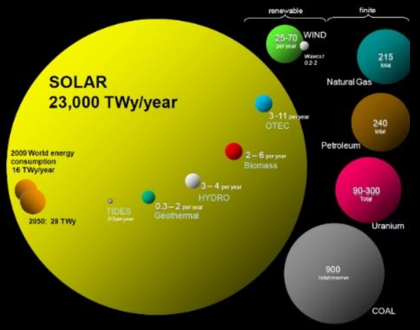


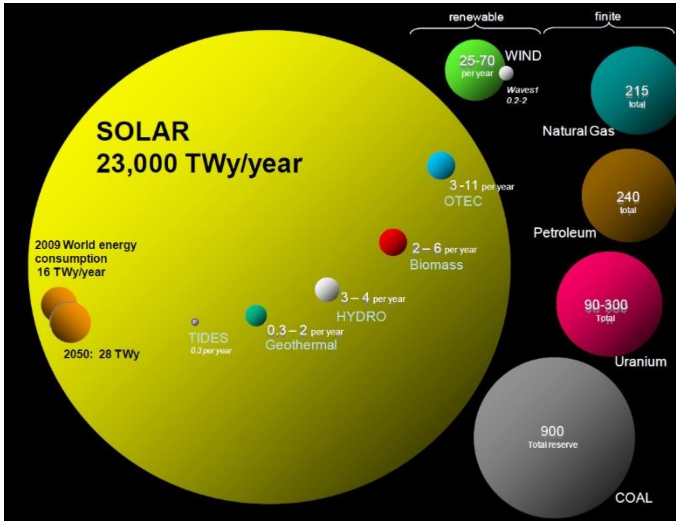
Wasserstoff für die globale Power-to-X Wirtschaft

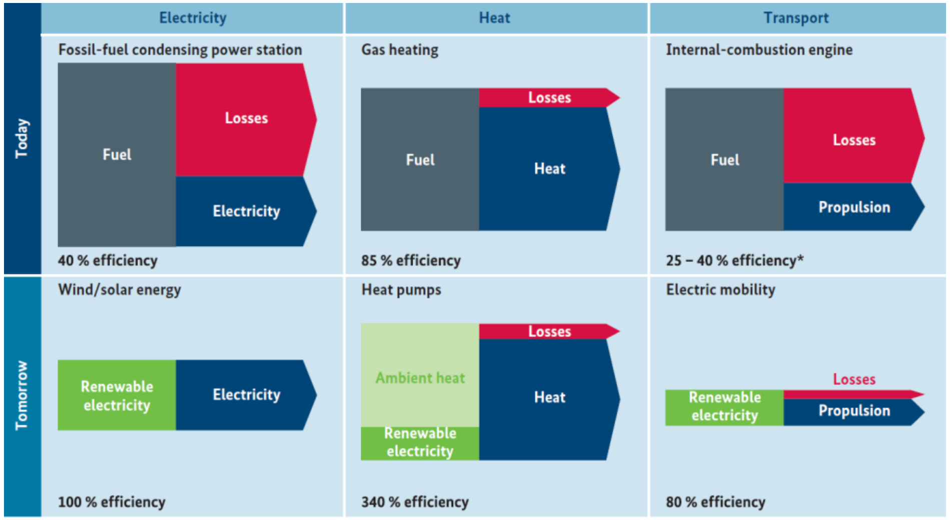
Open your mind. LUT.
Lappeenranta University of Technology

Christian Breyer
LUT University

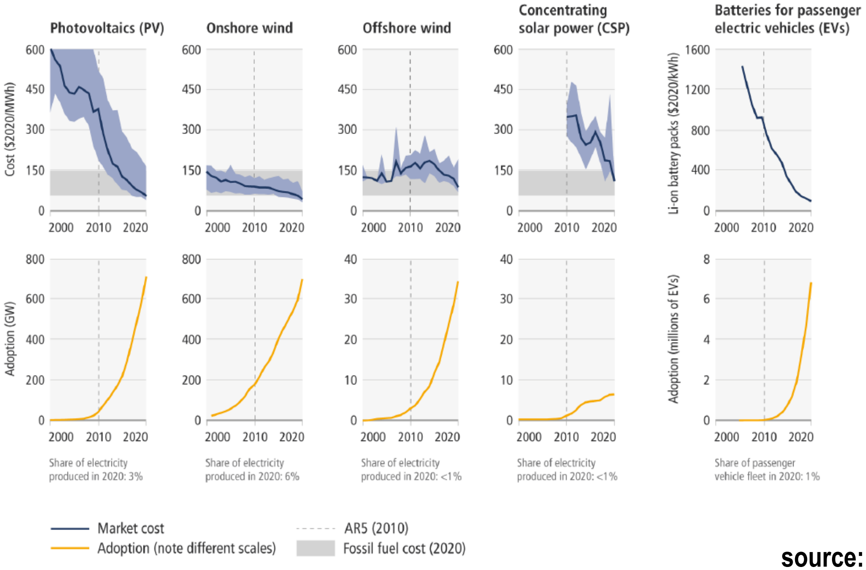
15. ExpertInnengespräche Power-to-X, OST
Rapperwil, April 9, 2024

Key Drivers: 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:

- Solar energy resource availability is 1000x larger than the global demand
- Direct electricity use is highly efficient
- 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 solar PV complemented by wind

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: 2007 - 2021

Empiric trends:

Electricity supply dominated by PV and wind power

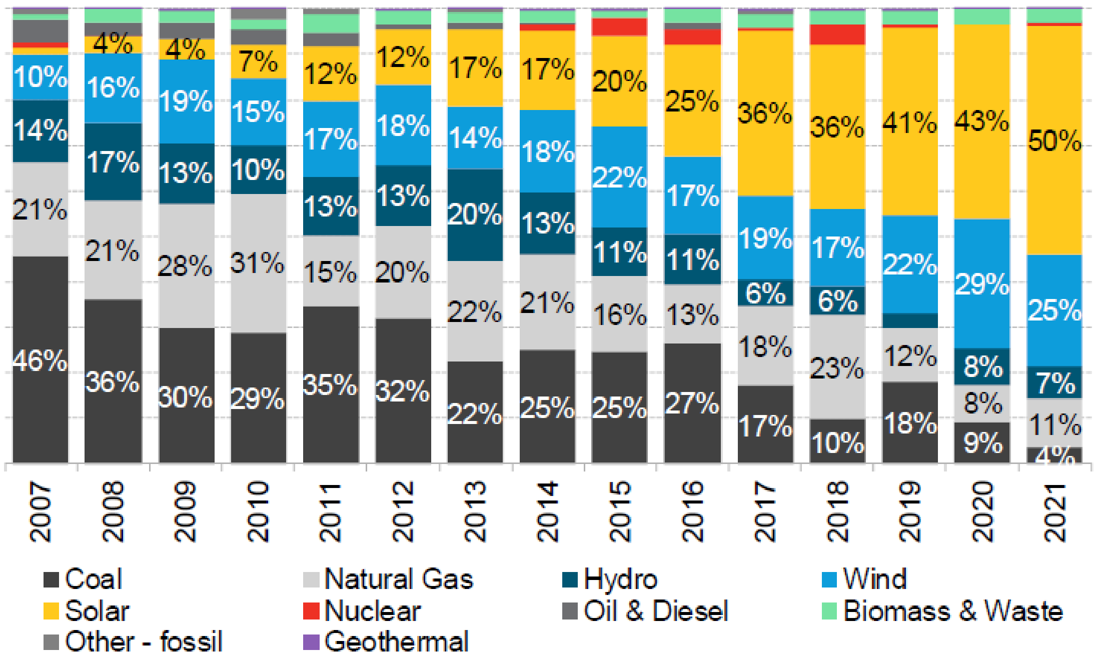
Generation mix will adapt to the mix of new installations, year by year

Fossil-nuclear generation will be increasingly irrelevant

Solar PV grew by +30% YoY in 2022, and +70% YoY in 2023 (note: newly PV electricity > wind)

PV is outside any historic experience

Share of global capacity additions by technology



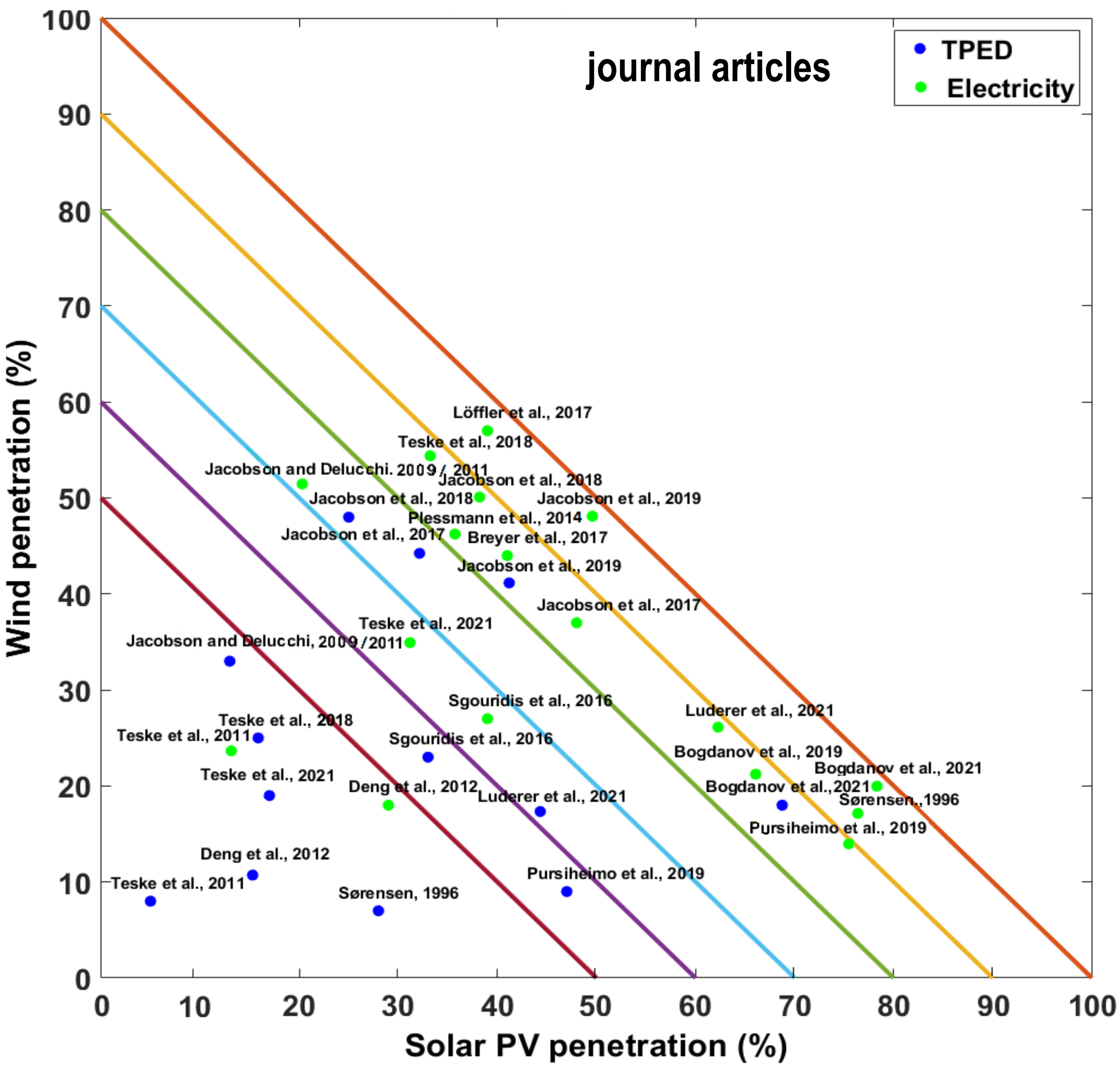
Source: BloombergNEF

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**

source: BNEF, Power Transition Trends 2022

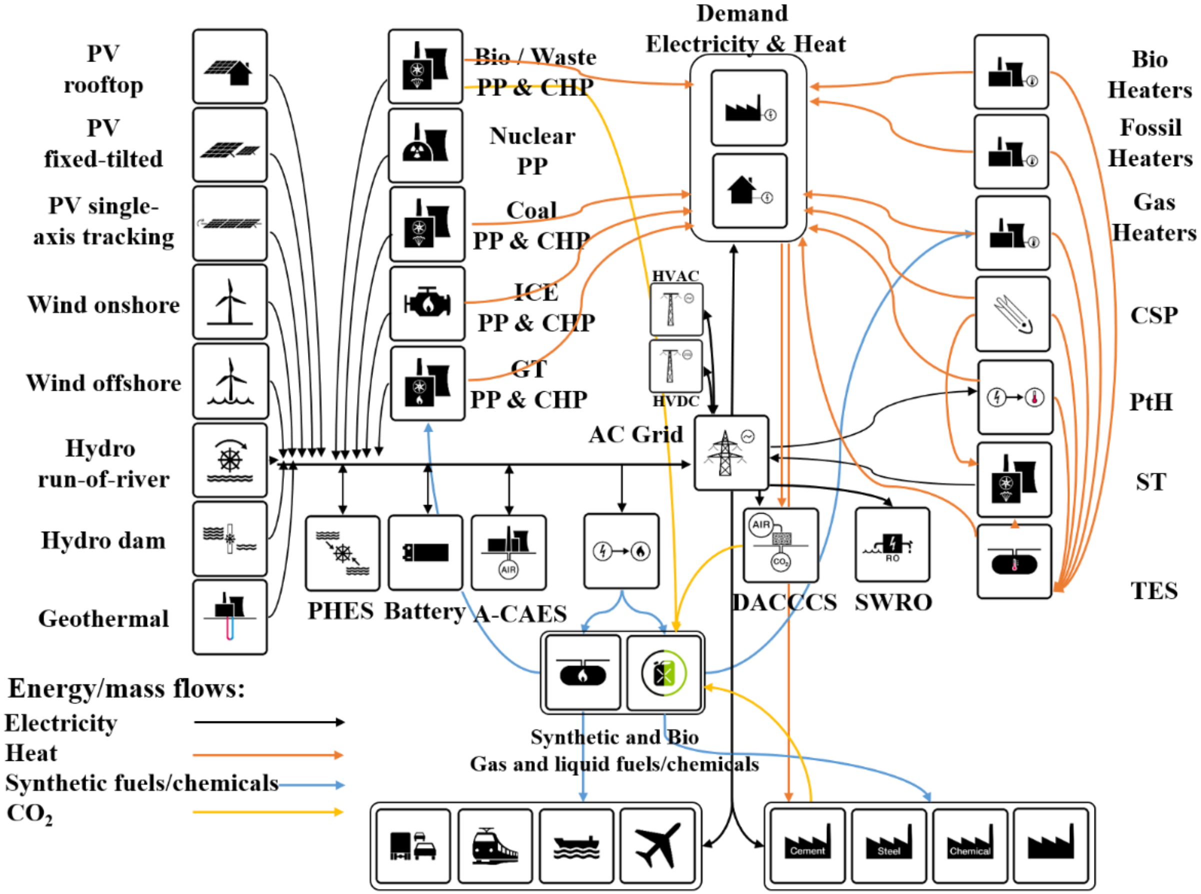
Global: PV & Wind Share in 100% RE Studies



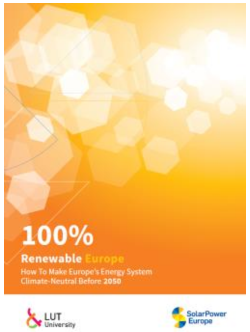
Key insights:
- 3 main groups:
  - High PV & wind: more PV
  - High PV & wind: more wind
  - Lower PV & wind
- PV share of around 50% by 2050 is standard
- Group of studies with high PV shares (70-80%) have all in common that they anticipate continued PV cost decline
- PV strongly benefits from electrification, low-cost batteries, low-cost electrolysers, and Power-to-X
- Two studies with highest shares of PV & wind in TPED have consequently worked in Power-to-X
- Reasons for lower PV & wind shares
  - High PV cost assumptions
  - CSP forced in the mix, despite cost
  - Bioenergy forced in the mix, despite biodiversity issues
  - Low electrification rates

source: Breyer et al., 2022. IEEE Access 10, 78176-78218

LUT Energy System Transition Model (LUT-ESTM)



recent reports


100%

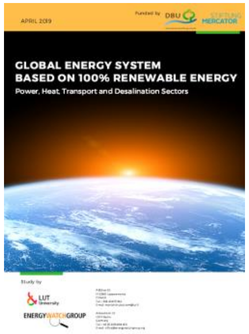
Renewable Europe

How To Make Europe's Energy System Climate-Neutral Before 2050

LUT University

SolarPower Europe

link to report


APRIL 2019

Funded by DBU STIFTUNG MERCATOR

GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY

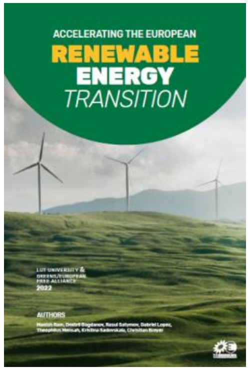
Power, Heat, Transport and Desalination Sectors

Study by

LUT University

ENERGYWATCHGROUP

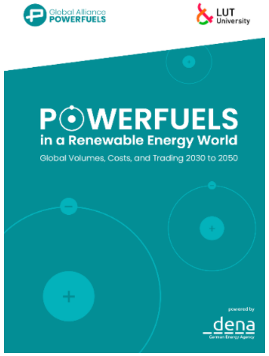
link to report


ACCELERATING THE EUROPEAN RENEWABLE ENERGY TRANSITION

LUT UNIVERSITY & GREENS/EUROPEAN FREE ALLIANCE 2022

AUTHORS

link to report


Global Alliance POWERFUELS

LUT University

POWERFUELS in a Renewable Energy World

Global Volumes, Costs, and Trading 2030 to 2050

powered by dena German Energy Agency

link to report

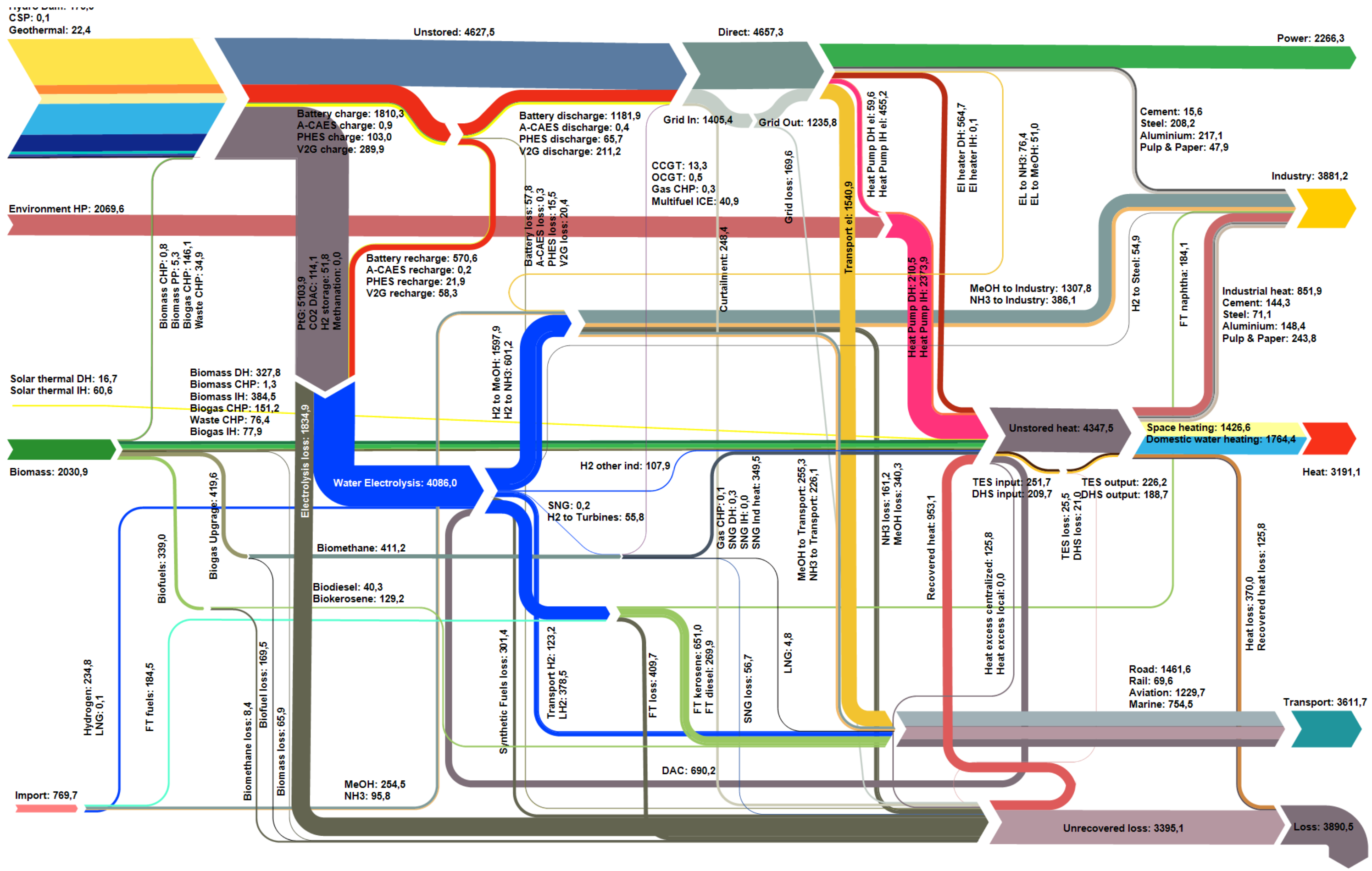
Key features:

- full hourly resolution, applied in global-local studies, comprising about 150 technologies
- used for several major reports, in about 75 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (heat, fuels, chemicals, materials, freshwater, CO_2, CDR, forests)

source: Bogdanov, Breyer et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, 283, 116273

Power-to-X Economy as new characteristic Term

- Zero CO_2 emission low-cost energy system is based on electricity
- Core characteristic of energy in future: Power-to-X Economy
  - 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; power-to-hydrogen-to-X

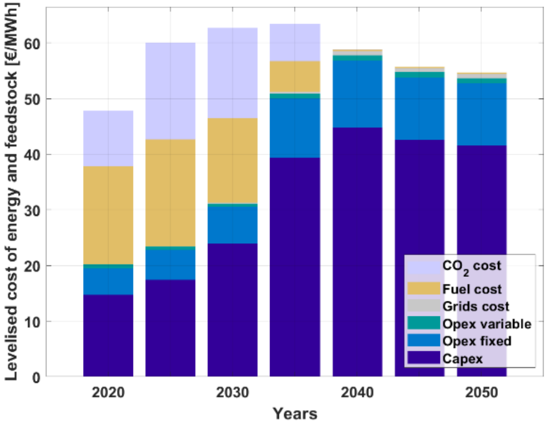


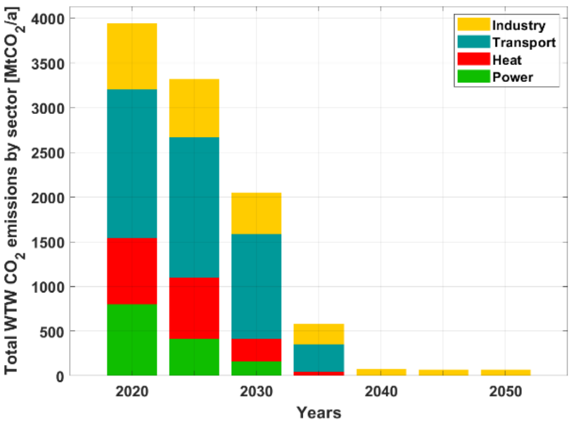
Source:
Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2023. Progress in Photovoltaics

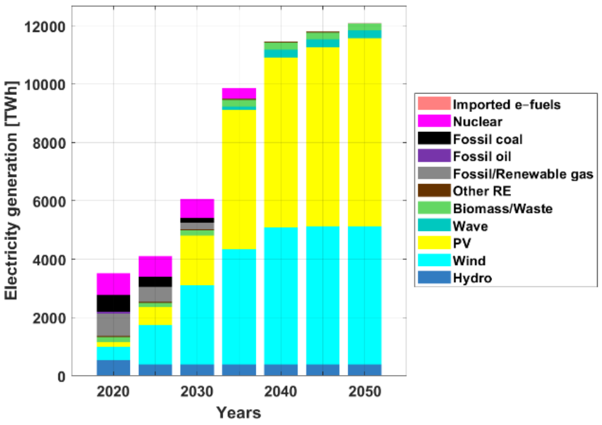
Breyer et al., 2024. International Journal of Hydrogen Energy

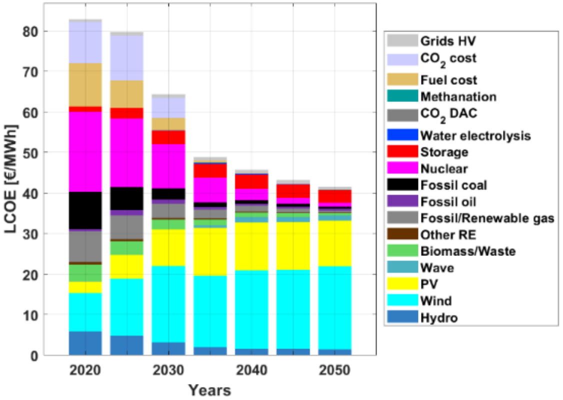
Diagram: Greens/EFA, 2022
scenario: RES-2040 for 2050

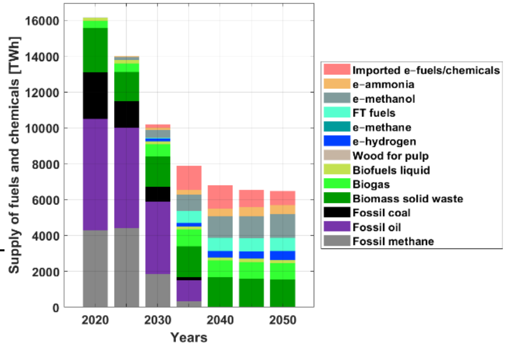
Europe: Highly ambitious Energy-Industry Transition







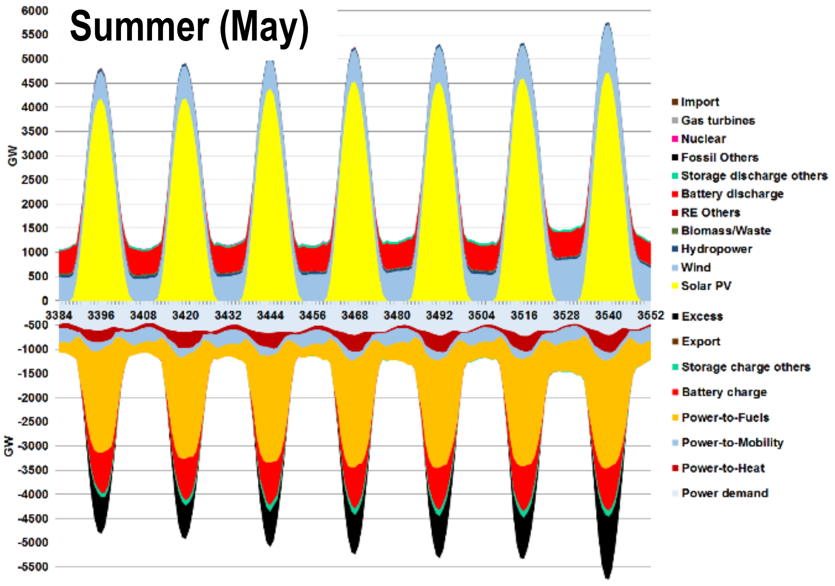


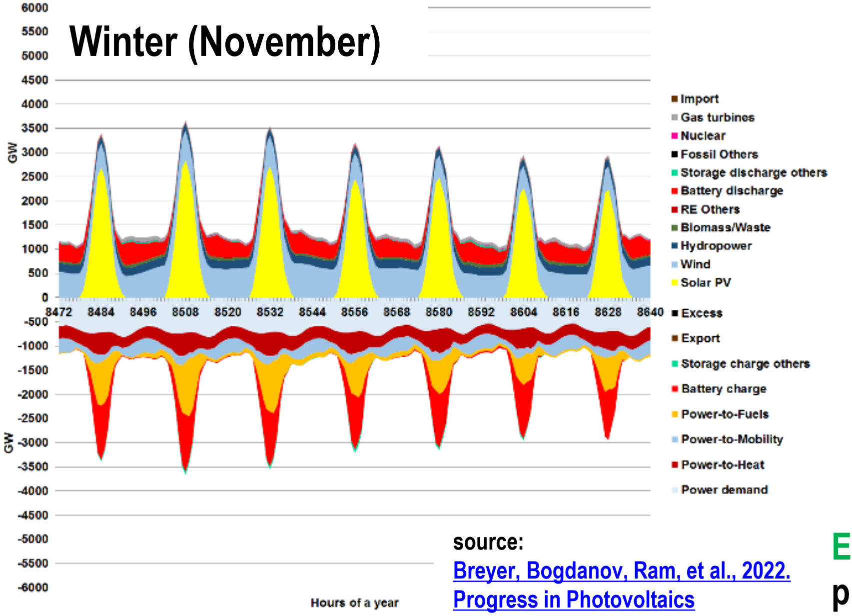


- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: zero CO_2 emissions in 2040
- Massive expansion of electricity 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; finally countries will decide how to proceed
- What's respected:
  - 1.5 ºC target & biodiversity & cost effectiveness & air pollution phase-out
  - renewal of European energy-industry system & jobs growth
- Why society should not go for such an option?

source: Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022

Hourly Operation and Balancing

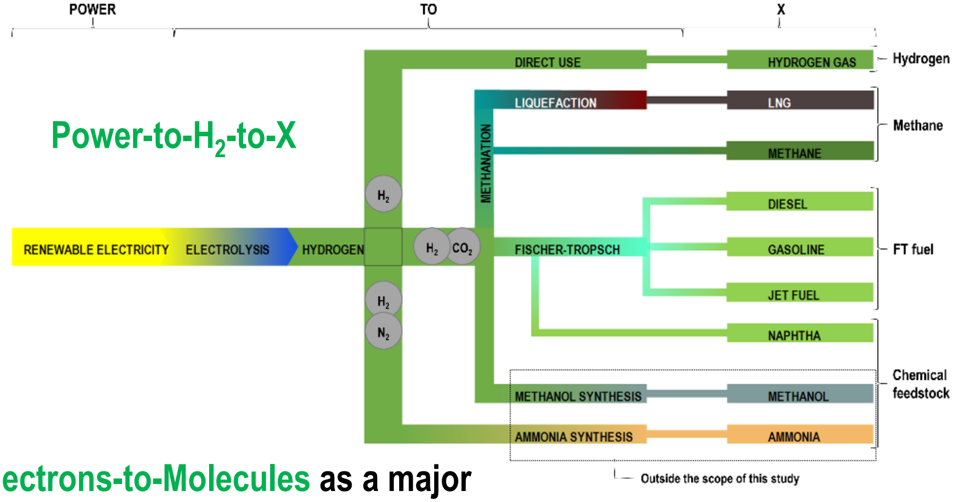




source:
[Breyer, Bogdanov, Ram, et al., 2022. Progress in Photovoltaics]

Key insights:

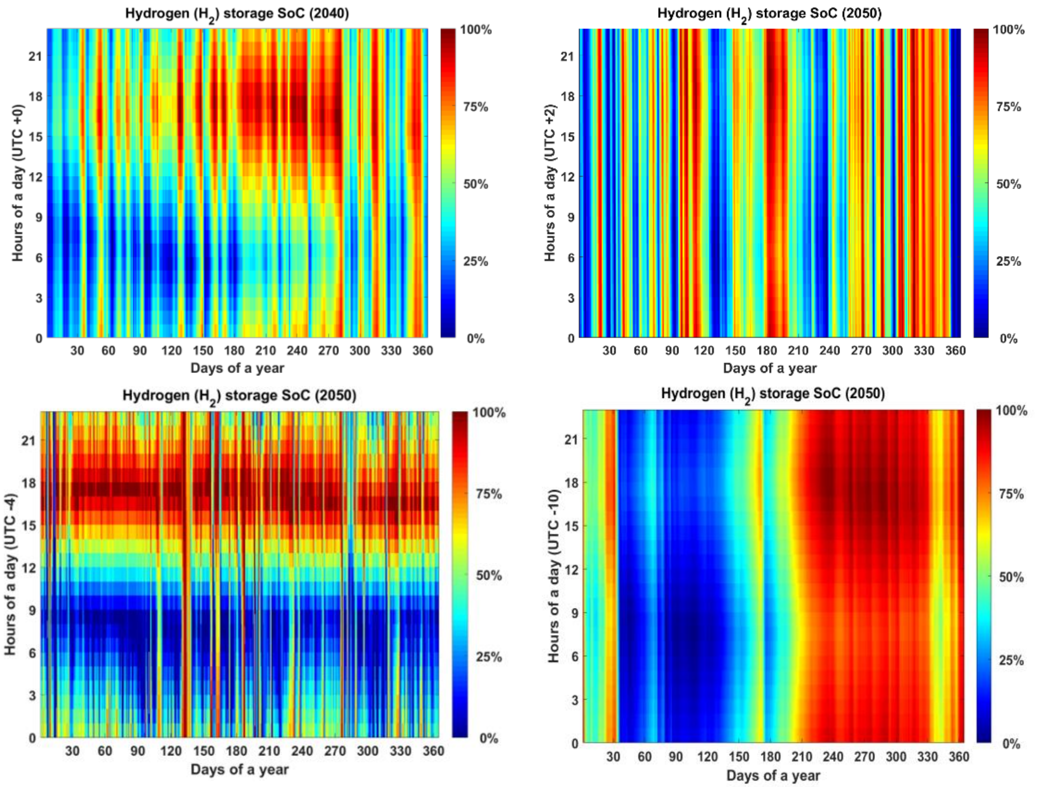
- Week of most renewables supply (spring) and least renewables supply (winter) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the region easily copes with energy demand
- Key balancing components are electrolysers (Power-to-H_2-to-Fuels) that convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability



Power-to-H_2-to-X

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

H_2 Storage in recent National Studies



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

Key insights:

- Most important, the used energy system model is identical and techno-economic assumptions are identical
- Differences originate from the structure of resources and demand for energy services
- H_2 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)
- H_2 storage is quite context and location dependent

source:

ElSayed 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., 2024. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, to be submitted

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., 2023. Role of Storage in the Power-to-X Economy: The Case of Hawaii, 17th IRES, Aachen; submitted

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

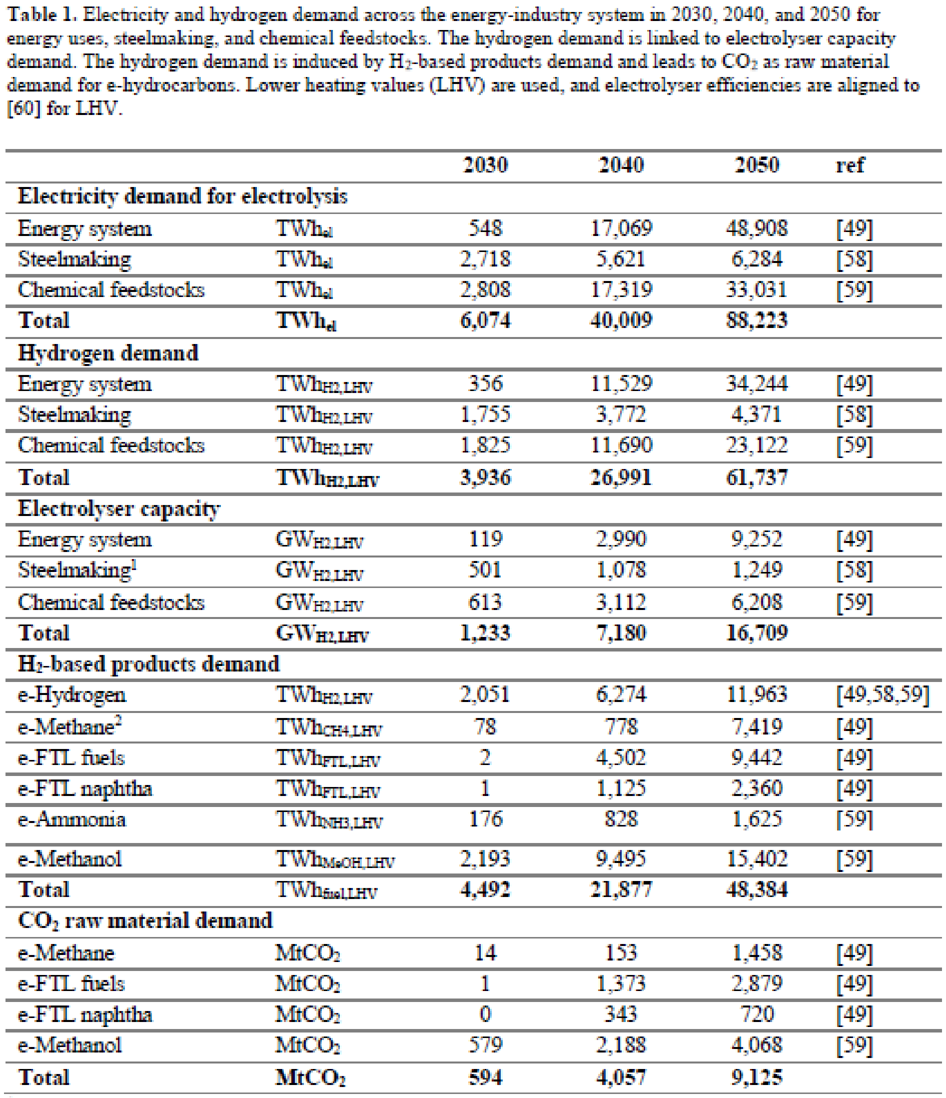


Table 1. Electricity and hydrogen demand across the energy-industry system in 2030, 2040, and 2050 for energy uses, steelmaking, and chemical feedstocks. The hydrogen demand is linked to electrolyser capacity demand. The hydrogen demand is induced by H_2-based products demand and leads to CO_2 as raw material demand for e-hydrocarbons. Lower heating values (LHV) are used, and electrolyser efficiencies are aligned to [60] for LHV.

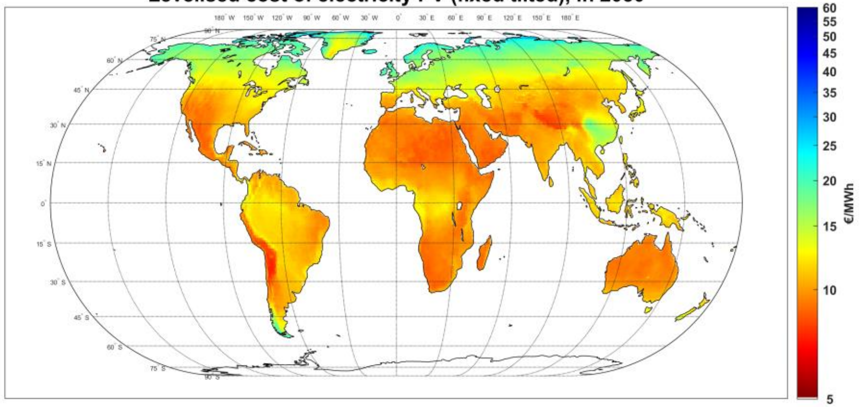
		2030	2040	2050	ref
Electricity demand for electrolysis					
Energy system	TWh_{el}	548	17,069	48,908	[49]
Steelmaking	TWh_{el}	2,718	5,621	6,284	[58]
Chemical feedstocks	TWh_{el}	2,808	17,319	33,031	[59]
Total	TWh_{el}	**6,074**	**40,009**	**88,223**	
Hydrogen demand					
Energy system	$TWh_{H2,LHV}$	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**	
H_2-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**	
CO_2 raw material demand					
e-Methane	$MtCO_2$	14	153	1,458	[49]
e-FTL fuels	$MtCO_2$	1	1,373	2,879	[49]
e-FTL naphtha	$MtCO_2$	0	343	720	[49]
e-Methanol	$MtCO_2$	579	2,188	4,068	[59]
Total	$MtCO_2$	**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**

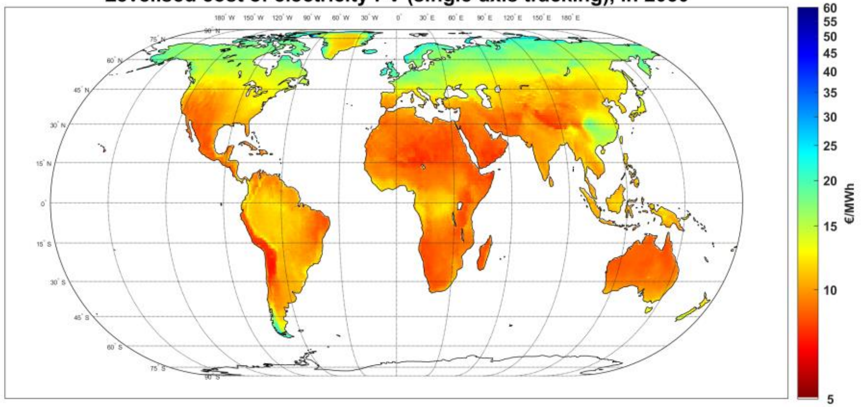
- **Numbers shown here represent the highest ever published H_2 and H_2-to-X demand**

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

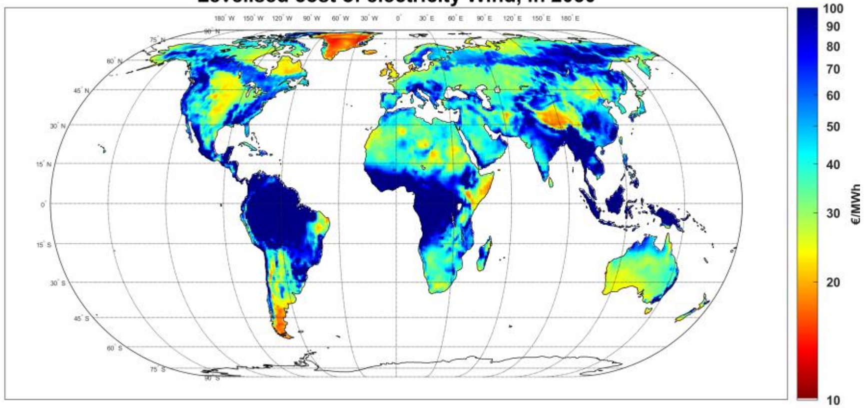
Levelised Cost of Electricity for PV and Wind



Levelised cost of electricity PV (fixed tilted), in 2050



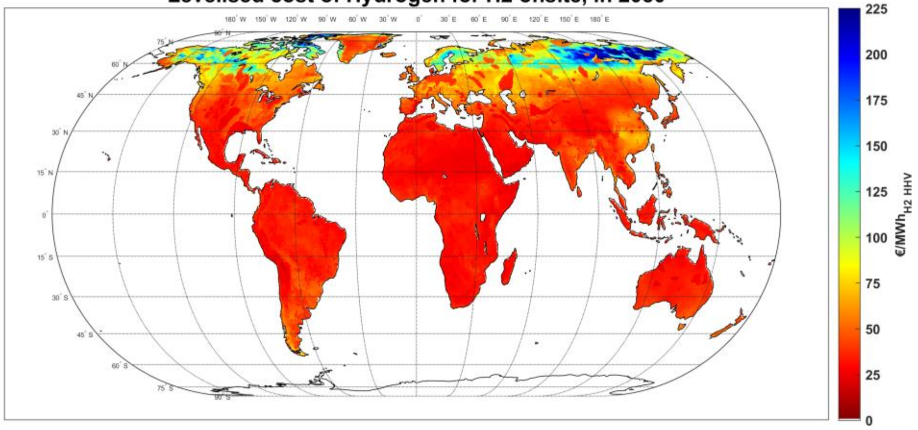
Levelised cost of electricity PV (single-axis tracking), in 2050



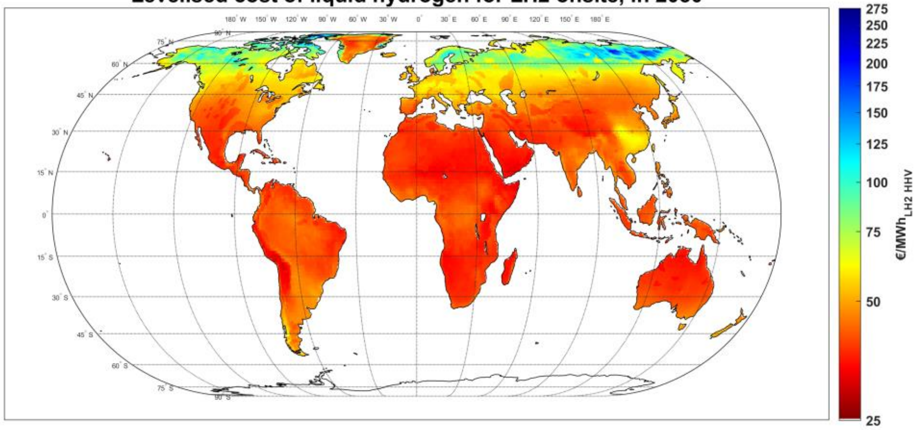
Levelised cost of electricity Wind, in 2050

- Low-cost electricity is a pillar of e-fuels
- Single-axis tracking PV provides lower LCOE at 20-30% higher FLh, compared to fixed tilted PV
- The least PV LCOE (in Atacama Desert) declines from about 12 to 7 €/MWh in 2030 to 2050, respectively.
- More than 10 real projects already announced for LCOE below 20 €/MWh.
- Low-cost PV would be accessible worldwide by 2030 and beyond.
- The least wind LCOE (in Patagonia) declines from about 18 to 15 €/MWh in 2030 to 2050, respectively

Levelised Cost of Hydrogen (GH2, LH2)



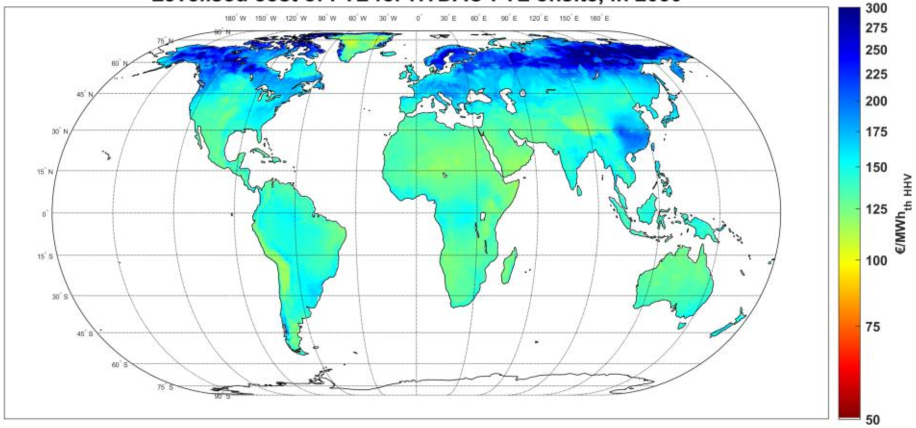
Levelised cost of Hydrogen for H2 onsite, in 2050

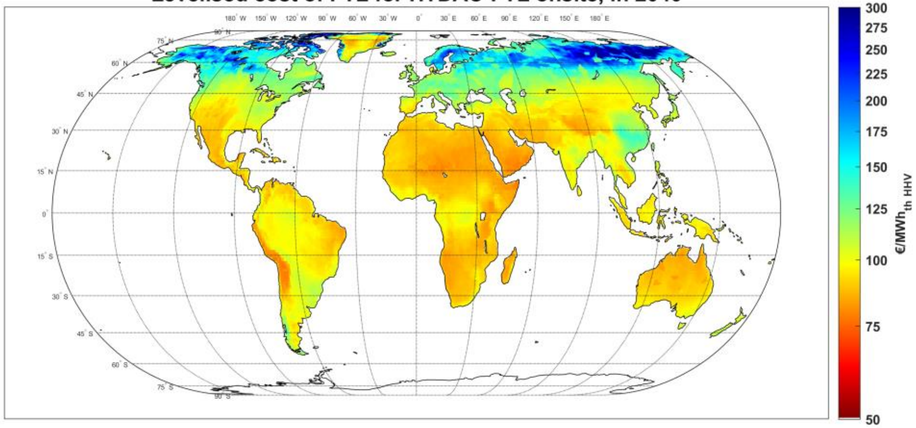


Levelised cost of liquid hydrogen for LH2 onsite, in 2050

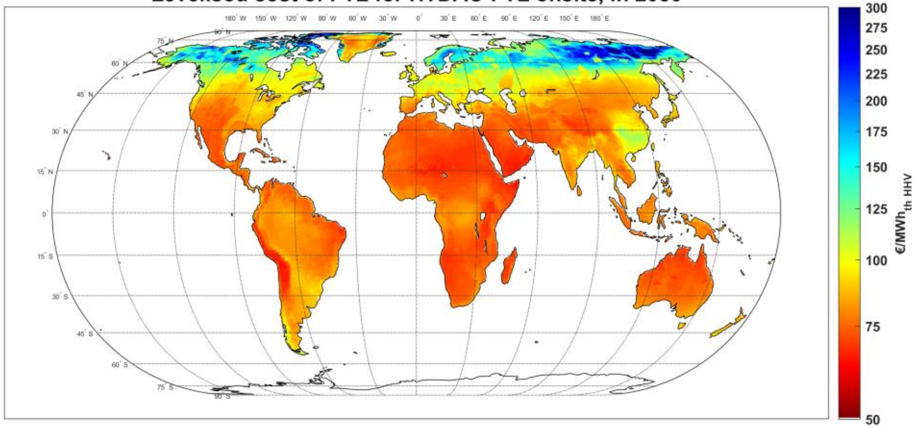
- By 2030, baseload GH_2 could be supplied for 40–60 €/MWh$_{H2,HHV}$ in all continents.
- The production costs at best sites could decline to 20–30 €/MWh$_{H2,HHV}$ by 2050.
- Baseload GH_2 production potential is 2 to 12 TWh$_{H2,HHV}$ per 1000 km^2 based on the location.
- Generation potential is higher at PV-dominated regions, due to higher installation capacity per area.
- By 2030, LH_2 could be produced for 70–85 €/MWh$_{LH2,HHV}$ in all continents.
- The production costs at best sites could decline to 35–40 €/MWh$_{LH2,HHV}$ by 2050.

Levelised Cost of e-Kerosene

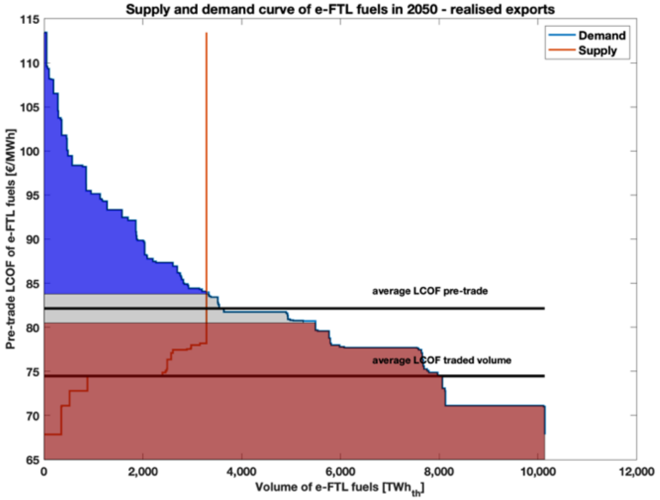

Levelised cost of FTL for HTDAC-FTL onsite, in 2030

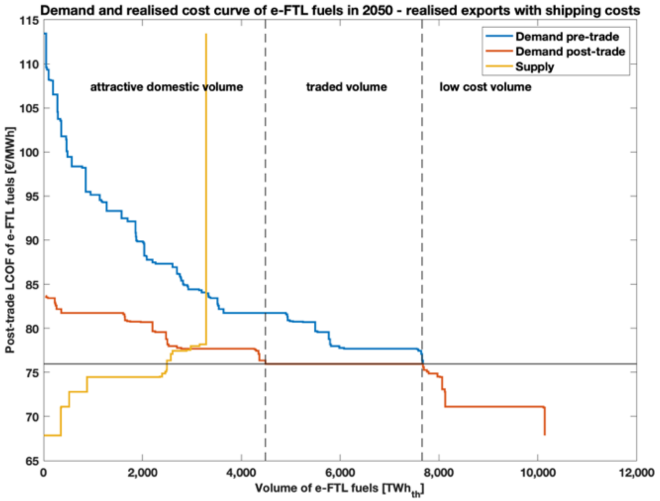

Levelised cost of FTL for HTDAC-FTL onsite, in 2040

- By 2030, e-kerosene could be produced for 120–150 €/MWh$_{FTL}$ (1.1–1.37 €/l) in all continents.
- The production costs at best sites could decline to 65–75 €/MWh$_{FTL}$ (0.59–0.69 €/l) by 2050.
- Patagonia loses its position as a least cost site to sunny sites beyond 2030.

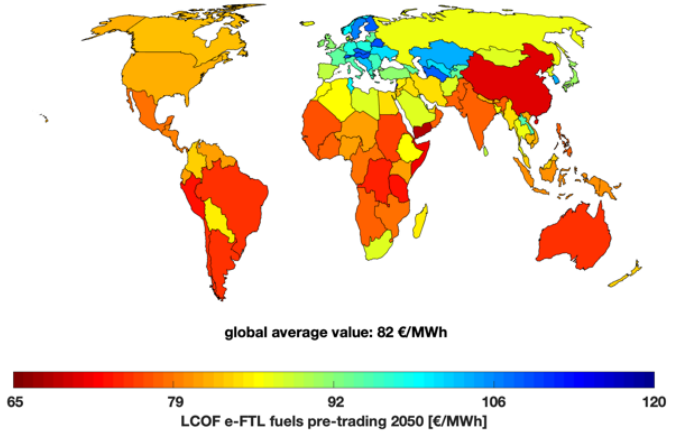

Levelised cost of FTL for HTDAC-FTL onsite, in 2050

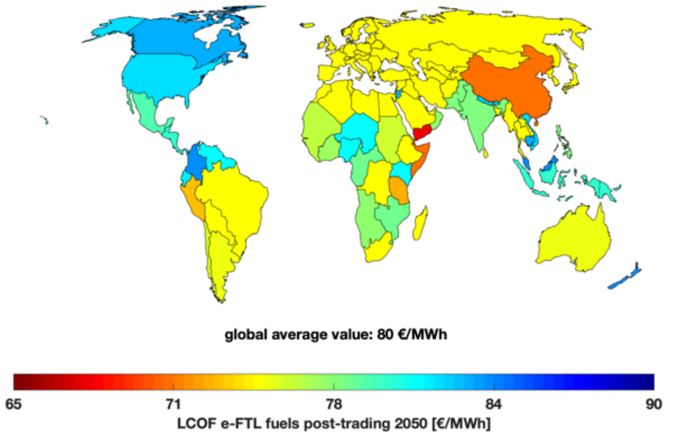
Global Cost Curves pre-/ post-trading





- High cost regions (blue) benefit from imports from low-cost regions (red)
- Three main groups of countries: importers, exporters, self-sufficient
- High cost countries can reduce their costs, partly substantially
- Global average cost do not benefit much, but for high cost countries cost decline significantly



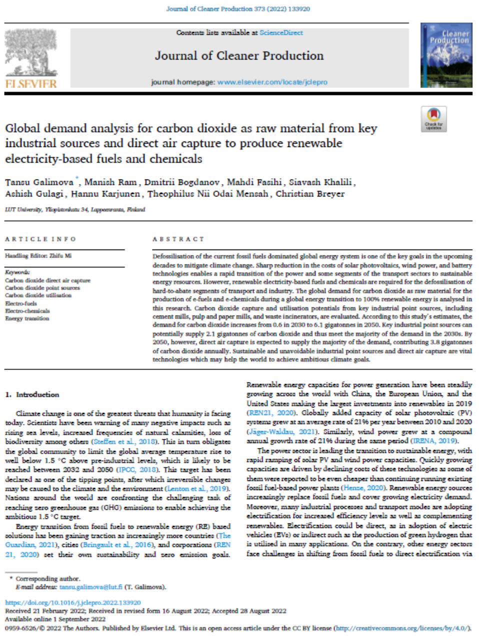


source: [Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, RSER]

CO_2 as Raw Material for e-Fuels Demand

Key insights:

- e-fuels demand in order of 40,000 TWh
- key e-fuels are e-methanol and e-kerosene, maybe some e-methane
- largest demand sectors: chemicals, transport (aviation, marine), and maybe high-temperature industrial process heat
- hydrocarbon-based e-fuels require CO_2 as raw material
- sustainable or unavoidable point sources are usable, such as waste incinerators, pulp and paper mills, maybe cement mills
- largest source for CO_2 as raw material will be direct air capture



Journal of Cleaner Production 373 (2022) 133920

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals

Tansu Galimova*, Manish Ram, Dmitrii Bogdanov, Mahdi Fasihi, Siavash Khalili, Ashish Gulagi, Hannu Karjunen, Theophilus Nii Odai Mensah, Christian Breyer

LUT University, Yliopistonkatu 34, Lappeenranta, Finland

ARTICLE INFO

Handling Editor: Zhifu Mi

Keywords:
Carbon dioxide direct air capture
Carbon dioxide point sources
Carbon dioxide utilisation
Electro-fuels
Electro-chemicals
Energy transition

ABSTRACT

Defossilisation of the current fossil fuels dominated global energy system is one of the key goals in the upcoming decades to mitigate climate change. Sharp reduction in the costs of solar photovoltaics, wind power, and battery technologies enables a rapid transition of the power and some segments of the transport sectors to sustainable energy resources. However, renewable electricity-based fuels and chemicals are required for the defossilisation of hard-to-abate segments of transport and industry. The global demand for carbon dioxide as raw material for the production of e-fuels and e-chemicals during a global energy transition to 100% renewable energy is analysed in this research. Carbon dioxide capture and utilisation potentials from key industrial point sources, including cement mills, pulp and paper mills, and waste incinerators, are evaluated. According to this study's estimates, the demand for carbon dioxide increases from 0.6 in 2030 to 6.1 gigatonnes in 2050. Key industrial point sources can potentially supply 2.1 gigatonnes of carbon dioxide and thus meet the majority of the demand in the 2030s. By 2050, however, direct air capture is expected to supply the majority of the demand, contributing 3.8 gigatonnes of carbon dioxide annually. Sustainable and unavoidable industrial point sources and direct air capture are vital technologies which may help the world to achieve ambitious climate goals.

1. Introduction

Climate change is one of the greatest threats that humanity is facing today. Scientists have been warning of many negative impacts such as rising sea levels, increased frequencies of natural calamities, loss of biodiversity among others (Steffen et al., 2018). This in turn obligates the global community to limit the global average temperature rise to well below 1.5 °C above pre-industrial levels, which is likely to be reached between 2032 and 2050 (IPCC, 2018). This target has been declared as one of the tipping points, after which irreversible changes may be caused to the climate and the environment (Lenton et al., 2019). Nations around the world are confronting the challenging task of reaching zero greenhouse gas (GHG) emissions to enable achieving the ambitious 1.5 °C target.

Energy transition from fossil fuels to renewable energy (RE) based solutions has been gaining traction as increasingly more countries (The Guardian, 2021), cities (Bringault et al., 2016), and corporations (REN 21, 2020) set their own sustainability and zero emission goals. Renewable energy capacities for power generation have been steadily growing across the world with China, the European Union, and the United States making the largest investments into renewables in 2019 (REN21, 2020). Globally added capacity of solar photovoltaic (PV) systems grew at an average rate of 21% per year between 2010 and 2020 (Jäger-Waldau, 2021). Similarly, wind power grew at a compound annual growth rate of 21% during the same period (IRENA, 2019).

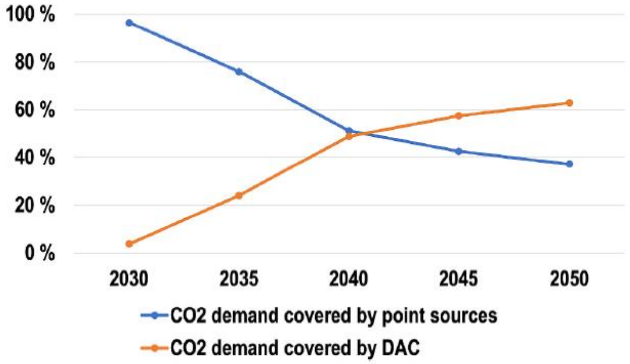
The power sector is leading the transition to sustainable energy, with rapid ramping of solar PV and wind power capacities. Quickly growing capacities are driven by declining costs of these technologies as some of them were reported to be even cheaper than continuing running existing fossil fuel-based power plants (Henze, 2020). Renewable energy sources increasingly replace fossil fuels and cover growing electricity demand. Moreover, many industrial processes and transport modes are adopting electrification for increased efficiency levels as well as complementing renewables. Electrification could be direct, as in adoption of electric vehicles (EVs) or indirect such as the production of green hydrogen that is utilised in many applications. On the contrary, other energy sectors face challenges in shifting from fossil fuels to direct electrification via

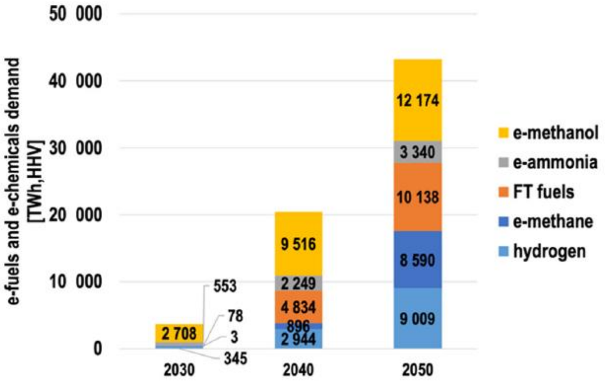
---

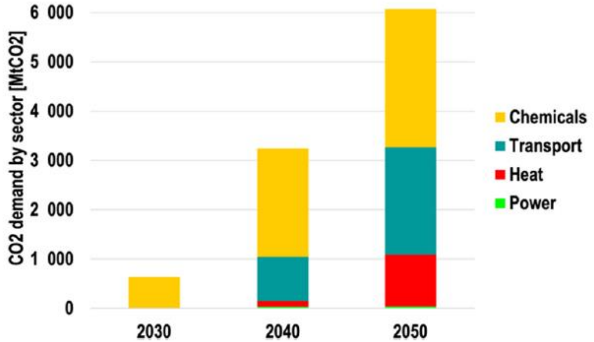
* Corresponding author.
E-mail address: tansu.galimova@lut.fi (T. Galimova).

https://doi.org/10.1016/j.jclepro.2022.133920
Received 21 February 2022; Received in revised form 16 August 2022; Accepted 28 August 2022

CO_2 supply for e-fuels and e-chemicals globally

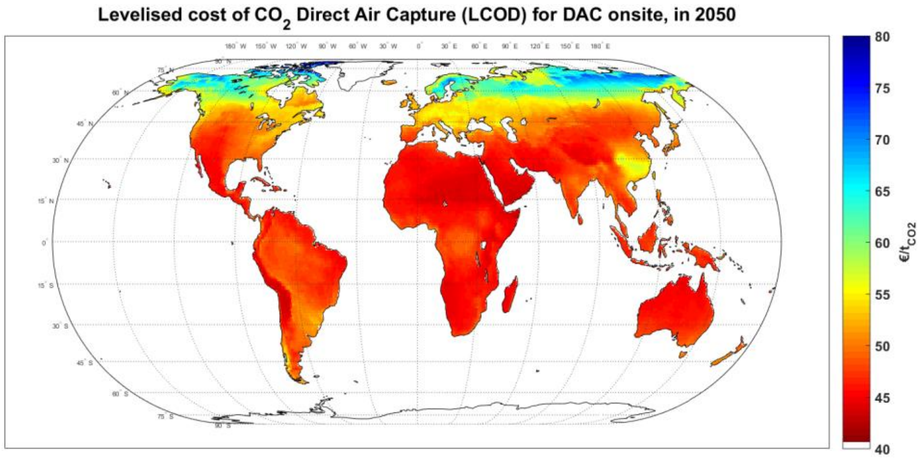






source: Galimova et al., 2022. J of Cleaner Production, 373, 133920

Role of CO_2 Direct Air Capture



source: [Fasihi M., et al., 2019. Journal of Cleaner Production, 224, 957-980](); [Breyer et al., 2020. Mitigation and Adaptation Strategies for Global Change, 25, 43-65]() ; [Breyer et al., 2019. Joule, 3, 2053-2057]()

Figure 4 Net area required to produce 1000 kilotonnes of kerosene per year from different primary energy sources

source: [dena, lbst, LUT, 2022. E-Kerosene for Commercial Aviation]()

- Area: sustainable CO_2 supply is limited by bio-CO_2 (wastes limited, energy crops lack area)
- Costs: views towards 2050 deviate strongly, between 50-500 €/tCO_2, while 50-100 €/tCO_2 may be the right range
- Share in e-kerosene: the DAC cost in the fuel may be in the range of 13-17%

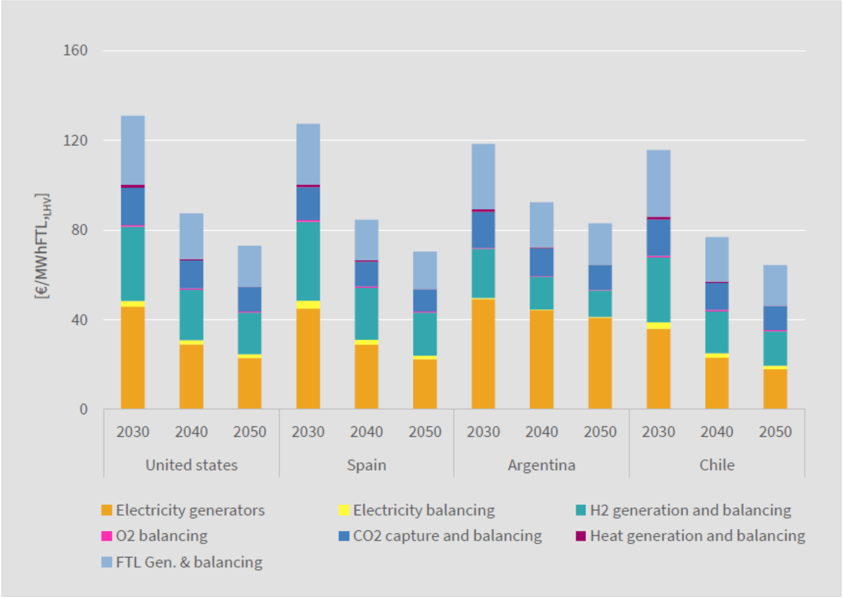


Figure 32 Levelised cost of fuel in selected locations from 2030 to 2050. The locations are the US for California, Southern Spain, Argentina Patagonia and Chile Atacama.

Summary & Outlook

Key elements of the arising energy-industry system are:

- Comprehensive electrification (direct, indirect) of all demands
- Dominating source of primary energy: solar PV and wind power complemented by others
- Hydrogen as a subset of the Power-to-X Economy

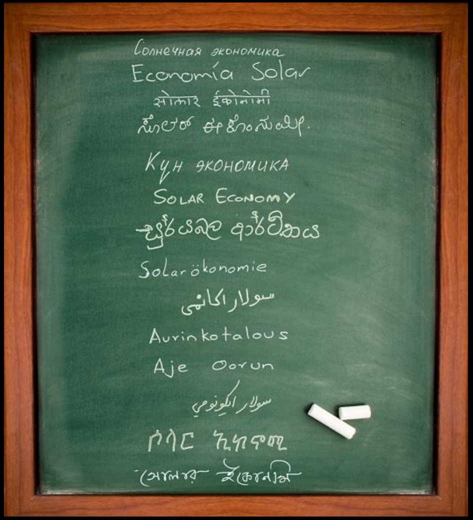
Role of flexibility:

- Flexibility is key in the Power-to-X Economy, and storage complements other flexibility options
- Key flexibilities: supply complementarity, grids, demand response, curtailment, and storage
- Hydrogen buffer: indirect regulation of the power sector, BUT, almost NO H_2-to-electricity need
- e-fuels & e-chemicals: almost baseload synthesis, thus, some storage for buffering demand

Role of hydrogen:

- Provide solutions when direct electrification is not possible, since the latter is typically more efficient and lower in cost
- Main demand for hydrogen: e-fuels & e-chemicals (e-ammonia, e-methanol, e-kerosene jet fuel, e-methane, e-hydrogen), e-materials (e-steel, e-carbon fibre)
- Hydrogen as an essential intermediate energy carrier in power-to-H_2-to-X routes as a subset of the Power-to-X Economy

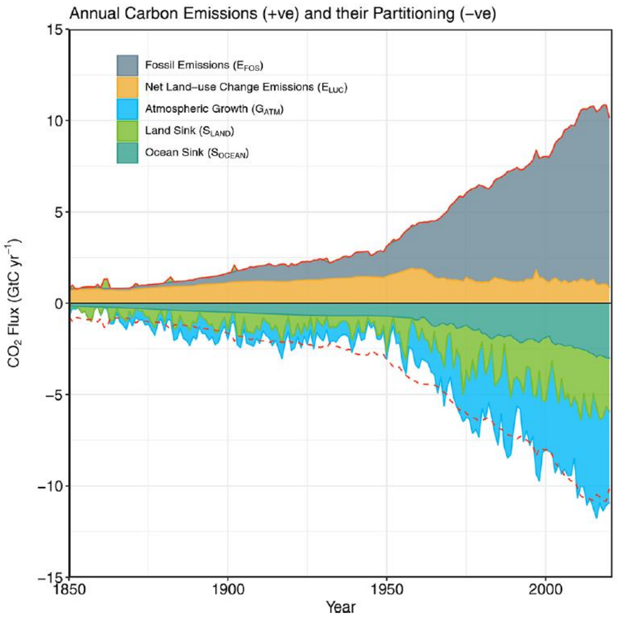
Thank you for your attention …
… and to the team!

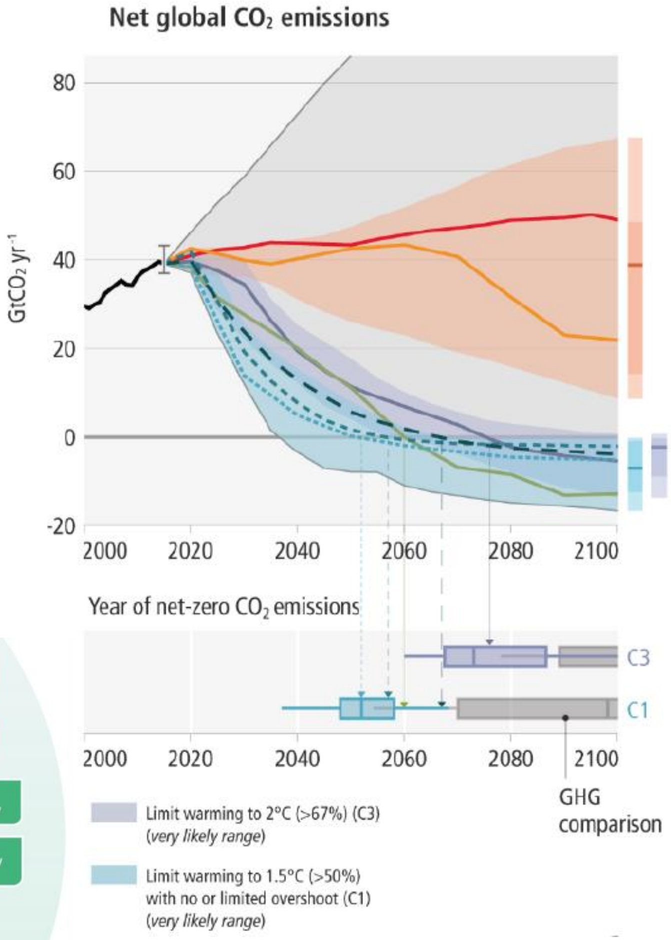


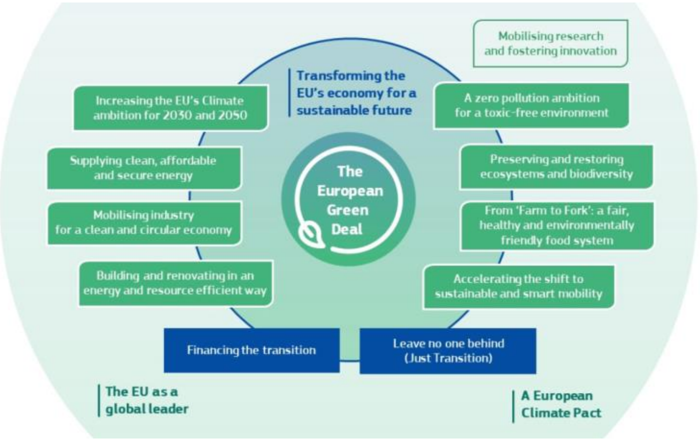
all publications at: www.scopus.com/authid/detail.uri?authorId=39761029000
new publications also announced via Twitter: [@ChristianOnRE](https://twitter.com/ChristianOnRE)

Open your mind. LUT.
Lappeenranta University of Technology

CO_2 Emissions: how it developed, where to go





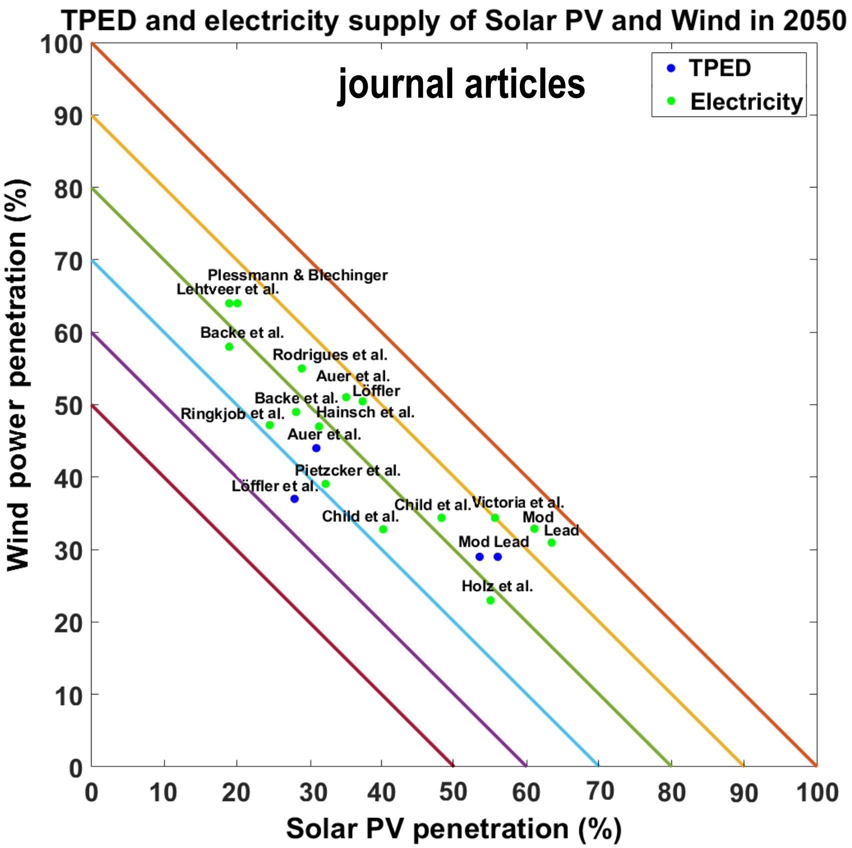


Key insights:

- CO_2 emissions are dominated by fossil fuels
- Emissions are at historic record levels
- Emissions have to reach absolute zero
- Carbon budget for 1.5ºC (67%) is to be used by 2030
- Carbon budget for 1.5ºC (83%) and uncertainty margin was consumed in 2022
- Faster transition and net negative CO_2 emissions are required
- Absolute zero CO_2 emissions around 2040 must be targeted

source: IPCC, 2020. 6th Assessment Report WG III

Europe: Wind & PV Share in 100% RE Studies



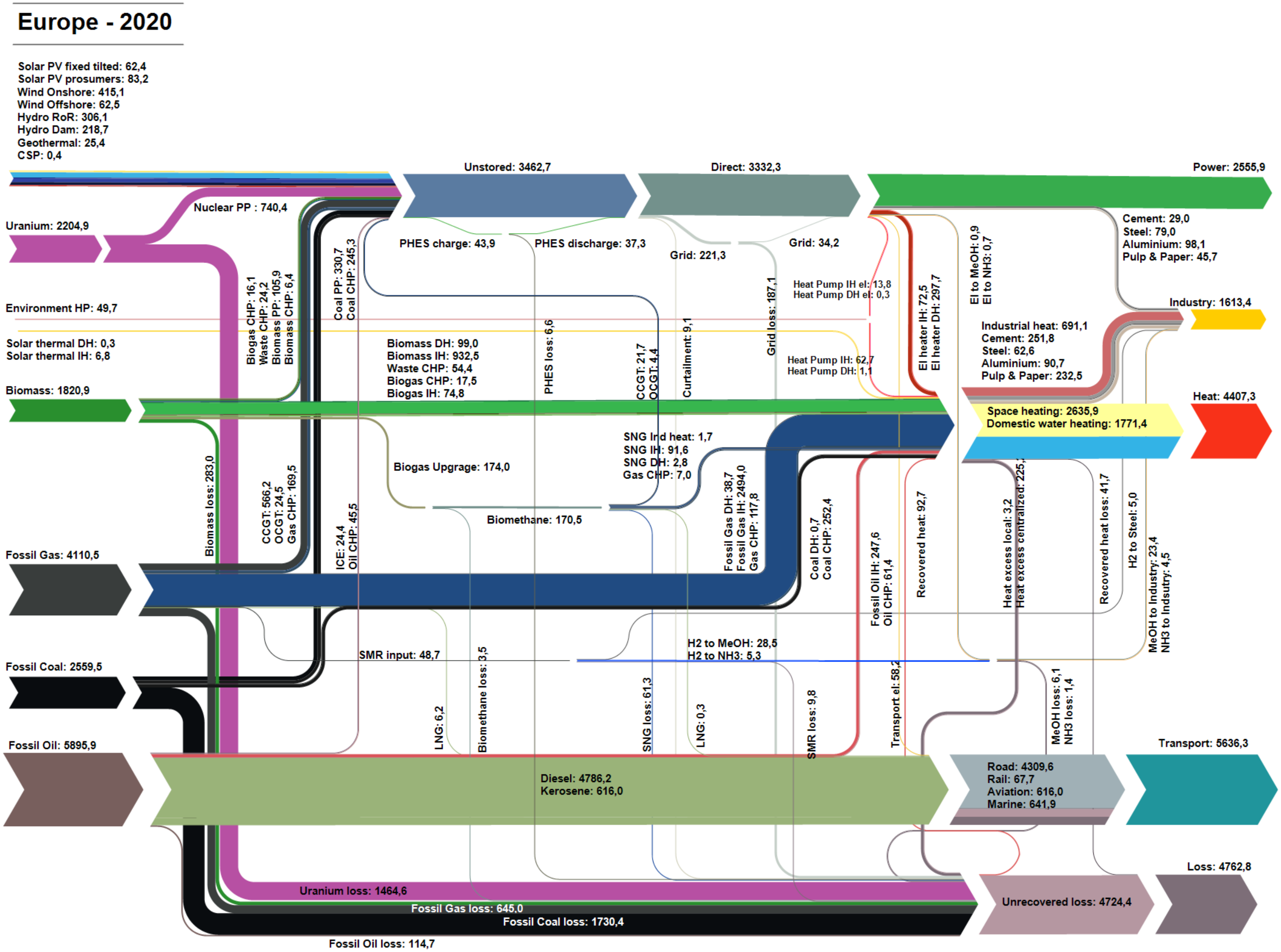
Key insights:

- 2 main groups:
  - high PV & wind: more PV
  - high PV & wind: more wind
- PV & wind electricity share >80% standard
- PV & wind TPED share in 65-85% range
- PV shares around 30-40% by 2050 standard for Europe
- Victoria et al. is very close with 56% PV share
- This research (link below) finds 61-63% PV share while a most recent one finds 54% PV share
- Reasons for PV shares >50%
  - low-cost of PV & batteries & electrolysers
  - high levels of electrification
  - high levels of PtX: PV benefits strongly from H_2 buffering
- Difference between 50% and 60% PV share
  - PV differentiation: PV prosumers (R/C/I), fixed and 1-axis
  - independent optimisation of PV options
  - forcing of supply, e.g. wind offshore, also wave, etc.

- Major reports for public discourse document lack of up-to-date knowledge of consultants
  - McKinsey (20% PV share in 2050), DNV (15%), Navigant (14%); IEA WEO SDS (13%) NZE without regional data
  - lack of ambition: no 100% RE scenario known, much fossil CCS and nuclear, low levels of electrification
  - oversimplified models: low temporal and spatial resolution, no cost optimisation, low levels of PtX and sector coupling
  - cost assumptions used often violate market trends (too high renewables cost, too low CCS & nuclear costs)

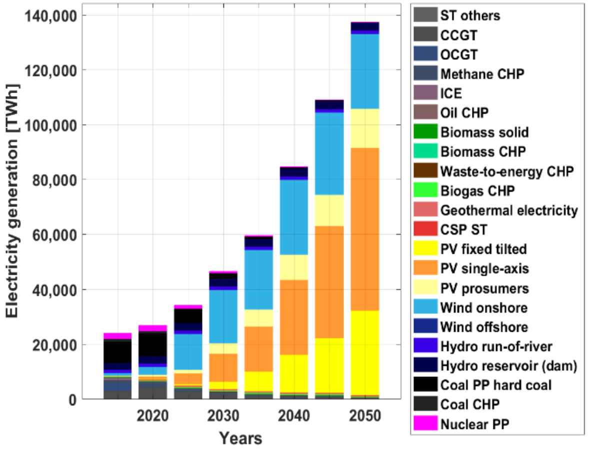
source: Breyer, Bogdanov, Ram, et al., 2022. Energy transition from a European perspective. Progress in Photovoltaics

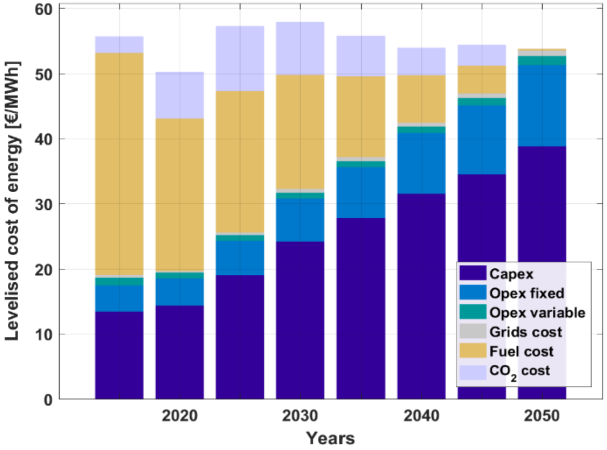
System Outlook – Energy Flows in 2020

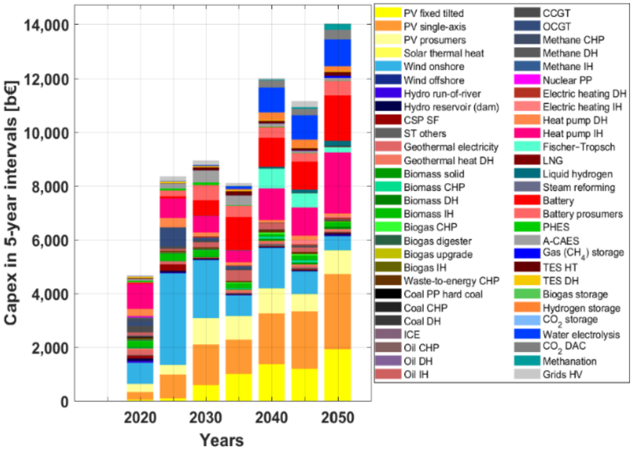


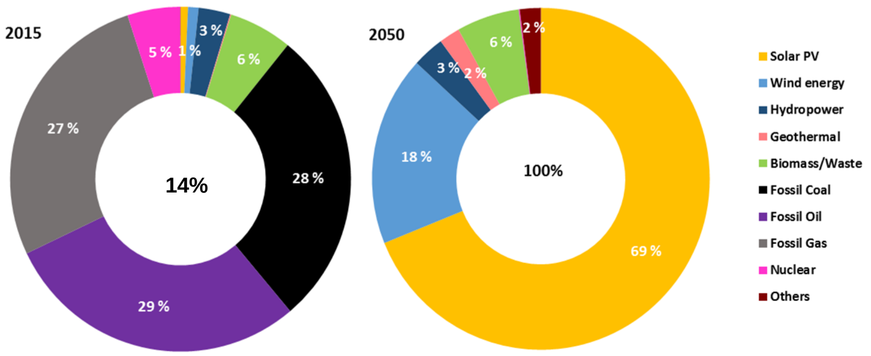
source: [Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022]

Global: 100% Renewable Energy System by 2050







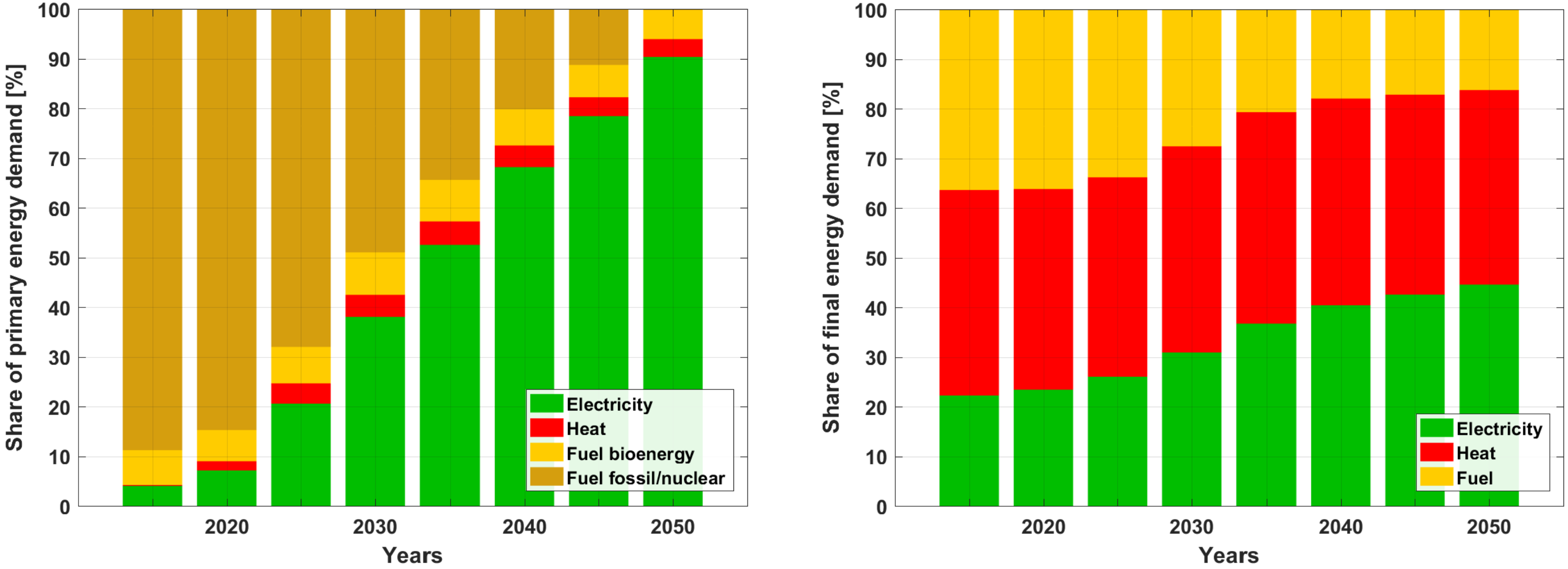


Key insights:

- Low-cost PV-wind-battery-electrolyser-DAC leads to a cost-neutral energy transition towards 2050
- This implies about 63 TW of PV, 8 TW of wind power, 74 TWh$_{cap}$ of battery, 13 TW$_{el}$ of electrolysers by 2050 for the energy system
- This leads to about 3 TW/a of PV, 850 GW$_{el}$ of electrolyser installations in 2040s
- PV contributes 69% of all primary energy
- Massive investments are required, mainly for PV, battery, heat pumps, wind power, electrolysers, PtX

source: Bogdanov et al., 2021. Energy, 227, 120467
EWG/LUT, 2019. Global Energy System based on 100% RE

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 is not structurally changing (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 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

source: Bogdanov et al., 2021. Energy, 227, 120467
EWG/LUT, 2019. Global Energy System based on 100% RE