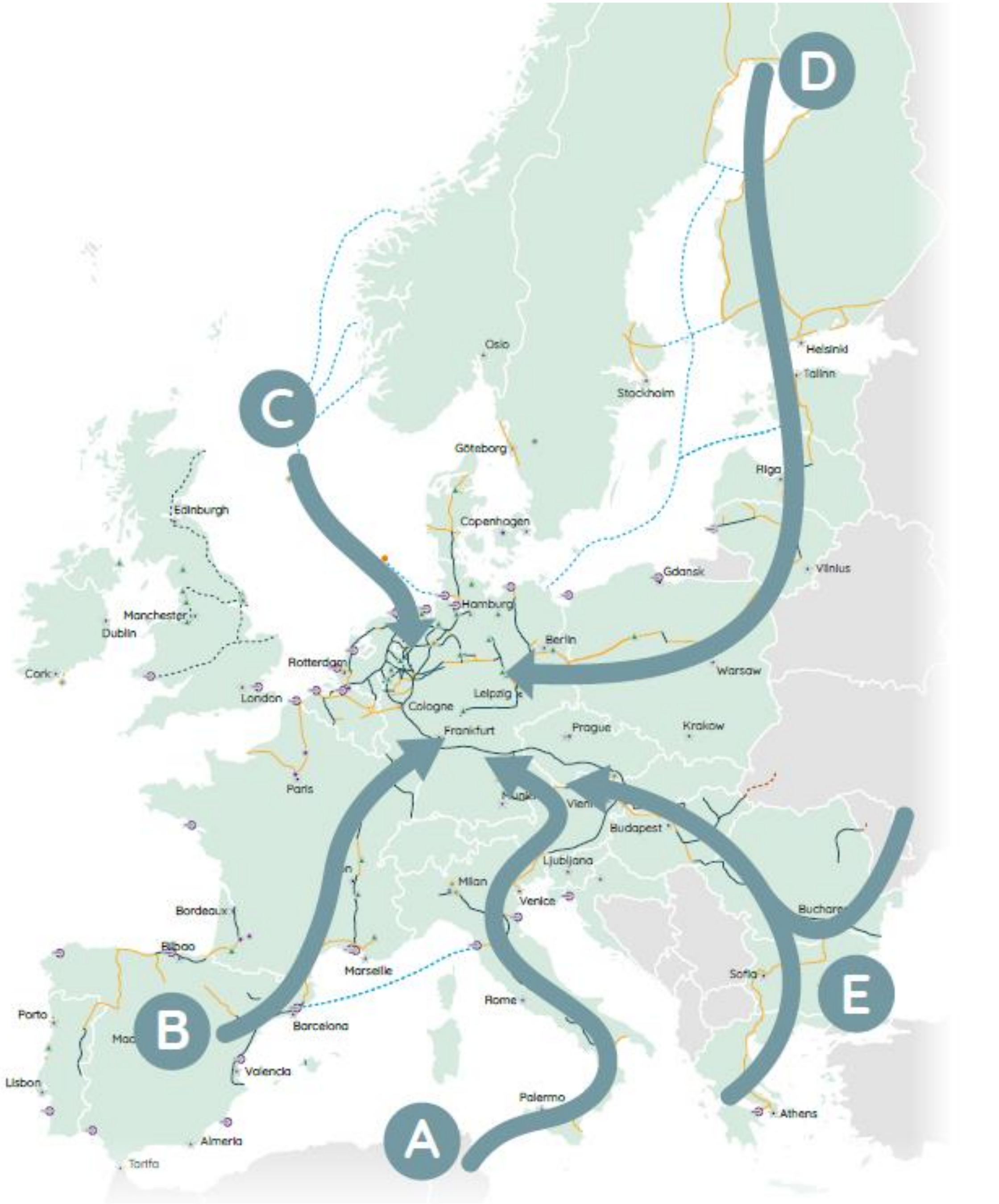



*Source: Eurostat (2015), PRIMES.*

(A Clean Planet for all -A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy" EU Commission, Nov 2018)

# European hydrogen backbone

- "Amongst other measures, REPowerEU introduces an ambition to reach an **additional 15 million tonnes (Mt) of renewable hydrogen on top of the 5.6 Mt foreseen** under Fit for 55, going beyond the targets of the EU's hydrogen strategy" (well before 2030)
- [https://www.ehb.eu/files/downloads/ehb-report-220428-17h0 interactive-1.pdf](https://www.ehb.eu/files/downloads/ehb-report-220428-17h0interactive-1.pdf)



# PtX planer i Danmark 2022

## Nordjylland

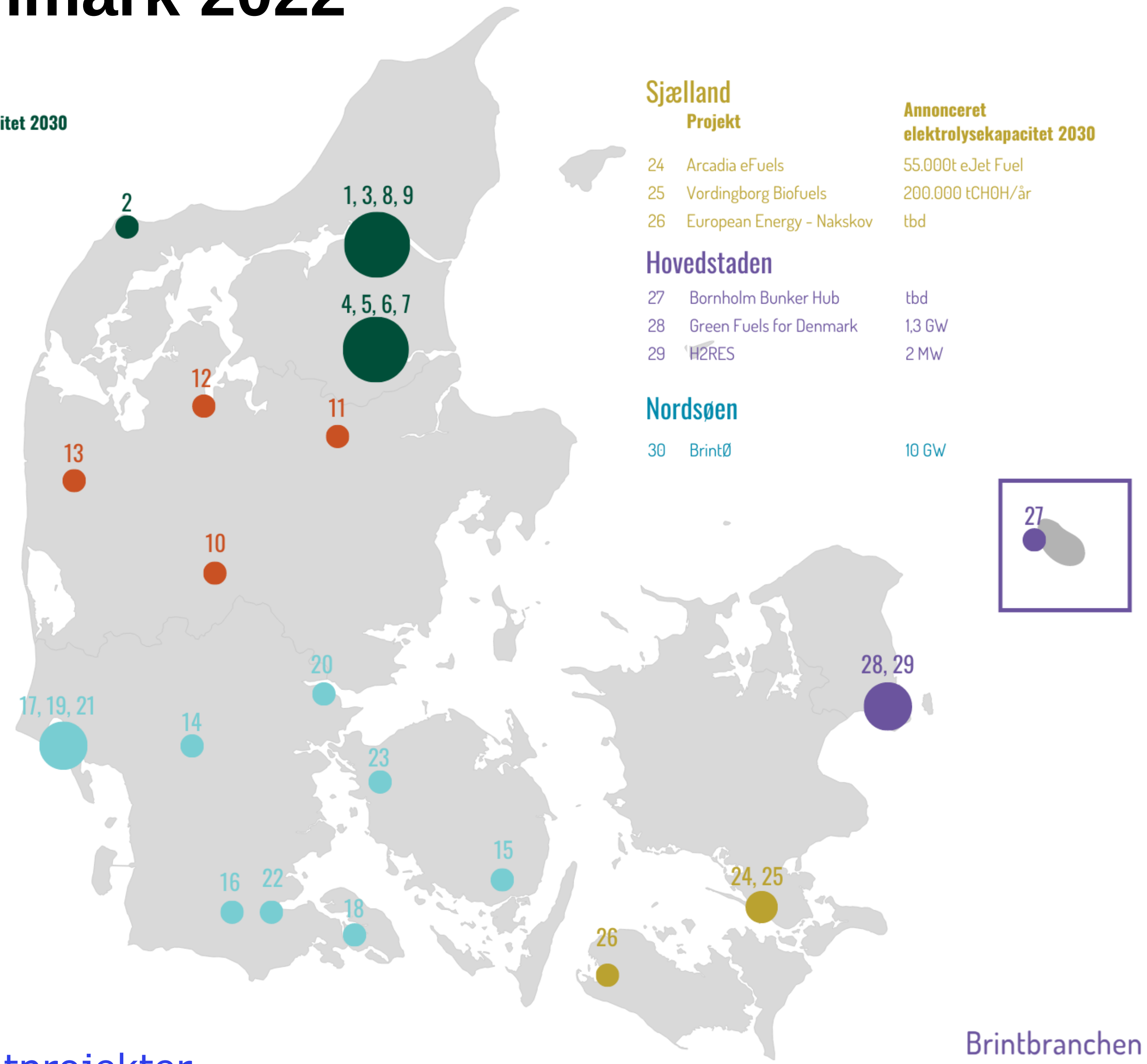
| | Projekt | Annonceret elektrolysekapacitet 2030 |
|---|---|---|
| 1 | Aalborg Havn - European Energy | 120 MW |
| 2 | Hanstholm Havn - European Energy | tbd |
| 3 | Green Hub CCU Aalborg | tbd |
| 4 | Handest | 50 MW |
| 5 | Hejring | 35 MW |
| 6 | HFC Marine | 0,5 MW |
| 7 | HyBalance | 1,2 MW |
| 8 | Metanolprojekt v. Nordjyllandsværket | 300-400 MW |
| 9 | Power2Met | 0,3 MW |

## Midtjylland

| | | |
|---|---|---|
| 10 | Brande - Flø Hydrogen | 0,4 MW |
| 11 | Green Hydrogen Hub | 1 GW |
| 12 | Greenlab Skive - GreenHyScale | 400 MW |
| 13 | REDDAP | 10 MW |

## Syddanmark

| | | |
|---|---|---|
| 14 | Biogas Holsted | 20 MW |
| 15 | Estech | 1t brint/dag |
| 16 | European Energy v. Kassø | 50 MW |
| 17 | European Energy v. Måde | 12 MW |
| 18 | Glansager | 6 MW |
| 19 | H2 Energy Europe | 1 GW |
| 20 | HySynergy | 1 GW |
| 21 | HØST | 1 GW |
| 22 | Linde - Aabenraa Havn | 100 MW |
| 23 | Strandmøllen | 0,5 MW |




## Sjælland

| | Projekt | Annonceret elektrolysekapacitet 2030 |
|---|---|---|
| 24 | Arcadia eFuels | 55.000t eJet Fuel |
| 25 | Vordingborg Biofuels | 200.000 tCHOH/år |
| 26 | European Energy - Nakskov | tbd |

## Hovedstaden

| | | |
|---|---|---|
| 27 | Bornholm Bunker Hub | tbd |
| 28 | Green Fuels for Denmark | 1,3 GW |
| 29 | H2RES | 2 MW |

## Nordsøen

| | | |
|---|---|---|
| 30 | BrintØ | 10 GW |

https://brintbranchen.dk/danske-brintprojekter

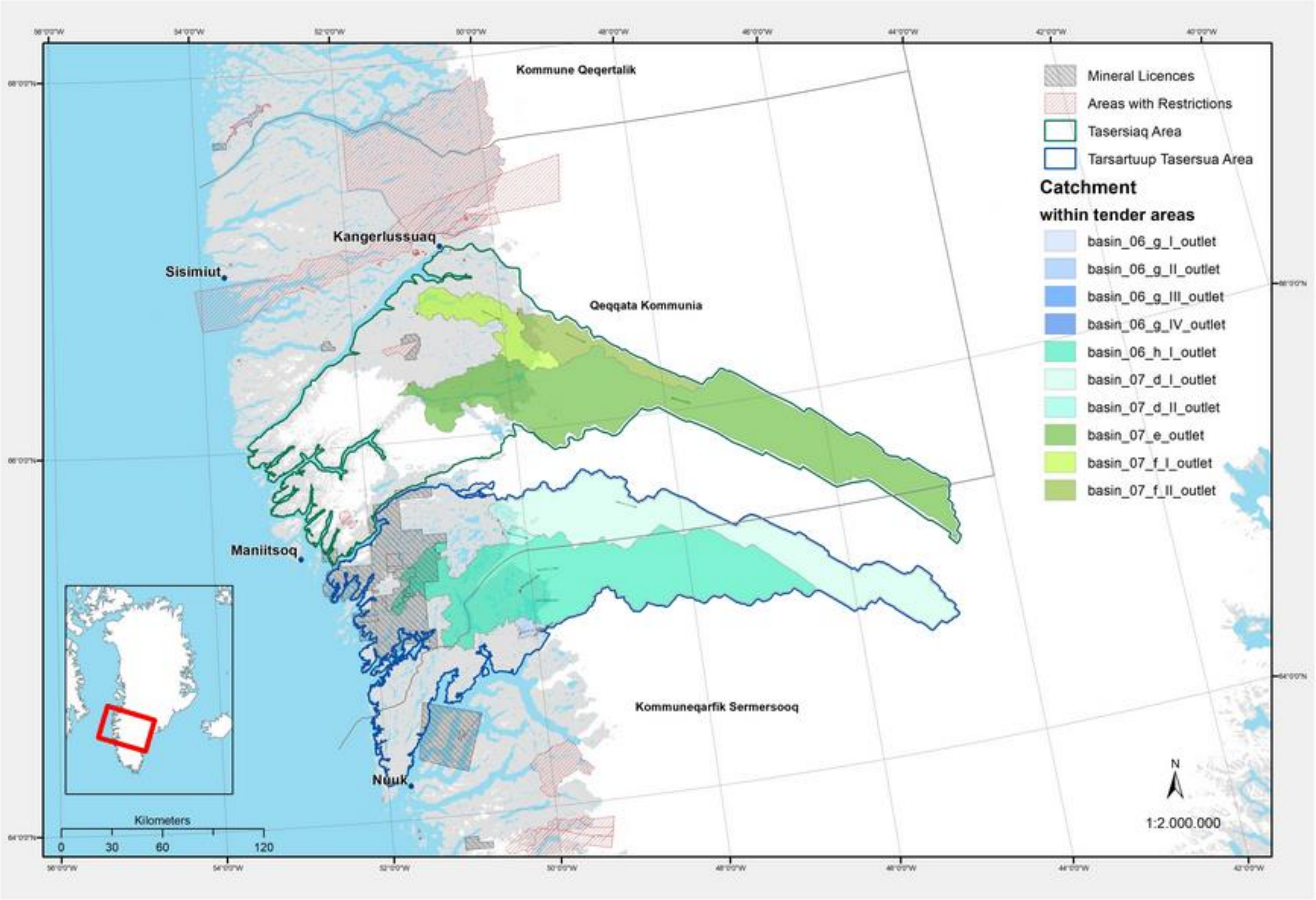
# Larger PtX project plans in Denmark 2022

| Name | Place | Capacity ($MW_{el}$) | Product | Partners |
|---|---|---|---|---|
| Green Fuels for DK | København | 1300 | Jet fuel | Ørsted, SAS, Copenhagen Airports, Mærsk, DFDS, DSV, Nel, Haldor Topsøe, Everfuel |
| H2 Energy Europe | Esbjerg | 1000 | Hydrogen for road transport | Trafigura and H2 Energy |
| HØST | Esbjerg | 1000 | Ammonia, district heating | CIP, DIN Forsyning, Danish Crown, DLG, Arla, Mærsk and DFDS |
| HySynergy | Fredericia | 1000 | Hydrogen for refining | Crossbridge Energy, Aktive Energi Anlæg, Trefor Elnet, Energinet, TVIS, EWII |

# PtX in Greenland?

- "Two hydropower plants north of Nuuk in Tasersiaq and Tarsartuup Tasersua. By next year already, the Greenlandic government expects to carry out a tender for the two facilities. With a capacity of 600MW and 200MW, respectively, construction of the projects is slated to start in 2027."
- "With a total energy consumption in all sectors of around 2.5TWh, however, the project is quite scaled to Greenlandic consumption solely. Preliminary studies also show that the two power stations will see annual generation of around 6.5TWh"

*EnergyWatch 11/5 2022*
[https://energywatch.com/EnergyNews/Renewables/article14008169.ece](https://energywatch.com/EnergyNews/Renewables/article14008169.ece)

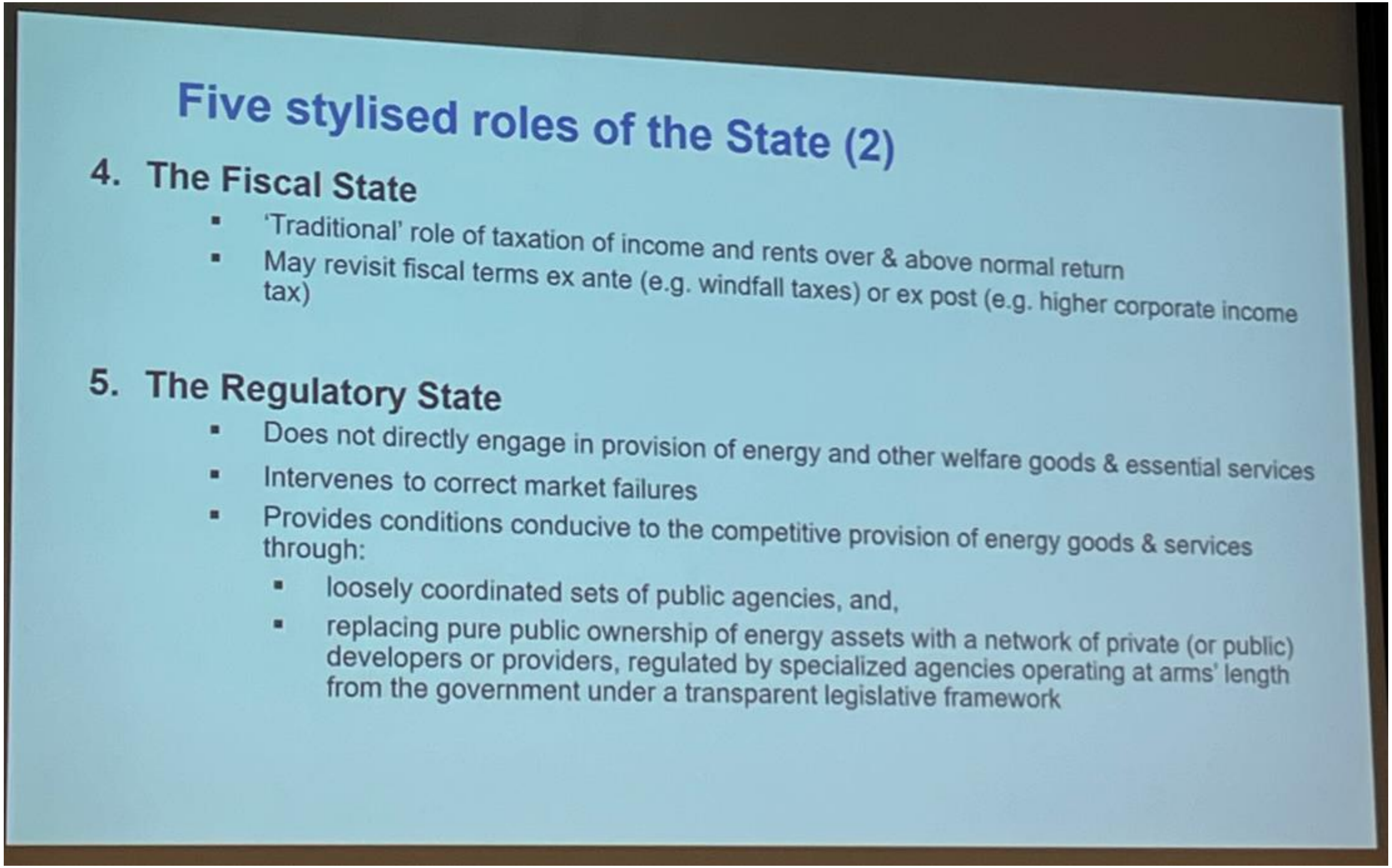


# Value creation/ roles of the state I/II


Norway has earned twice as much on their oil as the UK with a proprietory regime rather than a liberal taxation approach

By Anupama Sen, Oxford and Tooraj Jamasb, CBS

# Value creation/ roles of the state I/II



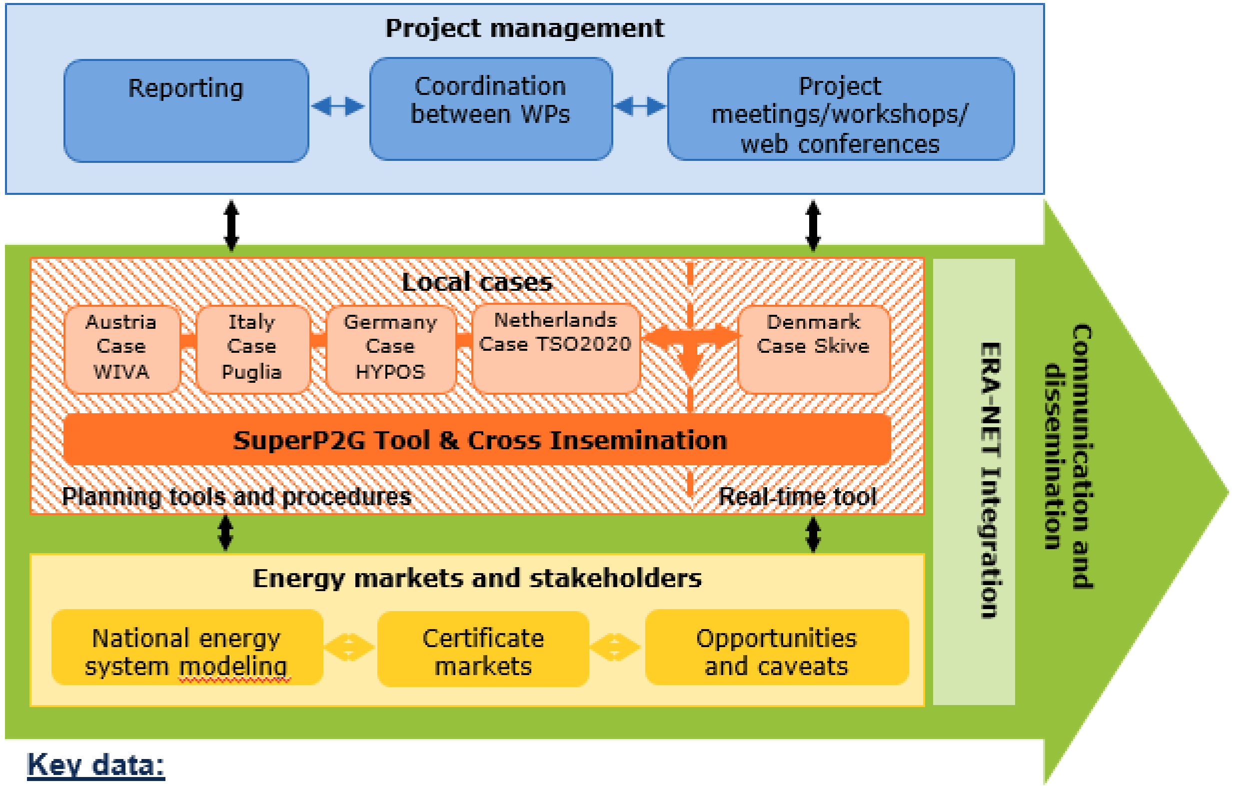

By Anupama Sen, Oxford and Tooraj Jamasb, CBS

# DTU PtX projects

# SuperP2G - Synergies Utilising renewable Power REgionally by means of Power-To-Gas

## The Project at a glance

- SuperP2G interconnects leading P2G initiatives in five countries, ensuring joint learning.
- Each national project focuses on different challenges, where researchers team up with local need-owners to co-create solutions.
- SuperP2G focuses on improving existing evaluation tools including open access.
- This is supplemented with analysis of regulation and markets, as well as stakeholder involvement.
- www.superp2g.eu




**Key data:**

- Duration: 36 Months
- Start: 01.11.2019

**Research partners:**

- **Denmark:** DTU ME, DTU Elektro, GreenLab Skive
- **Austria:** JKU Linz
- **Germany:** DBI-GTI, DVGW-EBI
- **Italy:** CNR, Uni Bologna
- **Netherlands:** RUG-FEB
- **Europe:** ERIG

DTU

| Project partners | | |
|---|---|---|
| Technical University of Denmark | DK | |
| Ballard Power Systems Europe | DK | |
| SINTEF | N | |
| CoorsTek Membrane Sciences | N | |
| Vard | N | |
| VTT | FIN | |

Contact: Prof Anke Hagen


Contact:

Project Coordinator

Prof. Dr. Dr. Anke Hagen

Technical University of Denmark

Department of Energy Conversion and Storage

Fysikvej B. 310, DK-2800 Kongens Lyngby, Denmark

Phone: +45 46775884

Email: anke@dtu.dk


Meet us here:

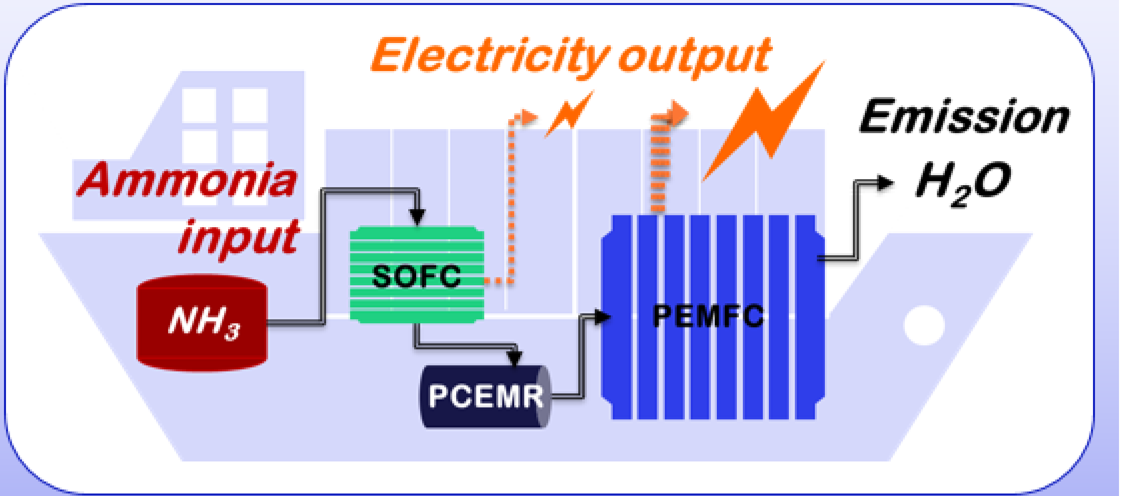
Internet: https://www.aegir-project.net/

# AEGIR

## Ammonia electric marine power for GHG emission reduction


This project has received funding from the Nordic Maritime Transport and Energy Research Programme through National Financiers: the Energy Technology Development and Demonstration Program (EUDP) in Denmark, the Norwegian Research Council (RCN) in Norway, and Business Finland in Finland.

- *Ships are responsible for 90% of international transport, their $CO_2$ emissions accounting for approximately 2.2% of the global total of such emissions*
- ***The overall target of the Aegir project is to develop, test and evaluate an environmentally friendly technological solution to power large marine vessels by using green ammonia as primary fuel.***
- *The Aegir concept:*
  - I. *Ammonia is cracked to $H_2$ and $N_2$ using a solid oxide fuel cell (SOFC);*
  - II. *$H_2$ is extracted and purified using a proton conducting electrochemical membrane (PCEMR)*
  - III. *Converted to electricity using a polymer exchange membrane fuel cell (PEM).*




- *By combining these three technologies, AEGIR aims at developing an ammonia-fueled ship propulsion system that offers high efficiency in combination with a low total system volume and weight, which is the key innovation of the project.*
- *The Aegir concept avoids emissions of $NO_x$ and allows for a drastic reduction of $CO_2$ emissions; the product of the fuel cell electricity process is water.*

- *The Aegir project will*
  - *Design the integrated concept,*
  - *Experimentally validate the three key enabling technologies*
  - *Demonstrate a reduction of greenhouse gas emissions by 90% compared to current state in a well-to-propeller analysis, and*
  - *Identify potential scale up issues for a 20 MW maritime system in a concept study.*

DTU

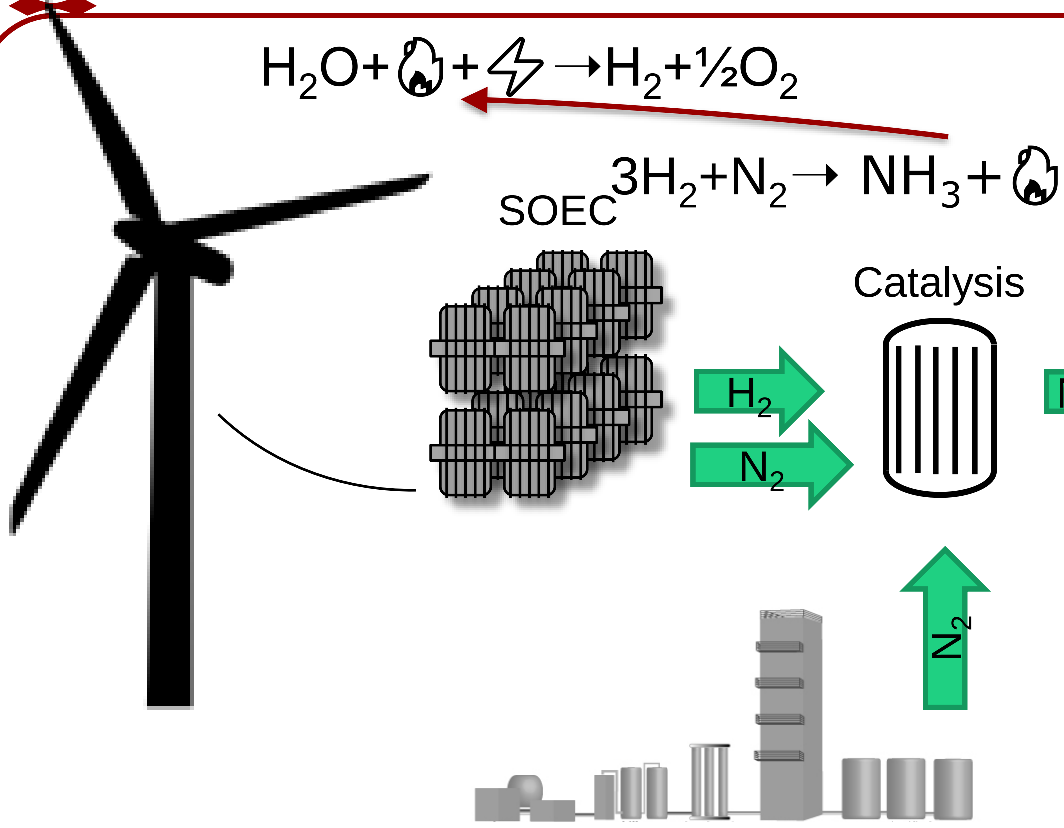
Contact: Prof Henrik Lund Frandsen

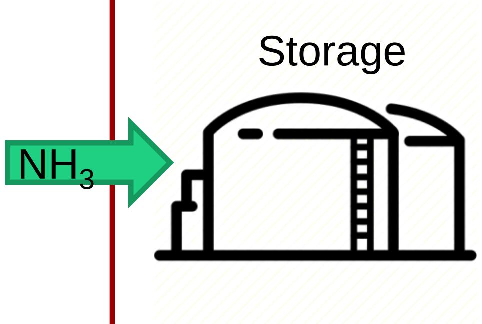
# Green ammonia

# For shipping

$H_2O$ + 🔥 + ⚡ → $H_2 + \frac{1}{2}O_2$

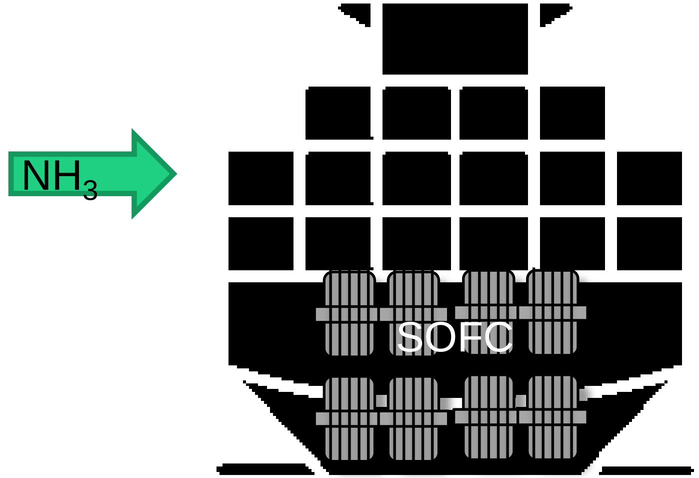
$3H_2 + N_2$ → $NH_3$ + 🔥




$2NH_3$ + 🔥 → $3H_2 + N_2$

$H_2 + \frac{1}{2}O_2$ → $H_2O$ + 🔥 + ⚡




| | | | |
|---|---|---|---|
| RTE NH3 (SOC): | 45-50 % | | ~25 % |
| RTE H2 (SOC): | 35-40 % | | |
| RTE H2 current | 25-30 % | | **~60 %** |

**SOC4NH3**

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**SOFC4Maritime**

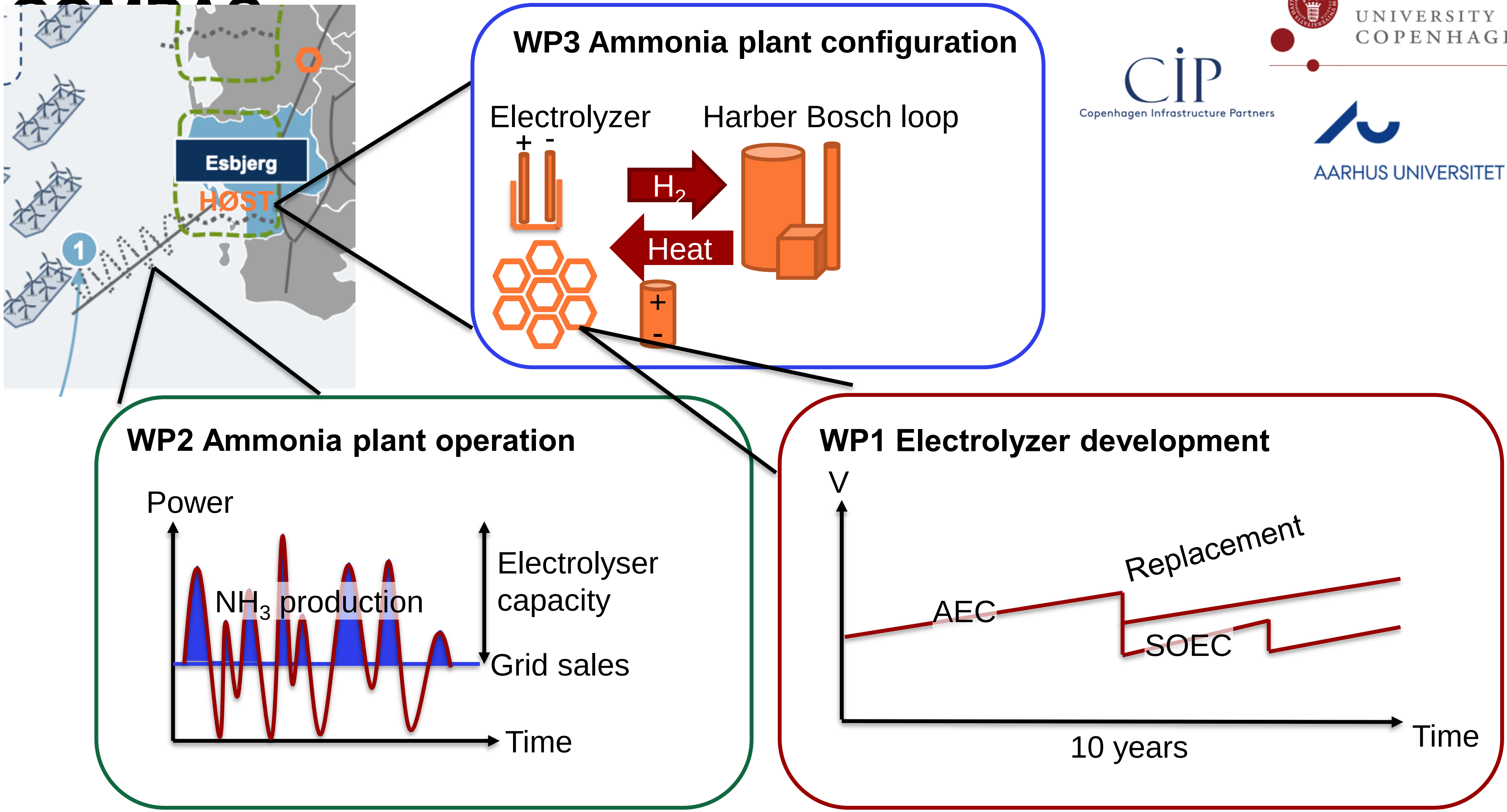
ALFA LAVAL · SVITZER · HALDOR TOPSØE · DTU Energy

**Mærsk Mc-Kinney Møller Center**
for Zero Carbon Shipping

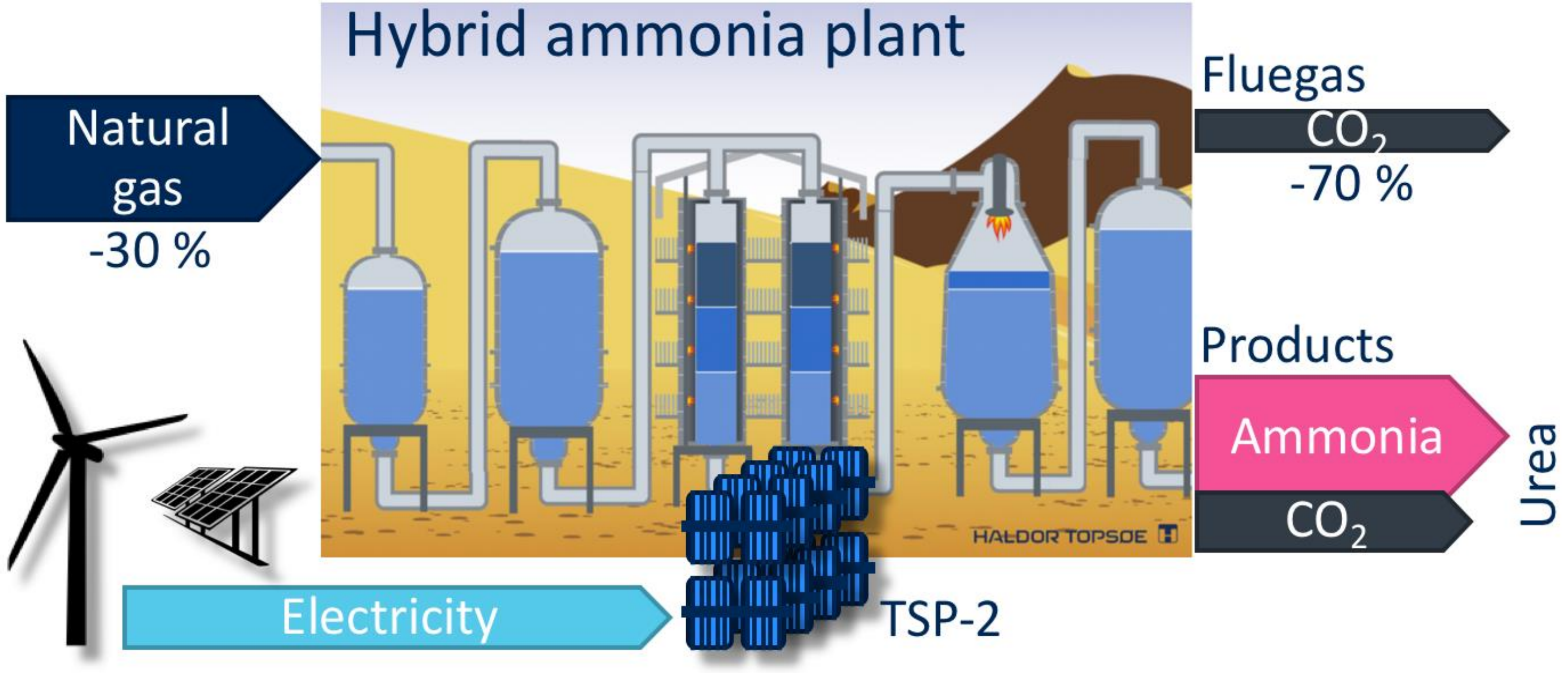
DTU

Contact: Prof Henrik Lund Frandsen

DTU HALDOR TOPSØE UNIVERSITY OF COPENHAGEN CIP Copenhagen Infrastructure Partners AARHUS UNIVERSITET



# Ammonia production, using hybrid plants, REFORGE




With hybrid plants electrolysis is already cost-competetive - where electricity cost is low

HALDOR TOPSØE

DTU Energy
Department of Energy Conversion and Storage

# The end ☺

Marie Münster, maem@dtu.dk
Twitter: @MarieMynster
LinkedIn: https://www.linkedin.com/in/marie-münster-b161293
Website: https://orbit.dtu.dk/en/persons/marie-münster

# Estimated costs of Green fuels, 2020, 2030 and 2050

## Cheapest is mixed own production and grid connected

Cost of Electricity
Cost of Biomass

Efficiency of plant

Capex of plant

Technology catalogue
Specific site, local Optimisation

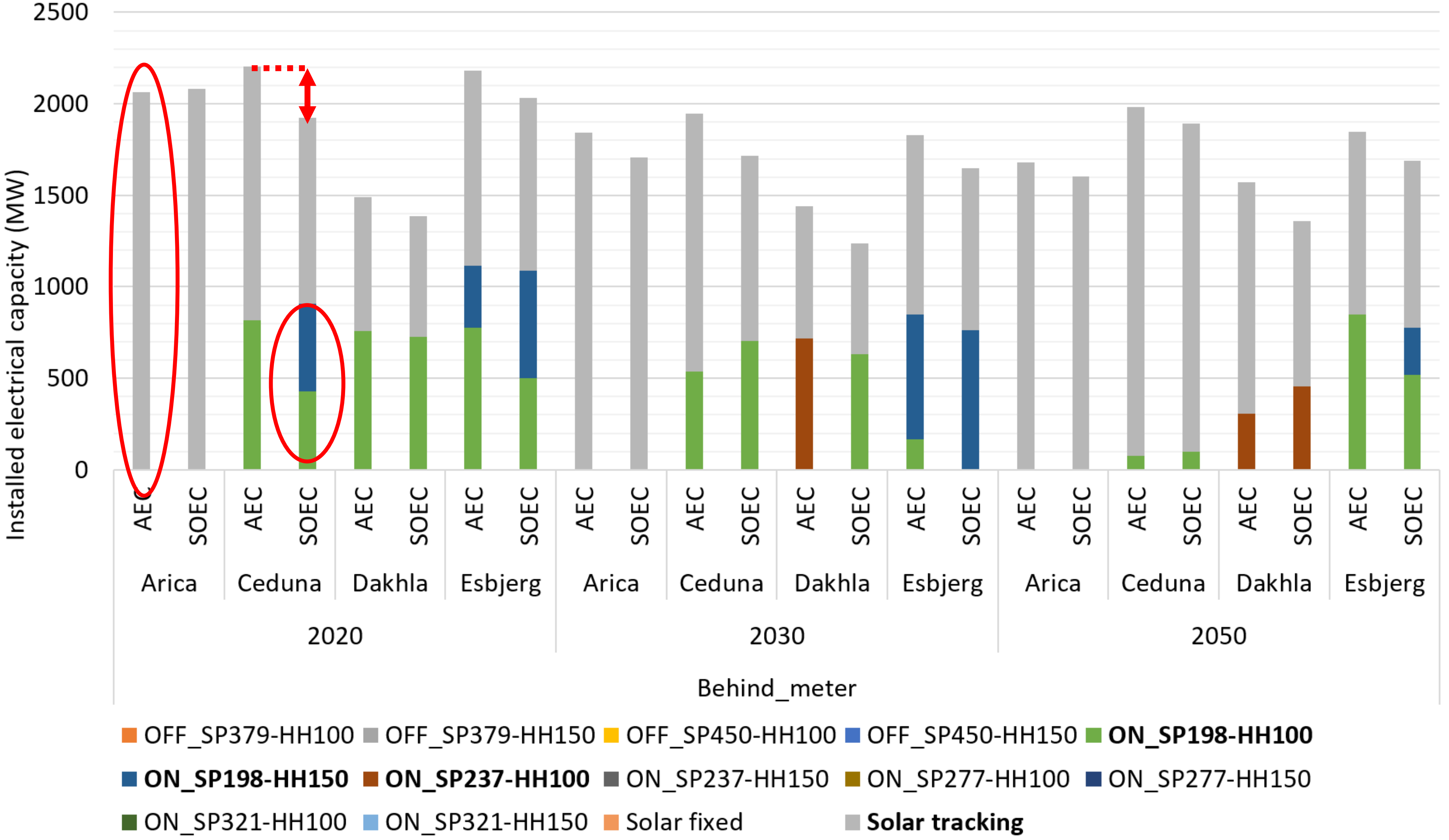
BOP modelling
BOP component cost assessment

| | 2020 | 2030 | 2050 |
|---|---|---|---|
| Cost of Electricity* (ammonia case) | 43 €/MWh AEC, Dakhla, Grid;19% | 21 €/MWh Arica, AEC, Grid; 48% | 17,4 €/MWh Arica, SOEC, Grid 54% |
| Cost of wood chips | 6,8 €/GJ | 7,4 €/GJ | 8,2 €/GJ |
| | | | |
| Green ammonia | 716 €/t | 536 €/t - 561 €/t | 355 €/t |
| Green methanol | 725 €/t | 570 €/t - 582 €/t | 453 €/t - 462 €/t |

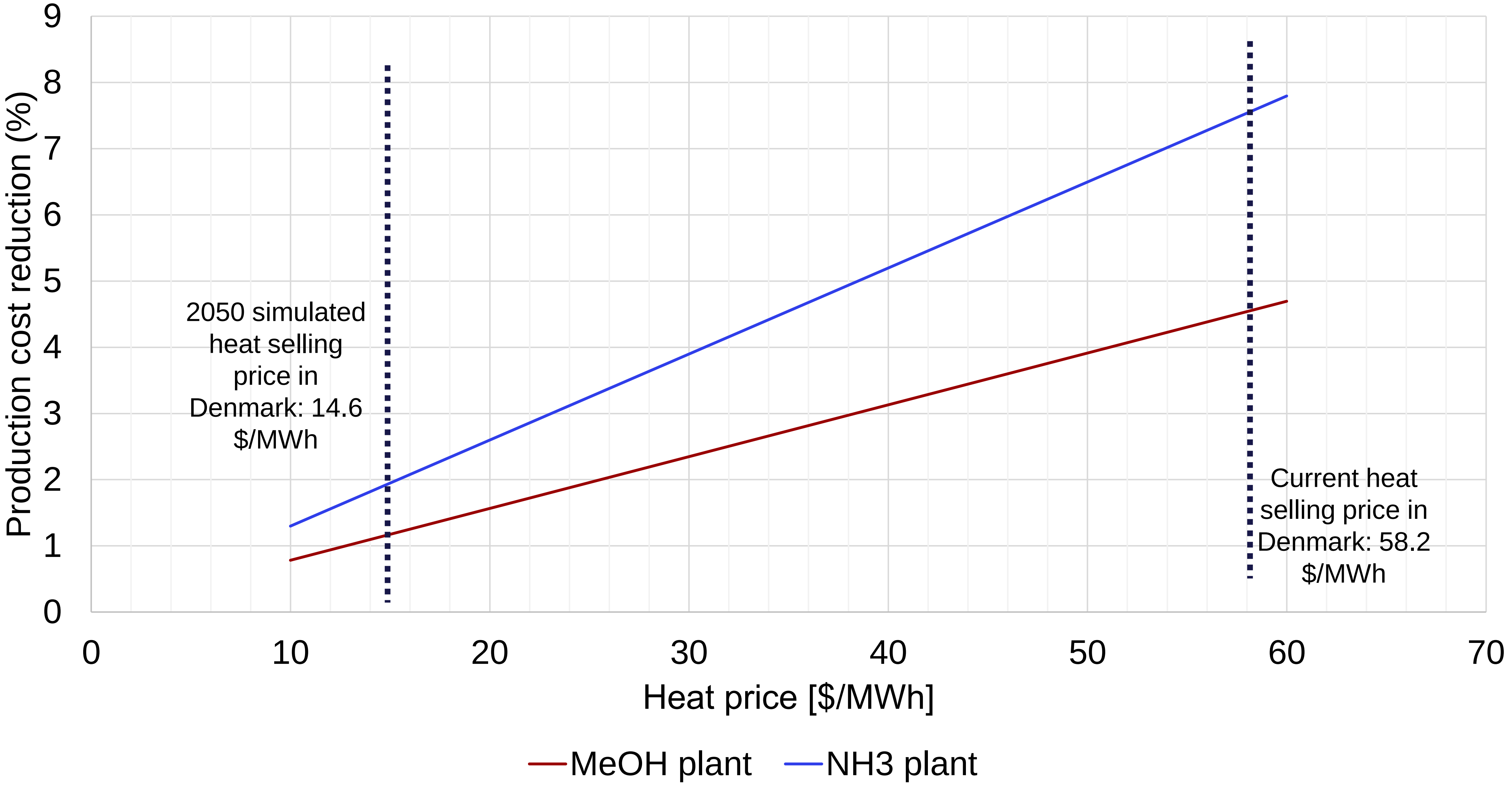
# Results off-grid: optimal installed power capacities

Solar tracking

Onshore wind turbines with **high capacity factor**. But not the lowest LCOE.



# Decrease of fuel production cost thanks to excess heat sale



# Biomass availability scenarios

| Resource availability | Low | Medium | High | Possible biofuel |
|---|---|---|---|---|
| Crop residues | 15 EJ | 43 EJ | 70 EJ | Methanol/ Pyrolysis oil |
| Forestry residues | 13 EJ | 14 EJ | 15 EJ | Methanol/ Pyrolysis oil |
| Black Liquor | 2 EJ | 2 EJ | 2 EJ | Methanol/ Pyrolysis oil |
| Manure | Used in industry | 7 EJ* | 13 EJ* | LBG |
| Organic waste | Used in industry | 1 EJ* | 2 EJ* | LBG |
| **Total** | **30 EJ** | **67 EJ** | **102 EJ** | |

*biogas potential

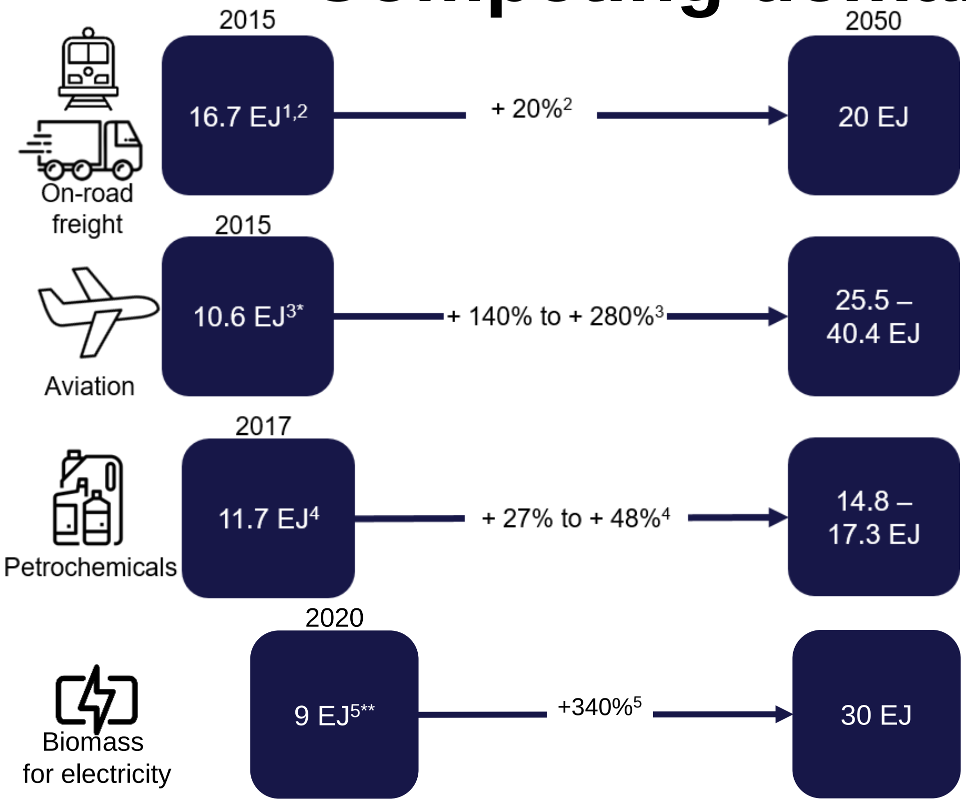
How much biomass is available for shipping fuels?

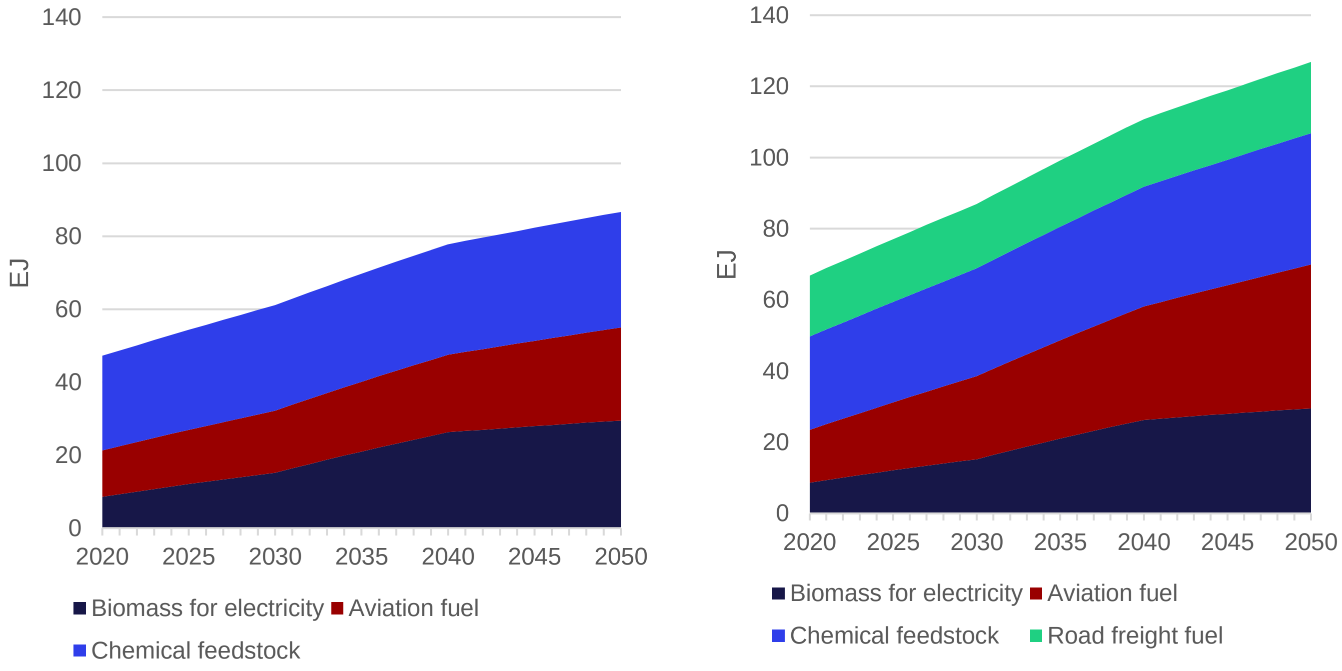
- Biomass is limited to residuals
- Competing sectors are served first
- No development in annual biomass availability over time

Scenarios for biomass availability to shipping sector:

- High biomass availability low competing demand
- Medium biomass availability medium competing demand
- Low biomass availability low competing demand

# Competing demand



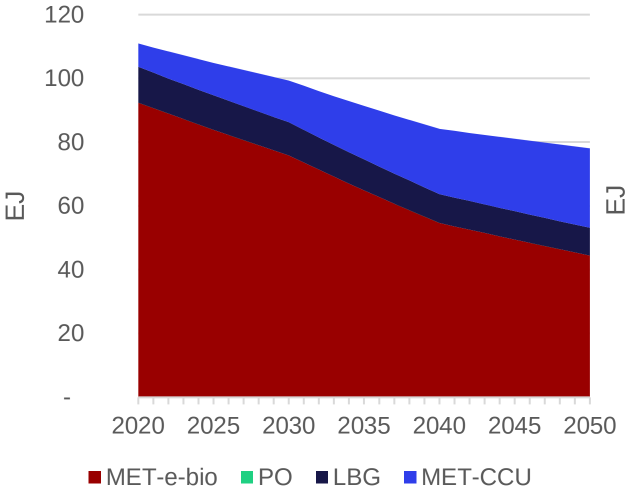

Projected low (left) and high (right) competing demand from 2020 to 2050. The medium scenario is the midpoint between the two.

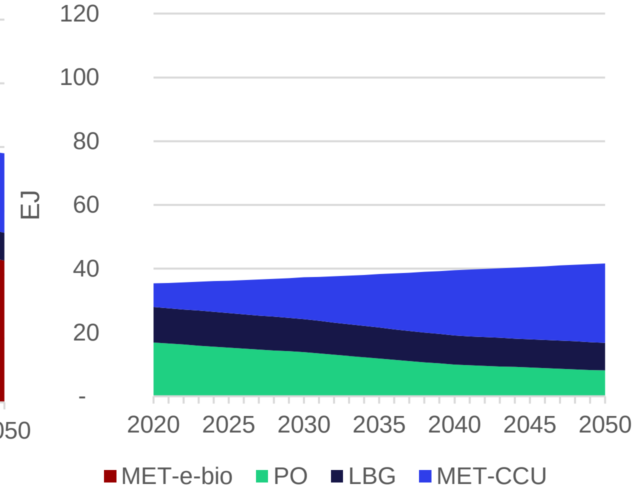
Own calculation using data from [1](IEA, 2019) [2](IRENA, 2020) [3](ICAO, 2019) [4](IEA, 2018) [5](IEA, 2021) *conversion factor for jet kerosene 43.15 MJ/kg **efficiency going from 30% in 2020 to 40% in 2050.


1. IEA. Marine bunkers product demand, 2015-2024 [Internet]. 2019. Available from: https://www.iea.org/data-and-statistics/charts/marine-bunkers-product-demand-2015-2024
2. IRENA. Global Renewables Outlook: Energy transformation 2050 [Internet]. International Renewable Energy Agency. 2020. 292 p. Available from: https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020
3. ICAO. Environmental Trends in Aviation to 2050 [Internet]. 2019 Environmental Report. 2019. Available from: https://www.icao.int/environmental-protection/pages/envrep2019.aspx
4. IEA. The Future of Petrochemicals. 2018.
5. IEA. Net zero by 2050. 2021.

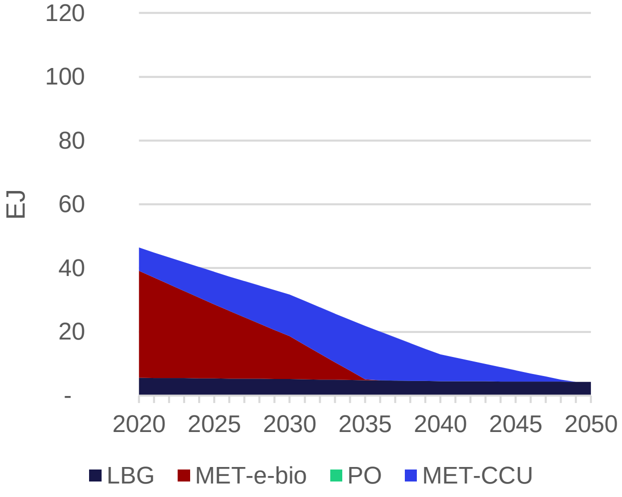
# Biofuel availability for shipping

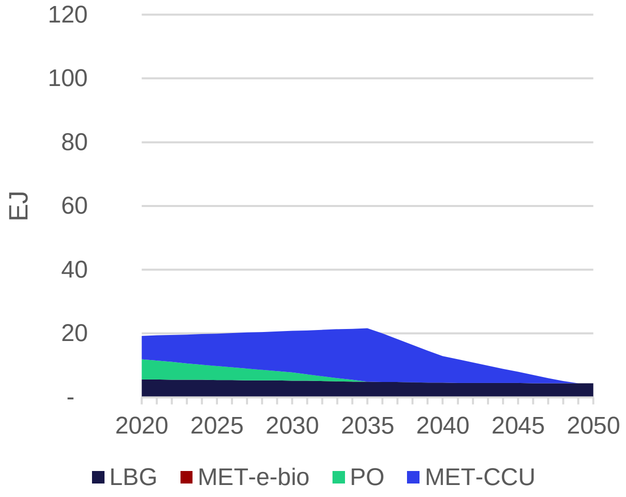
## High biomass availability low competing demand (HBLD)



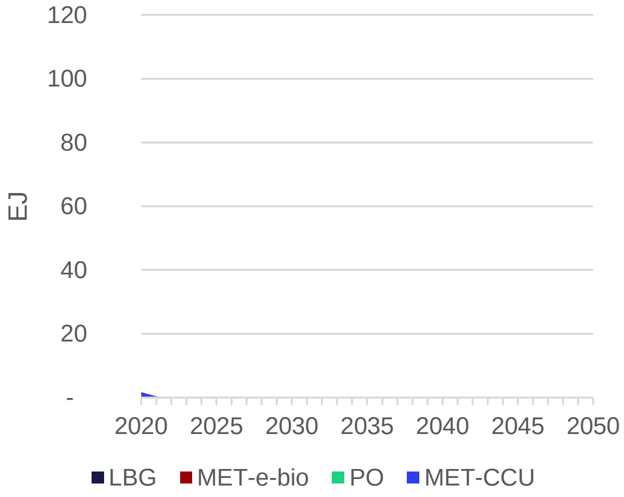




## Medium biomass availability medium competing demand (MBMD)




## Low biomass availability low competing demand (LBLD)




HBLD: A very optimistic scenario with room for producing low carbon efficient fuels.

MBLD: An optimistic scenario with some availability on the short term, but if the pyrolysis oil route is chosen these are very limited.

LBLD: With low biomass availability there is essentially no biofuel availability to the shipping sector even with a low competing demand.

# Sector coupling in EU

**Focus on electrification**

**Technological overview**

1. Power to heating and cooling (PtH)
2. Power to mobility (EV)
3. Power to gas/ fuels (PtX)
    - Status
    - Potential
    - Barriers

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