aramco

Concawe
Environmental Science for European Refining

LBST
ludwig bölkow systemtechnik

E4tech

E-Fuels: A techno-economic assessment of EU domestic production and imports towards 2050

Concawe Symposium
27th September 2021

Alba Soler (Concawe): alba.soler@concawe.eu
Patrick Schmidt (LBST): patrick.schmidt@lbst.de

E-fuel concept

Agenda

1. Background
2. Technical assessment
3. Economic assessment
4. Conclusions

Agenda

1. **Background**
2. Technical assessment
3. Economic assessment
4. Conclusions

1. Background

Joint collaboration Concawe & Aramco, and LBST & E4tech as consultants

Joint collaboration between:

- **Concawe & Aramco: Technical assessment and GHG impact**
- **LBST & E4tech: Economic assessment**
- **OGCI & Concawe Member Companies experts: Steering Committee**

Previous Concawe reports on e-fuels:

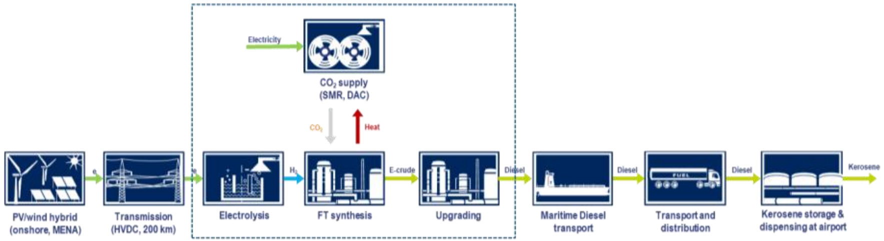
Refinery 2050

E-fuels literature review

E-fuels Concawe Review

Scope:

- **Timeframe:** 2020 / 2030 / 2050
- **Pathways:** e-hydrogen, e-methane, e-methanol, e-OMEx, e-methanol-to-gasoline, e-methanol-to-kerosene, e-ammonia, e-Fischer-Tropsch kerosene & diesel
- **Regions:**
  - Domestic production in North EU (Norway), Central EU (Germany) and South EU (Spain)
  - Production in Middle East (Saudi Arabia) and import into EU
  - Sensitivities to production in Morocco, Chile & Australia, and import to EU
- **Full fuel supply cycle:**
  - Energy production
  - Conversion
  - Storage
  - Transport/distribution
  - Dispensing



9 base cases for 4 geographies + sensitivities => >100 pathways assessed

Concawe

Agenda

1. Background
2. **Technical assessment**
3. Economic assessment
4. Conclusions

2. Technical assessment

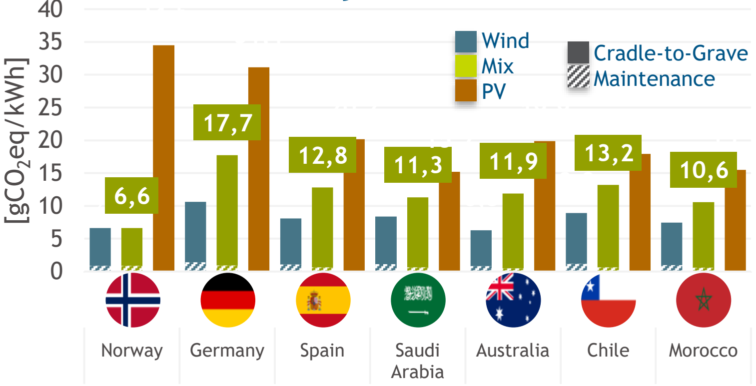
Key assumptions

Electrolysis efficiency and CO_2 source

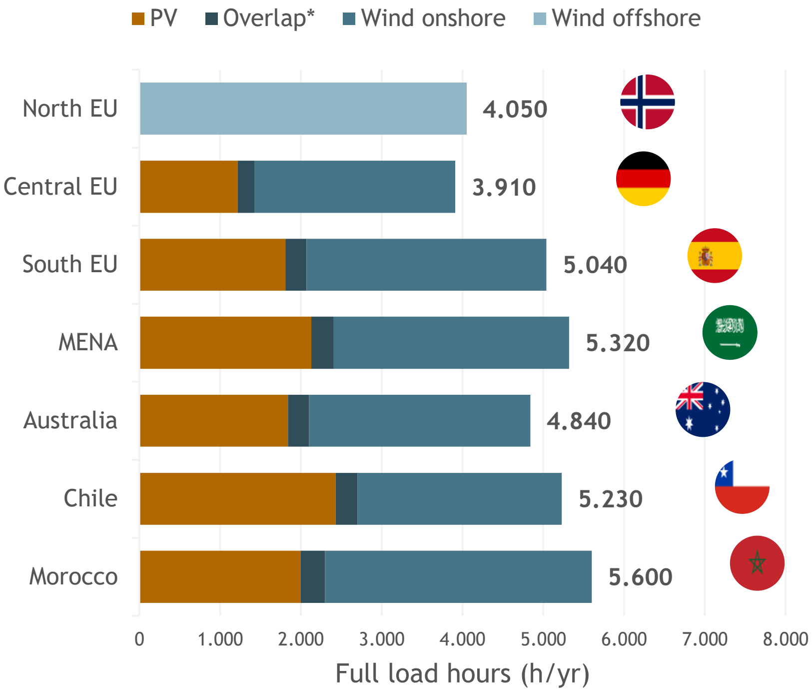
	2020	2030	2050
Electrolysis efficiency	66.5%	68%	75%
Source of CO_2	Concentrated source	Concentrated source	Concentrated source and DAC[1]
CO_2 concentration (%)	45	45	45% (Conc. source) 0.04% (DAC)

[1] EU: Mix (33% concentrated source, 33% average source and 33% DAC)
North Africa: 100% DAC. Middle East: 50% Concentrated source, 50% DAC). DAC: Direct air capture

Renewable electricity GHG emissions



Full load hours (h/yr)



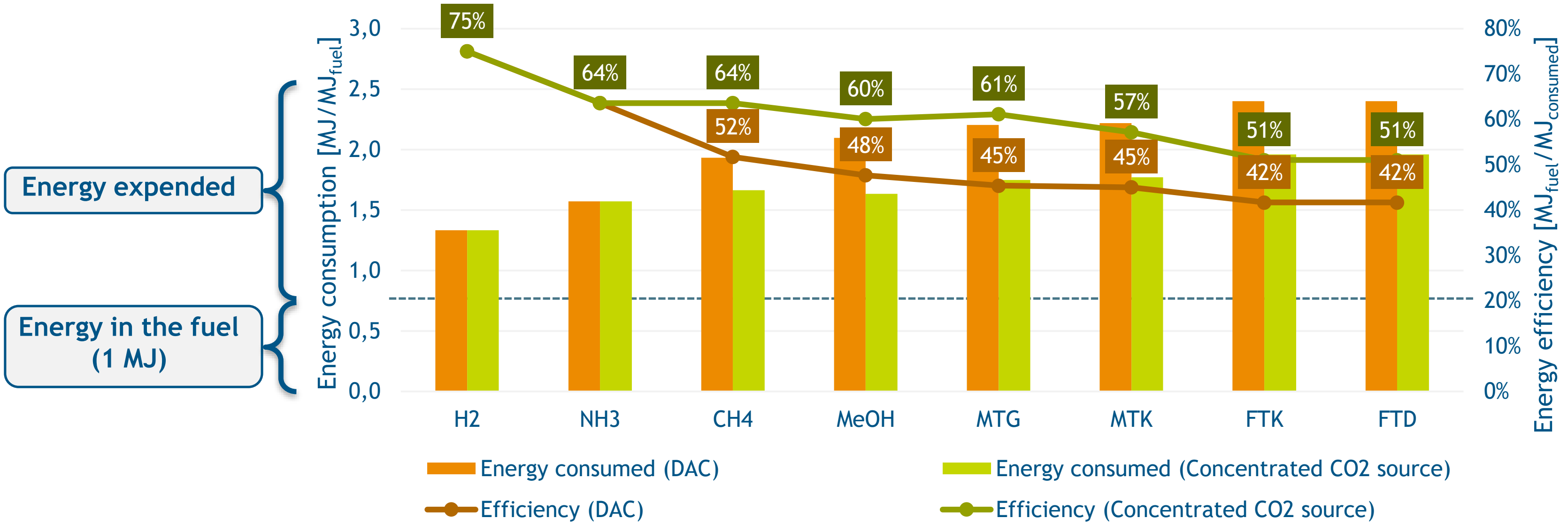
Note: Curtailed overlap estimated at 5% [Fasihi et al 2017]

2. Technical assessment

Results: Energy balance - North EU, 2050

Lower energy efficiency linked to higher processing fuel routes: routes with higher drop-in fossil replacement in existing fleet

Increase of ~10% points in efficiency if concentrated CO_2 source vs DAC



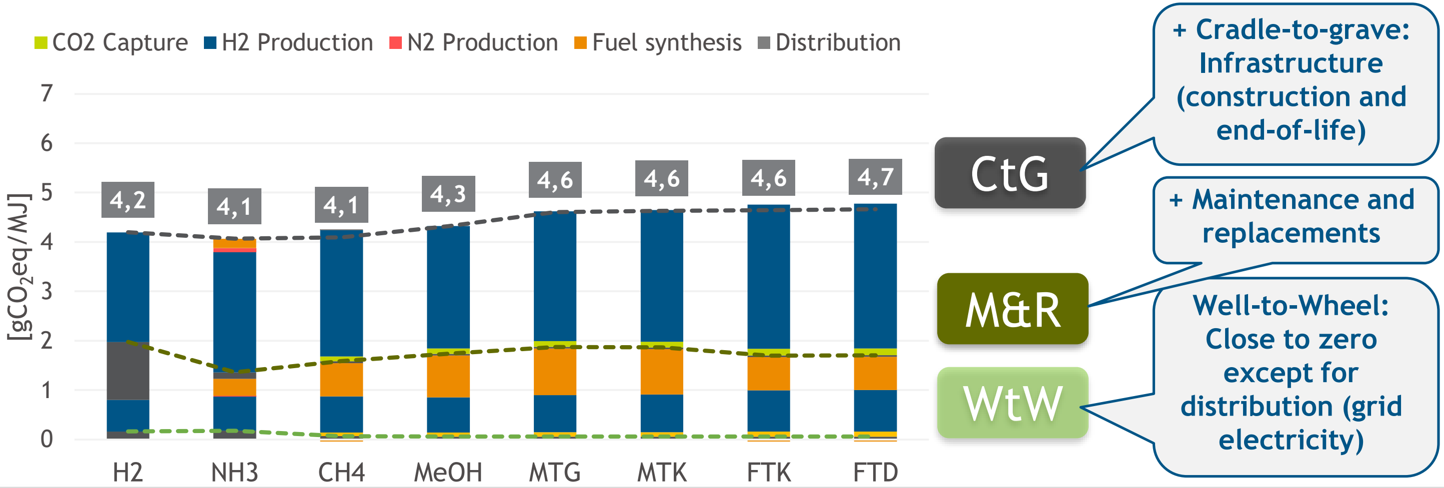
Legend:
MTG: Methanol-to-gasoline
MTK: Methanol-to-kero
FTK: Fischer-Tropsch kero
FTD: Fischer-Tropsch diesel

Not shown is e-OMEx with 34% (DAC) and 28% (concentrated source) efficiency due to high processing needs

2. Technical assessment

Results: GHG emissions - North EU, 2050

Cradle-to-Grave (CtG) emissions are similar for all the pathways: The ones less energy-intensive to produce are more energy-intensive to transport



	H2	NH3	CH4	MeOH	MTG	MTK	FTK	FTD
Fossil reference* →	113.0	121.4	67.6	100.6	90.4	83.0	83.0	92.1
Reduction vs fossil →	-96%	-97%	-94%	-96%	-95% **	-94% **	-94% **	-95% **

*Source: JEC WtT Study v5, GaBi Database

**Additional reduction if RED II fossil fuel comparator (94 gCO$_2$eq/MJ) is used

E-fuels achieve up to 94-97% GHG reduction vs fossil alternatives

Concawe

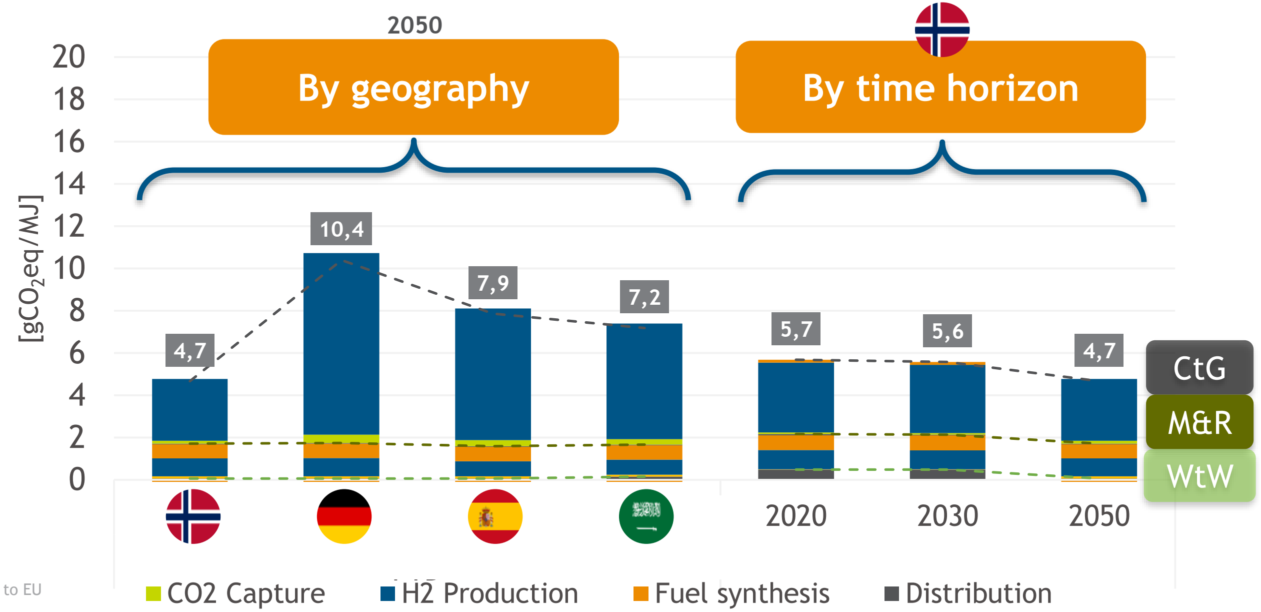
Excluding e-OMEx with 10.6 g CO$_2$eq/MJ due to the higher processing due to the complexity of the molecule

2. Technical assessment

Sensitivities: Impact of geography & time (example: e-kerosene)

E-fuels produced in North EU show the lowest emissions, followed by MENA(1), South and Central EU due to source types and full load hours of renewable electricity available

CtG emissions decrease by 18% between 2020 and 2050 due to improvement of electrolysis efficiency & use of e-fuels for transport, despite lower availability of CO_2 concentrated sources



* E-fuels produced in MENA and imported to EU

Agenda

1. Background
2. Technical assessment
3. **Economic assessment**
4. Conclusions

3. Economic assessment

Approach & key assumptions

- Comparison of 9 e-fuels and 4+ geographies via >100 different e-fuel supply pathways requires a ‘helicopter view’
- **Full cost** assessment, i.e. no business case/cashflow analysis, no NPV
- Costs comprise **CAPEX** (annualized via Excel ‘PMT’ function) and **OPEX** (all nominal, no accounting for inflation)
- All costs are expressed in real terms in constant euros (2020)
- Depreciation time = process-specific **lifetime**, typically **20-25 years**
- **Discount rate: 8%** (baseline), 4% (sensitivity low) and 12% (sensitivity high)
- **New plants** (renewables, conversion, upgrading) are assumed for each time horizon (2020, 2030, 2050)
- **Technology learning** is taken into account
- **Electricity costs**[1]: The CAPEX and OPEX of renewable electricity are based on real plants and extrapolated to the future via technology learning curves.
- **Electricity mix**: 50%/50% installed capacity of wind/PV plants (EU North: offshore wind); region-specific capacity factor
- **Electrolyser cost** (proxy: alkaline):
  - CAPEX decreases from 1027 €/kW_e in 2020 to 393 €/kW_e in 2050 based on [Zauner et al. 2019] (component costs) and [H2A 2018] (indirect costs)
  - OPEX including stack replacement are assumed to be 2% of CAPEX without indirect costs base on [Zauner et al. 2019]
- **DAC capex**: 940 M€ for a capacity of 433 t CO_2/h

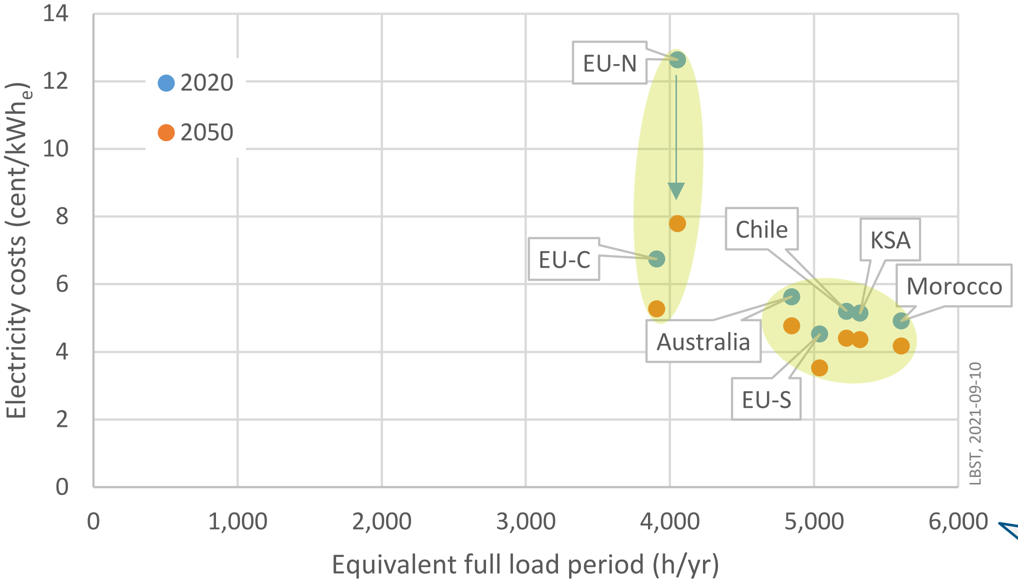
[1] <u>Sources</u>: [BET et al. 2019], [Collgar Wind Farm 2021], [Cossu et al. 2021], [CWP 2021], [Deutsche WindGuard 2015], [Deutsche WindGuard & ZSW 2018], [Edify 2021a[, [Edify 2021b], [Enel 2021a], [Enel 2021b], [Enel 2021c], [Fasihi et al. 2016], [IRENA 2019a], [IRENA 2019b], [ISE 2018], [IWES 2017], [Masen 2019], [NAREVA 2021a], [NAREVA 2021b], [NEOEN 2021], [Power Technology 2014], [Power Technology 2017], [REN21 2021], [Renewables Now 2021], [REVE 01/2020], [REVE 04/2021], [REVE 10/2020], [The Wind Power 2017], [Wind Energy – The Facts 2021], [Windpower Monthly 2020]

Concawe

3. Economic assessment

Key assumptions: Electricity supply costs (€ct/kWh$_e$) for baseline assessments*

The spread in renewable electricity supply costs may be greater within a single country than across countries with similar geographies



EU-North: Offshore wind
Other regions: PV/wind hybrid

Example (€/kWh$_e$):

RE source / Region	PV	Wind onshore	Hybrid plant
EU-Central 2020	0.055	0.069	0.067*
EU-Central 2050	0.037	0.061	0.053*

Same values assumed for PtX plant operation (incl. buffer storage)

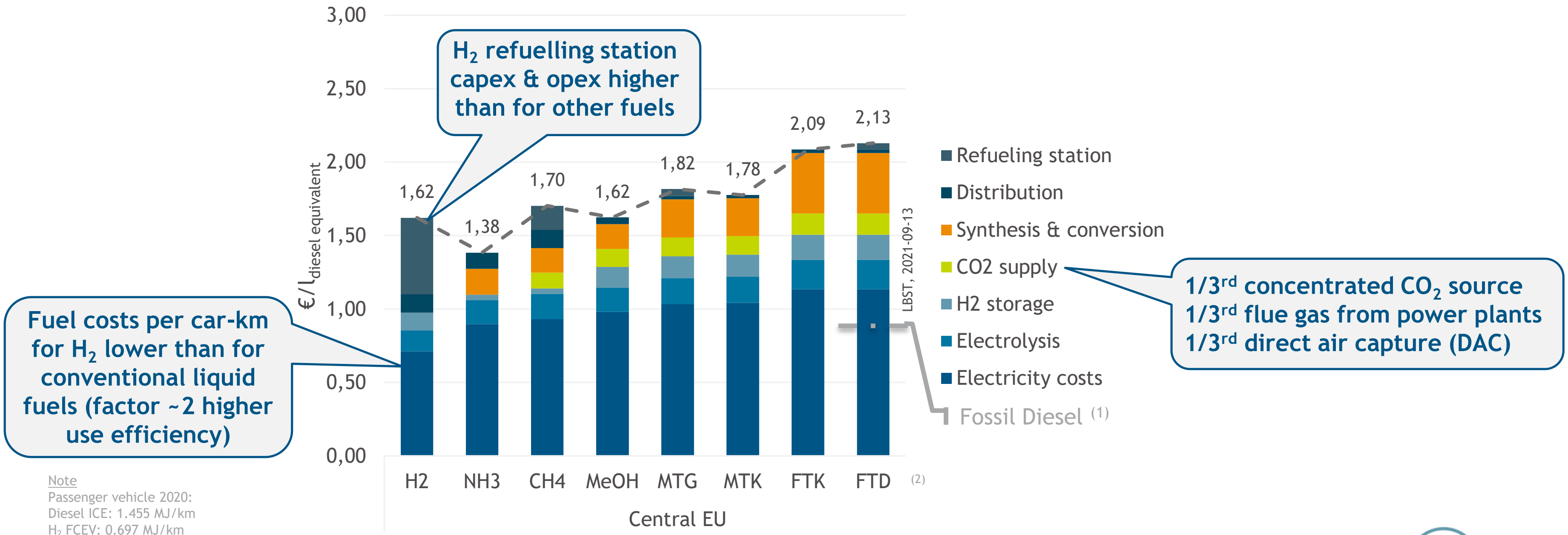
** 5% overlap (curtailed) analogous to [Fasihi et al. 2016] for PV/wind hybrid and including HVDC in regions outside Europe*

Concawe

3. Economic assessment

Results: Costs of fuel supply - Example (EU Central, 2050)

E-fuels that are less energy-intensive generally lead to lower costs of fuel supply



Note
Passenger vehicle 2020:
Diesel ICE: 1.455 MJ/km
H_2 FCEV: 0.697 MJ/km
=> Factor 2.09 [JEC WTW 2020]

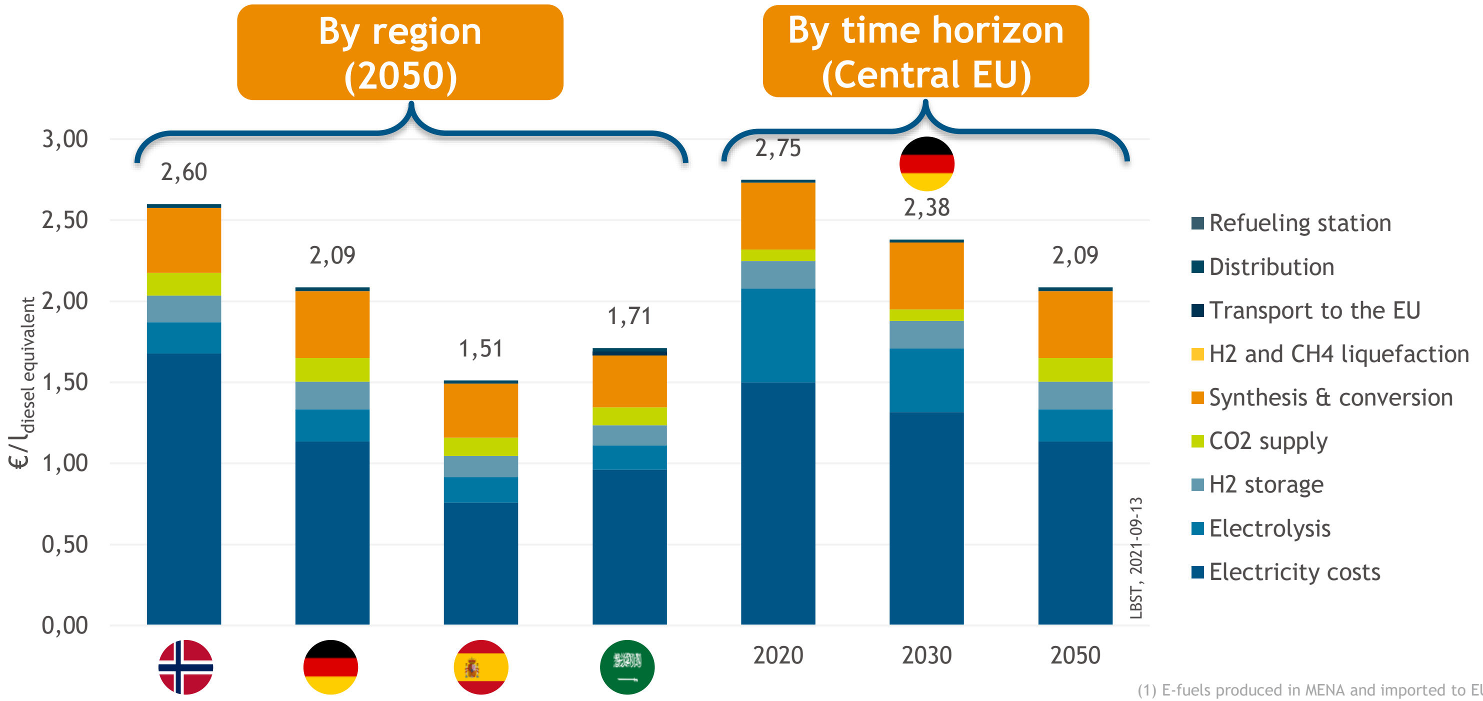
Note
(1) Diesel price: 0.3 €/l (2020) - 0.8 €/l (2050), with crude-oil prices (40 €/bbl (2020)-110 €/bbl (2050) taken from the EU Commission Impact Assessment
(2) e-OME$_x$ production cost: 2.67 €/l

3. Economic assessment

Results: Impact of geography & time (example: e-kerosene)

E-fuels produced in South EU shows the lowest fuel costs, followed by **MENA[(1)]**, **Central** and **North EU**

E-fuels costs are reduced with time (24%) due to decreasing CAPEX for wind & PV plants, electrolysis, and improvement of electrolysis efficiency despite lower availability of CO_2 concentrated sources



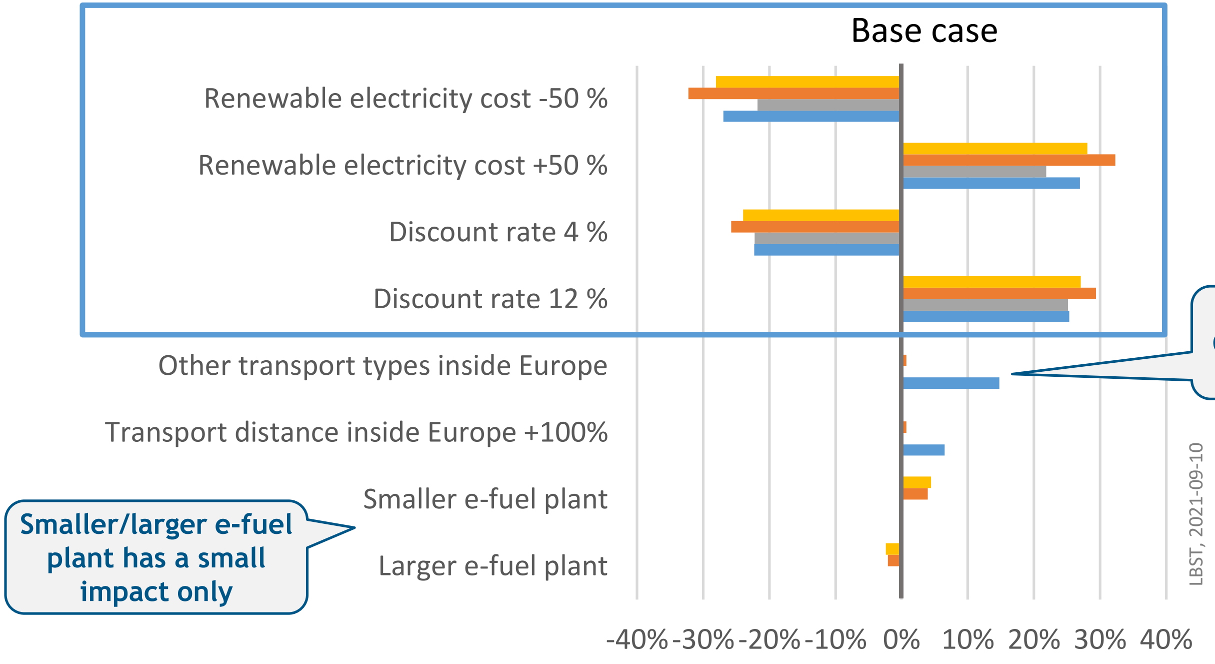
(1) E-fuels produced in MENA and imported to EU

Concawe

3. Economic assessment

Sensitivities - A sub-set of 2050 pathways has been sensitivity-tested

Electricity costs and discount rate have a significant impact on overall fuel supply costs



Base case assumptions:

- Electricity EU-N: 7.8 €ct/kWh
- Electricity MENA: 4.4 €ct/kWh
- Discount rate: 8%
- Transport inside Europe:
  - Liquid fuels: 150 km pipeline/FT plant + 150 km truck
  - Hydrogen: ~5.5 km pipeline/refuelling station
- Capacity e-fuel plant: 1 Mt diesel equivalent/yr (114 t/h)

Note: The choice of ±50% just implies a "symmetrical" range of probability, is hypothetical and does not reflect a real probability. Ditto for the discount rate 4-12% range which actually associates with different countries; the range for a single country is smaller.

Concawe

Agenda

1. Background
2. Technical assessment
3. Economic assessment
4. **Conclusions**

4. Conclusions

Key results

- 9 base cases for 4 geographies + other sensitivities => **>100 pathways assessed**

- Based on the assumptions taken, this techno-environmental-economic assessment of e-fuels towards 2050 shows that:

  - **E-fuels efficiency**
    - **Lower energy efficiency linked to higher processing fuel routes (routes with higher drop-in fossil replacement in existing fleet, that would require new fleet and infrastructure, such as e-H_2 or e-NH_3)**
    - **Increase of ~10% points in efficiency if concentrated CO_2 source vs DAC**

  - **E-fuels GHG emissions**
    - **E-fuels CtG emissions are similar for all the pathways analysed and achieve reductions up to 93-96% vs fossil alternatives (North EU 2050)**
    - **E-fuels produced in North EU show the lowest emissions, followed by MENA[(1)], South and Central EU**
    - **Decrease of CtG emissions of ~18% expected between 2020 and 2050**

  - **E-fuels production costs**
    - **Fuel supply costs of 1.5 – 4.1 €/l of diesel-equiv. in 2020 and 1.0 – 2.6 €/l in 2050[(2)], mainly influenced by electricity costs assumptions**
    - **E-fuels produced in South EU shows the lowest fuel costs, followed by MENA[(1)], Central and North EU**
    - **Key sensitivities: ±50% change of electricity supply costs or discount rate assumptions resulted in ±25% supply cost**

* E-fuels produced in MENA and imported to EU. Import terminal: South of EU

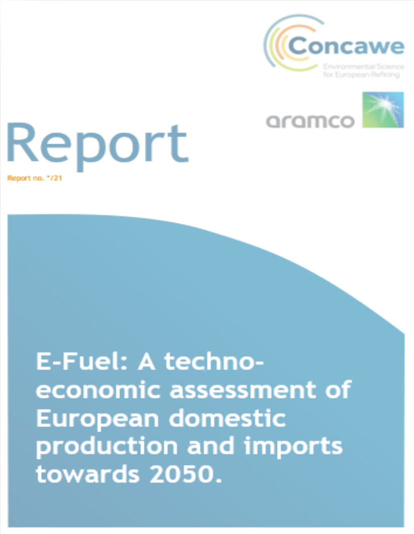
[2] Across geographies, excluding outlier OMEx with 2.6-5.4 and 1.9-3.5 €/l respectively

Concawe

4. Conclusions

We invite you to have a look to the final publication!

- The full techno-economic assessment will also include (work-in progress):
  - An optimization of the intermittency of the renewable electricity source vs storage capacity and conversion plant size
  - A comparison of an e-fuel plant integrated into a refinery vs. a stand-alone plant



Report to be published by end 2021!

Thank you!

aramco

Concawe
Environmental Science for European Refining

LBST
ludwig bölkow systemtechnik

E4tech

Thank you for your attention

Alba Soler (Concawe): alba.soler@concawe.eu
Patrick Schmidt (LBST): Patrick.Schmidt@lbst.de
Victor Gordillo (Aramco): victor.gordillo@aramcooverseas.com

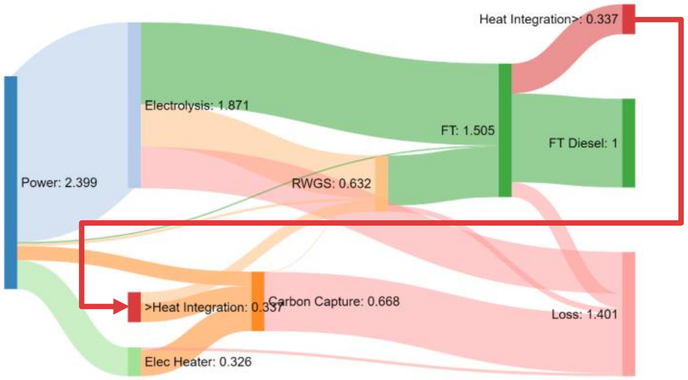
A

Annex

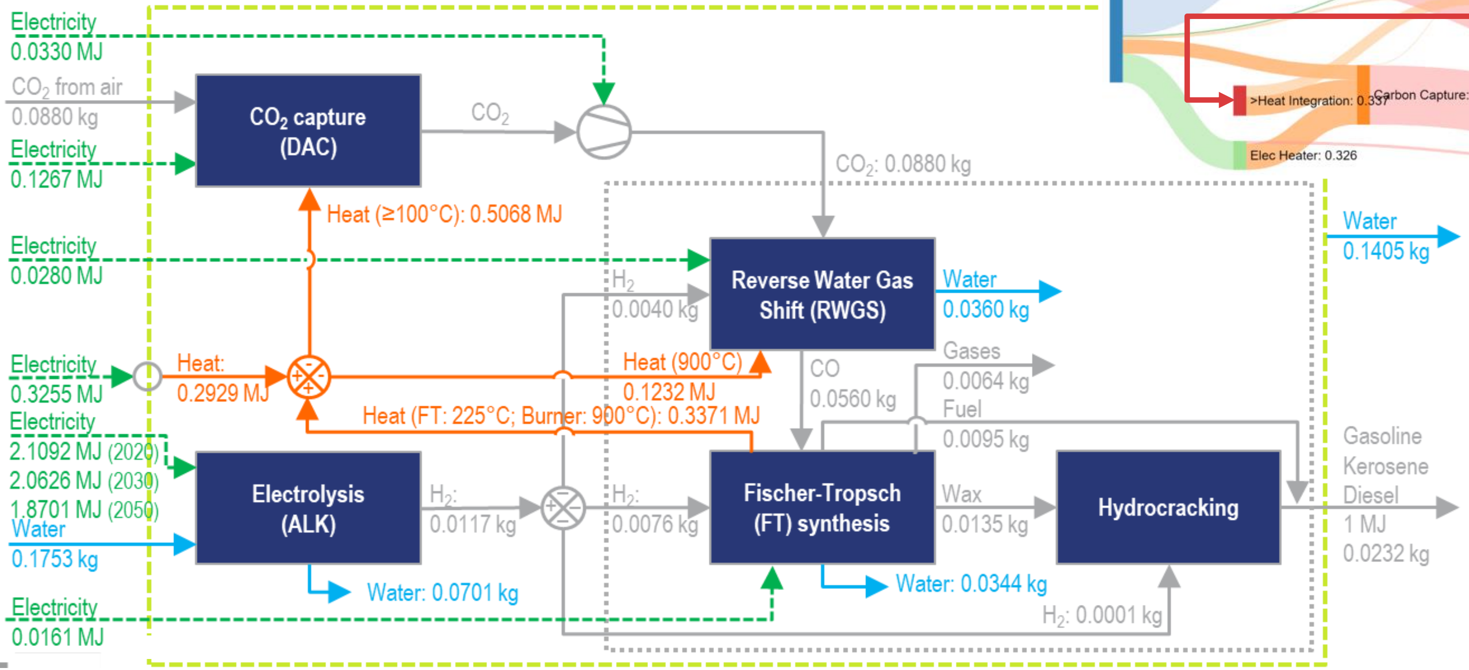
2. Technical assessment

E-fuels pathways – Fischer-Tropsch via DAC

Energy Sankey diagram



Mass and energy balances



Concawe