PSI Center for Nuclear Engineering and Sciences
Center for Energy and Environmental Sciences

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Global cost drivers and regional trade-offs for low-carbon fuels: a prospective techno-economic assessment

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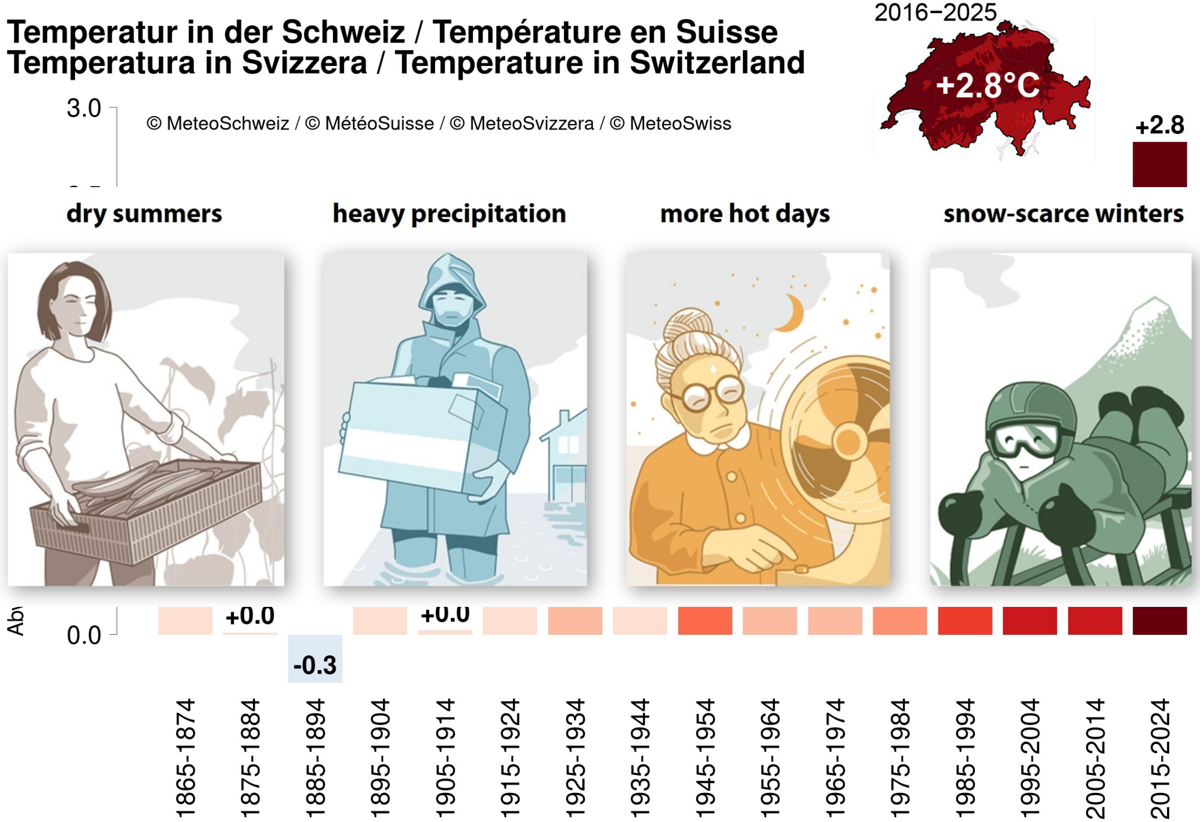
30. Januar 2026, Kloster Disentis

Outline

1. **Introduction**
2. **Methodology**
3. **Results**
4. **Conclusion**



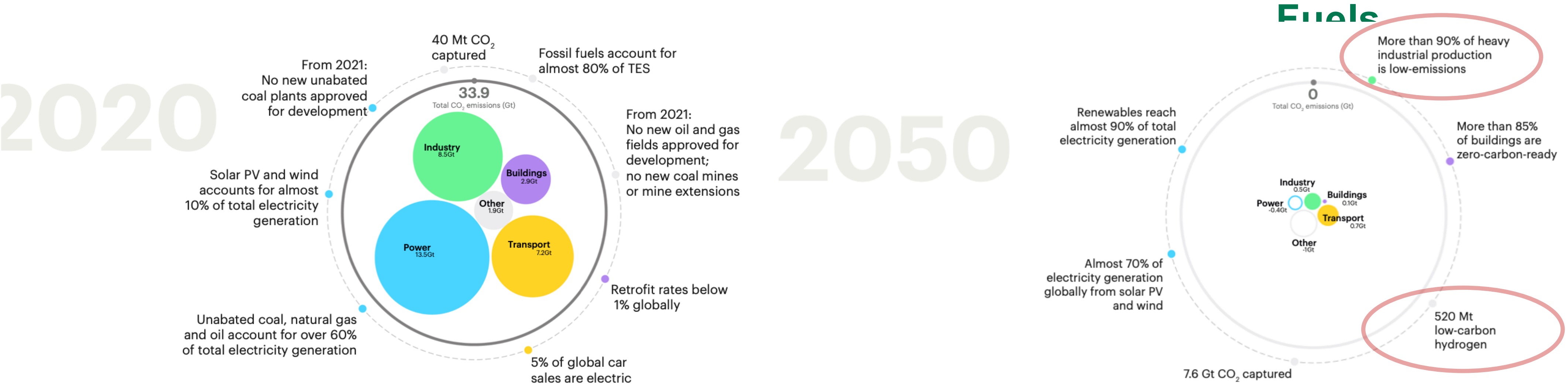
Temperatures in Switzerland since 1864. Every year is shown in a different colour. Years with red colour-coding are warmer, and those with blue are cooler than the mean of 1961–1990.
Sources: Climatology MeteoSwiss

Introduction: Net-Zero?

1.5°C ? X **Paris Agreement**

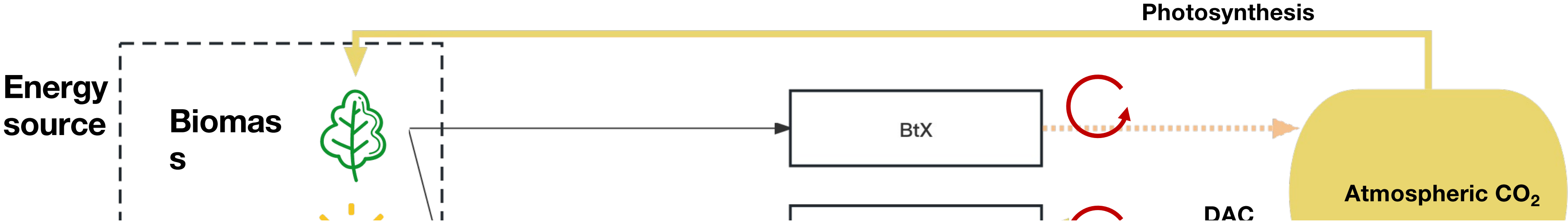
45% → 0 **emission reduced by 2030 and reach net zero by 2050.**

How to reach Net-Zero?

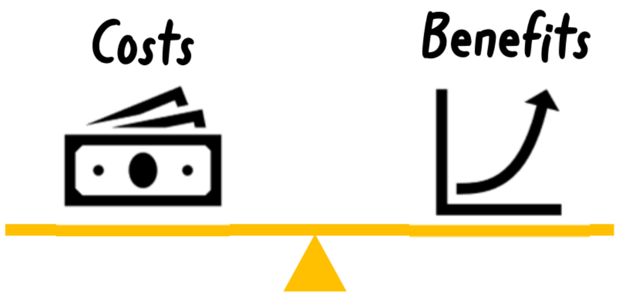


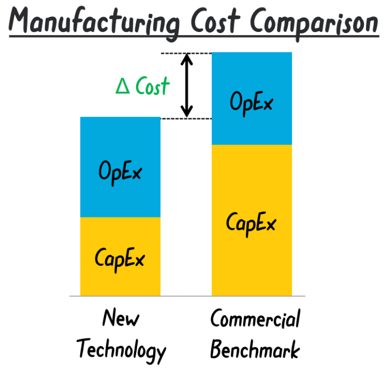
References:
https://www.un.org/en/climatechange/net-zero-coalition
https://www.iea.org/reports/net-zero-by-2050

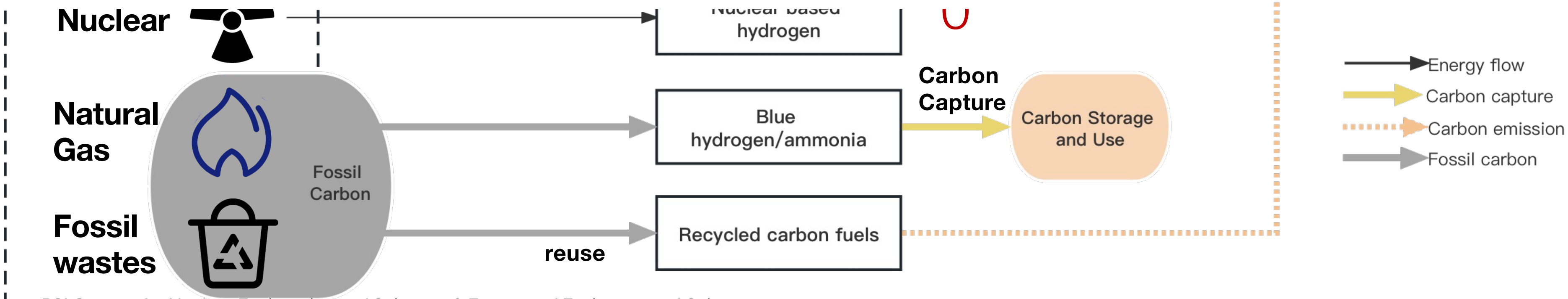
Introduction: What are low carbon fuels (LCFs)



A TEA assesses the overall value of a technology







Introduction

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Introduction: Research gaps on TEA of LCFs

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Literature (Author, Year)	Region count	Time scope	LCF tech count	LCF fuel category	WACC (cost of capital)	CAPEX learning
Brändle et al. 2021	94	2020-2050	4	synfuels, DME, MeOH, biodiesel, Olefin	8%	yes
Do et al. 2022	1	2020-2030	16	hydrogen, ammonia, synfuels	8%	yes
Martin et al. 2023	1	2020-2050	3	hydrogen	6%	no
Lopez et al. 2023	145	2020-2050	5	hydrogen	7%	yes
Xiang et al. 2024	1	2020-2050	14	hydrogen, ammonia, synfuels	8%	no
Allgoewer et al. 2024	4	2035	9	ammonia, MeOH, Olefins, aromatics, bio CCS	6%	yes
Fasihi and Breyer. 2024	Global pixels	2020-2050	1	MeOH	7%	no
Radner et al. 2024	6	2020	1	hydrogen	national	no
Kigle et al. 2024	Global pixels	2020	1	hydrogen	national	no
Egli et al. 2025	Africa pixels	2030	2	hydrogen and ammonia	national	no
This study	151	current-2050	21	hydrogen, ammonia, synfuels, DME, biofuel, Methane	national, technological	yes

Research gaps

- Existing LCF TEAs are often **technology specific**, **region-specific**, and **static: inconsistent and incomparable**
- Most studies apply fixed or simplistic assumptions for **CAPEX, WACC, input material costs**, ignoring **geospatial and financial variability**.

Research questions:

1. How do LCF production costs and trade-offs **evolve globally** across scenarios and time?
2. What are the **key cost drivers** and sensitivities by technology?
3. Which technologies and supply chains become cost-competitive, and where are the **regional winners**?

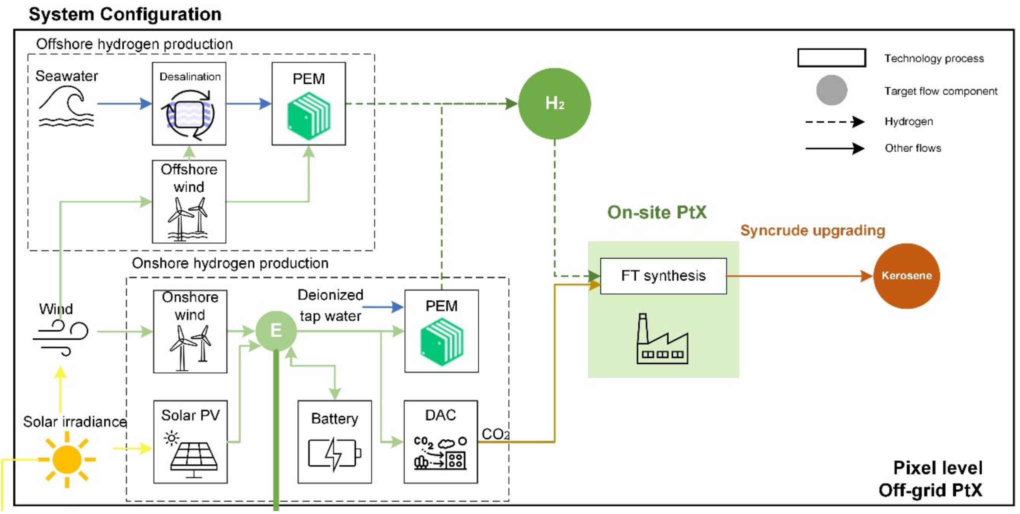
Methodology: Technology Specification

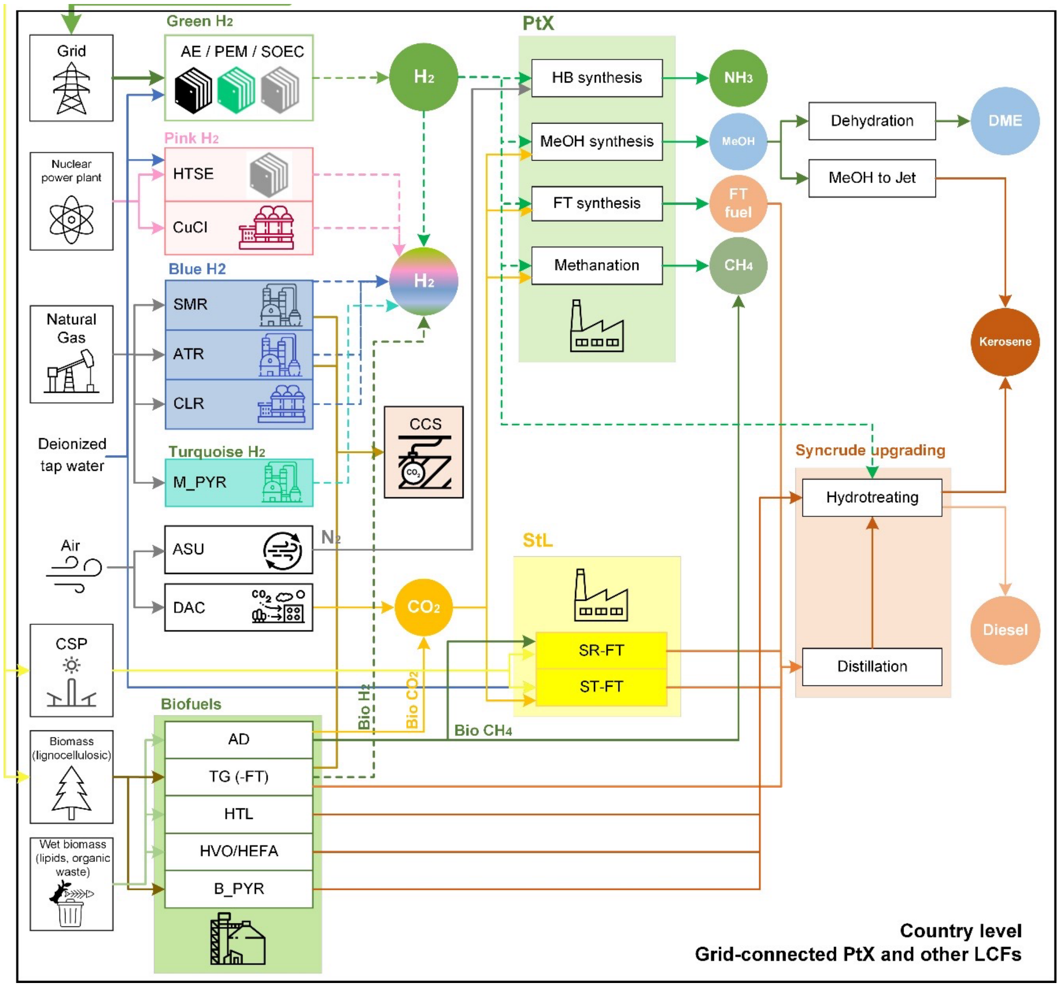
21 technology pathways + DAC, and 5 fuel types, based on 3 main feedstock categories:

- PtX fuels: based on solar PV, onshore wind, offshore wind, nuclear
- GtL fuel: based on natural gas and CCS
- StL and BtX fuel: based on Solar CSP & Biomass

Fuel type	No.	Main raw material	LCF category	Technology	Technology Acronyms	TRL
Hydrogen	1	Water, RE	Green Hydrogen (Power to X)	Proton Exchange Membrane Electrolysis	PEM	8~9
	2	Water, RE		Alkaline Electrolysis	AE	8~9
	3	Water, RE		Solid Oxide Electrolysis Cell	SOEC	6~7
	4	Nuclear Elec/Heat	Pink Hydrogen	High-Temperature Steam Electrolysis	HTSE	6~8
	5	Nuclear Elec/Heat		Nuclear Thermochemical Copper-Chlorine Cycle	CuCl	5~6
	6	Natural gas w CCS	Blue Hydrogen	Steam Methane Reforming with CCS	SMR+CCS	8~9
	7	Natural gas w CCS		Autothermal Reforming with CCS	ATR+CCS	8~9
	8	Natural gas		Chemical Looping Reforming	CLR	6~7
	9	Natural gas	Turquoise Hydrogen	Methane Pyrolysis	M_PYR	5~6
	10	Biomass	Bio/Green Hydrogen	Biomass Thermal Gasification with CCS	BG+CCS	5~6
Kerosene/Diesel (StL and PtL)	11	Solar, $BioCH_4$	Sun to Liquid	Solar Reforming FT	SR-FT	5~7
	12	Solar, CO_2, H_2O		Pure Solar Thermochemical FT	ST-FT	5~6
	13	Green H_2, CO_2	Power to X	Reverse Water Gas Shift FT	RWGS-FT	6~8
	14	Green H_2, CO_2		Reverse Water Gas Shift MeOH Synthesis	RWGS-MeOH	6~8
Biofuel (Biokerosene/Diesel)	15	Biomass	Bio(jet)fuel	Biomass Thermal Gasification FT	TG-FT	6~8
	16	Biomass		Hydrothermal Liquefaction and Upgrading	HTL	6~8
	17	Biomass		Hydrotreated Vegetable Oil/Hydroprocessed Esters and Fatty Acids	HVO/HEFA	6~8
	18	Biomass		Biomass Pyrolysis and Upgrading	B_PYR	5~6
Methane	19	Green H_2, CO_2	Power to X	Power To Methane	PTM	7~9
	20	Biomass	Biofuel	Anaerobic Digestion	AD	7~9
Green ammonia	21	Green H_2, N_2	Power to X	Habor Bosch (with Green Hydrogen)	HB	8~9

System Configuration





PtX fuel: PEM hydrogen, DAC-PEM-FT-SAF (kerosene)

- Off-grid
- Grid connected

Scope:

- Global (151 countries) production
  & Transport to Switzerland
- Current 2024, near term 2030, long term 2050

Z.L., T.T. et al., preprint DOI: 10.26434/chemrxiv-2025-3fns5, submitted to Energy & Environmental Science

Methodology Overview

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Technology specification and system configuration

Optimal off-grid system (pixel level)
- Optimal design of H_2 system
- Optimal renewable share wind & solar PV
- PEM hydrogen - kerosene

Renewable electricity →

Grid connected hydrogen, PtX fuels and other LCFs (country level)
- Green/blue/pink/turquoise hydrogen
- Power to X fuels (methanol, kerosene, diesel, methane, ammonia) from green hydrogen and DAC/bioCO_2
- Sun to liquid and biomass to liquid kerosene/diesel

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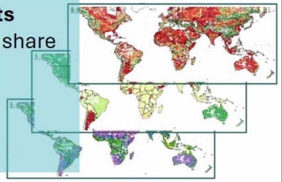
Input data collection and preprocessing, scenario setting

Techno-economic data
- CAPEX, OPEX, efficiency, etc.
- Cumulative capacity, learning rate, WACC, etc.
- Energy and material balance
- Conversion and transport

Input material costs
- Renewable electricity share
- Natural gas, CCS
- Solar CSP, biomass
- Nuclear electricity



System modeling and techno-economic calculation

technology x in country y in year t, the levelized cost of fuel is calculated through:

Modelling factors → cost components

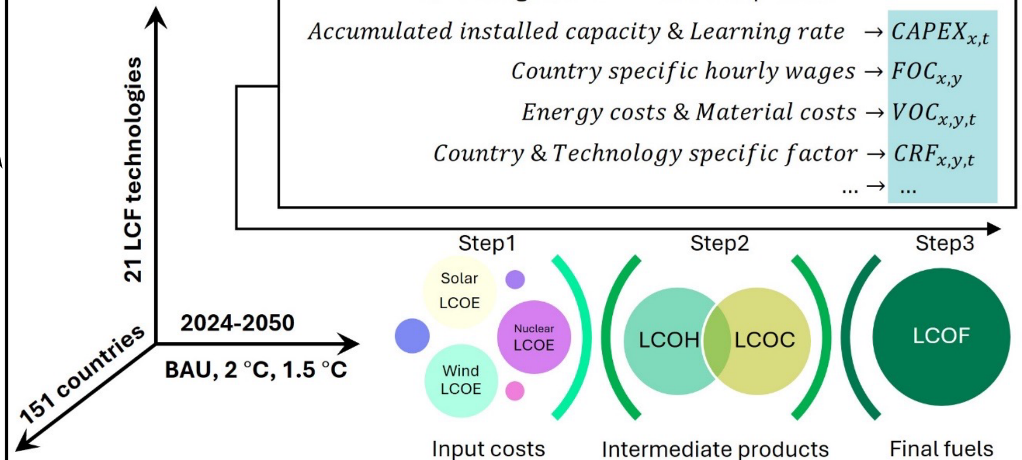
$Accumulated\ installed\ capacity\ \&\ Learning\ rate \rightarrow CAPEX_{x,t}$

$Country\ specific\ hourly\ wages \rightarrow FOC_{x,y}$

$Energy\ costs\ \&\ Material\ costs \rightarrow VOC_{x,y,t}$

$Country\ \&\ Technology\ specific\ factor \rightarrow CRF_{x,y,t}$

$\ldots \rightarrow \ldots$



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Uncertainty and sensitivity analysis

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Result aggregation and scenario policy analysis

Novelties

- Comprehensive LCF portfolio
- Global scope with **consistent future scenario-aligned assumptions**
- **Dynamic WACC modeling** across countries, time, and technology maturity
- **Learning-based CAPEX evolution**

Z.L., T.T. et al., preprint DOI: 10.26434/chemrxiv-2025-3fns5, submitted to Energy & Environmental Science

Scenario and Variable Identification

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Scenario design

Scenario	Technology assumptions	IEA scenario	REMIND scenarios
Business as usual (BAU)	Slow progress: TRL +1 by 2030, TRL 9 by 2050	Stated Policies Scenario (STEPS)	>2 °C 2050 (SSP2-Base)
2 °C	Moderate progress: TRL +2 by 2030, TRL 9 by 2050	Announced Pledges Scenario (APS)	2 °C 2050 (SSP2-PkBudg1150)
1.5 °C	Fast progress: all major technologies reach TRL 9 by 2030	Net Zero Emissions by 2050 Scenario (NZE)	1.5 °C 2050 (SSP2-PkBudg500)

Variable specification dimensions

Variable	Unit 2020chf	Technology specific	Time (year) specific	Scenario specific	Country specific
CAPEX	**EUR/kW**	**Yes**	**Yes**	**Yes**	**No**
OPEX	% of CAPEX	Yes	No	No	Yes
WACC	%	**Yes**	**Yes**	**Yes**	**Yes**
Lifetime	years	Yes	No	Yes	No
Efficiency	% (LHV)	Yes	Yes	Yes	No
Material input	kg/kWh	Yes	No	No	No
Energy input	kWh/kWh	Yes	No	No	No
Material price	EUR/kg	No	Yes	Yes	Yes
Energy price	EUR/kWh	No	Yes	Yes	Yes

Country/Scenario specific input variables:

- Capacity factor of **renewable electricity production**: Projected solar, wind, and CSP resource quality, varying by scenario and country.
- **Input material costs**: Levelized cost of supporting/linked technologies (e.g., DAC, CSP, Nuclear power) used as inputs for PtX or hybrid processes.
- **Raw material/feedstock costs** (e.g., biomass, natural gas) based on scenario projections and regional price evolution.
- **Grid electricity mix LCOE**: Driven by national grid mix, renewable share, and grid carbon intensity.

Cost Modeling Highlights: TEA & CAPEX Learning

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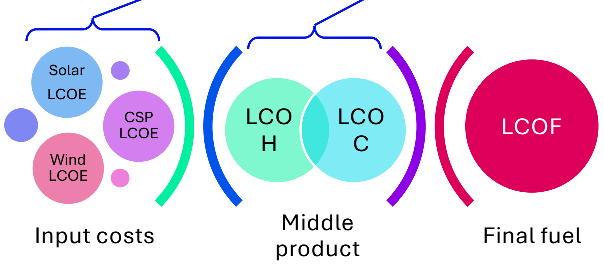
LCOF: Levelized cost of fuel from total capital investment cost

$$LCOF_{x,y,t} = \frac{CRF_{x,y,t} * \left(CAPEX_{x,t} + FOC_{x,y}\right)}{8760 * CF_x * \eta_{x,t}} + VOC_{x,y,t}$$

VOC: Variable operating cost, material and utilities input cost (LCOE, LCOC, …)

$$CRF_{x,y,t} = \frac{WACC_{x,y,t} * \left(1 + WACC_{x,y,t}\right)^{N_x}}{\left(1 + WACC_{x,y,t}\right)^{N_x} - 1}$$

$$VOC_{x,y,t} = \sum_j e_{j,x} \times c_{e_j,y,t} + \sum_i m_{i,x} \times c_{m_{i,y,t}}$$



Fuel upgrade and product allocation

$$A_{x,p} = \frac{LHV_P \cdot \dot{m}_p}{\sum_k \left(LHV_k \cdot \dot{m}_k\right)}$$

$$LCOF_{x,p,y,t} = \frac{CRF_{x,y,t} \cdot \left(CAPEX_{x,t} + FOC_{x,t} + CAPEX_{upgrade,p}\right)}{8760 \cdot CF_x \cdot \eta_{x,p,t} \cdot A_{x,p}} + VOC_{x,p,y,t}$$

Prospective CAPEX learning

$$CAPEX_{x,t} = CAPEX_{x,0} \times \left(\frac{I_{x,t}}{I_{x,0}}\right)^{-\lambda_{x,t}}$$

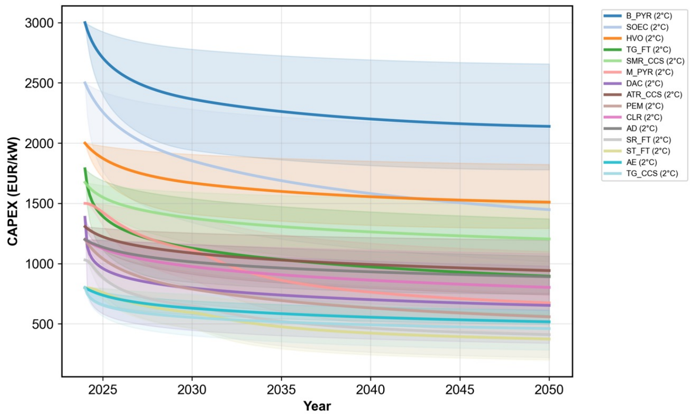
$$LR_{x,t} = 1 - 2^{-\lambda_{x,t}}$$

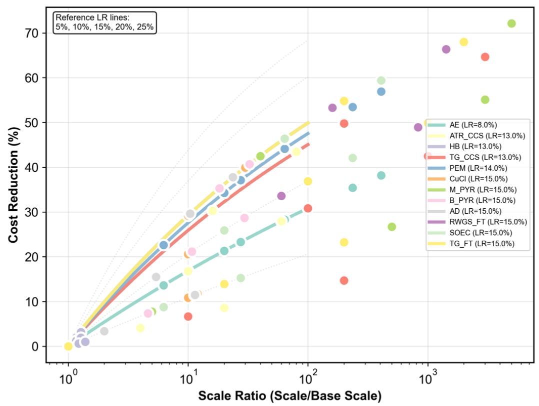
- **Accumulated installed capacity $I_{x,t}$:** Scenario and technology specific deployment trajectories
- **Technology learning rate $LR_{x,t}$:** Scenario and technology-dependent

Country specific OPEX

$$FOC_{x,y} = r_x^{tech} \times \frac{W_{h,y}}{W_{h,ref}}$$

$W_{h,y}$: hourly wages in country y





Z.L., T.T. et al., preprint DOI: 10.26434/chemrxiv-2025-3fns5, submitted to Energy & Environmental Science

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Cost Modeling Highlights: Dynamic WACC model

For the WACC value of technology x in country y in year t :

$$WACC_{x,y,t} = \underbrace{WACC_{base}}_{8\%} \times f_{wacc,x}(x,t) \times f_{wacc,y}(y)$$

$$WACC = \frac{E}{V}K_e + \frac{D}{V}K_d$$

equity share * cost of equity + debt share * cost of debt

$$K_e = r_f + ERP + CRP + T_p$$

risk-free rate + equity & country risk premium + technology premium

$$K_d = r_f + CDS + L_m$$

country default spread + lender margin

country-specific factor

$$f_{wacc,y}(y) = \frac{WACC_y}{WACC_{base}}$$

$$\begin{aligned} WACC_y &= \frac{E}{V}K_{e,y} + \frac{D}{V}K_{d,y} \\ &= \frac{E}{V}(r_f + ERP + CRP_y + T_{p,0}) \\ &+ \frac{D}{V}(r_f + CDS_y + L_{m,0}) \end{aligned}$$

technology-specific factor: TRL and Scale

$$f_{wacc,x}(x,t) = \frac{WACC^*(x,t)}{WACC_{base}}$$

$TRL_{target} = 9$ $\quad S_{x,t} = \frac{I_{x,t}}{I_{x,0}}.$

$$T_p(x,t) = [T_{p,0} - \alpha_x(TRL_{x,t} - TRL_{x,0})] \cdot S_{x,t}^{-\lambda_e}$$

$$L_m(x,t) = [L_{m,0} - \beta_x(TRL_{x,t} - TRL_{x,0})] \cdot S_{x,t}^{-\lambda_d}$$

linear interpolation of risk premiums

$$\frac{D}{V}(x,t) = (D/V)_0 + \gamma(TRL_{x,t} - TRL_{x,0}) + \delta \ln(S_{x,t})$$

$$K_e(x,t) = r_f + ERP + CRP_0 + T_p(x,t)$$

$$K_d(x,t) = r_f + CDS_0 + L_m(x,t)$$

$$WACC^*(x,t) = [1 - D/V\ (x,t)]K_e(x,t) + [D/V\ (x,t)] \cdot K_d(x,t)$$

Cost Modeling Highlights: Dynamic WACC Input

For the WACC value of technology x in country y in year t : $WACC_{x,y,t} = WACC_{base} \times f_{wacc,x}(x,t) \times f_{wacc,y}(y)$

$$WACC = \frac{E}{V}K_e + \frac{D}{V}K_d$$

$$K_e = r_f + ERP + CRP + T_p$$

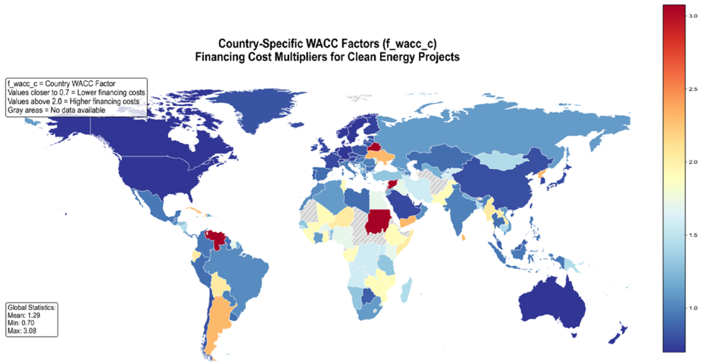
$$K_d = r_f + CDS + L_m$$

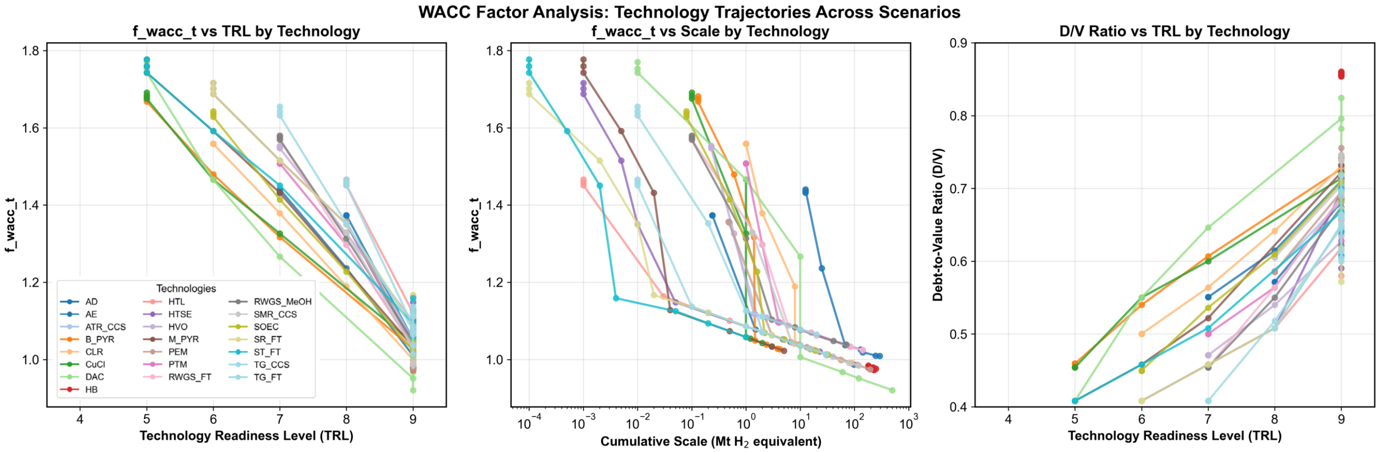
country-specific factor

$$f_{wacc,y}(y) = \frac{WACC_y}{WACC_{base}}$$

technology-specific factor: TRL and Scale

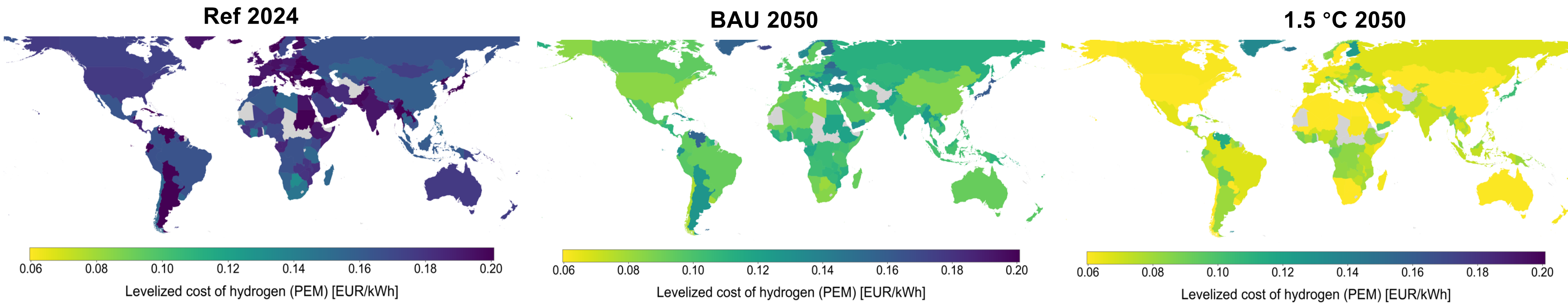
$$f_{wacc,x}(x,t) = \frac{WACC^*(x,t)}{WACC_{base}}$$



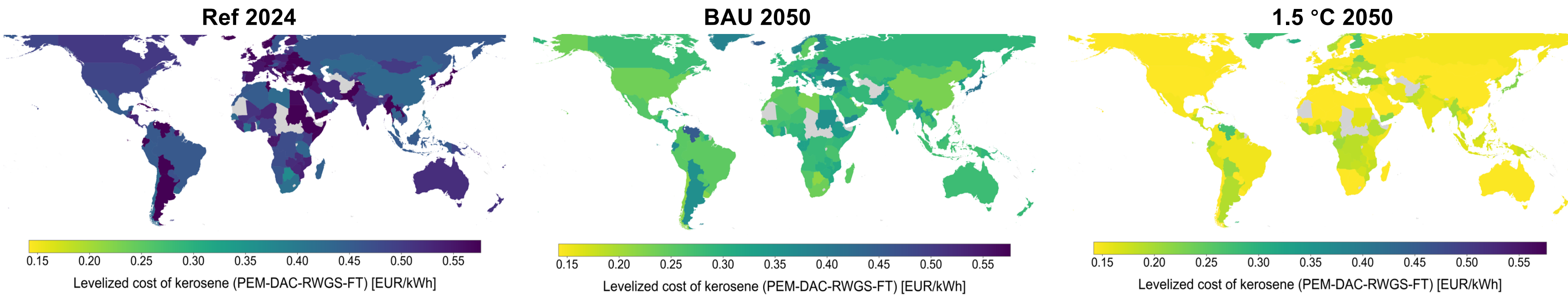


Key Results 1 — Global Cost Maps

Levelized cost of grid connected PEM H_2 production cost [EUR/kWh]



Levelized cost of PEM-DAC-FT fuel production cost [EUR/kWh]



Key Results 2 — Cost Breakdown: Hydrogen & Kerosene (SAF)

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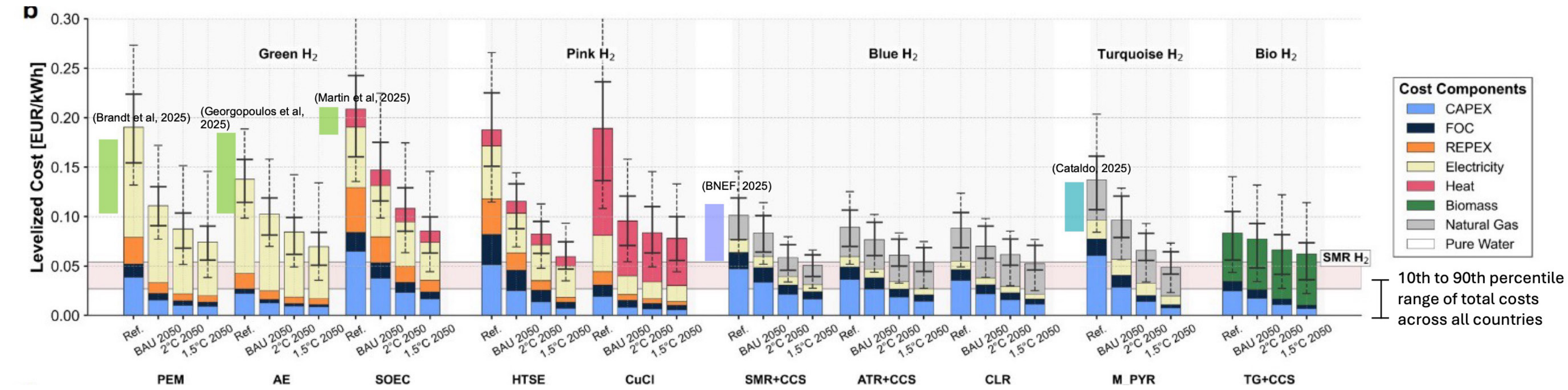
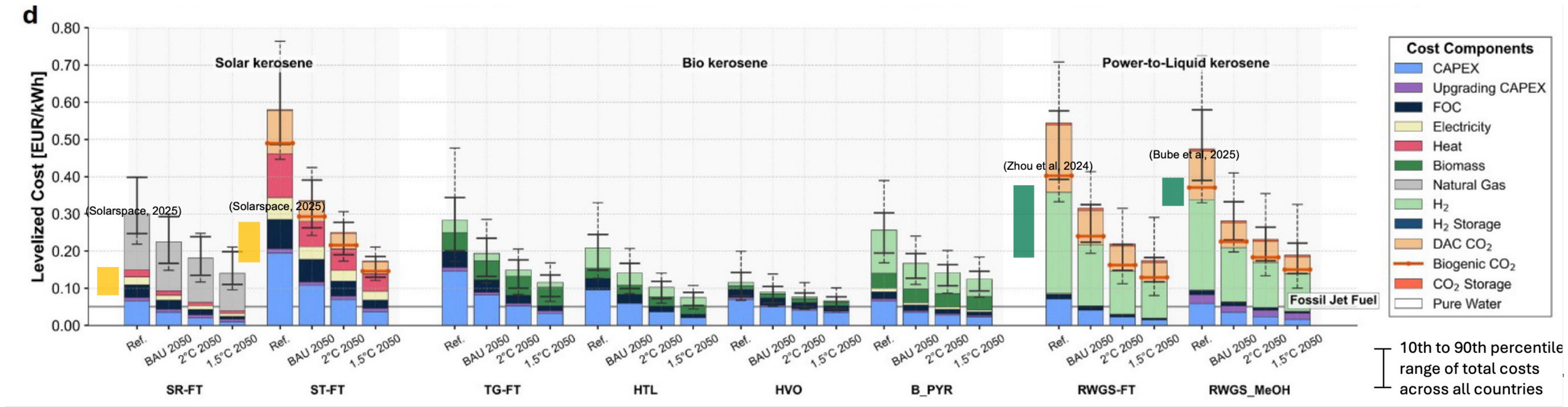
Hydrogen

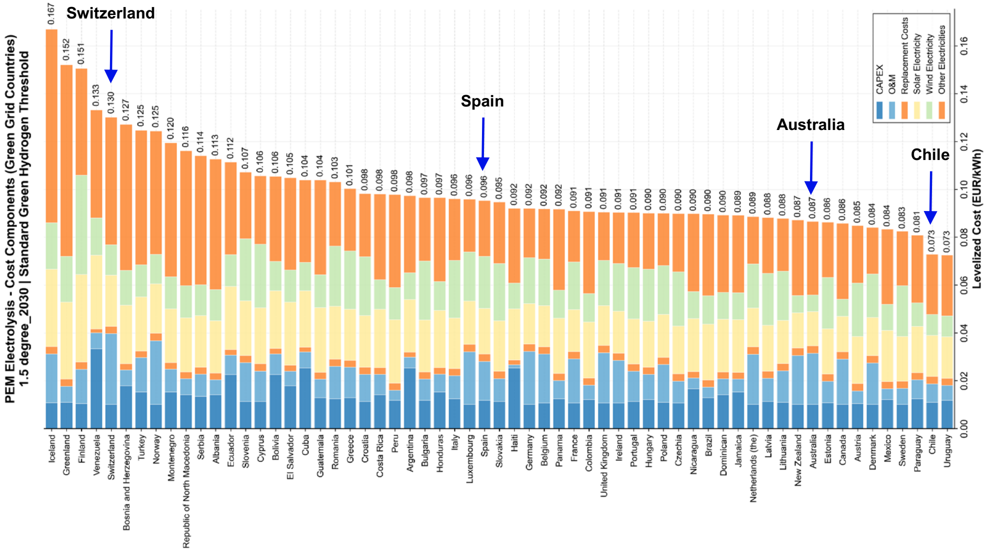


Kerosene (SAF)



Key Results 3 — Green-Grid Eligibility and National LCOH Rank

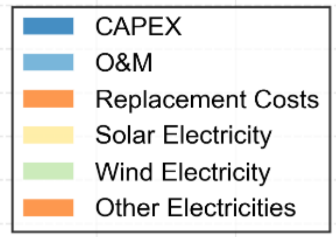
PEM hydrogen
2030
1.5 °C scenario



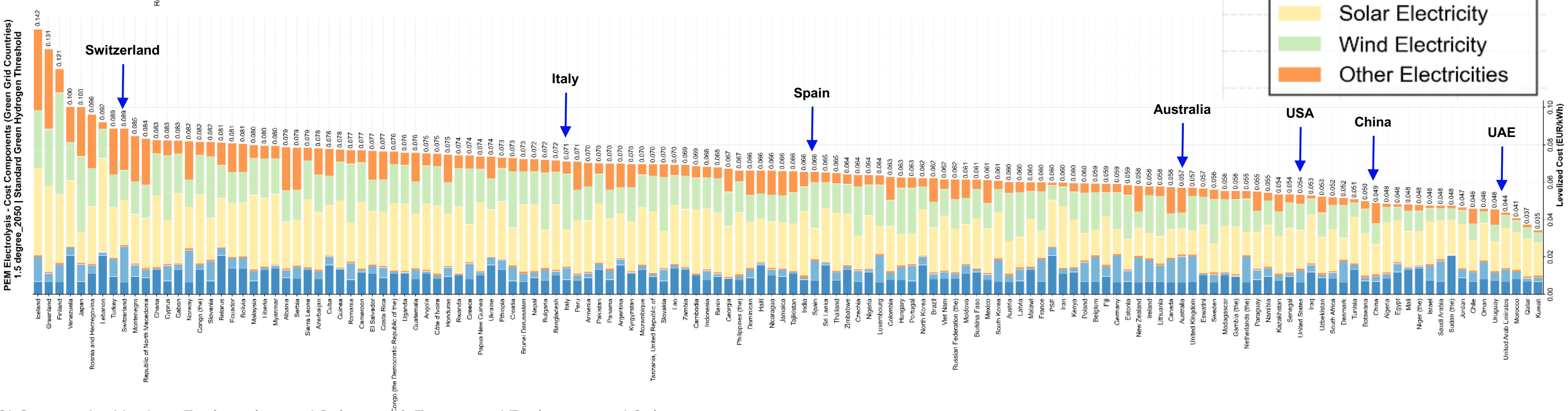
Green-Grid Definition

- **Strict threshold:** ≤ 0.038 kg CO_2/kWh
- **Standard threshold:** ≤ 0.050 kg CO_2/kWh

These align with CertifHy

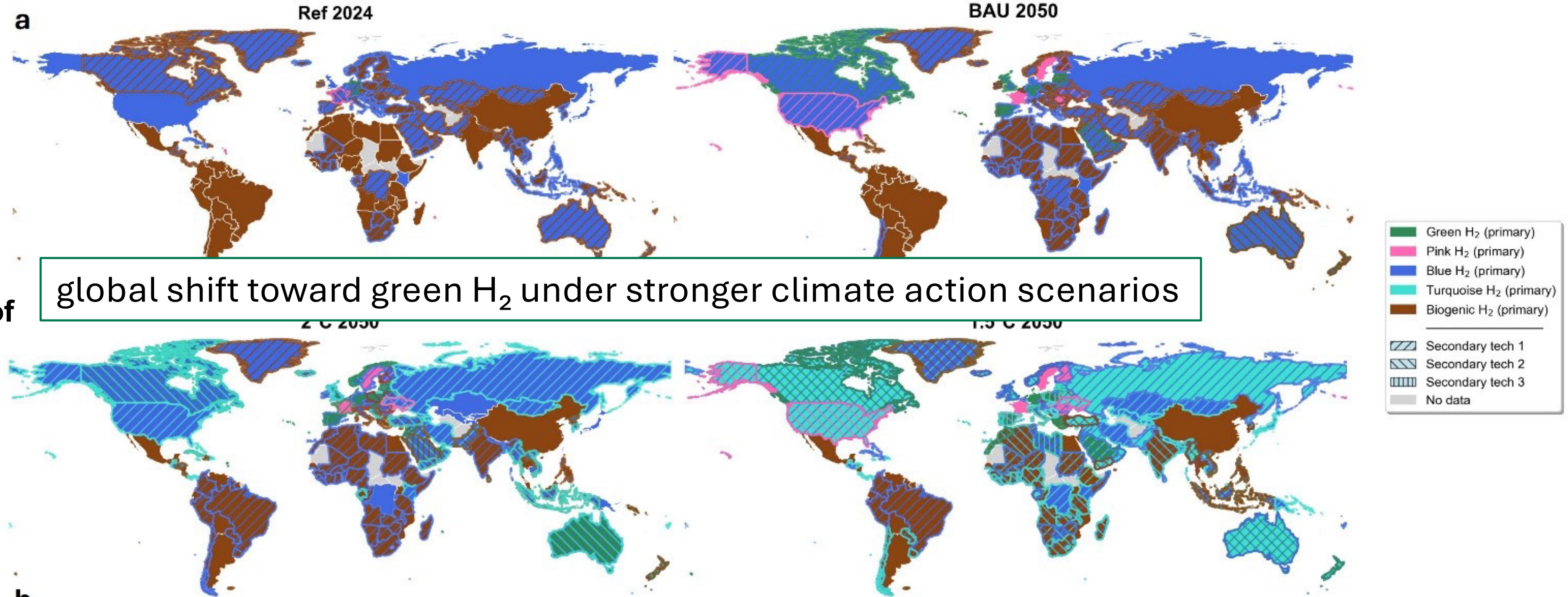


PEM hydrogen
2050
1.5 °C scenario



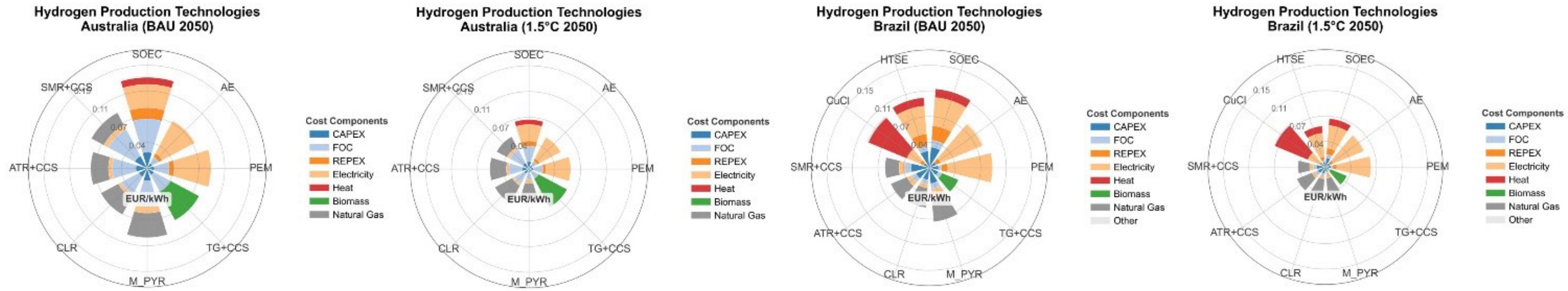
Key Results 4 — Tech & Regional Winners

World maps of primary (solid) and secondary (hatched) hydrogen technologies within 10% of lowest cost



global shift toward green H_2 under stronger climate action scenarios

Country Radar (Cost Transition of hydrogen technology cluster)



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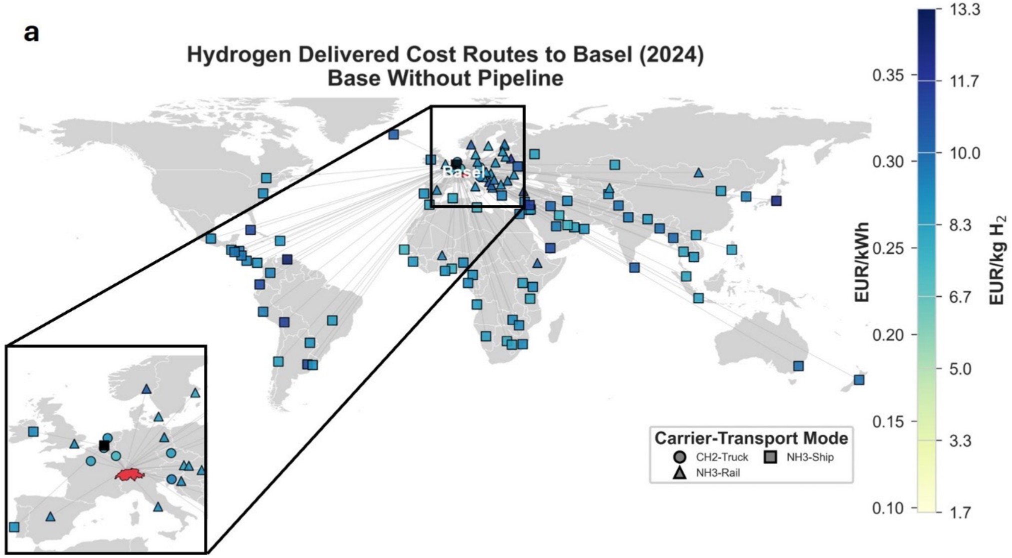
Key Results 5 — Global Transport and Import to EU

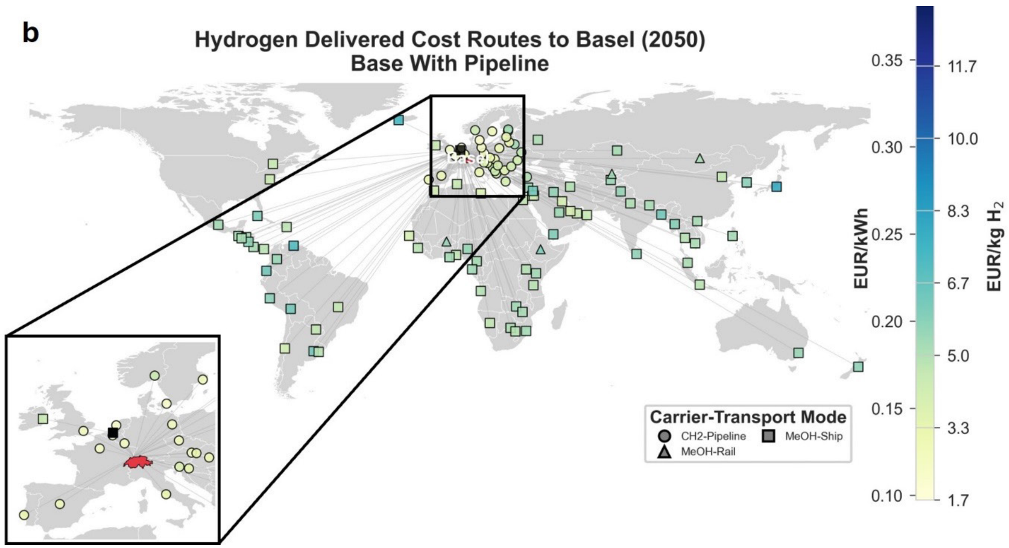
Global Transport Cost Calculation

$$C_{SC} = C_{compose} + C_{transport} + C_{decompose} + C_{storage}$$

Cheapest cost combinations for a certain distance range:

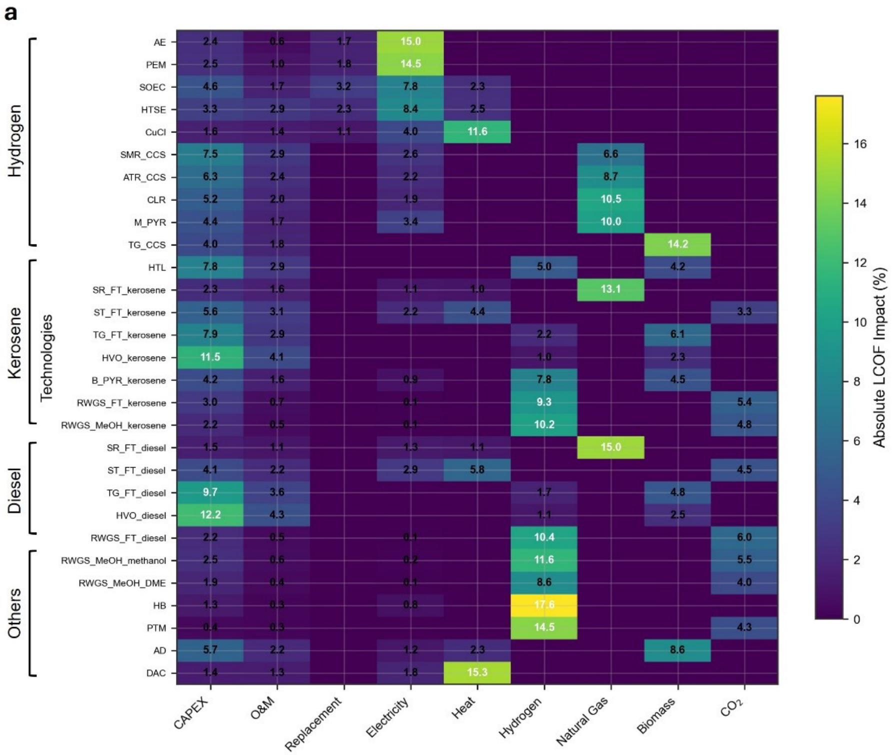
- Within EU: Pipeline (EHB)/Rail + Truck
- Outside EU: Country port to Antwerp to Basel, Switzerland
- Off-grid: from pixel production sites to country port



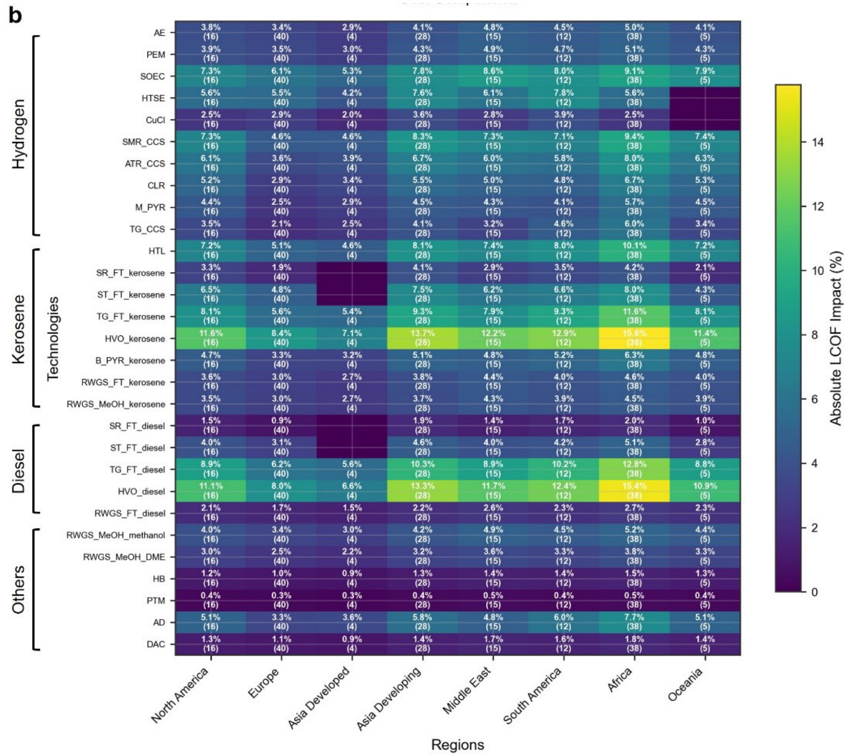


Key Results 6 — Sensitivity Analysis

Sensitivity Analysis Across Technologies and Cost Components



LCOF Impact from ±20% WACC Variation by Region



- **Electricity** dominates sensitivity of green hydrogen and e-fuels
- **Capital costs matter for emerging techs** - CAPEX sensitivity is significant for newer technologies

- **Regional financing sensitivity varies** - Asia Developing and Africa show highest sensitivity to WACC changes (2-4% LCOX impact)
- **Technology robustness differs** - Capital-light technologies show lower regional WACC sensitivity, making them more suitable for higher-risk regions
- **Green finance opportunity** - High regional sensitivity indicates substantial benefits from concessional financing and green bonds in developing regions

Take Away Messages

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1. **2050 costs can be competitive (1.5°C technology learning):**
   - Green Hydrogen: €0.07–0.10/kWh (2.3–3.3 EUR/kg)
   - Synthetic Kerosene: €0.15–0.18/kWh, becoming competitive with fossil equivalents
2. **Winners are not just "best sun/wind**
   - Abundant renewable resources (sun/wind) are insufficient on their own. In developing regions (e.g., Africa, South America), high financing costs often negate natural resource advantages.
   - Financial de-risking strategies are as critical as technological innovation to unlock global production potential.
3. **Infrastructure Reshapes the Map: Pipelines vs. Shipping**
   - The lowest production cost does not guarantee the lowest delivered cost to Europe.
   - Nearby regions (North Africa, Iberia) connected via pipeline will undercut distant producers (e.g., Australia, Chile).
4. **No single tech winner globally**
   - green H_2 dominates long-term, **turquoise** in gas-rich regions, **biofuels** where sustainable biomass is abundant.

Innovation + *finance de-risking* + *infrastructure planning* must move together.

Limitations and Outlook

Limitations

- **Cost, not market price:** excludes volatility, margins, tariffs
- **Smooth scale-up assumed:** ignores permitting / supply-chain bottlenecks
- **Resource constraints simplified:** biomass/CO_2 sustainable potentials not fully enforced
- **National-level resolution:** sub-national heterogeneity not captured

Outlook

- **Move to high-resolution siting:** sub-national resources + corridor infrastructure
- **Integrate TEA + LCA + sustainable potentials:** avoid "cheap but unsustainable" pathways
- **Improve finance realism:** project-level WACC, de-risking levers, country/tech evolution
- **Add market dynamics:** trade barriers, carbon policy, price volatility

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Thank you!

Q&A?

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SHELTERD project

Paper preprint

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