PSI Center for Energy and Environmental Sciences

Global Production and Trade Pathways of Low-Carbon Fuels

Trade-offs between liquid bio- and e-fuels

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Today, global trade of energy carriers is fossil. Tomorrow?

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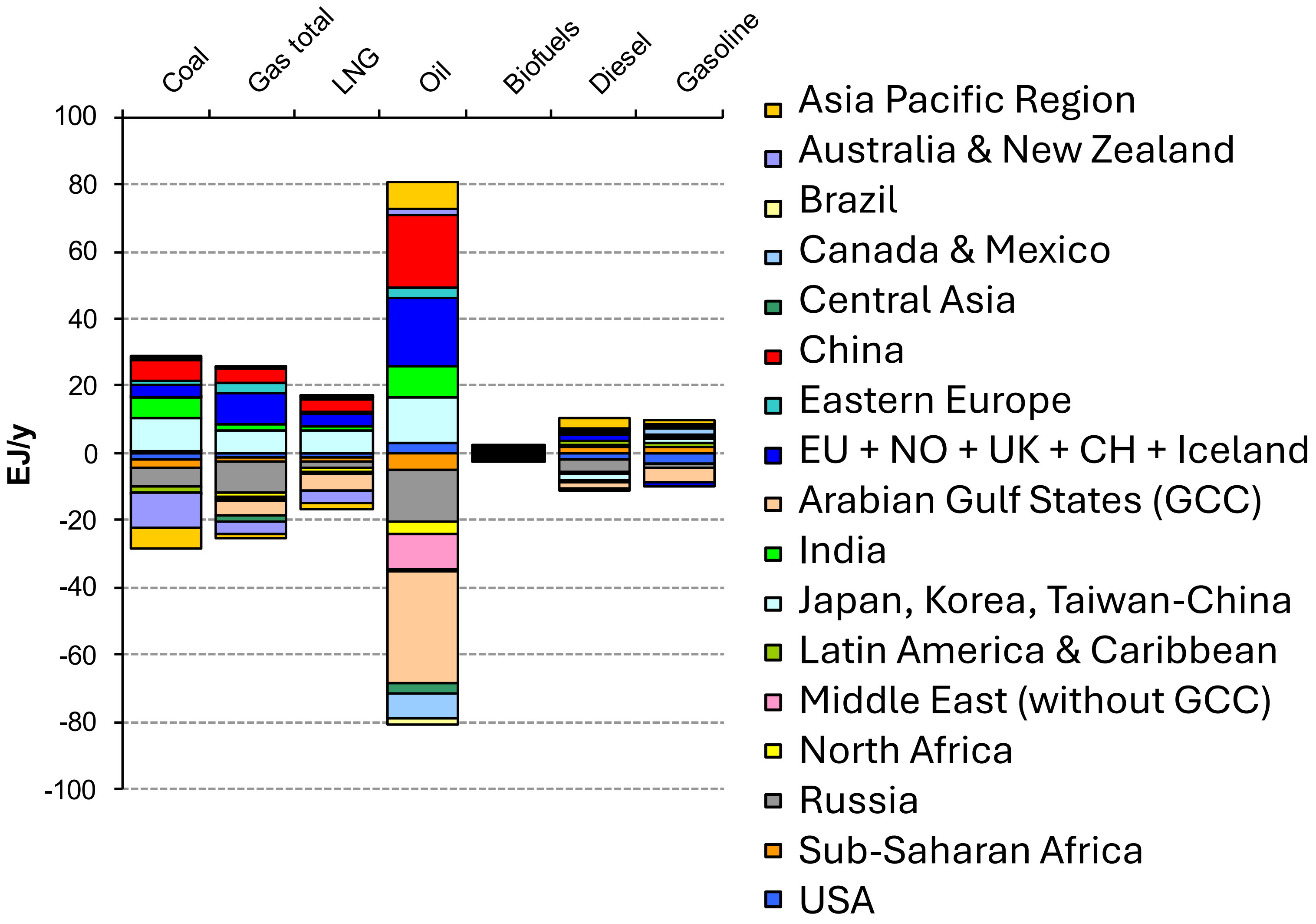
Energy carrier import (+) / export (-) among world regions



Year 2020 values (IEA, Energy statistics, 2022)

NEOM, Saudi Arabia, 4 GW electrolyzer from wind & solar in year 2027+

https://nghc.com/news/worlds-largest-green-hydrogen-plant-reaches-80-construction-completion-across-all-sites/

Motivation

Several global studies on low carbon-fuels either:

- are **Europe-centric:** Rest of the world has the role of a supplier for Europe
- use **normative** scenarios with regional (autarchy) targets or single-sector use
- Consider either **biofuels,** or **e-fuels,** or only **100% green** alternative fuels
  - Liu, Zhang, Bauer, McKenna (2025): Review on low-carbon fuels in Energy-System Models
  - IEA (2024): Report on E-fuels in Decarbonising Transport; World Energy Outlook Scenarios

Our analysis:

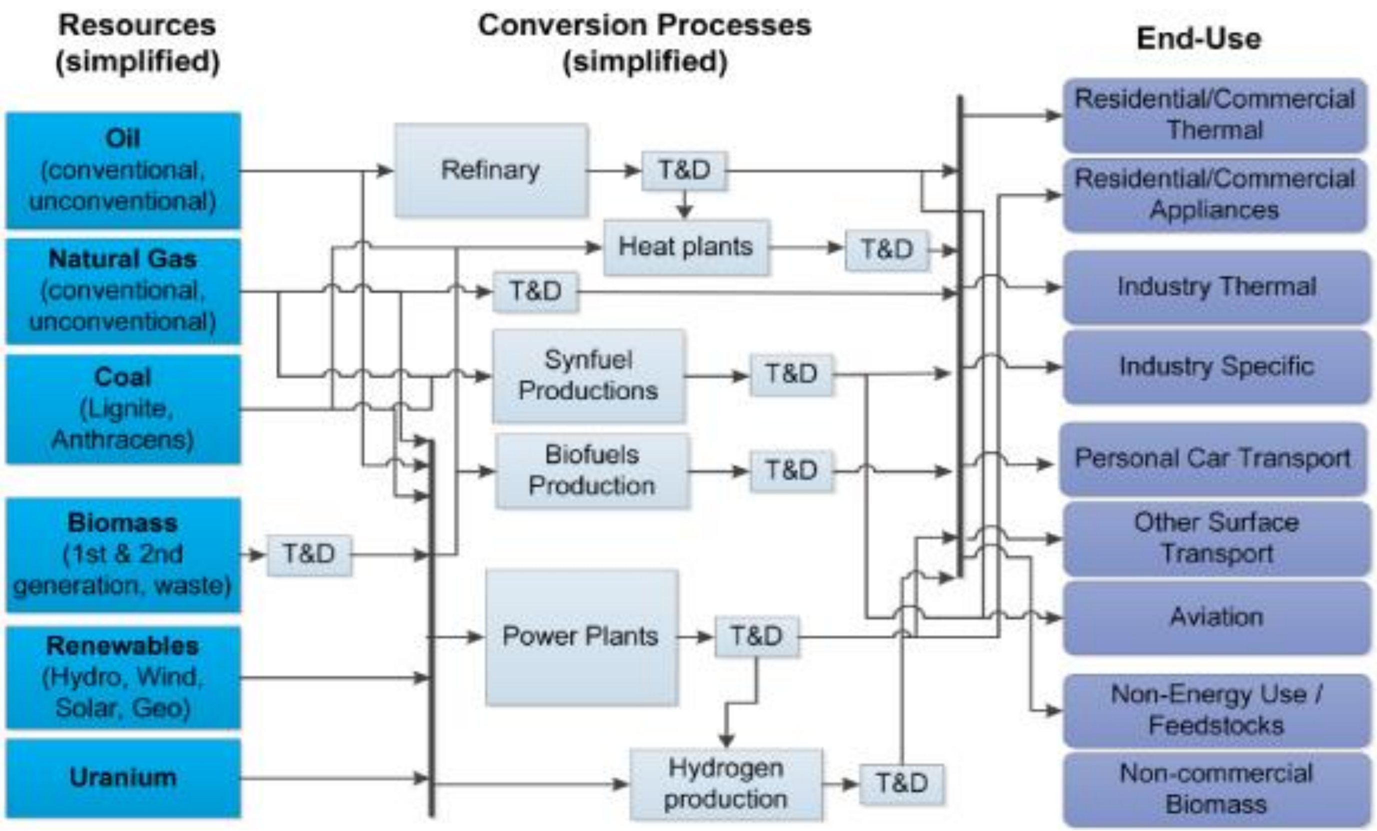
- Future production mixes & usage of low-carbon-fuels under stringent climate scenario
- Focus on major export world regions
- Assumption: On a macro-scale, the world is market-driven and trade-oriented, at least for exporter regions (i.e., outside the EU)

  → Single major policy driver is an internationally stringent carbon price proxy.

Traditional cost-optimal analysis

GMM = Global Multi-Regional Market-Allocation (MARKAL) model:

- Detailed **supply-side** energy-system model to satisfy sectorial useful energy demands
- 400+ technologies with technical-economic characteristics

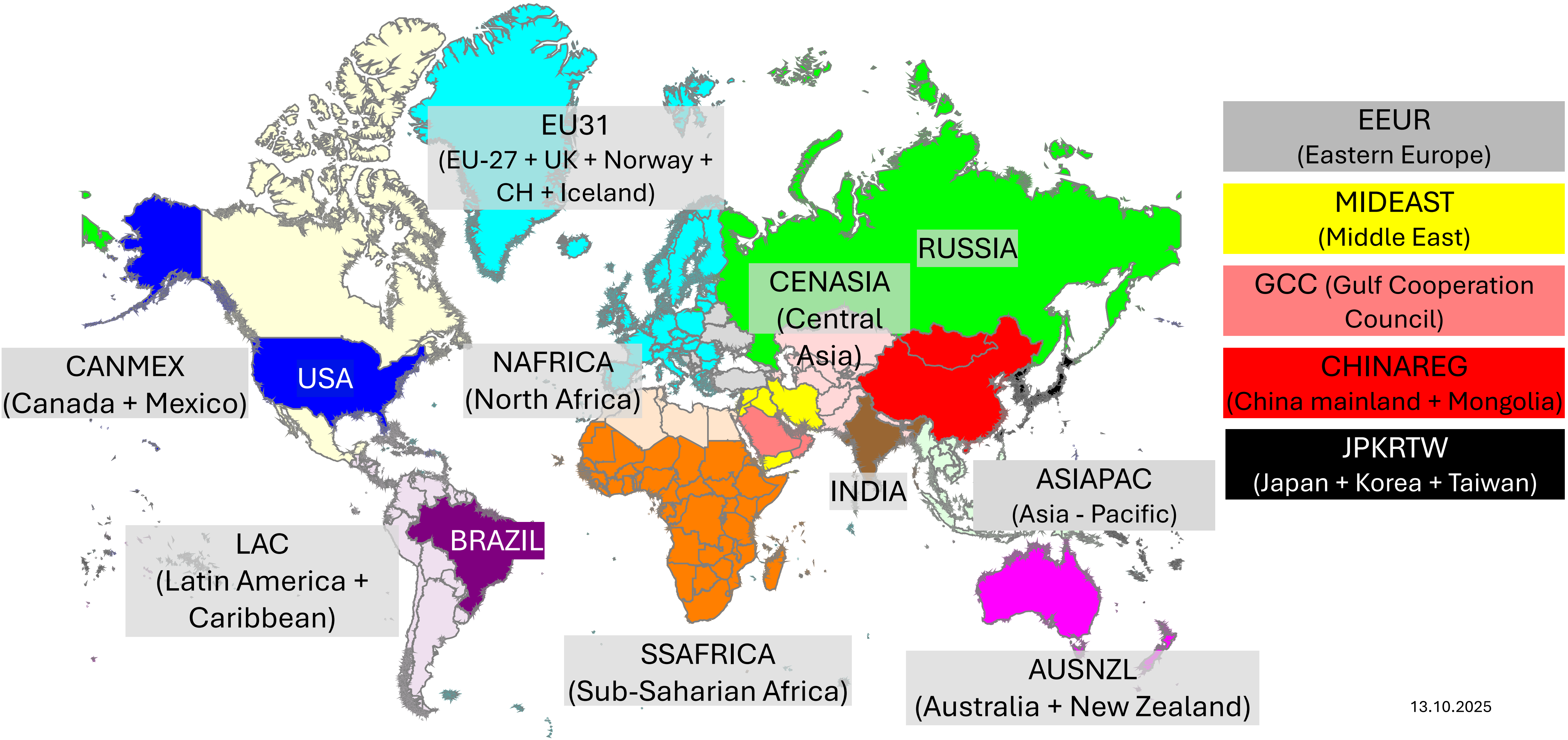


- System-cost minimization through optimal build-up/allocation of technologies under CO2 prices
- Aggregated demand sectors: E.g. “Other Surface Transport” (= Bus, Truck, Rail, Ship)
- 10-year investment time-steps; 6 time-slices per year for electricity: Winter / Intermediate / Summer and Night/Day.
- Reported time-horizon is 2060; model is run until 2110 (resource depletion)
- 17 world regions

«T&D» = transport and distribution

17 World Regions are Modelled

Regions are different in energy resource potentials, demand growths, power sector costs



Nomenclatura of alternative fules (in this talk only!)

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1st gen Biomass

- Human-edible: Corn grains, Sugar cane, oil crops,
- Domestic waste

2nd gen Biomass

Ligno-cellulosic biomass:

- Wood (residues)
- Stover

Biofuels (conventional)

Bio-diesel, -ethanol, -methanol (from 1st gen biomass)

Synfuels (ren, “green”)

- **Liquid** fuels from **hydrogen (ren.), solar processes, 2nd gen biomass** (via syngas or other thermo-chemical conversion)
- **CO2 only from DAC** (in base case)

Synfuels (fossil, n-ren)

- **Liquid** e-fuels (from any hydrogen or carbon source)
- **Liquid** biofuels from any biomass via any process

Liquid e-fuels from hydrogen

Hydrogen (ren, “green”)

From:

- renewable electricity, or
- 2nd gen biomass

Hydrogen (fossil, n-ren)

From any source:
“Grey”, “pink”, “blue”, “turquoise”

- **Single, international pooled markets** for each fuel
  - **H2 transport:** long-distance transport with ammonia (or existing LPG) tanker ships. Equal costs for each world region. Inside regions: Truck or pipeline (if not decentral)
- **Data of synthetic fuel production technologies:** Project of Swiss Federal Office of Energy (report under revision)

Alternative fuel production technologies in GMM (I)

Fuel	Technology	Output
from fossil fuels		
Natural gas	SMR - FT; ATR - FT	Liquid Fuel
Natural gas	Solar reforming - FT	Liquid Fuel
Coal	Gasification - FT	Liquid Fuel
Natural gas	SMR - catalyst	Methanol

from biomass		
Sugar crops, corn grains, stover	conventional via Fermentation; Cellulosic dissection	Ethanol
Wood	Gasification	Bio-Methanol
Oil crops, wood	Transesterification; Pyrolysis	Biodiesel, incl. FAME (fatty acid methyl esters)
Oil crops	Esterification	Liquid Biofuel, incl. FAEE (fatty acid ethyl esters)
Wood, domestic waste	Anaerobic Domestic Waste Digestion (electricity co-generation)	Biogas, incl. DME (dimethyl ether)
2nd gen biomass	Gasification - FT	(sustainable) Liquid Fuel
2nd gen biomass	Pyrolysis	(sustainable) Liquid Fuel

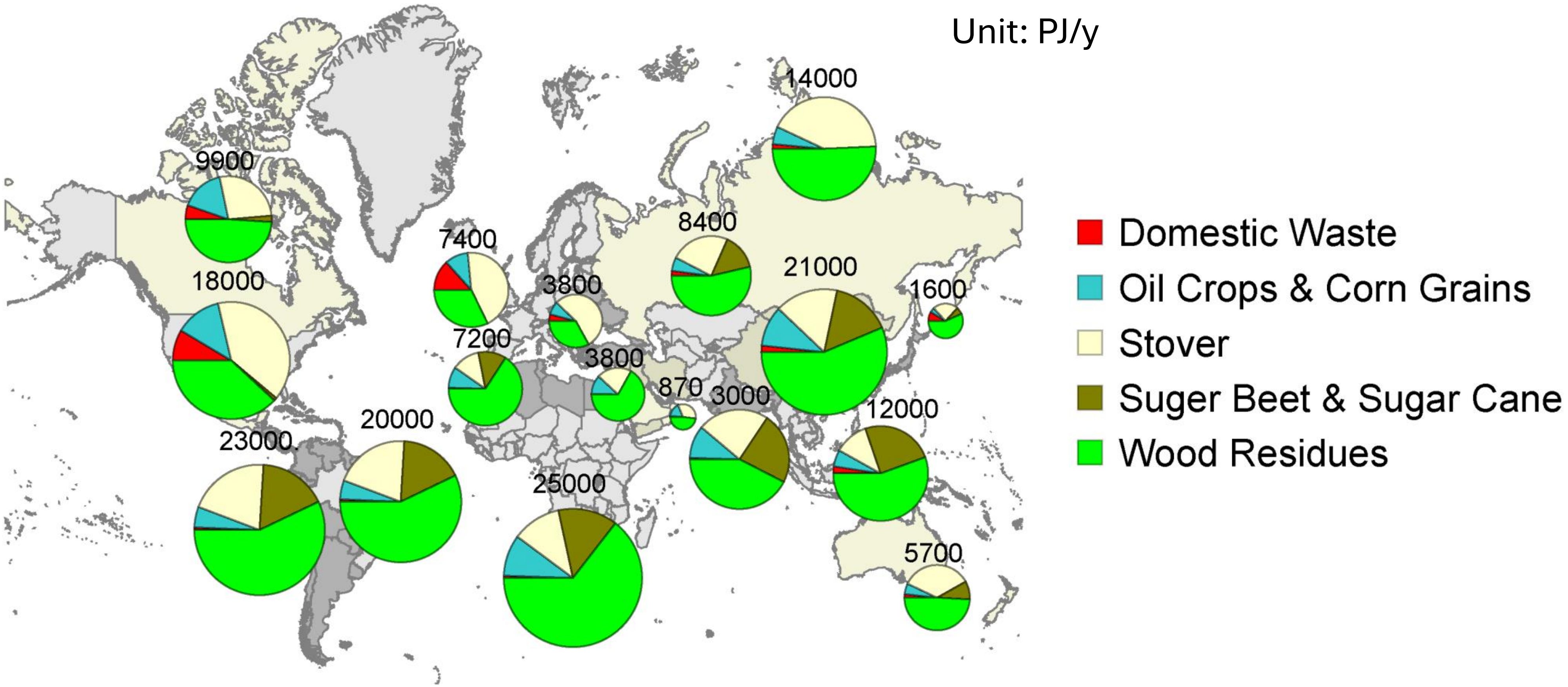
Alternative fuel production technologies in GMM (II)

Fuel	Technology	Output
from hydrogen or solar		
Hydrogen (renewable and non-renewable), any CO_2 source	RWGS - FT	Liquid Fuel
Hydrogen (renewable and non-renewable), any CO_2 source	RWGS	Methanol
Renewable hydrogen, DAC	RWGS - FT	Renewable liquid Fuel
Water, DAC	Solar thermal - FT	Renewable liquid Fuel

Hydrogen production		
Grid electricity	PEM, AE	“Grey” hydrogen
Nuclear heat/electricity	Cu-Cl and others	Pink hydrogen
Natural gas	SMR; ATR; CLR; with CCS	Blue/Grey hydrogen
Natural gas	Pyrolysis	Turquoise hydrogen, solid carbon
Renewable electricity	PEM, AE, SOE	Green (sustainable) hydrogen
2nd generation biomass	Gasification, with CCS	Green (sustainable) hydrogen

Methane production		
Hydrogen	Methanation	Methane

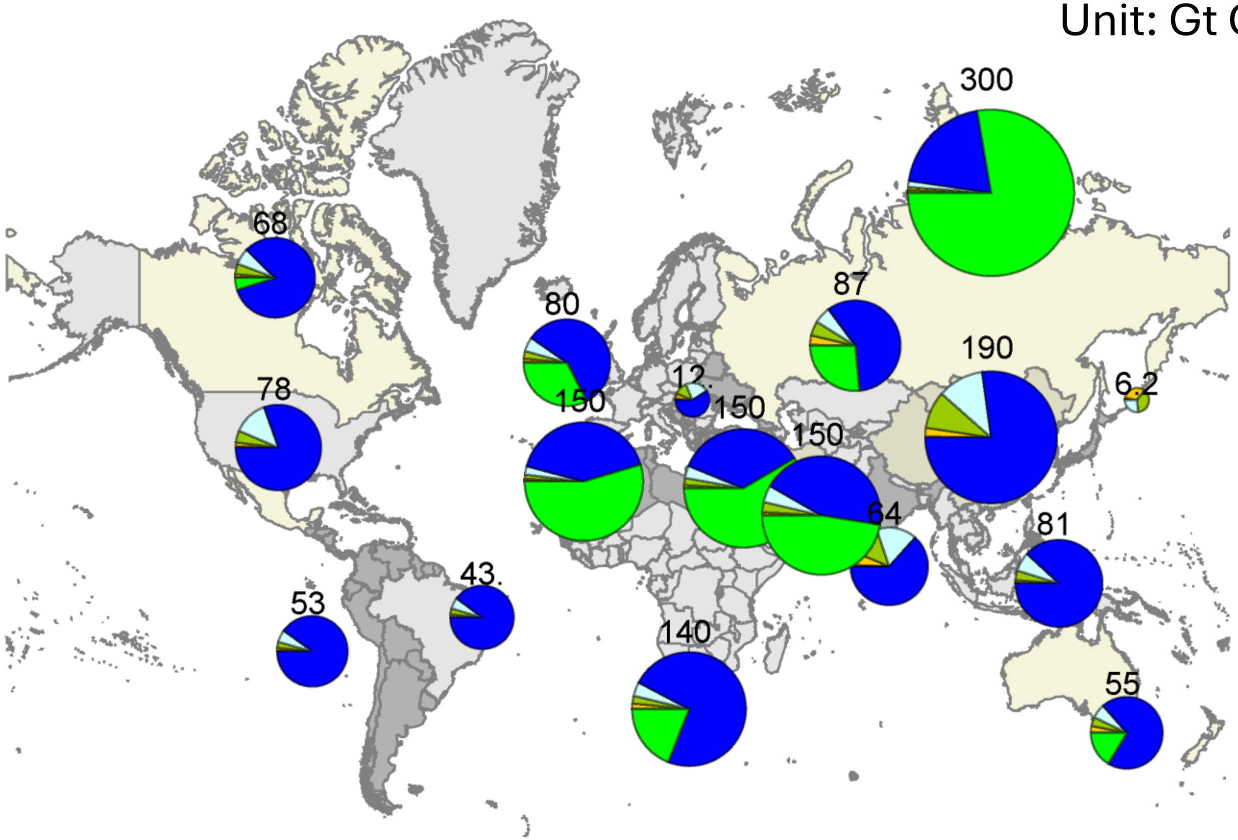
Biomass Potential in GMM



- In year 2020, global biomass use for energy = 60 EJ, primary energy supply = 609 EJ [IEA, 2023]
- Our potential assumption = 195 EJ/y (const. over time)
  - Share of wood residues > 50%
- Other estimates: 107 – 1'723 EJ/y (Slade et al., 2014), 90 – 1'590 EJ/y (Thrän et al., 2010) , 215 – 1'272 EJ/y (Smeets et al, 2007)

Carbon-Storage Potential in GMM (and results)

Unit: Gt CO2



Usage (from results):

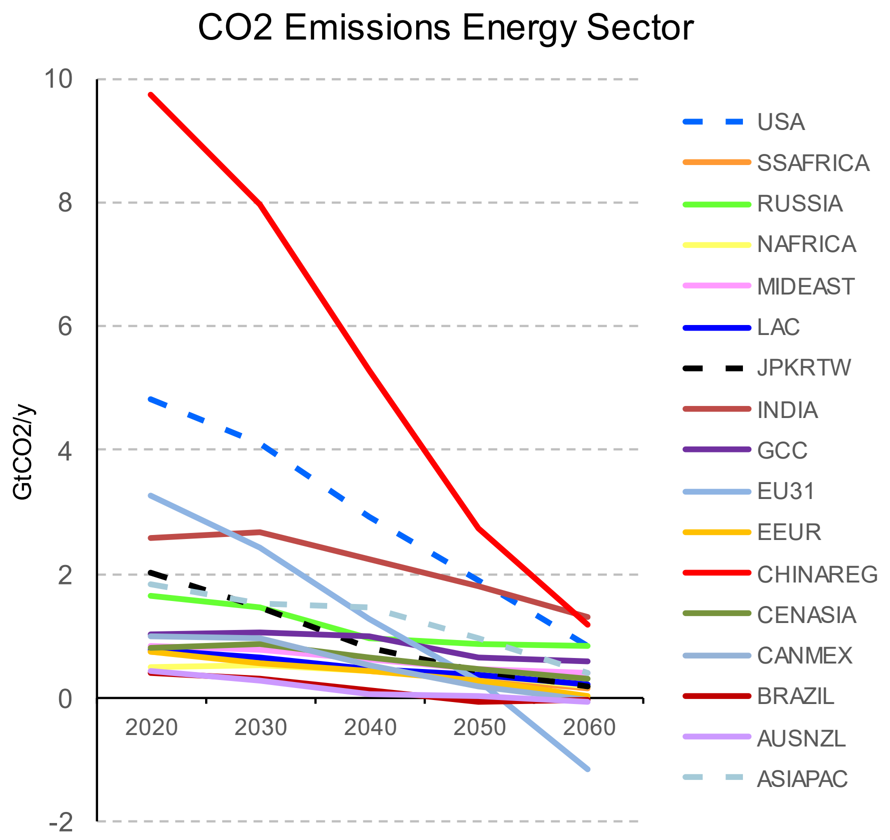
- 2020–2030
- 2030–2040
- 2040–2050
- 2050–2060
- 2060–2070
- 2070–2120
- not used until 2120

- Results: Potential is used up in region Japan/Korea/Taiwan until 2070

- Assumed potential: 1’700 Gt CO2 (Hendriks et al., 2004)
- Other estimates: 8’000 Gt CO2, «low, practical» (Kearns et al., 2017); 14’000 GtCO2 (Global CCS Institute, 2023) ; minimally practically 290 Gt CO2 (Grant et al., 2022)
- Large variation in estimates of regional costs: 4 – 45 $/tCO2 (Smith et al., 2021)

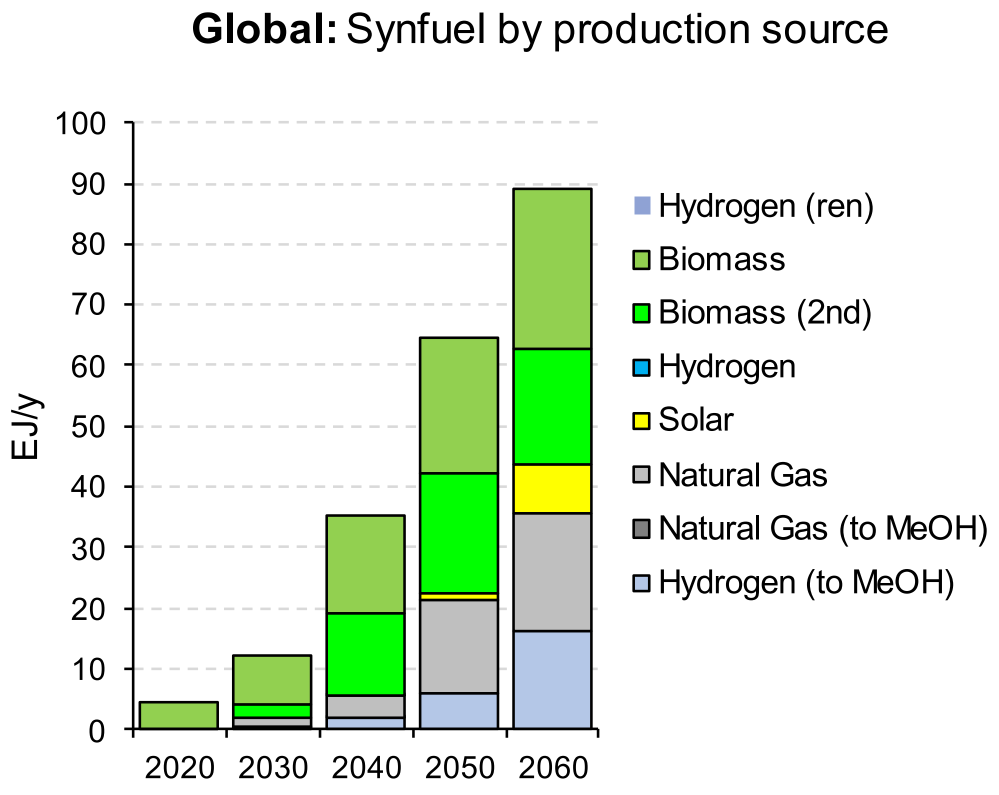
Scenario Assumptions; Result on CO2 emissions

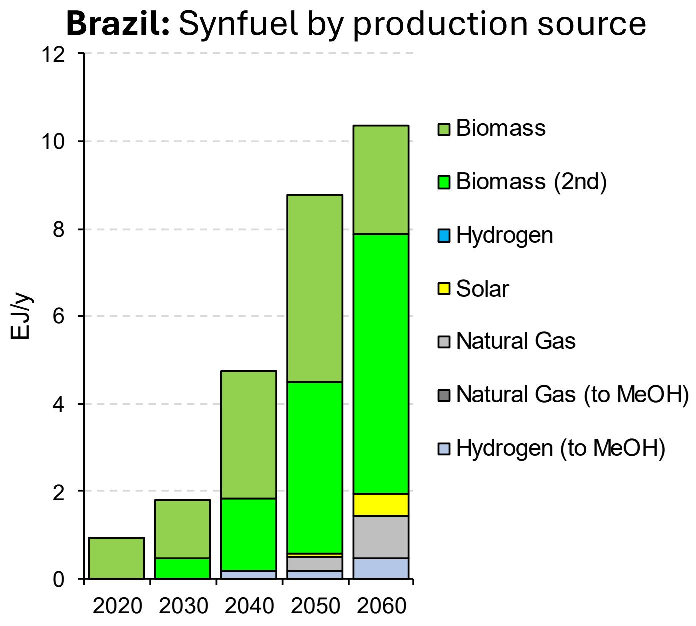
- **Strong CO2-reduction by CO2 price proxy, convergent across world regions**
- General scenario assumptions from **World Energy Council's SYMPHONY scenario (WEC & PSI, 2019):**
  - Medium growth rates of GDP & useful demands (**no major behavioural changes**)
  - Investment in CAPEX-intensive technologies possible (if cost-effective): Nuclear, new hydropower
  - CCS (Carbon-Capture & Storage) accepted and cost-effectively deployed (base case)
- Cost-driven development, only few other policy targets:
  - EU31: slightly stronger CO2 price proxy, and aviation synfuel target

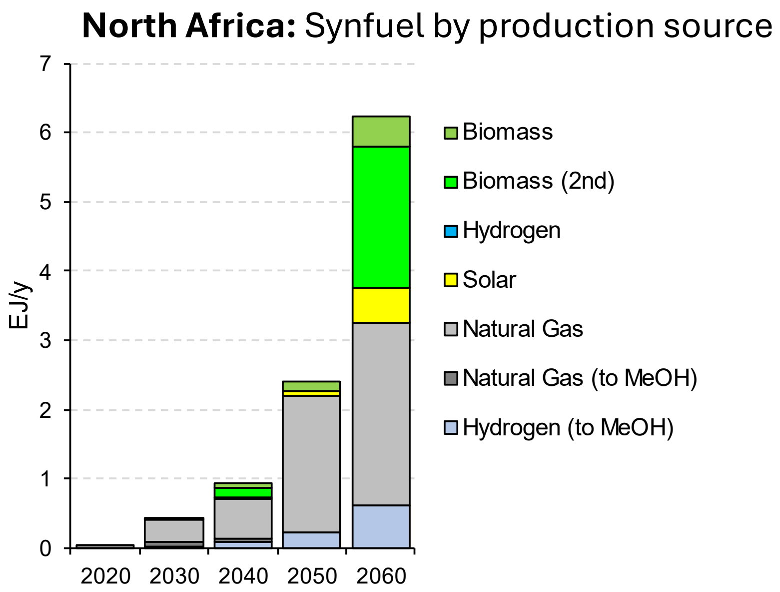


- EU31: 3.3 GtCO2/y (in 2020) → 0.3 GtCO2/y (in 2050)
- Global emissions in 2024: 37.8 Gt CO2 [IEA, 2024]
- Reduction is in IPCC's C2/C3 range **(**<= 1.5°C (>50%) after a high overshoot, <= 2°C (>67%))

Results: Cost-minimal Sources of (liquid) Synfuel Production

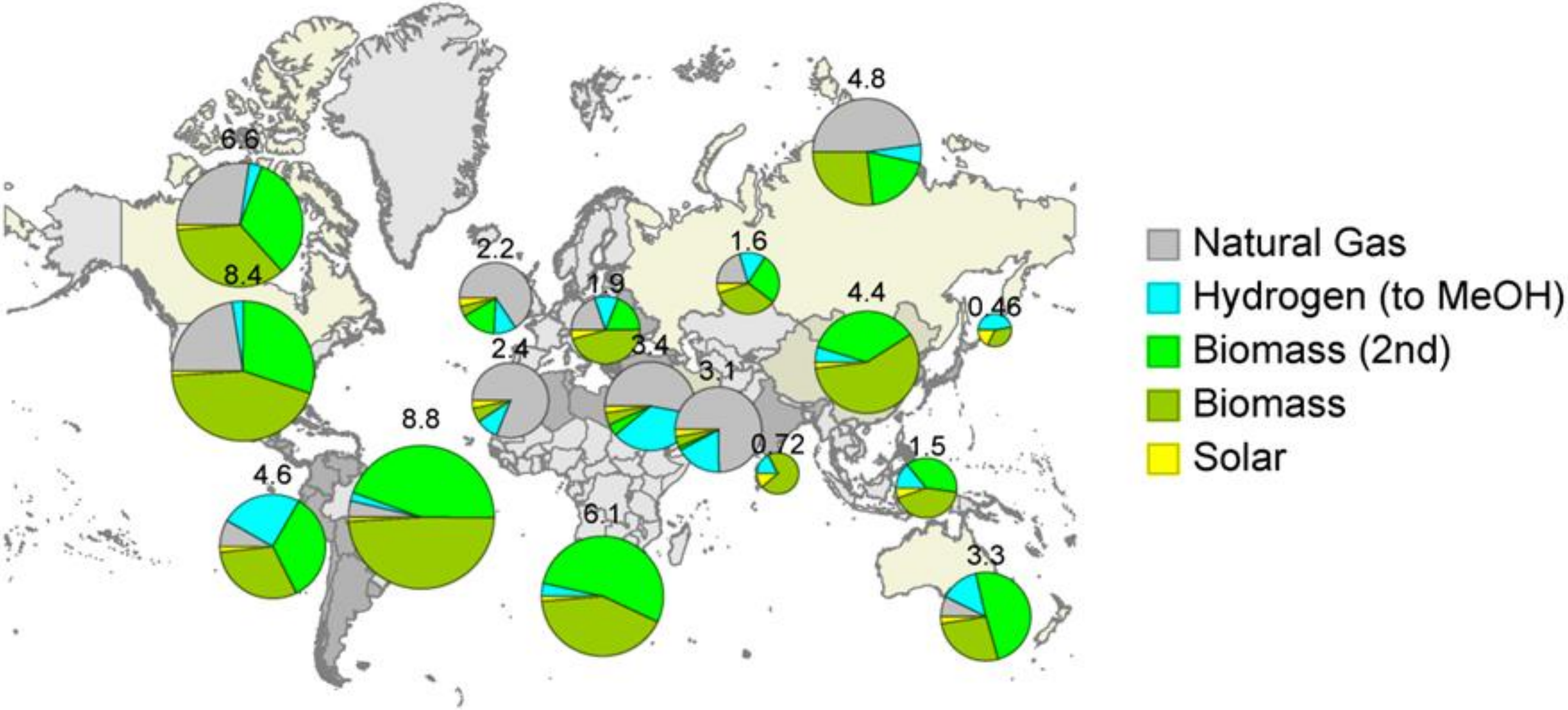






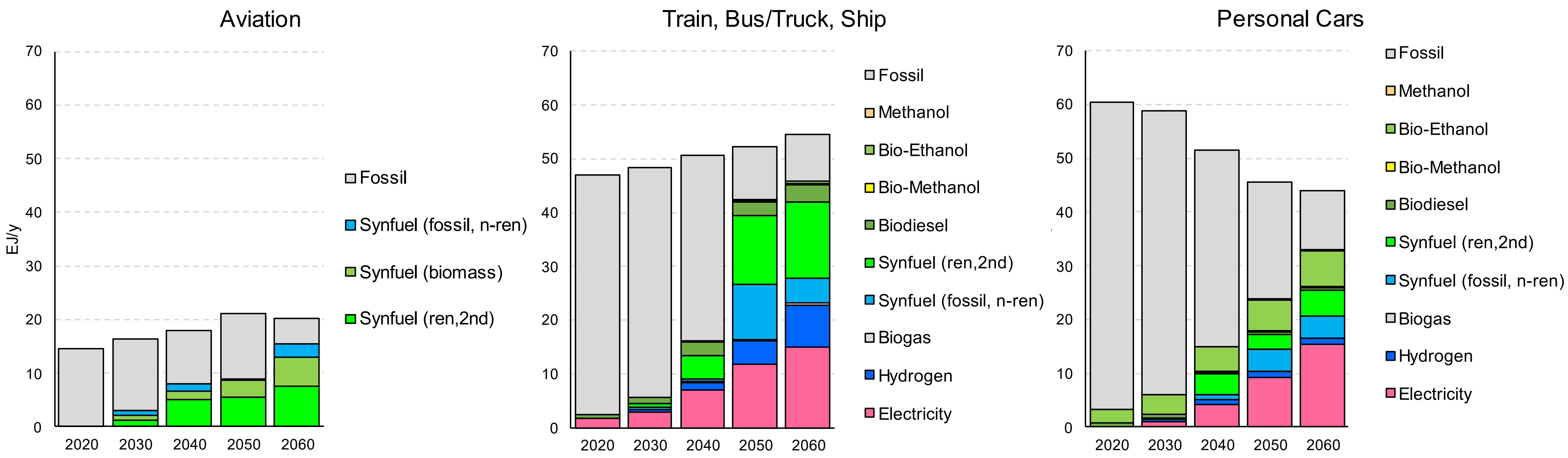
- **«Biomass»:** Mainly 1st gen. (3 EJ/y biodiesel, 8 EJ/ y ethanol in 2050)
- **«Hydrogen»**:
  - “Hydrogen (ren)” stays zero 2060+. Comparison: IEA’s range in year 2050: 2,10,13 EJ/y («low carbon hydrogen»)
  - “Hydrogen” (all sources) > 0 after 2060 in some regions

Overview: Synfuel production 2050



- Large producers: USA, Brazil, Sub-Saharan Africa
- Similar results in study McKinsey (2023): 76% investments in biofuels vs. only 24% in e-fuels in 2050

Synfuel use is mostly in transport



- Note: Personal car energy-demand decreases because of electrification
- Hydrogen: mostly for heavy surface-transport (also in form of ammonia), only marginally for personal cars
- Comparison with IEA: H2 in transport in year 2050: 6 EJ/y in IEA's APS scenario
- Methanol: very small shares in transport, but increased use in energy system (mostly from H2 in 2050)

Hydrogen Production

Examples of exporter regions:

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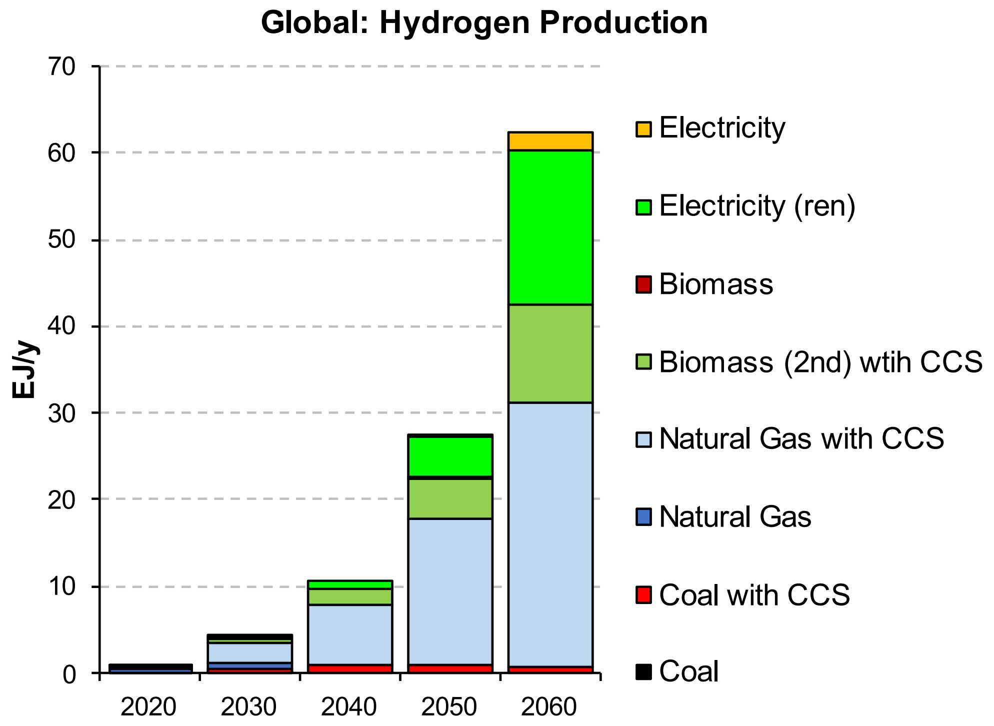
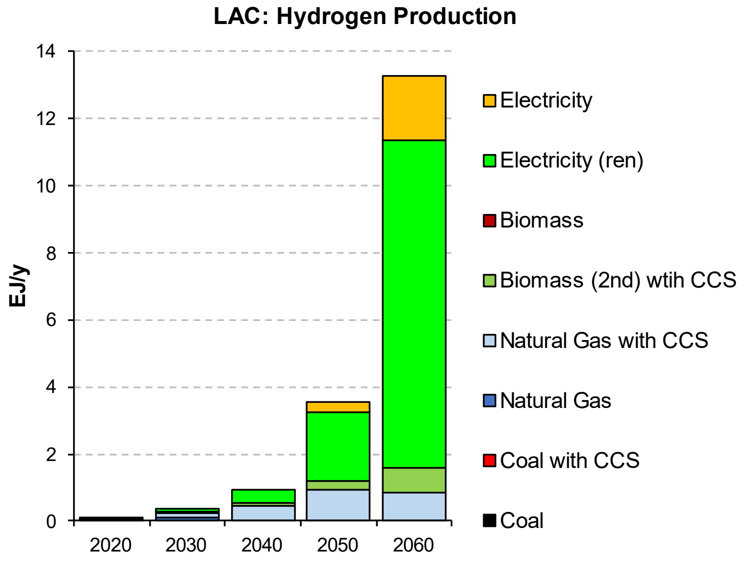
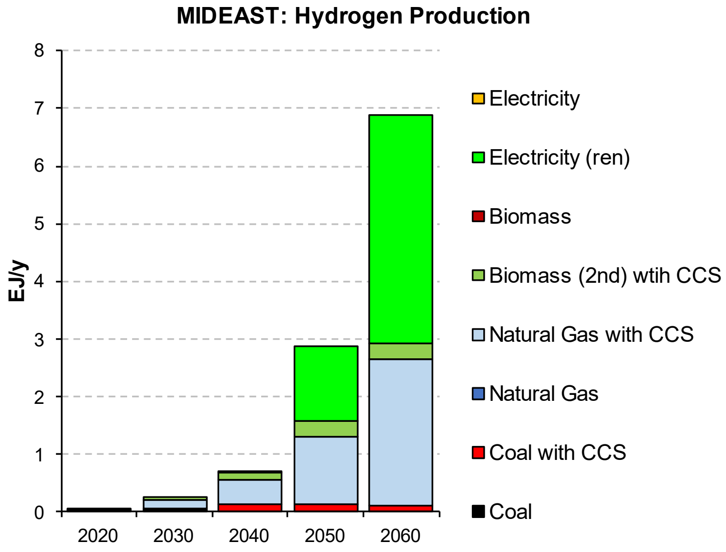
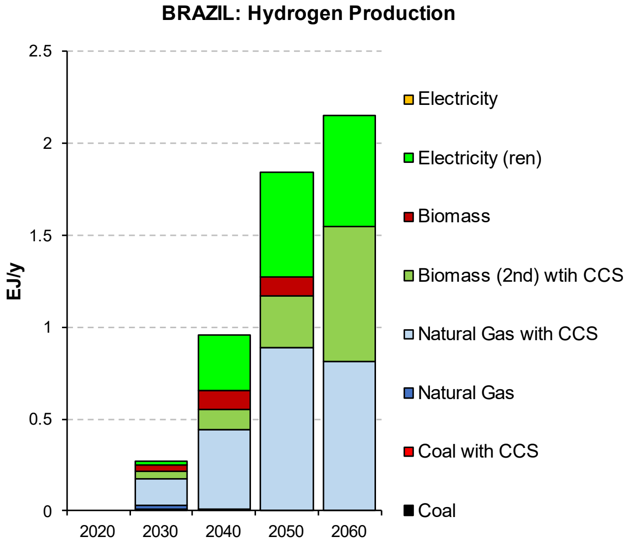




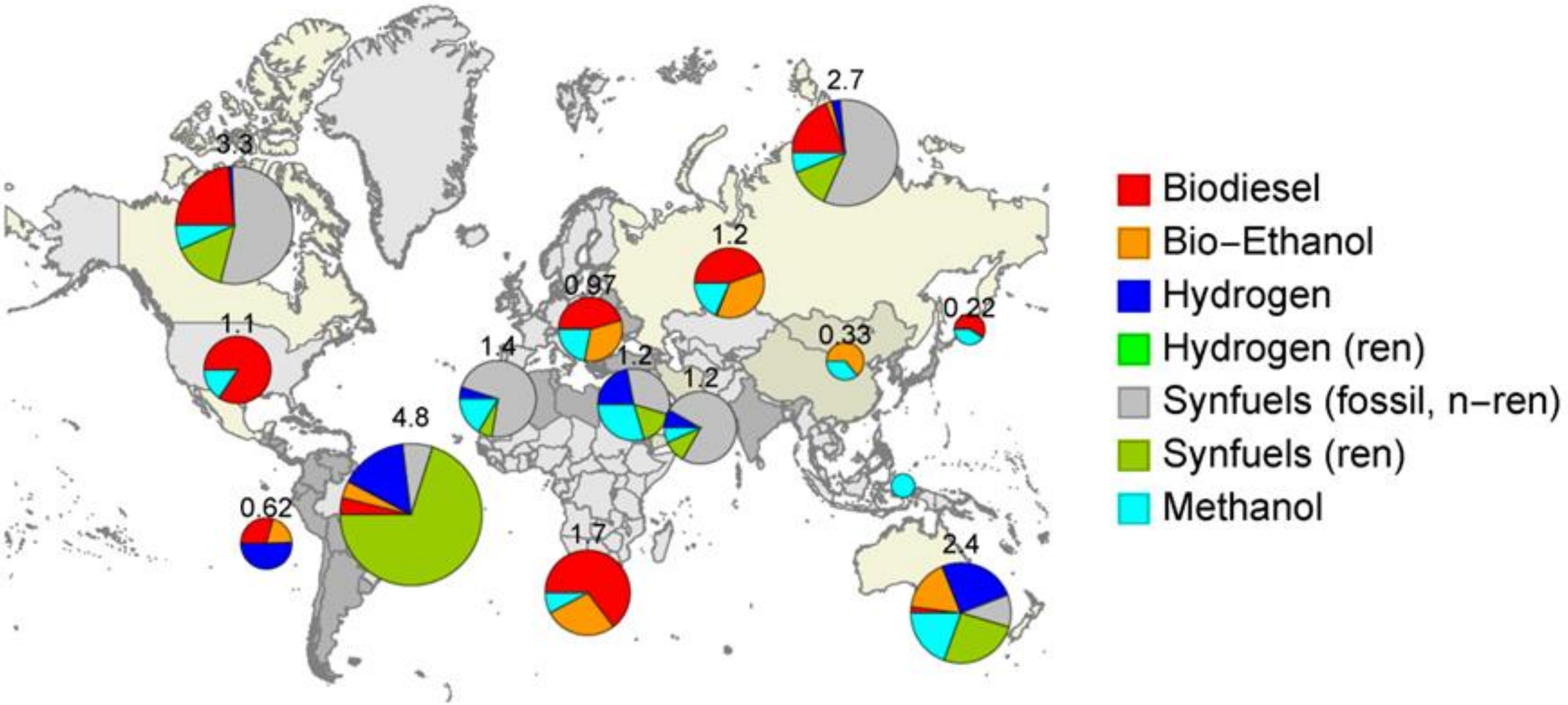
LAC: largest producer region (contains Chile)





- Methane pyrolysis in year 2050: 5 EJ/y (“turquoise” H2)
- Compare: IEA’s (normative) NEZ scenario:
  - 380 Mt H2 in year 2050 = 46 EJ (with LHV 120 MJ/kg)
- Use in 2050: Half of it (15 EJ) goes to end-use sectors (FC-CHP and heavy transport)

Overview: Alternative Fuel Export in 2050 (EJ/y)



- H2: Trade across 17 world regions in 2050: 2 EJ/y (IEA's WEO 2024: 3-9 EJ/y).
  - Renewable H2 (2nd gen biomass, electrolyzer with REN) is barely traded; traded H2 is mostly from Gas + CSS
- "Synfuels (ren)": mostly from biomass.
- Conventional biofuels have more diversity in export regions

Sensitivity Analyses

1. **Biomass:** Reduced potential and doubled cost

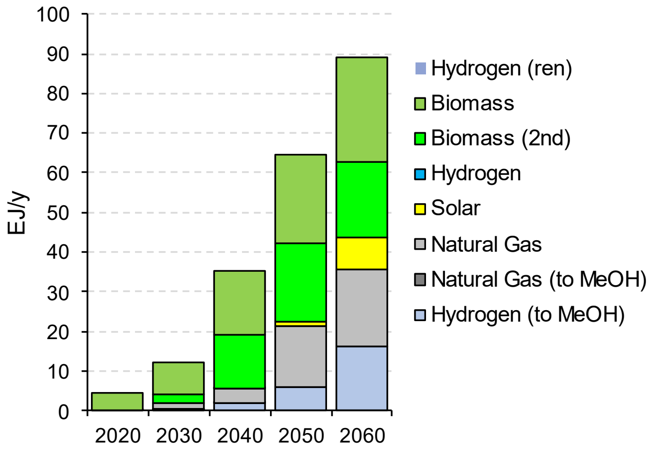
2. **Carbon Capture and Storage:** Reduced potential and higher costs

3. **DAC:** not required for hydrogen-based liquid fuels (any source is valid at cost of CCS)

1) Biomass: -30% reduced potential & doubled extraction costs

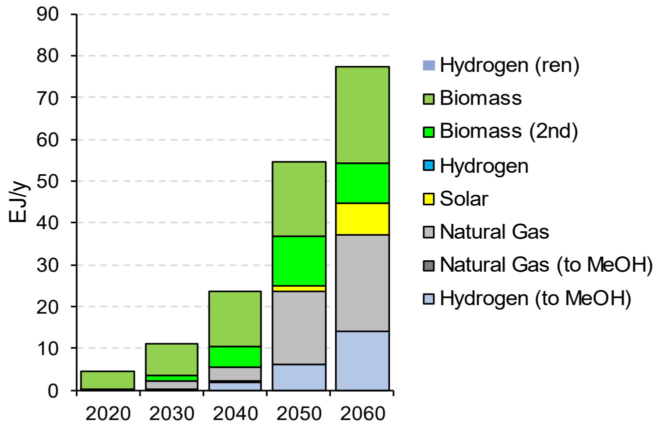
Base Case:

Global Synfuel production by source



Reduced* Biomass:

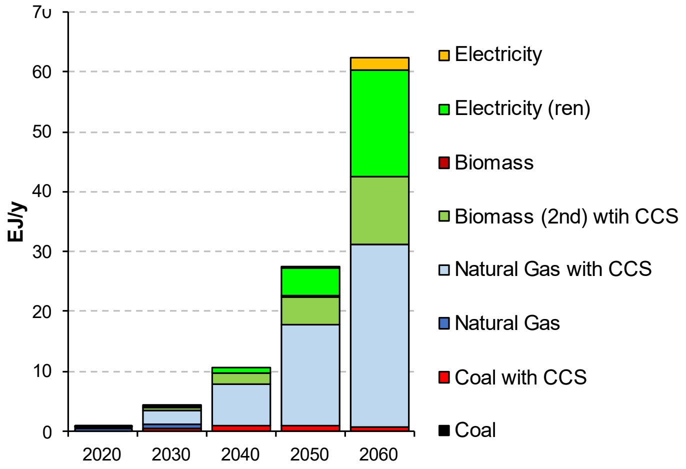
Global Synfuel production by source



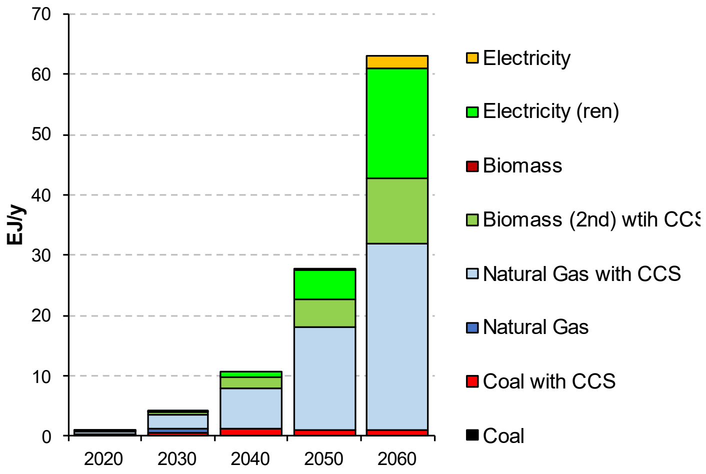
*: -30% biomass potential, uniform across egions; -10% in INDIA, EU31 (more stringent eduction leads to infeasibility of optimization problem)

- Biomass extraction reduced from 143 EJ/y to 114 EJ/y in year 2050 (now similar to IEA's WEO 2024)
- Liquid alternative fuel production: smaller scale-down for biomass

Global Hydrogen production by source



Global Hydrogen production by source

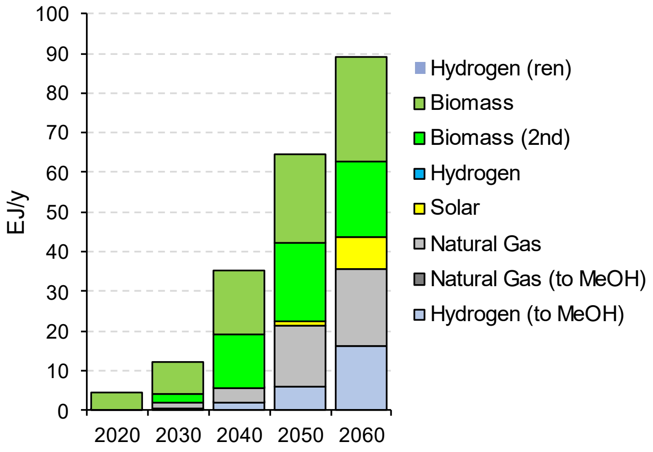


- No effect on H2 production

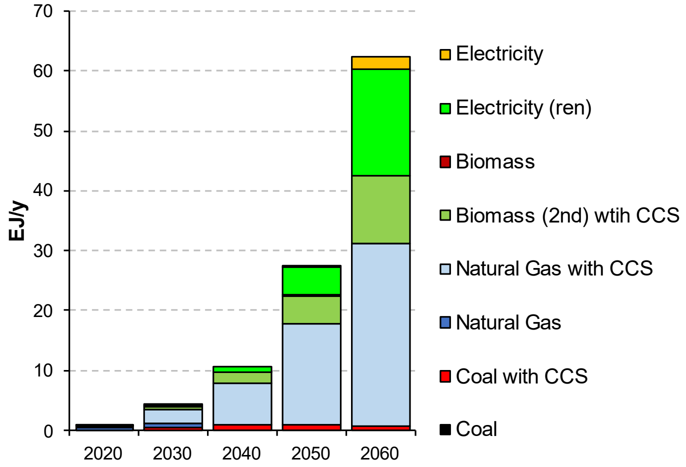
2) CCS: Reduced potential to 1%; Costs 18$ → 73$ / tCO2

Before:

Global Synfuel production by source

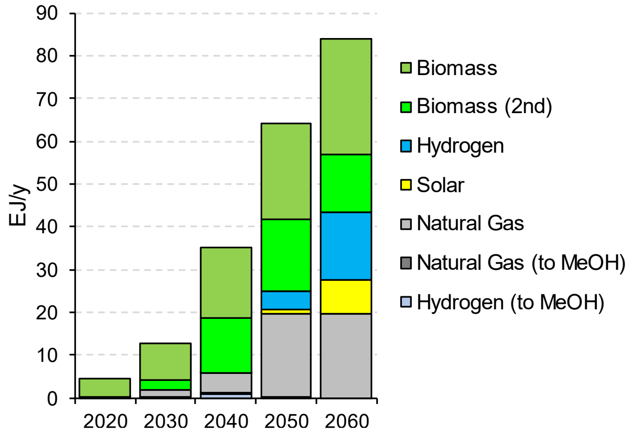


Global Hydrogen production by source

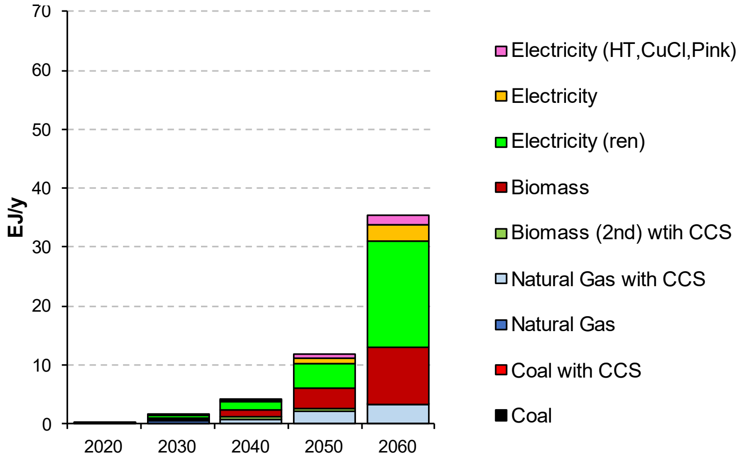


Reduced CCS Potential:

Global Synfuel production by source



Global Hydrogen production by source



- Liquid e-fuels (cat. “Hydrogen”) with DAC are cost-effective in 2050+
- But in response: Commercial MeOH from hydrogen vanishes

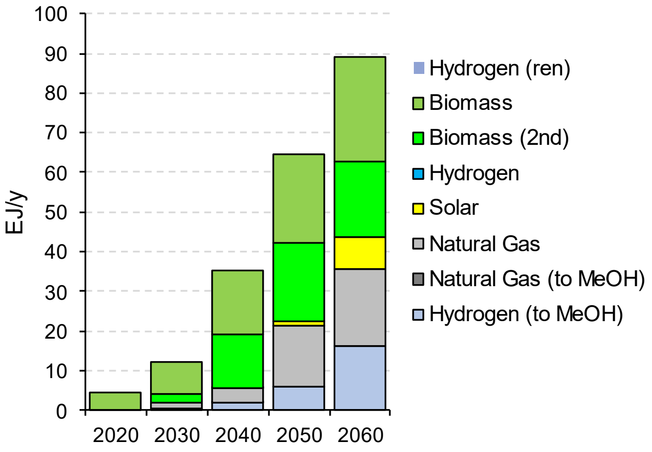
→Total amount of liquid alternative fuel production similar

- H2 production is approx. halved
- BECCS is replaced by generic biomass (without CCS)
- Electrolyzers and newly “pink” hydrogen are used.

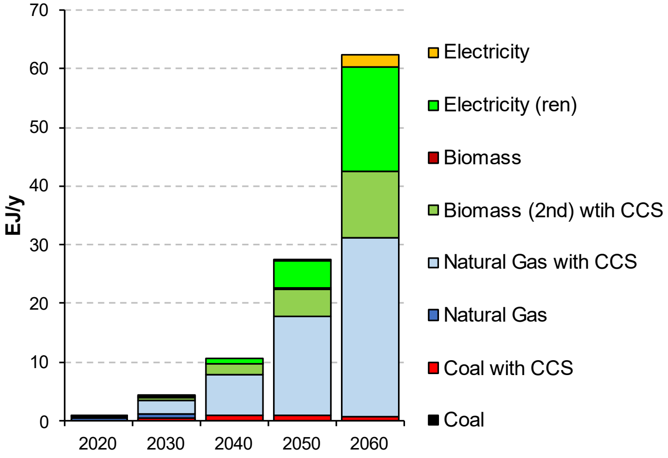
3) DAC is not required for liquid e-fuels

Before:

Global Synfuel production by source

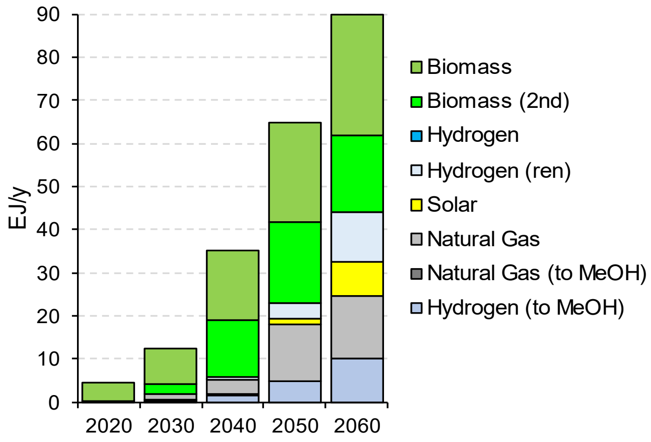


Global Hydrogen production by source

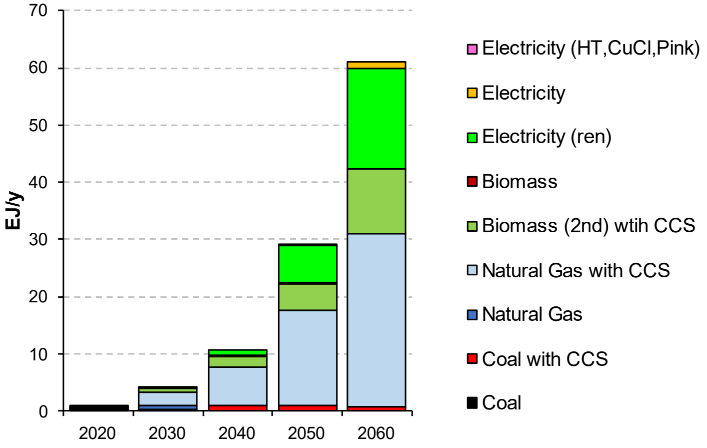


no DAC required:

Global Synfuel production by source



Global Hydrogen production by source



- Now, **liquid e-fuels** (from renewable hydrogen) come in 2050+

- H2 production nearly the same

Conclusions

Under a stringent, global climate policy and a free global market:

- **Liquid e-fuels.** Without a cheap source of carbon, will likely not be cost-effective before 2050
  - **Direct Air Capture** is likely not an economical source of carbon for e-fuels
  - **CCS** has pivotal role: with large CCS deployment, liquid e-fuels will likely not enter

- **Biomass.** Seems to be cost-effective for liquid fuel production
  - Biomass is re-directed away from power & heat sectors (in our results: power balanced by Gas + CCS)

- **Hydrogen.** Boosted by BECCS. Limiting CCS boosts electrolysers (year 2040+), but reduces H2 amounts.
  - **Rising useful energy demands + Phasing-out fossil electricity + Electrification of demand-sectors** delays electrolyser deployment **globally** by at least a decade (regionally-diverse) with respect to normative scenarios

Limitations / Future Research

- **E-fuels.** Cost-effectiveness may depend on hourly modeling of intermittent renewables.

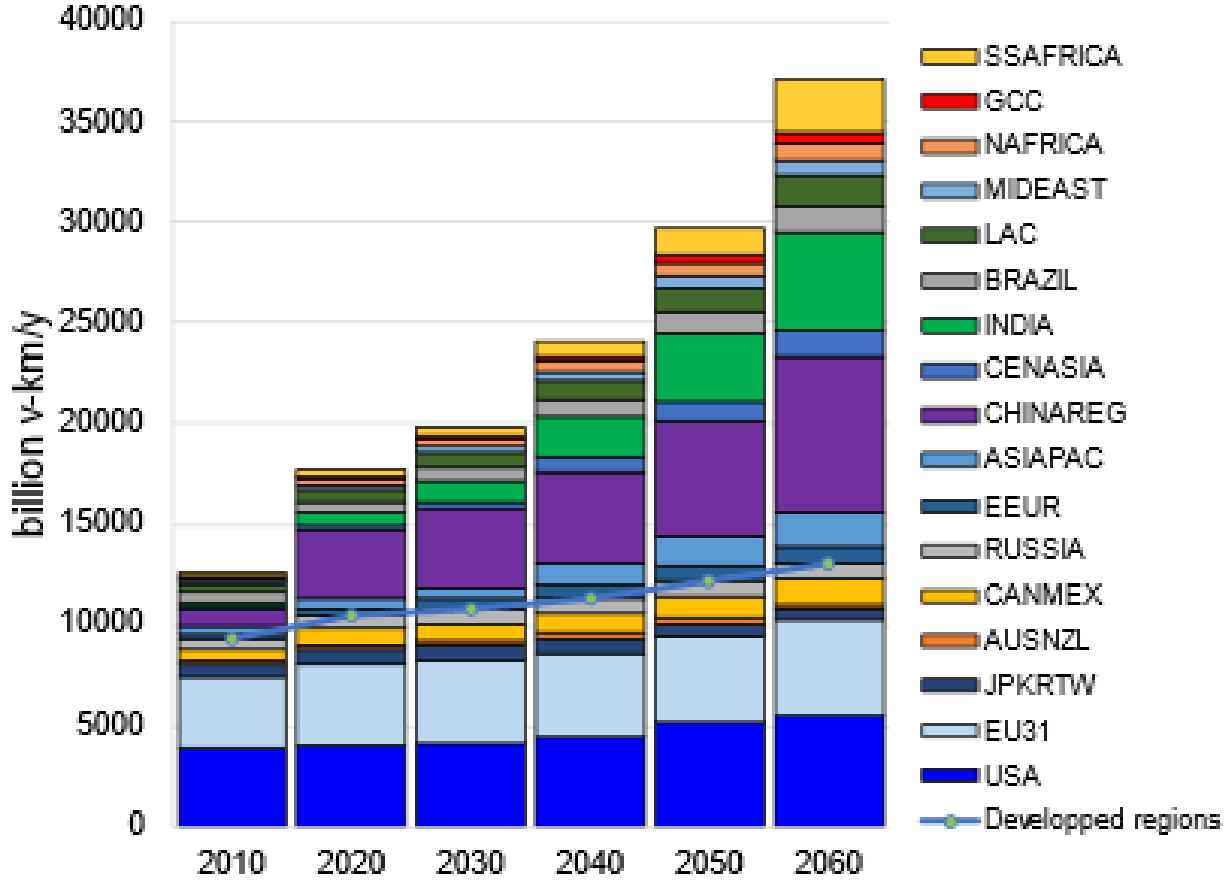
- **Chemical industry.** Synfuels pathways intersect with non-energy sectors. Modelling possible?
  - Modeling of other synergies, e.g., H2 may be shipped as ammonia, which can also drive ships.

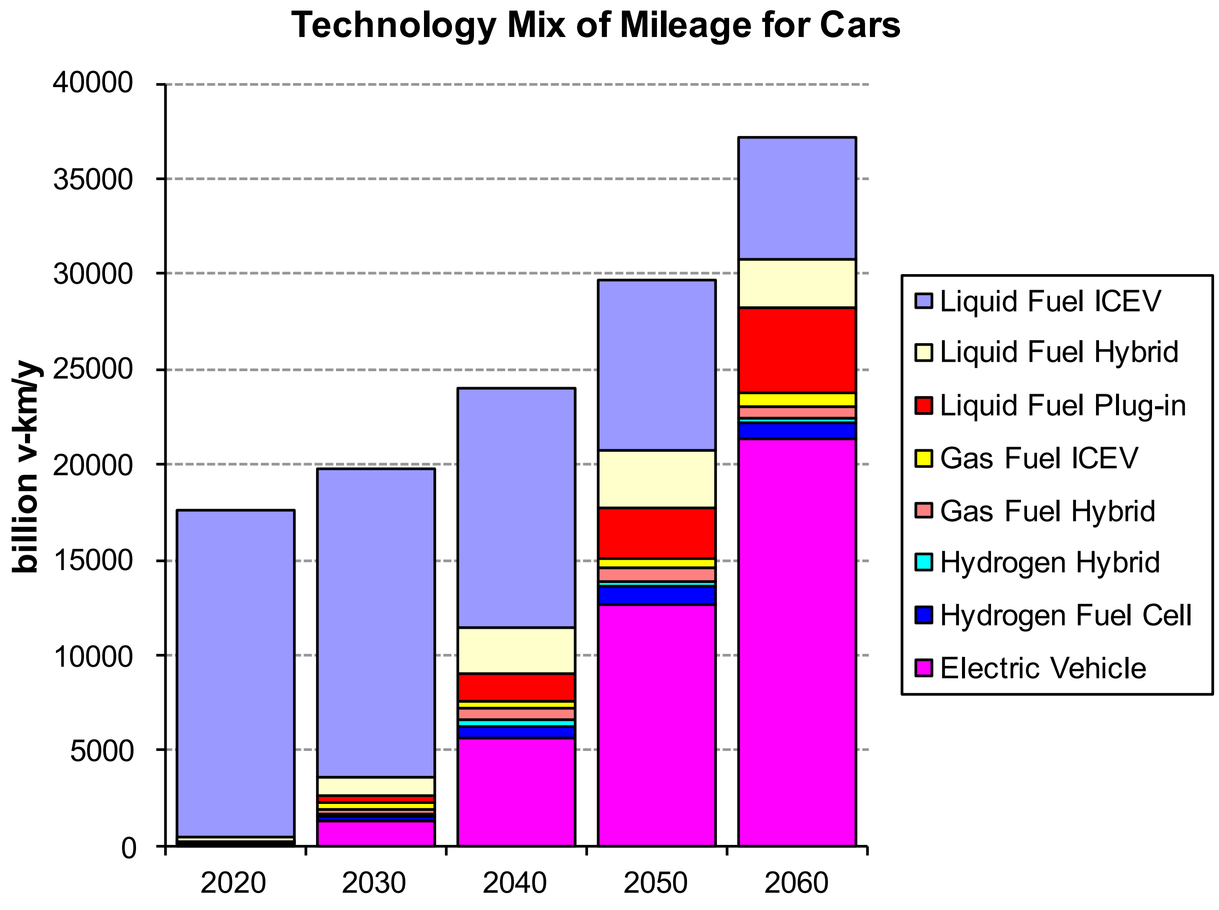
- **Carbon leakage** in trade between global regions:
  - In GMM : CO2 source accounted, trade for generic alternative fuels is with an average of CO2 content → perhaps reason for liquid fuels from natural gas)
  - Exact tracing of CO2 in all traded energy and chemical pathways required

    → Implementable in real-world? Examples:
    - Increased bureaucracy of EU’s Carbon Border Adjustment Mechanism
    - Variation & metering issues of H2-blending into the existing methane grid

BACKUP

Global car sector: Assumption on v-km & Result on Techs





- Comparison with WEO2024: “Zero-emission vehicles” in year 2035: 30%, 35%, and 45% in the STEPS, APS, and the NZE scenario (BEV, PHEV, H2); we have 34% in year 2040.