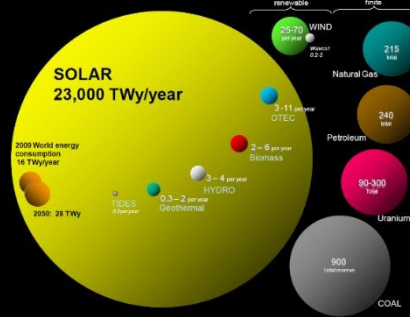




CO₂ Management : From waste to raw material to planetary climate control

Christian Breyer
Professor for Solar Economy
LUT University
5th Sustainable Energy Day
Copenhagen, September 11, 2026



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 Lappeenranta University of Technology

Core Narrative



Time frame

Today

towards Mid-Century

Beyond

CO₂ characteristic

Emission/ Waste

Raw Material

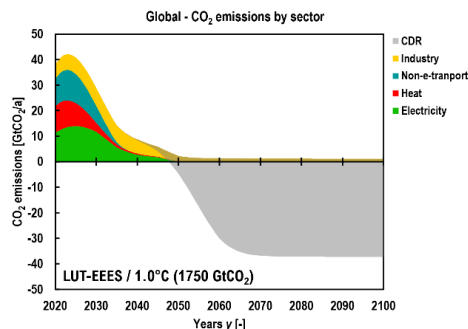
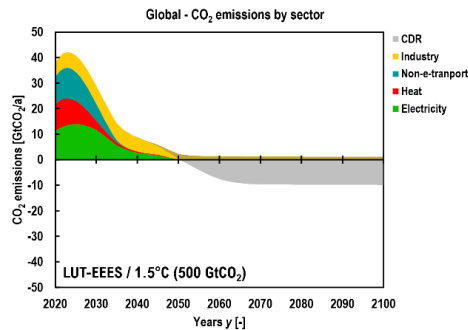
Planetary Climate Control

CO₂ management

renewable electrification
(fossil CO₂ phase-out)
CCS (rather little)

CCU, CCUS

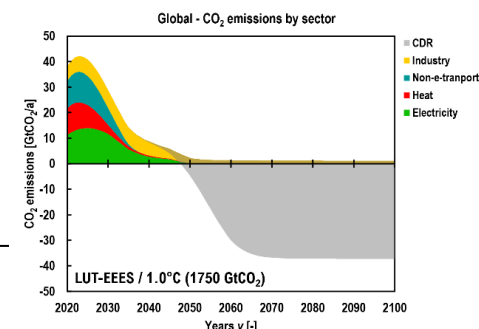
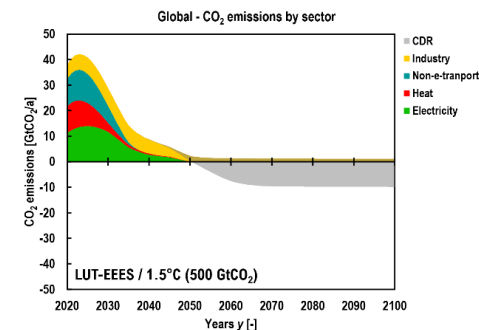
CDR



		2030	2040	2050	ref
CO₂ raw material demand					
e-Methane	MtCO ₂	14	153	1,458	[49]
e-FIL fuels	MtCO ₂	1	1,373	2,879	[49]
e-FIL naphtha	MtCO ₂	0	343	720	[49]
e-Methanol	MtCO ₂	579	2,188	4,068	[59]
Total	MtCO₂	594	4,057	9,125	

CCUS (re-scoped):

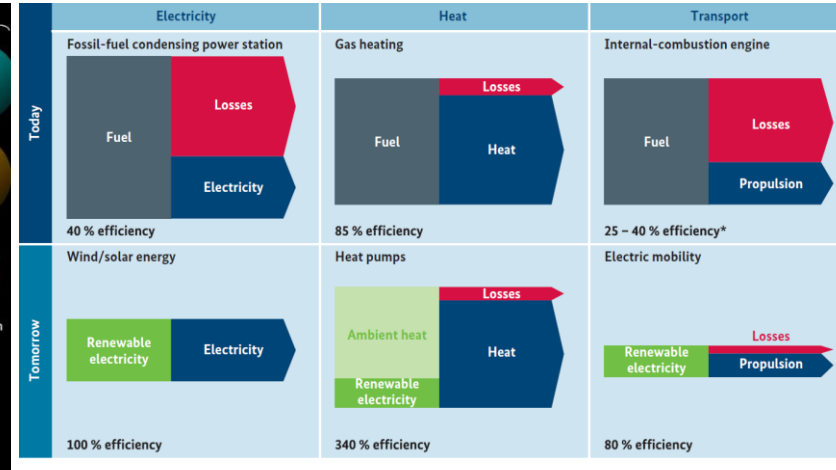
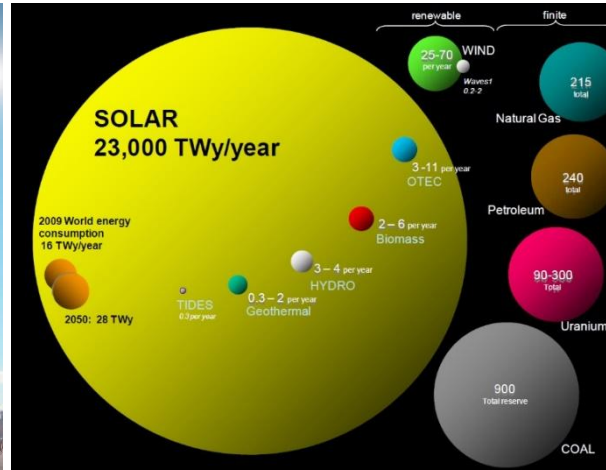
- CCU & permanent CO₂ sequestration
- electricity-based carbon fibres
- electricity-based silicon carbide
- electricity-based graphene
- building materials



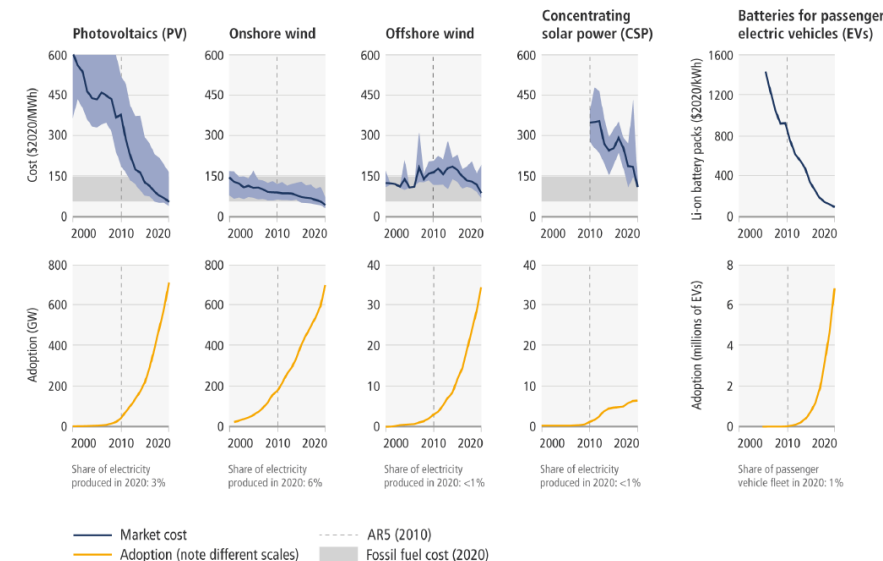
w Material to Climate Control

@lut.fi @ChristianOnRE

Drivers: Climate, Availability, Electrification, Cost



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.



Key insights:

- Climate change requires emissions phase-out asap
- Solar energy **resource availability** is 1000x larger than the global demand, plus 2-3x wind, plus others
- **Direct electricity** use is highly efficient
- **Indirect electrification** is important for remaining 50% of final energy demand
- Renewables **costs have declined** steeply and continued: solar PV, wind power, batteries, electrolyser, and others
- Combination of these three major drivers leads to massive uptake of renewables, esp. solar PV

source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50
[Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847](#)
 IPCC, 2020. 6th Assessment Report WG III

Power Market Development: 2008 - 2022



Empiric trends:

Electricity supply dominated by PV and wind power

Generation mix will adapt to the mix of new installations, year by year

Fossil-nuclear generation will be increasingly irrelevant

Solar PV grew by +30% YoY in 2022, +70% YoY in 2023, +24% YoY in 2024, +20% YoY in 2025

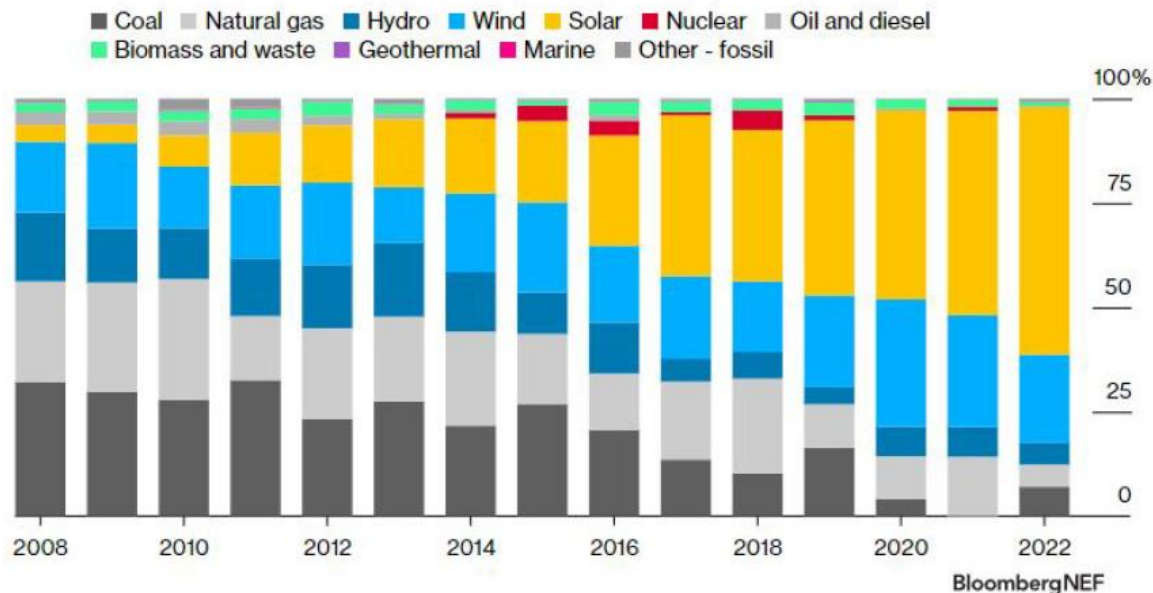
(note: newly PV electricity > wind)

PV is outside any historical experience

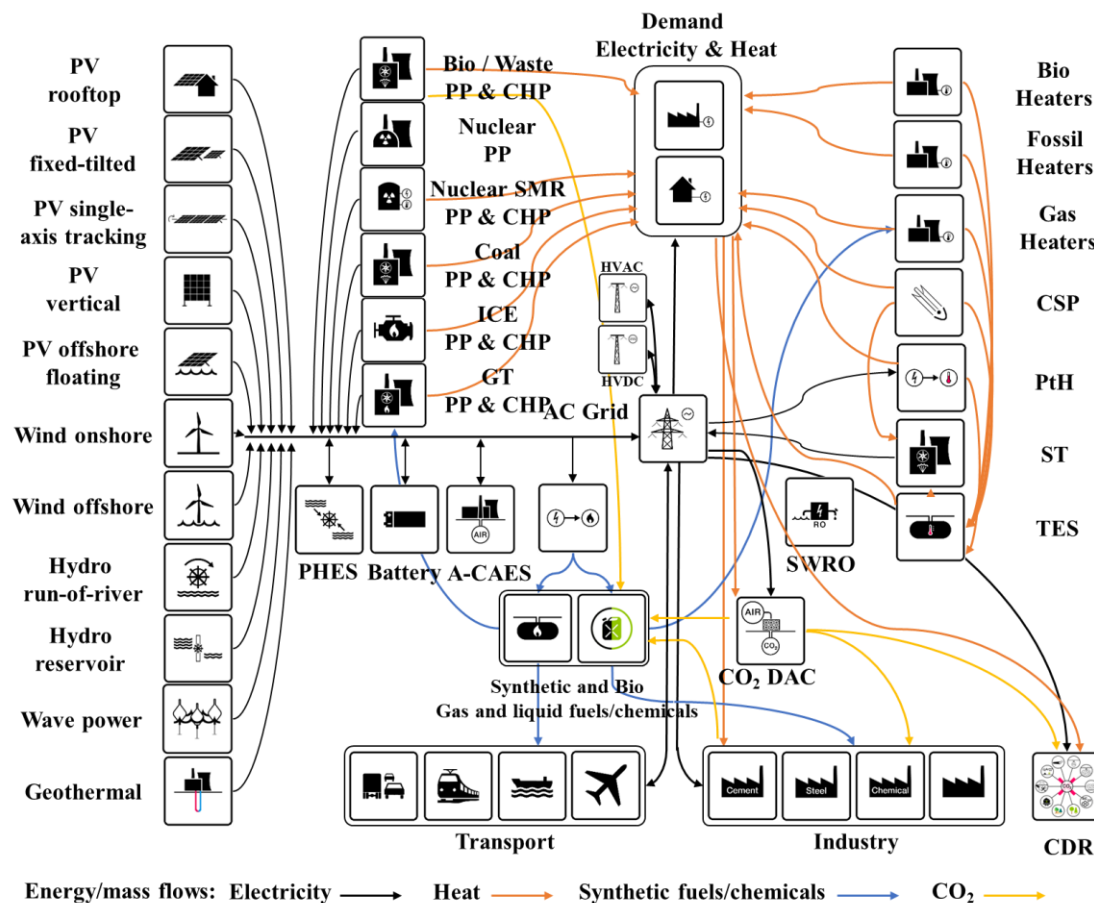
Key insights:

- Solar PV and wind power dominate new installations, with clear growth trends for PV
- Hydropower share declines, a consequence of overall capacity rise, and sustainability limits
- Bioenergy (incl. waste) remain on a constant low share
- New coal plants are close to fade out
- New gas plants decline, with very high gas prices pushing them towards peaking operation
- Nuclear is close to be negligible, the heated debate about new nuclear lacks empirical facts

Share of global electricity capacity additions by technology



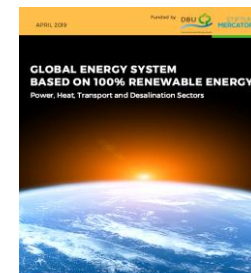
LUT Energy System Transition Model (LUT-ESTM)



reports



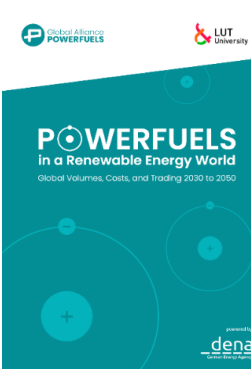
[link to report](#)



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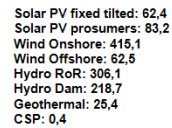


[link to report](#)

Key features:

- full **hourly** resolution in global-local studies for **energy-industry-CDR** systems, comprising 150+ technologies
- used for several major reports, in about 75+ scientific studies, published on all levels
- strong consideration on all kinds of **power-to-X** (heat, fuels, chemicals, materials, freshwater, CO₂, CDR, forests, food)

Solar PV fixed tilted: 62,4
Solar PV prosumers: 83,2
Wind Onshore: 415,1
Wind Offshore: 62,5
Hydro RoR: 306,1
Hydro Dam: 218,7
Geothermal: 25,4
CSP: 0,4

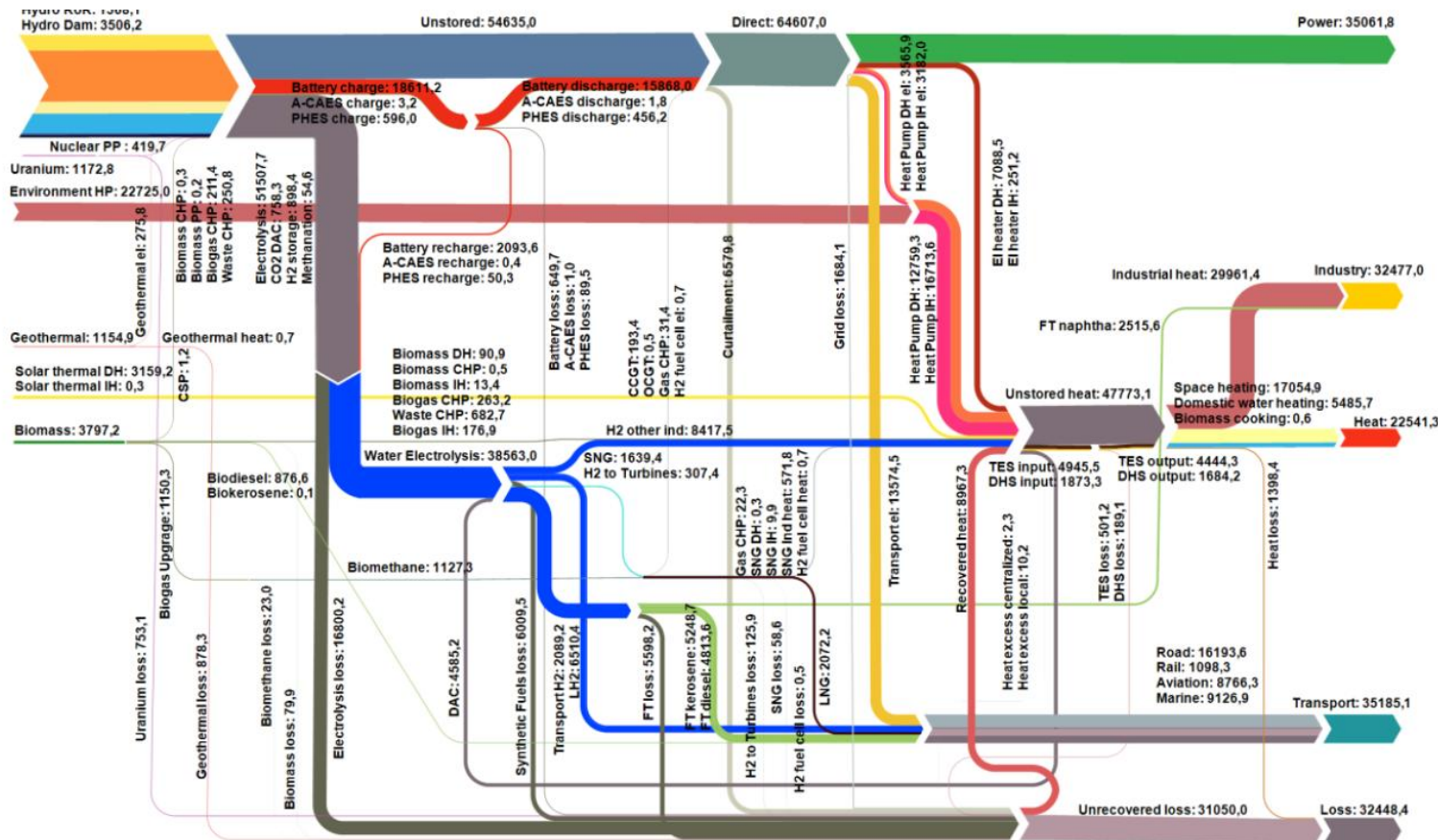




Power-to-X Economy: Global Solar-to-X Economy

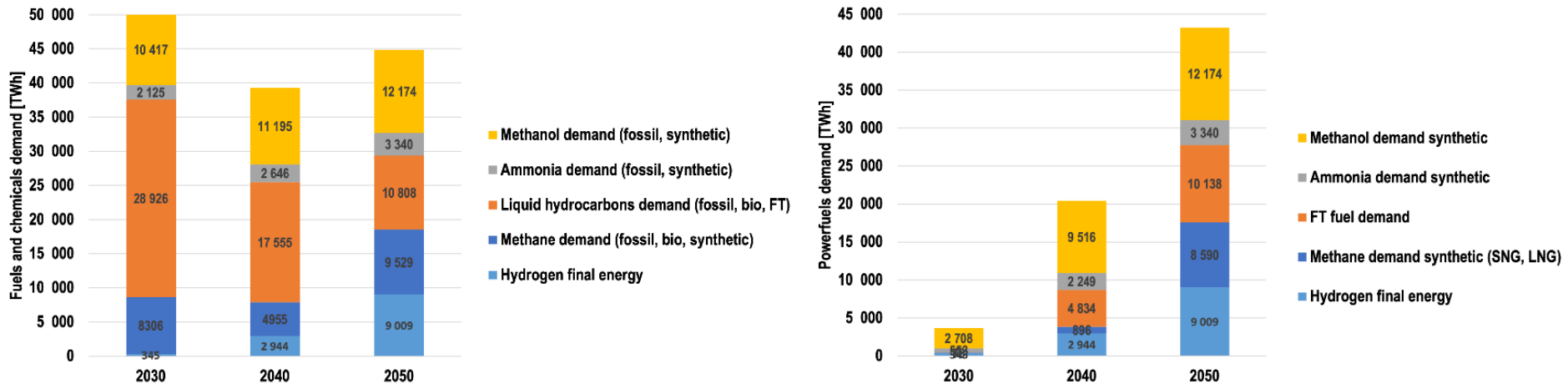


- Solar PV contributes **76%** to global electricity generation and **70%** to global primary energy supply
- Core characteristic of energy in future: **Solar-to-X Economy**
 - Model version is a bit older as for Europe (energy system vs energy-industry system)
 - Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
 - Indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel; **power-to-hydrogen-to-X**
 - **Fossil CO₂ emissions are phased out, CO₂ as raw material ramped up** (non-fossil point sources, DAC)



Source:
[Aghahosseini et al., 2026.](#)
[IET Renewable Power Generation, 20, e70225](#)
 scenario: BPS-2050 for 2050

Global Demand for e-fuels and e-chemicals



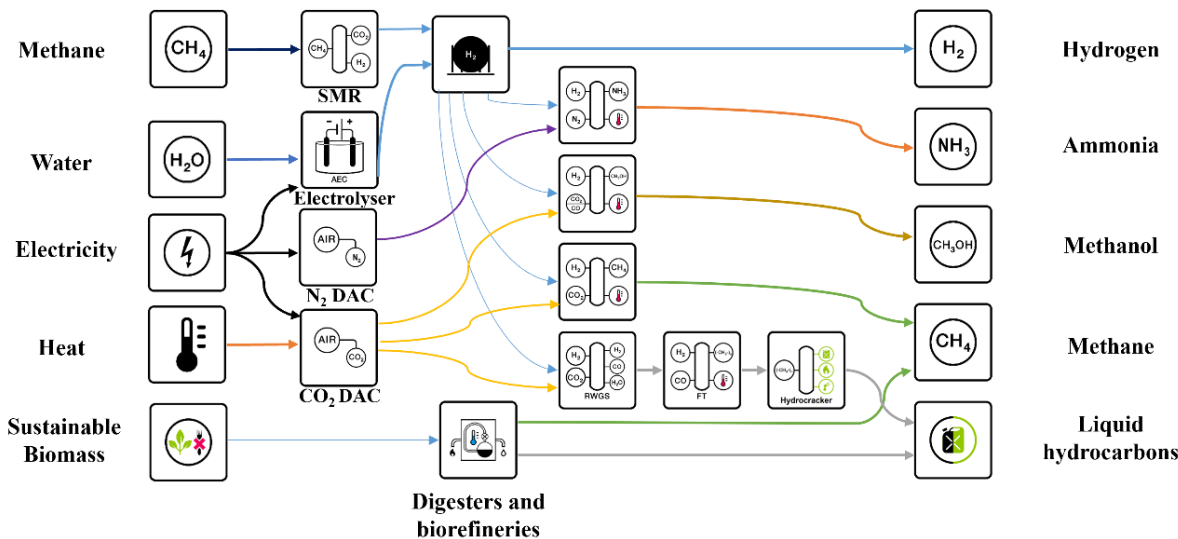
Fuels and Chemicals in general:

- steady growth of chemicals
- **methanol** represents non-ammonia chemicals
- **liquid hydrocarbons** are in steady **decline**, mainly due to electrification of road transportation
- **methane** demand in decline until 2040 with increase till 2050, with **uncertainty** for hydrogen substitution

e-fuels and e-chemicals:

- first markets during 2020s by 2030
- strong growth over the decades reaching a volume of more than 40,000 TWh
- less uncertainty for e-chemicals
- highest uncertainty for e-methane demand due to substitution by e-hydrogen, e-ammonia, e-methanol

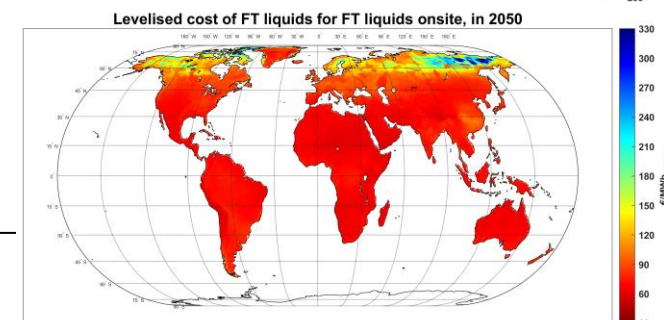
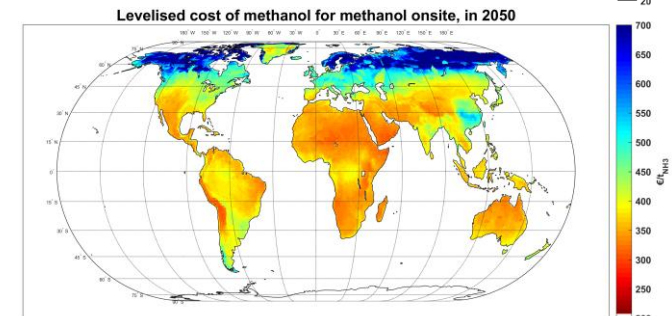
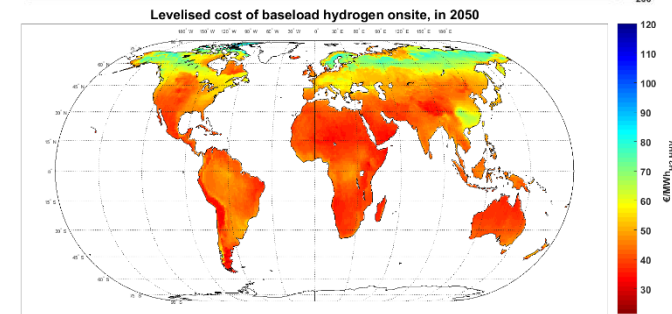
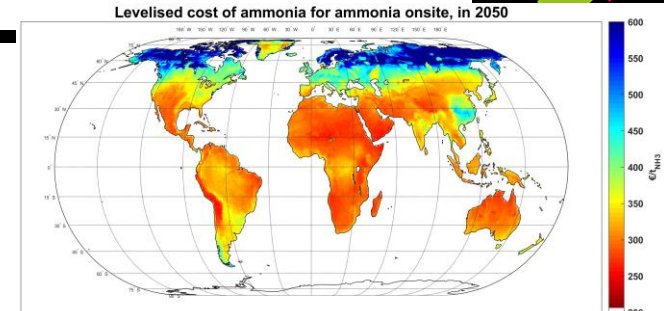
Sustainable e-fuels and e-chemicals



Key insights:

- Sustainable biomass is quite limited, since energy crops shall be limited to zero due to food supply and biodiversity restrictions
- All fuels can be produced based on electricity, water, and air
- All **e-fuels** production routes are technically available at high TRL
- Methane is still listed but may not be required, as technically it is not necessary, relatively high cost, AND high GWP due to leakage
- Major challenge ahead: stable business environment & **DAC** ramping

source: e-fuels/ e-chemicals [PtL](#); [PtA](#); [PtH2](#); [PtCH4](#); [PtMeOH](#)
 transport infrastructure: [H2](#); [NH3](#); [MeOH](#)
 sectoral demand: [chemicals](#); [aviation](#); [maritime](#)



Global: CO₂ Demand in a Power-to-X Economy



Table 1. Electricity and hydrogen demand across the energy-industry system in 2030, 2040, and 2050 for energy uses, steelmaking, and chemical feedstocks. The hydrogen demand is linked to electrolyser capacity demand. The hydrogen demand is induced by H₂-based products demand and leads to CO₂ as raw material demand for e-hydrocarbons. Lower heating values (LHV) are used, and electrolyser efficiencies are aligned to [60] for LHV.

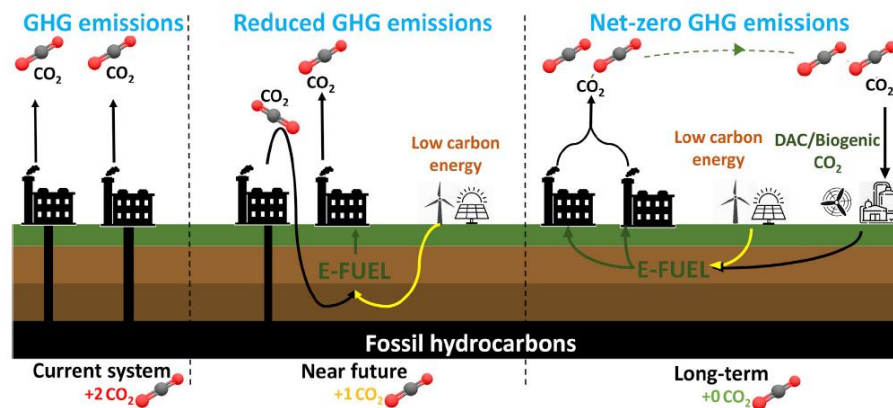
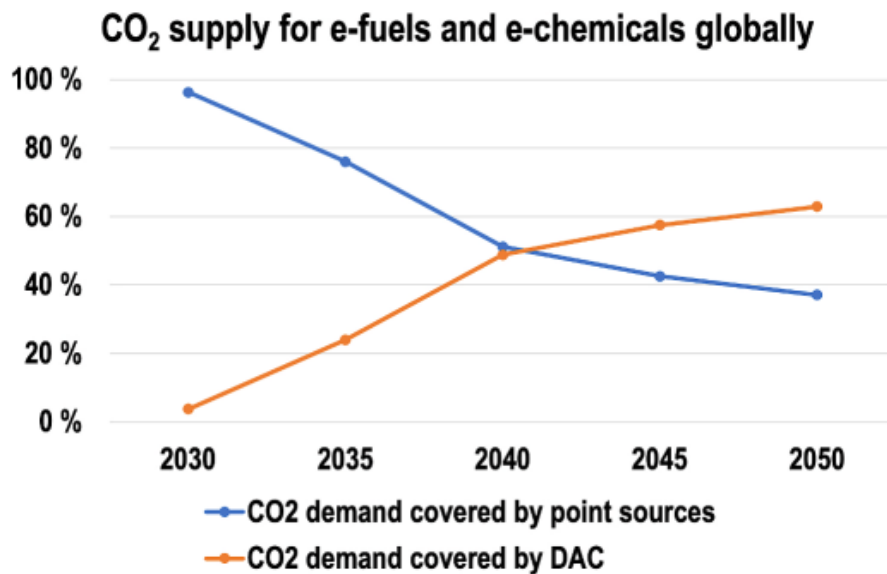
		2030	2040	2050	ref
Electricity demand for electrolysis					
Energy system	TWh _{el}	548	17,069	48,908	[49]
Steelmaking	TWh _{el}	2,718	5,621	6,284	[58]
Chemical feedstocks	TWh _{el}	2,808	17,319	33,031	[59]
Total	TWh_{el}	6,074	40,009	88,223	
Hydrogen demand					
Energy system	TWh _{H₂,LHV}	356	11,529	34,244	[49]
Steelmaking	TWh _{H₂,LHV}	1,755	3,772	4,371	[58]
Chemical feedstocks	TWh _{H₂,LHV}	1,825	11,690	23,122	[59]
Total	TWh_{H₂,LHV}	3,936	26,991	61,737	
Electrolyser capacity					
Energy system	GW _{H₂,LHV}	119	2,990	9,252	[49]
Steelmaking ¹	GW _{H₂,LHV}	501	1,078	1,249	[58]
Chemical feedstocks	GW _{H₂,LHV}	613	3,112	6,208	[59]
Total	GW_{H₂,LHV}	1,233	7,180	16,709	
H₂-based products demand					
e-Hydrogen	TWh _{H₂,LHV}	2,051	6,274	11,963	[49,58,59]
e-Methane ²	TWh _{CH₄,LHV}	78	778	7,419	[49]
e-FTL fuels	TWh _{FTL,LHV}	2	4,502	9,442	[49]
e-FTL naphtha	TWh _{FTL,LHV}	1	1,125	2,360	[49]
e-Ammonia	TWh _{NH₃,LHV}	176	828	1,625	[59]
e-Methanol	TWh _{MeOH,LHV}	2,193	9,495	15,402	[59]
Total	TWh_{fuel,LHV}	4,492	21,877	48,384	
CO₂ raw material demand					
e-Methane	MtCO ₂	14	153	1,458	[49]
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e-FTL naphtha	MtCO ₂	0	343	720	[49]
e-Methanol	MtCO ₂	579	2,188	4,068	[59]
Total	MtCO₂	594	4,057	9,125	

- **Hydrogen** is a subset of the **PtX Economy**
- Main demand: **e-fuels** (marine, aviation), **e-chemicals**, **e-steel** – ammonia, methanol kerosene jet fuel
- Primary energy supply from renewable electricity: mainly PV plus wind power
- Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
- Indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel;
- Most routes are **power-to-hydrogen-to-X**
- Numbers shown here represent the highest ever published H₂ and H₂-to-X demand
- CO₂ as raw material demand reaches about a quarter of today's emissions

Source:

[Breyer, Lopez, et al., 2024. The role of electricity-based hydrogen in the emerging Power-to-X Economy, International J of Hydrogen Energy](#)
[Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, RSER](#)

CO₂ as Raw Material for e-fuels and e-chemicals



- Finally, 60% of global CO₂ **raw material** demand needs to be covered by direct air capture (**DAC**), while the DAC demand in Europe is higher at 76%
- Industrial phase-in of DAC is critical in the 2020s, as point sources are available, while DAC requires a first market ramp-up for massive scaling in 2030s and 2040s
- DAC and carbon utilisation (**DACCU**) for e-fuels/chemicals is the first huge phase-in DAC deployment
- DAC of carbon and storage (**DACCS**) is expected to be the second huge phase for DAC demand starting in 2040s (not included in diagrams)

Need for CDR



Need for safe and just climate planetary boundary for a stable civilisation

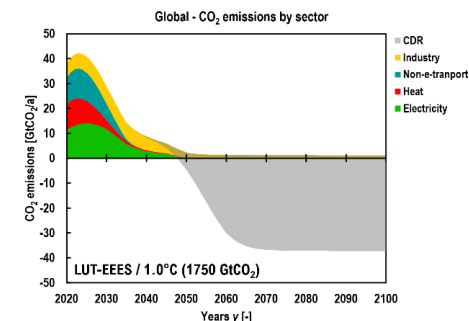
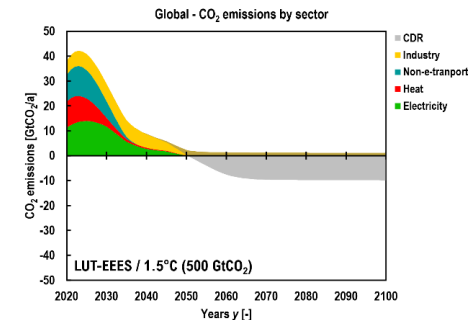
- Safe and just **planetary boundary** is at **1.0°C/ 350 ppm CO₂** (as of late 1980s)
- In 2024, the world was at **>1.5°C/ >420 ppm CO₂** with not yet declining greenhouse gas emissions on a global level
- **Beyond 1.5°C** the planet and our societal systems enter a **high-risk zone** with increasing negative climate impacts and risk of triggering tipping points

Pathways to rebalance within planetary climate boundary

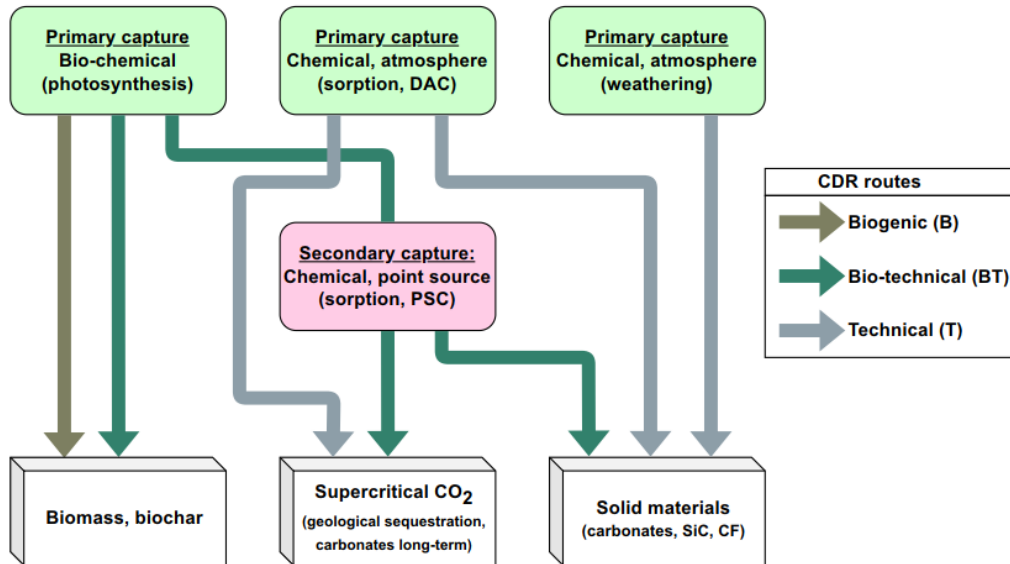
- First, comprehensive **defossilisation** is needed to stop additional emissions
 - **Solid techno-economic understanding** of defossilisation paths with about 1500 scientific papers in the field spanning all energy & feedstock
- Second, net-negative CO₂ emissions, i.e. **CDR on substantial level** needed
 - **CDR portfolios** needed with balanced profiles in maturity, costs, sustainability, permanence, among others
 - Lack of knowledge on **societal preferences** for CDR portfolios
 - Lack of **financing schemes** in a net-negative world
 - **High societal profitability** as benefits **MASSIVELY** exceed costs; co-benefits are reduced climate risk, less biodiversity loss, less societal distortion, etc.



Present loss of ice in Greenland within one hour and accelerating.



CDR Options

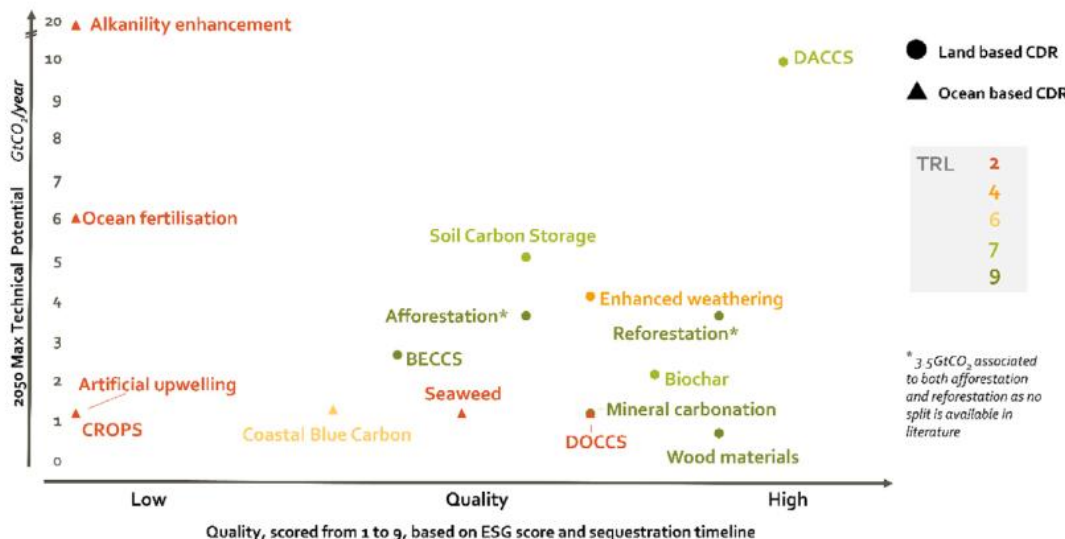


Fundamental CDR and disposal options

- **Biogenic**, e.g. forests (rainfed, desalination)
- **Bio-technical**, e.g. biochar, BECCS
- **Technical**, e.g. DACCS, EW
- **CO₂ waste disposal**: permanence challenge (biochar, forests, maybe geological sequestration), **permanence** (carbonates, durable materials)

Societal value and permanence vs potential

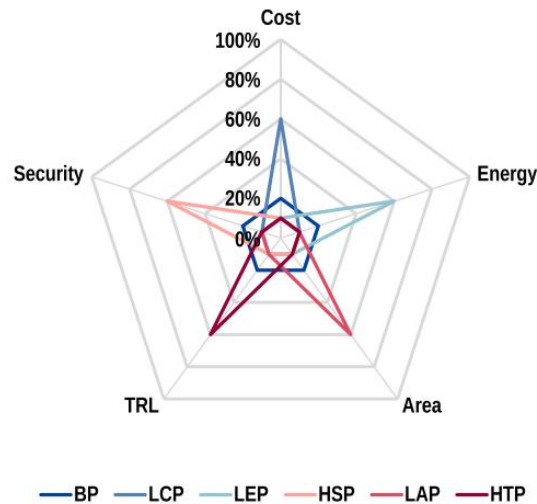
- CDR portfolio approach becomes obvious
- DACCS & mineral carbonation, EW, RF/AF, SCS, wood material
- **DAC**: **inacceptable low R&D and deployment effort**; this is the by far most neglected technology for a successful energy transition (defossilisation, CDR)



Keiner et al., 2025. ERL;

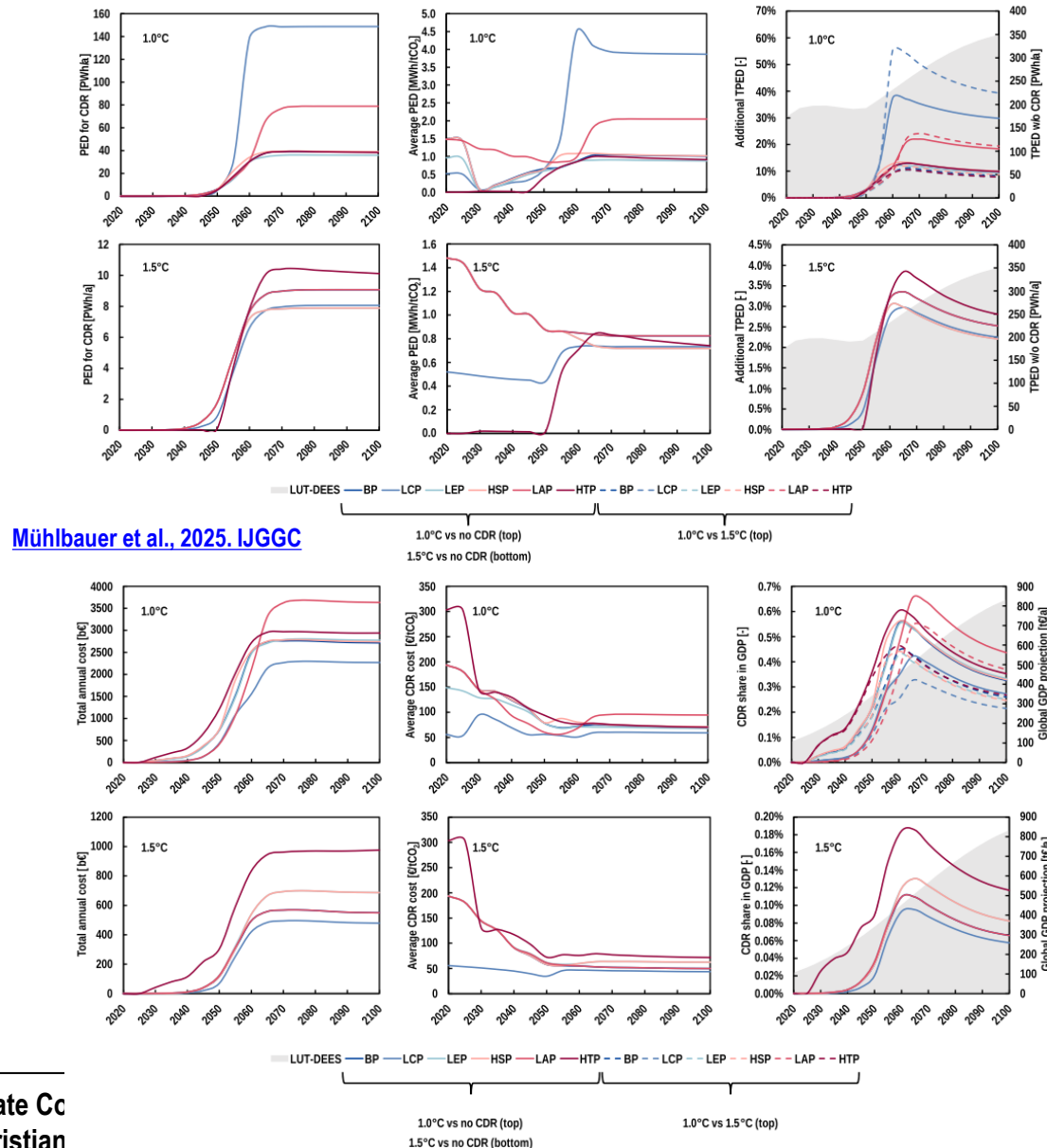
Mertens et al., 2024. iScience

CDR Portfolios



Structural insights on CDR portfolios

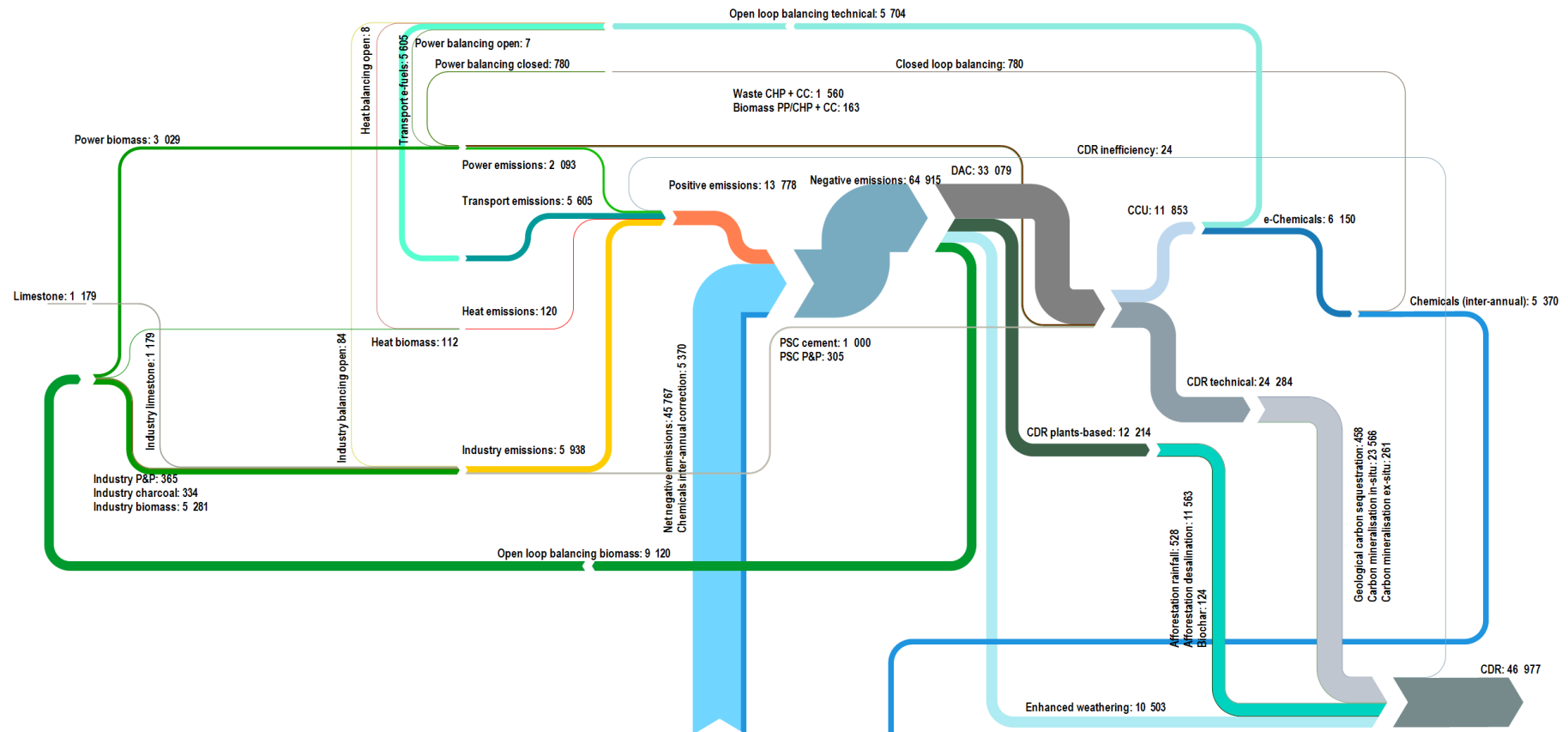
- Societal choice needed whereas preferences not yet clear
- **Energetically affordable** (1.0°C):
ca. 1 MWh/tCO₂, +10% PED
- **Economically affordable** (1.0°C):
<100 €/tCO₂, ca. 0.5% of GDP
- **Highly attractive** (global commons)
investment compared to cost of climate change



CO₂ flows: Waste to raw material to climate control



Diagram	Region	Scenario	Year
Carbon dioxide flow [MtCO ₂]	Global	LEES-1.0-HSP	2100

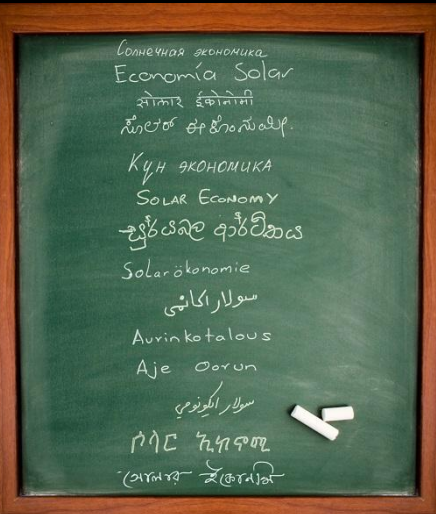


Summary



- Core perception of CO₂: from **emission/ waste**, to **raw material**, to **climate control**
- CO₂ management measures
 - **direct electrification** and respective **fossil CO₂ phase-out**
 - Some **CCS** for non-avoidable CO₂-related processes (mainly cement)
 - **CCU** for hydrocarbons-based products that cannot be substituted
 - **CDR** to control planetary climate for civilisation survival
 - ranking of **energy carriers**: electricity, hydrogen, methanol
- **CCU** demand for CO₂ mainly for synthesis of **e-methanol**, **e-kerosene**, maybe others
- **CDR** requires a **portfolio** of different **options**, **DACCS** may emerge as the largest
- **Power-to-X Economy** is THE core characteristic of the energy-industry system with CO₂ transitioned from waste to raw material (for non-fossil CO₂)

Thank you for your attention and to the team!

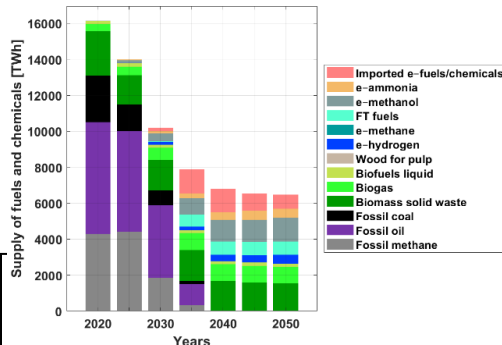
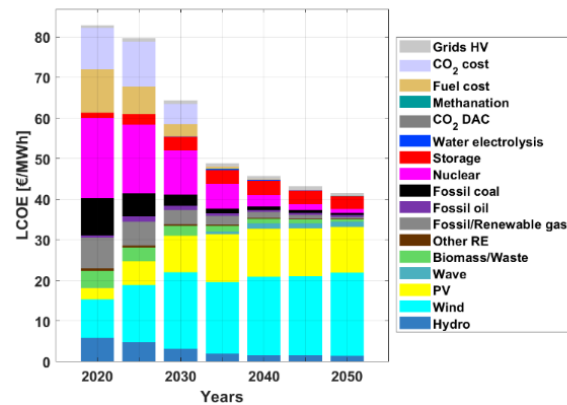
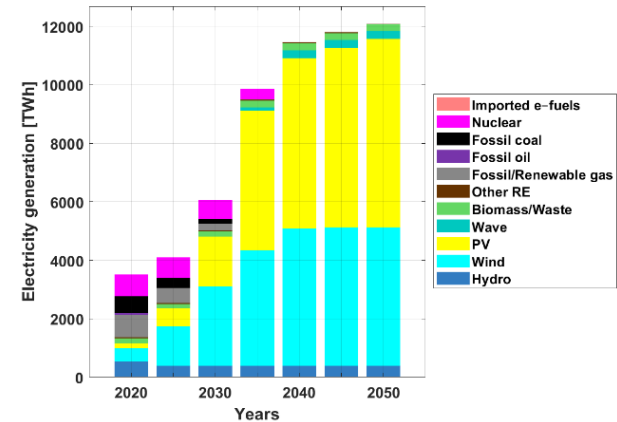
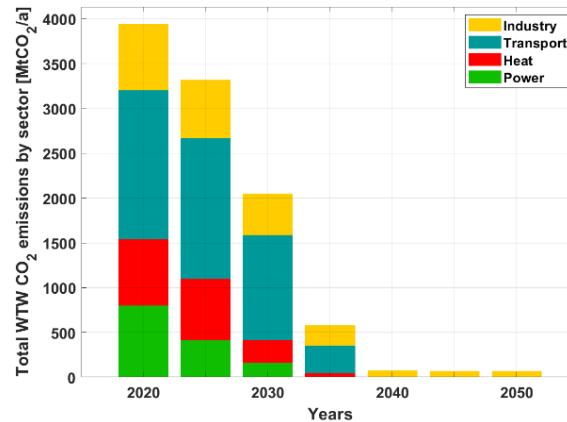
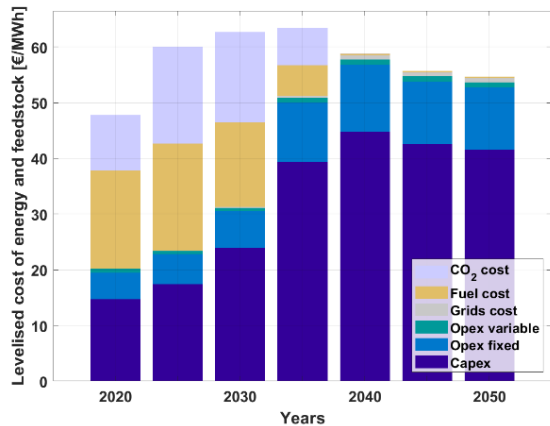


all publications at: www.scopus.com/authid/detail.uri?authorId=39761029000
new publications also announced via BSky/Twitter/LinkedIn: [@ChristianOnRE](https://twitter.com/ChristianOnRE)
podcasts of the papers: <https://www.youtube.com/@ChristianOnRE>



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Europe: Highly Ambitious Energy-Industry Transition



- Methods: [LUT-ESTM](#), 1-h, 20-regions, [full sector coupling](#), cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: zero CO₂ emissions in 2040
- Massive expansion of electricity generation would be required
- e-fuels & e-chemicals ensure stable operation of transport & industry
- Nuclear: by scenario default phased out by 2040; it is NO critical system component; countries will ultimately decide how to proceed
- What's respected:
 - 1.5 °C target & biodiversity & cost effectiveness & air pollution phase-out
 - renewal of European energy-industry system & jobs growth
- Why should society not go for such an option?

Methanol Economy - Overview

- the term Methanol Economy was introduced by George Olah (1923-2017, Nobel Prize for Chemistry in 1994) in 2005 as a solution for the energy transition building on research and overcoming limitations of the term Hydrogen Economy
- Research insights (but not yet very common as most still ignore methanol in modelling!), reveal the **order** of key **energy carriers**: electricity, H_2 , MeOH
- Applications** for methanol: chemicals (MTO), marine fuel, aviation fuel (MTK), general diesel fuel (MTD)
- Challenge** for e-methanol: sourcing of sustainable and affordable CO_2
- Demand** for methanol (tentative estimate): 15,400 TWh_{MeOH,LHV} as the **largest** final e-fuel/chemical with **upside potential** as aviation fuels with 9,400 TWh_{FTL,LHV} is still assumed via the Fischer-Tropsch route
- Important: MeOH **interacts** with the **entire energy-industry** system ...
- Open **questions** – more will arise the deeper we dig in ...:
 - relative competitiveness of **e-kerosene** via MeOH or FTL route
 - international MeOH **trade** as intermediate product (MeOH-X)
 - CO_2 and H_2 **infrastructure** (pipeline, shipping) and CO_2 **point sources** influencing the MeOH capacities allocation

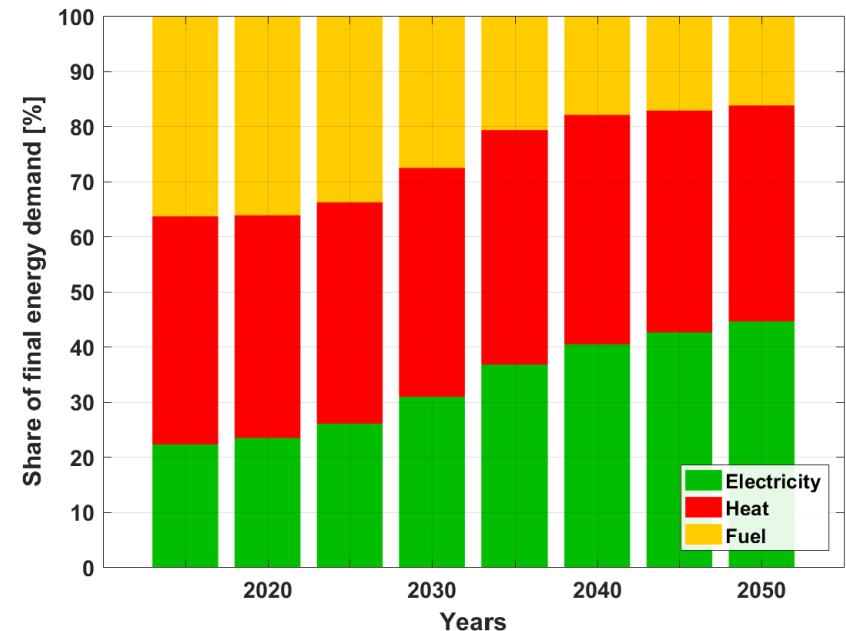
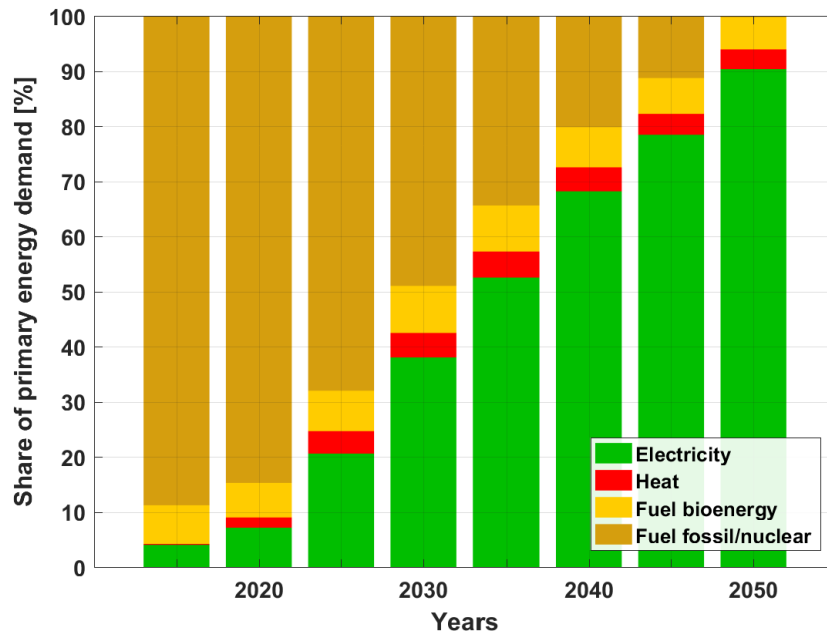


H_2 -based products demand

	TWh _{H₂,LHV}	2,051	6,274	11,963	[49,58,59]
e-Hydrogen	TWh _{H₂,LHV}				
e-Methane ²	TWh _{CH₄,LHV}	78	778	7,419	[49]
e-FTL fuels	TWh _{FTL,LHV}	2	4,502	9,442	[49]
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Source:
[Breyer, Lopez, et al., 2024. The role of electricity based hydrogen in the emerging Power-to-Economy, International J of Hydrogen Energy](#)
 – [Galimova et al., 2023. Global trading and renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, RSER](#)

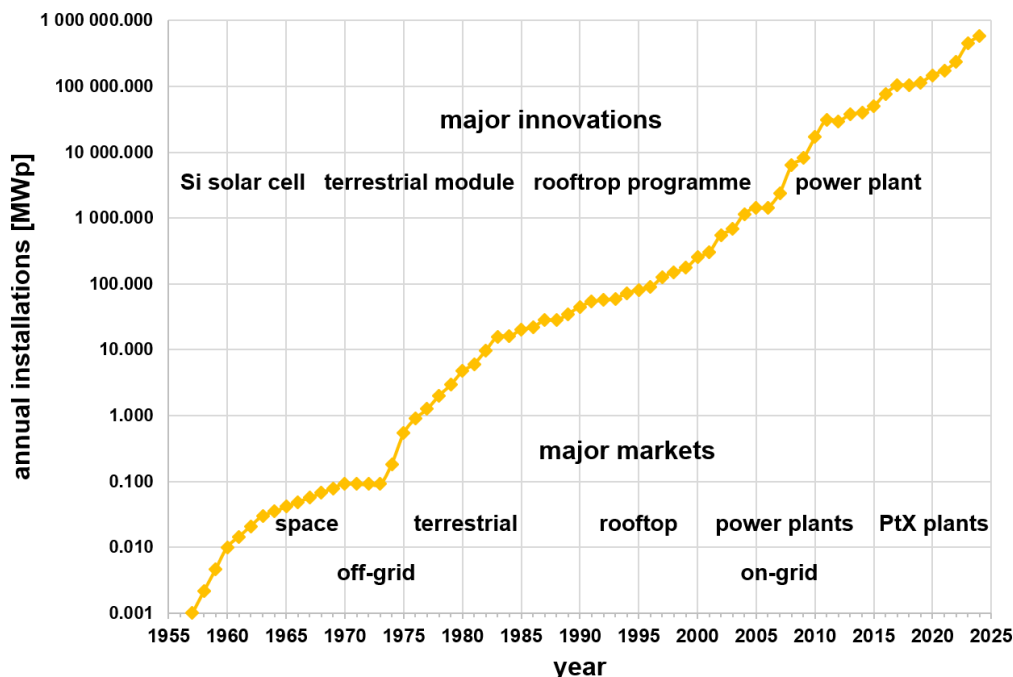
Role of electricity: Primary vs Final Energy



Key insights:

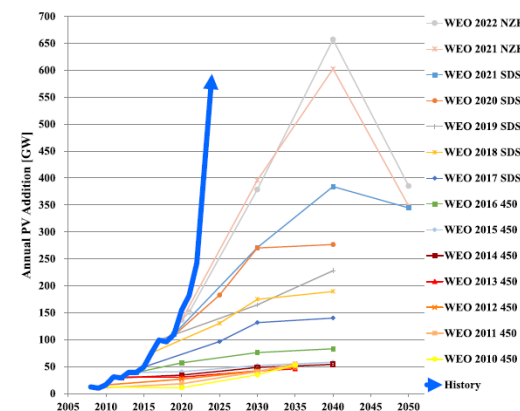
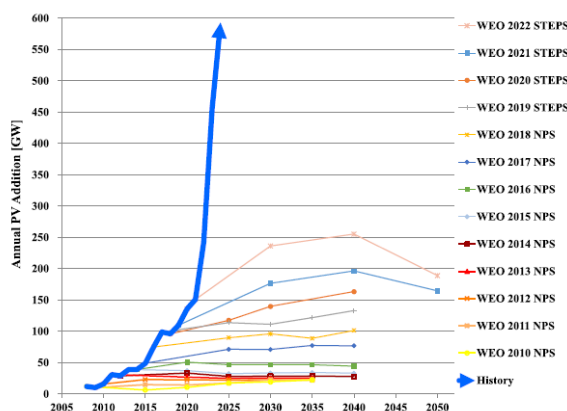
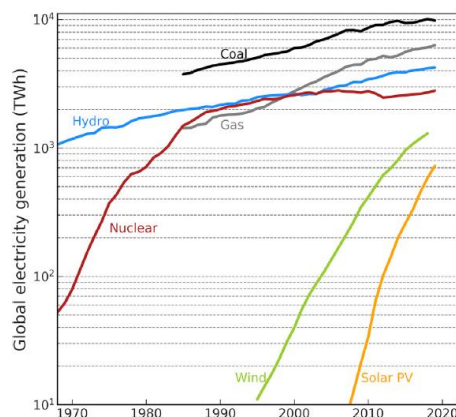
- Electricity emerges to the dominant primary energy source (<5% ► 90%), driven by low-cost and efficiency
- Electricity share in final energy does not structurally change (22% ► 45%)
- Transition from combustion-based to electron-based society is the fundamental driver, due to efficiency and low-cost
- Power-to-X (heat, fuels, mobility, clean water, refined materials, chemicals) explains the discrepancy of TPED vs TFED
- Electricity becomes challenging in discussions, as it can be primary energy, secondary energy, energy carrier, final energy
- It is NO contradiction to generate electricity and sell molecules, it's just upstream and downstream business

Solar PV Installations: how it developed



Key insights:

- low-cost PV dominates one market after another, now Power-to-X plants
- no energy source has been ever phased in as steeply as PV
- wind power is similar to solar PV, but slightly slower in the phase-in
- solar PV manufacturing capacity soon around 1 TW/a across the entire value chain
- **solar PV shows the fastest phase-in in history** (+30% annual installs in 2022; +70% in 2023)
- WEO of IEA structurally fails to get the least cost source of electricity right

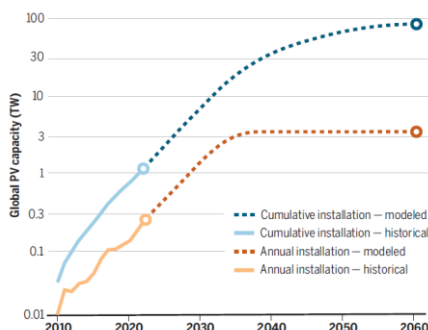


Solar PV Installations: where to go



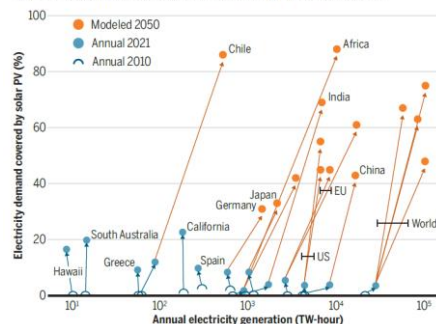
PV installations and growth toward 75 TW by 2050

Modeled cumulative capacity going forward is based on sustaining 25% production rate growth over the next 7 years and then reducing slowly to steady state. Replacement needs are included by simple subtraction of installations 25 years before the modeled date.



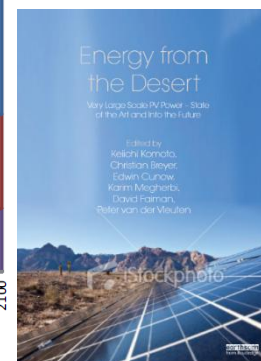
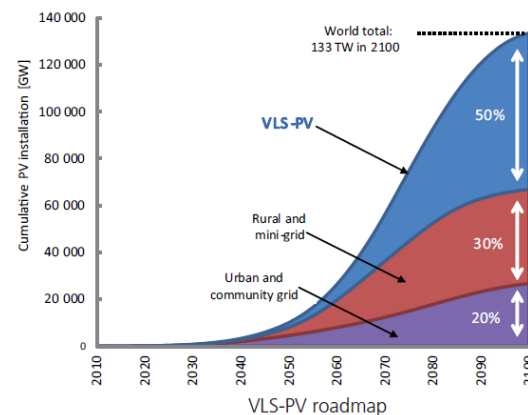
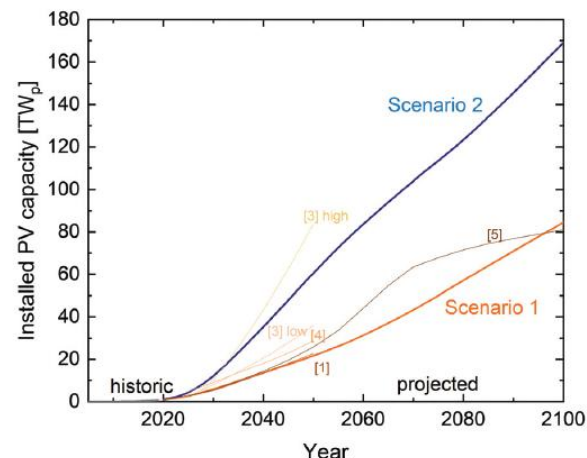
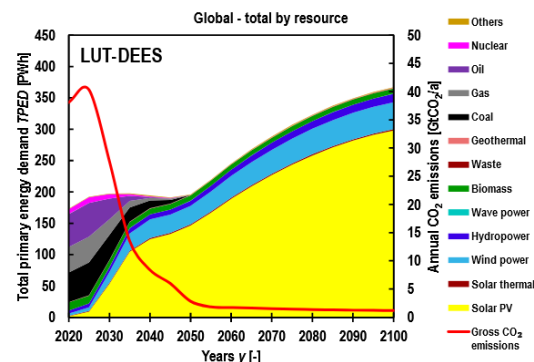
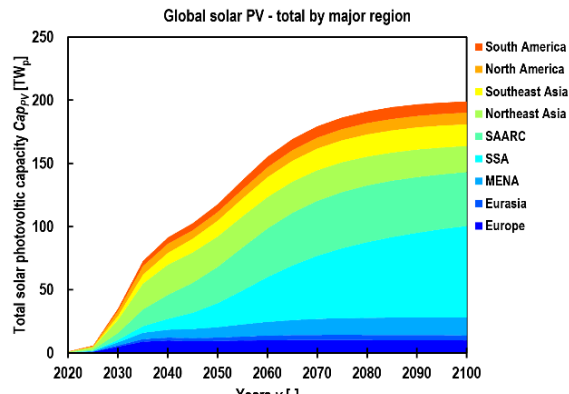
Regional electricity demand supplied by solar PV

The data reflect annual percentages of historical regional demand (2010 and 2021) and modeled demand projections (2050). See supplementary materials for details.

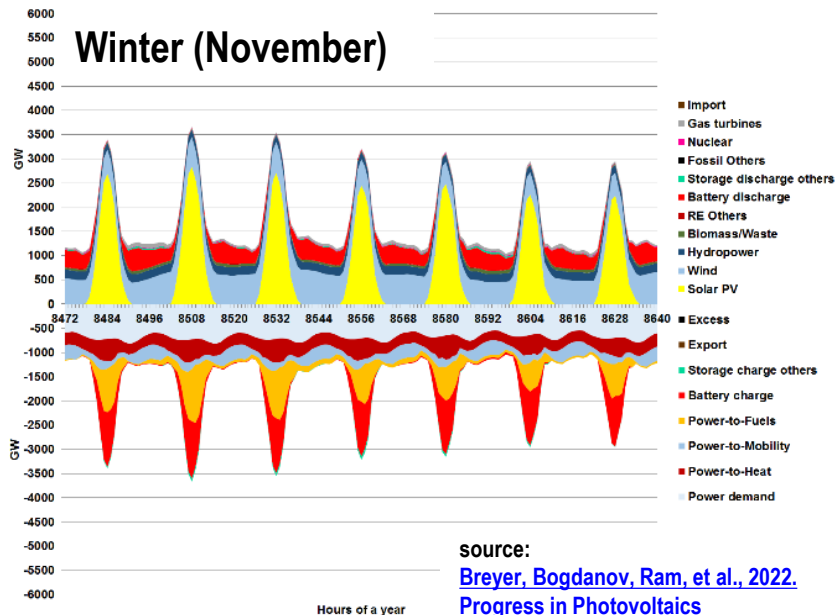
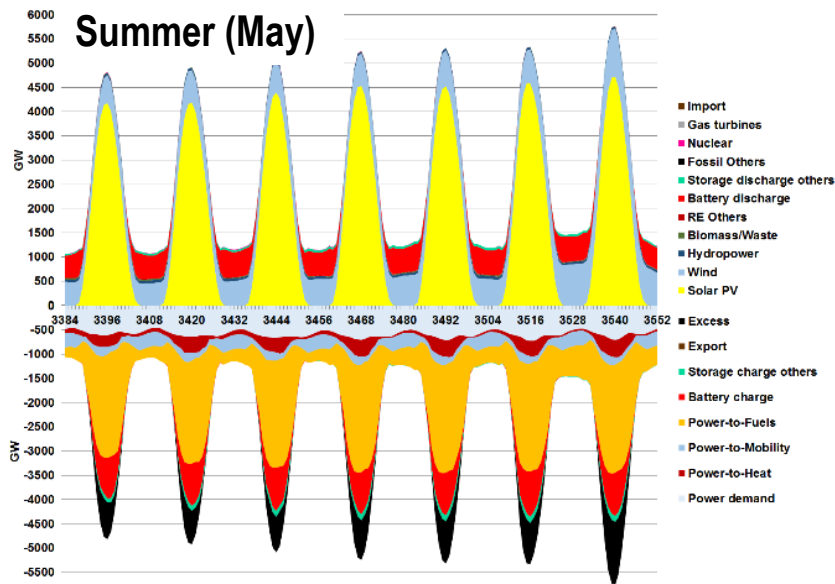


Key insights:

- low-cost PV leads to a cost-neutral energy transition towards 2050
- about **75 TW of PV by 2050** required for the energy-industry system and **~3 TW/a of PV installations** in 2040s
- long-term PV capacities are found up to **170-200 TW by 2100**
- energy-industry-CDR system to rebalance to **1.0°C/ 350 ppm**
- **Sunbelt** regions may reach 60-90% PV share; **Northern Hemisphere**: US 60%, Europe ~50%, China 60%



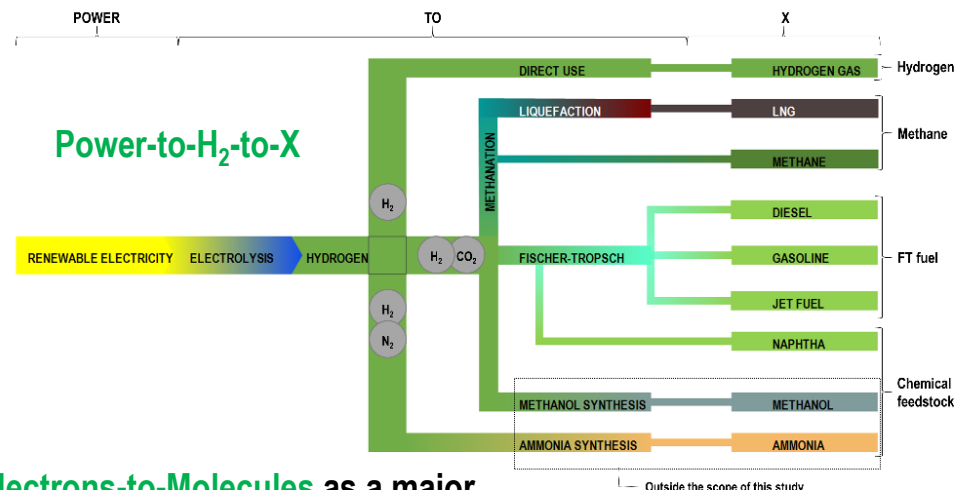
Hourly Operation and Balancing



source:
[Breyer, Bogdanov, Ram, et al., 2022.](#)
[Progress in Photovoltaics](#)

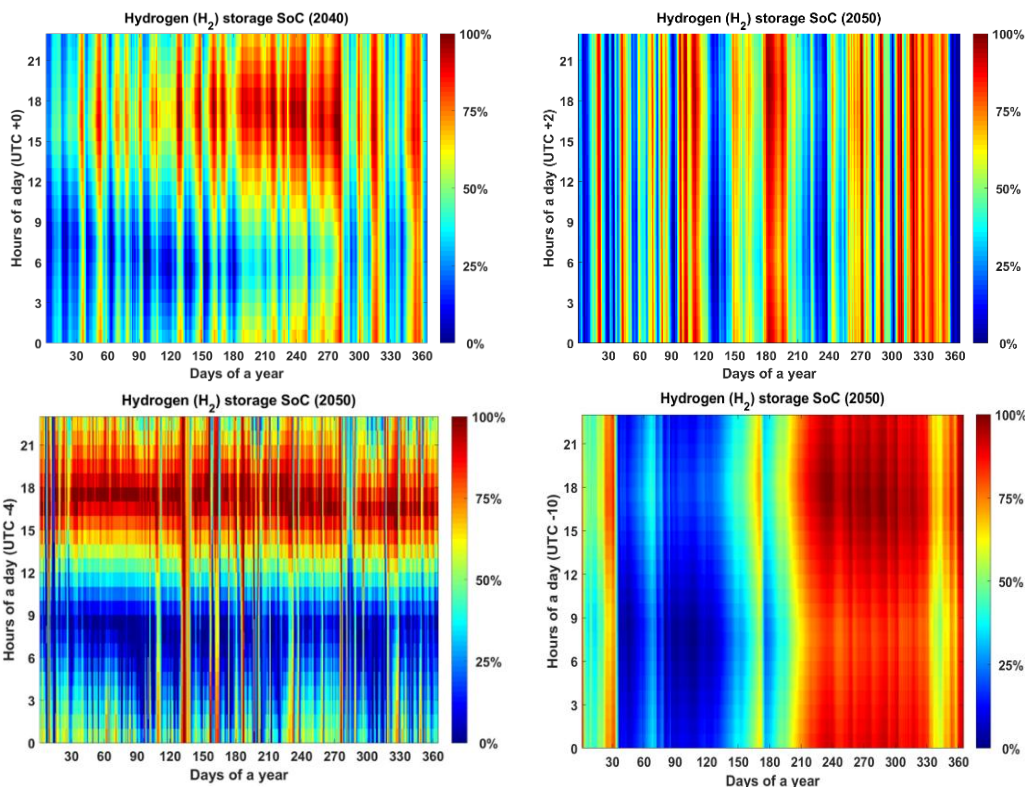
Key insights:

- Week of most renewables supply (spring) and least renewables supply (winter) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the region easily copes with energy demand
- Key balancing components are electrolyzers (Power-to-H₂-to-Fuels) that convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability



Electrons-to-Molecules as a major piece of **Power-to-X Economy**

H₂ Storage in recent National Studies



Iberia (top left), Finland (top, right)
Puerto Rico (bottom left) Hawaii (bottom right)

Key insights:

- Most important, the energy system model used is identical and techno-economic assumptions are identical
- Differences originate from the structure of resources and demand for energy services
- H₂ storage can be:
 - buffer storage (case Finland)
 - seasonal storage (case Hawaii)
 - daily storage with impact of wind (case Puerto Rico)
 - daily, seasonal, buffer in one (case Iberia)
- H₂ storage is quite context and location dependent

source:

EISayed et al., 2023. 2023, On the full potential and role of different solar photovoltaic system technologies in the Iberian energy transition, EU PVSEC, Lisbon

Satymov et al., 2025. [Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, Energy](#)

Breyer et al., 2023. [Role of solar PV for a sustainable energy system in Puerto Rico in the context of the entire Caribbean featuring the value of offshore floating systems, IEEE Journal of Photovoltaics](#)

Lopez et al., 2024. [Role of Storage in the Power-to-X Economy: The Case of Hawaii, J of Energy Storage](#)