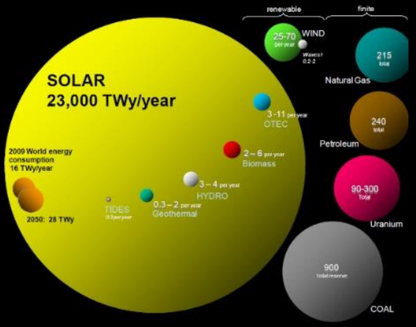


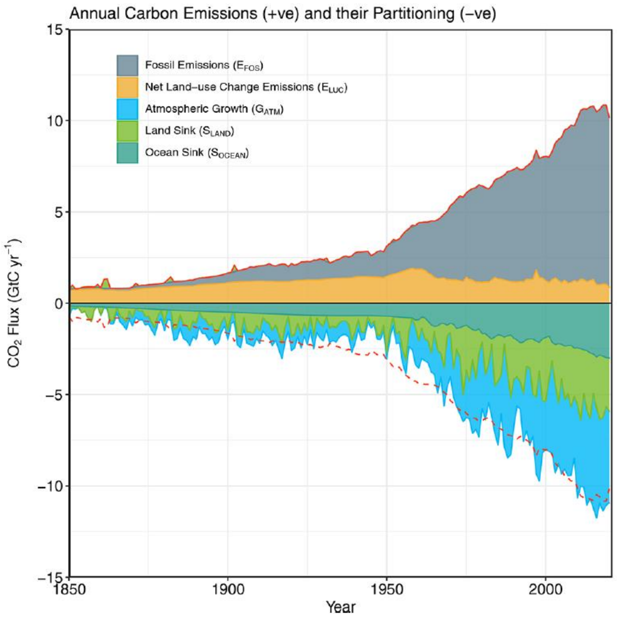
Role of Storage in the Power-to-X Economy

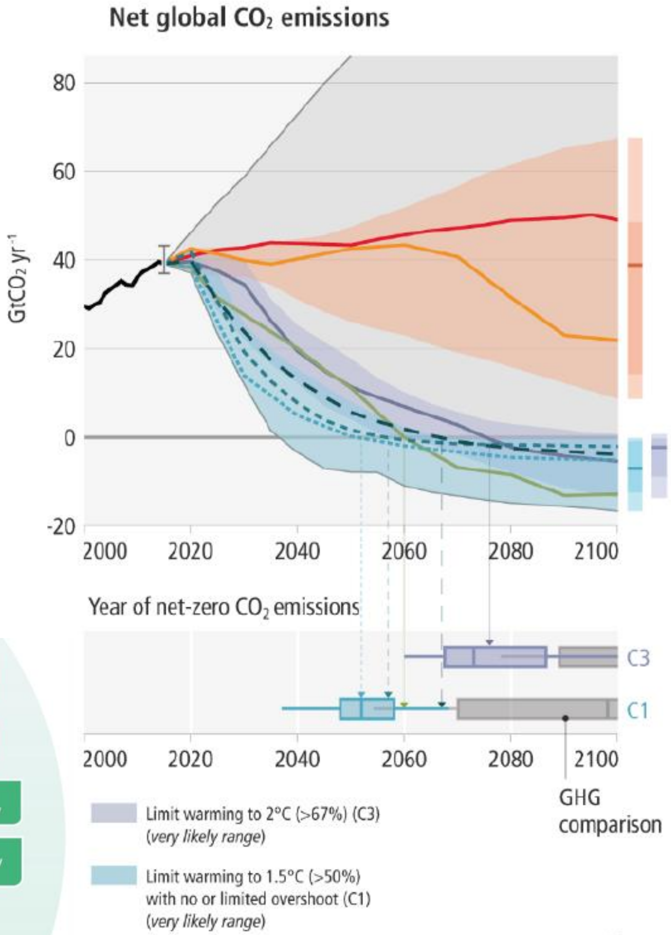
Open your mind. LUT.
Lappeenranta University of Technology

Christian Breyer
LUT University

7. Workshop „Energiespeichersysteme“ an TU Dresden
Dresden, January 23, 2024

CO_2 Emissions: how it developed, where to go





The European Green Deal

Transforming the EU's economy for a sustainable future

Increasing the EU's Climate ambition for 2030 and 2050

Supplying clean, affordable and secure energy

Mobilising industry for a clean and circular economy

Building and renovating in an energy and resource efficient way

Mobilising research and fostering innovation

A zero pollution ambition for a toxic-free environment

Preserving and restoring ecosystems and biodiversity

From 'Farm to Fork': a fair, healthy and environmentally friendly food system

Accelerating the shift to sustainable and smart mobility

Financing the transition

Leave no one behind (Just Transition)

The EU as a global leader

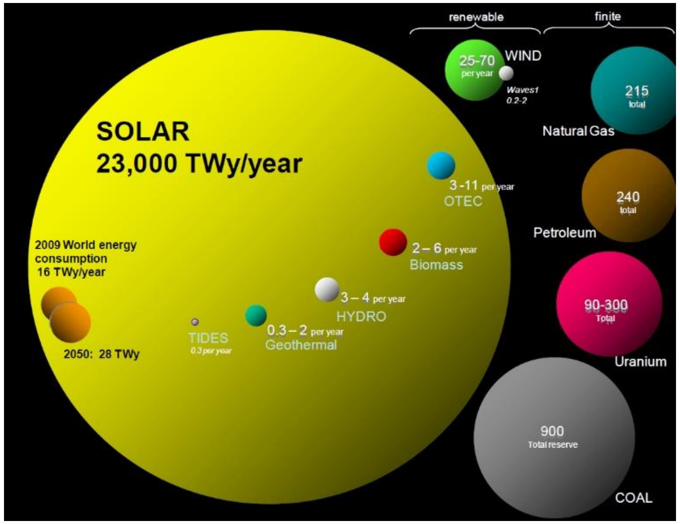
A European Climate Pact

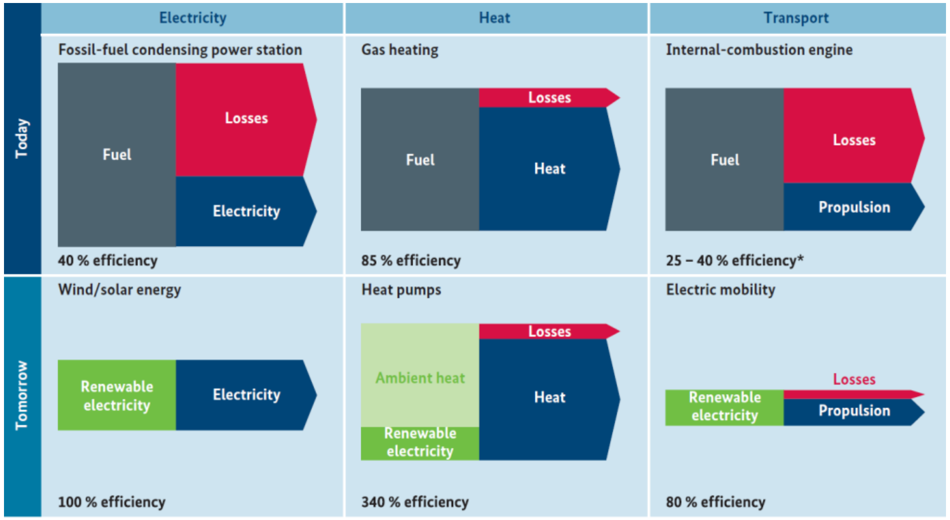
Key insights:

- 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

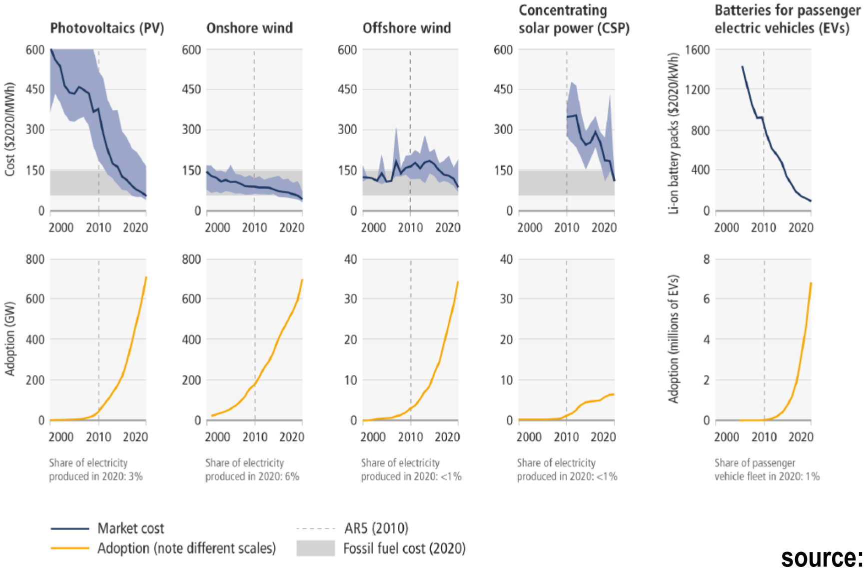
source: IPCC, 2020. 6th Assessment Report WG III

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:

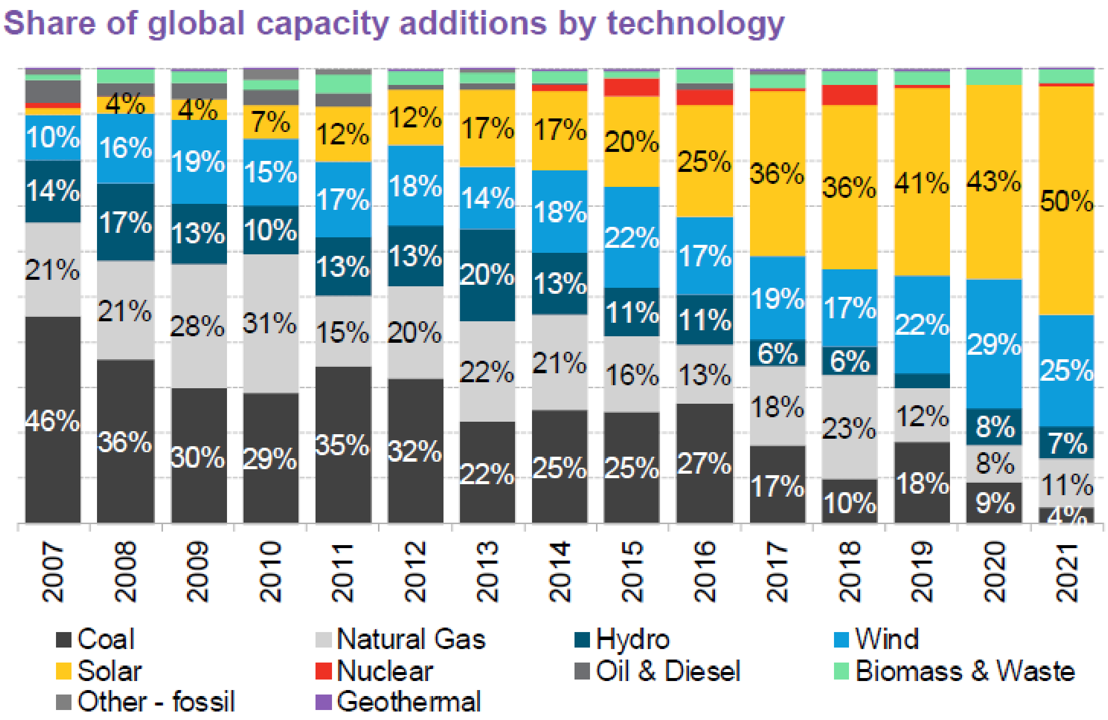
Electricity supply dominated by PV and wind power

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 (note: newly PV electricity > wind)

PV is outside any historic experience



Share of global capacity additions by technology

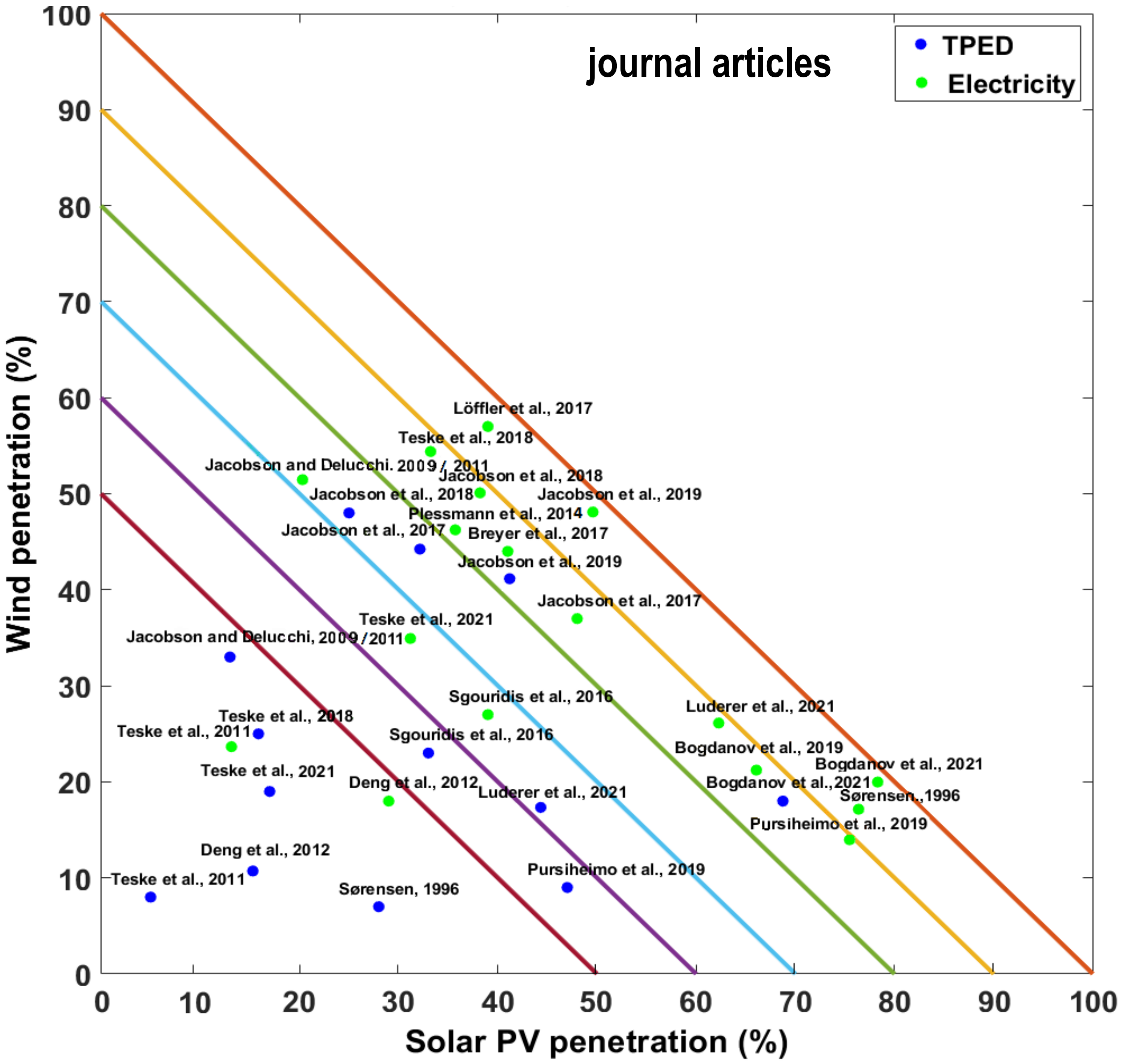
Source: BloombergNEF

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

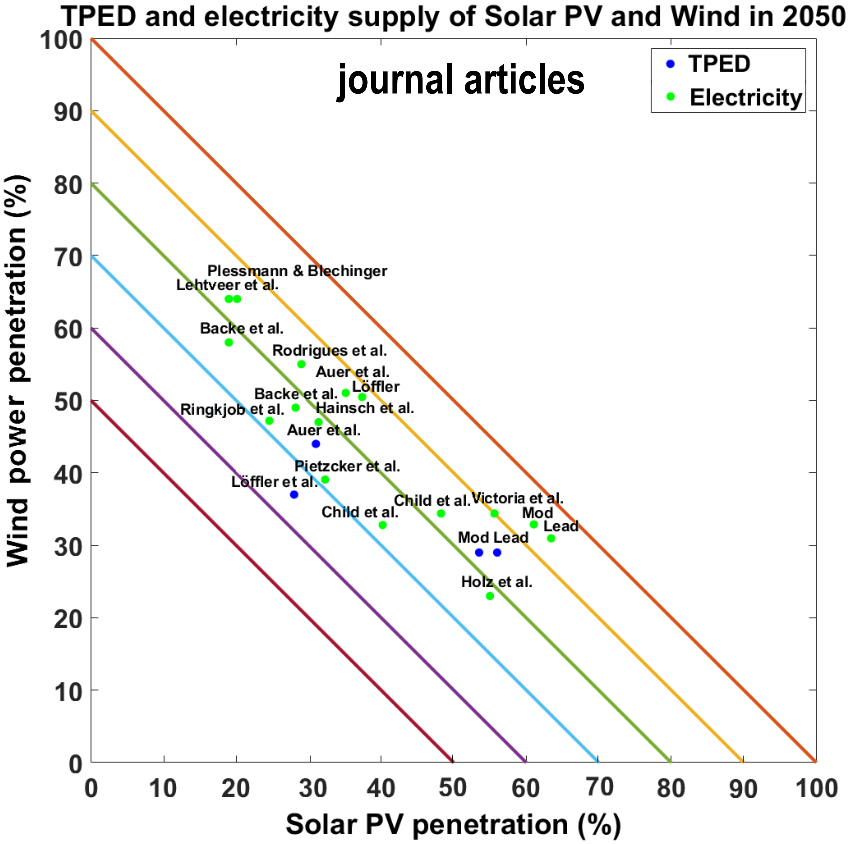


Key insights:

- 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

Europe: Wind & PV Share in 100% RE Studies



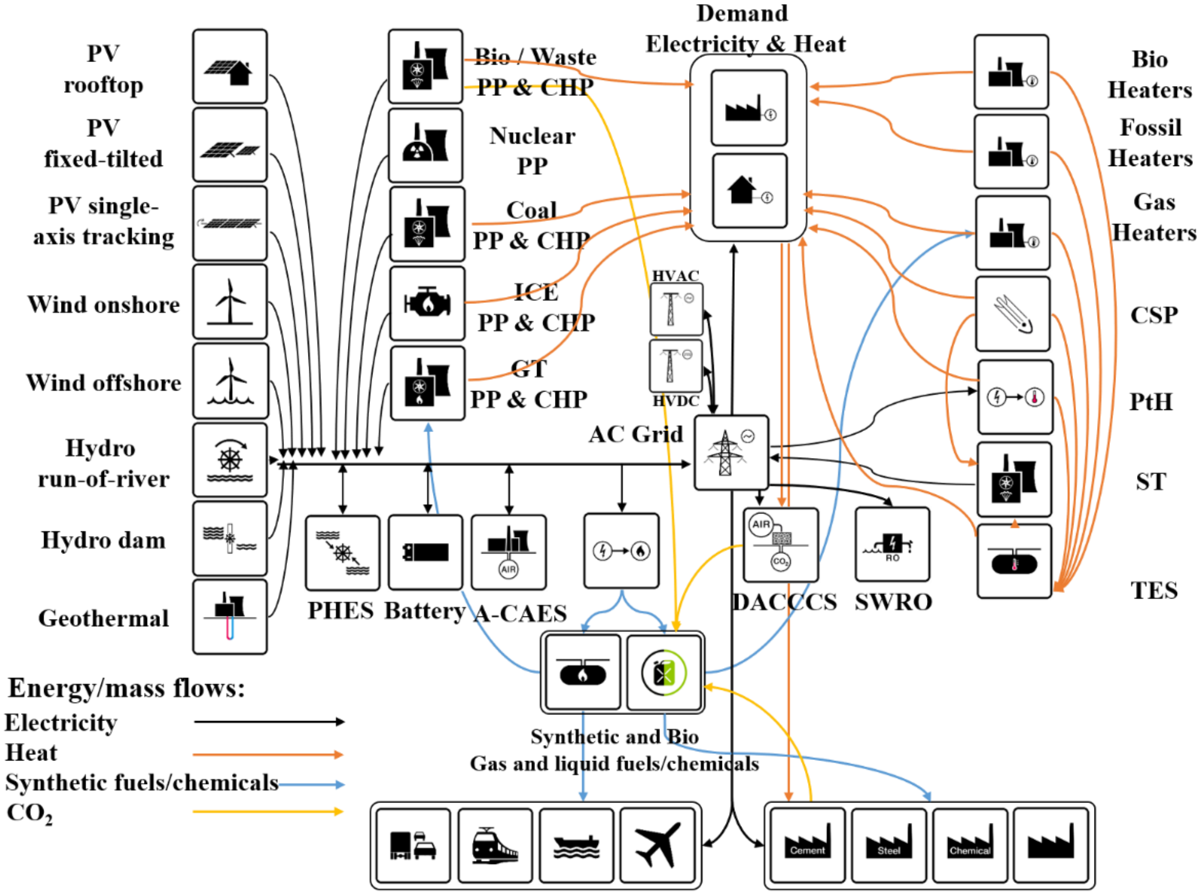
Key insights:

- 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.

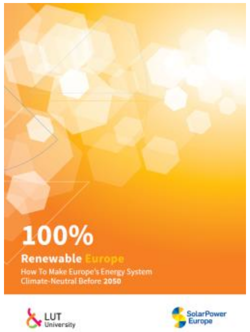
- Major reports for public discourse document lack of up-to-date knowledge of consultants
  - McKinsey (20% PV share in 2050), DNV (15%), Navigant (14%); IEA WEO SDS (13%) NZE without regional data
  - lack of ambition: no 100% RE scenario known, much fossil CCS and nuclear, low levels of electrification
  - 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

LUT Energy System Transition Model (LUT-ESTM)



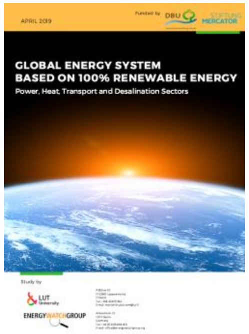
recent reports


100% Renewable Europe

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

LUT University SolarPower Europe

[link to report](#)

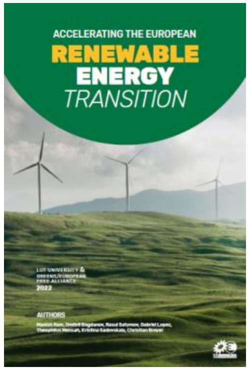

APRIL 2019

GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY

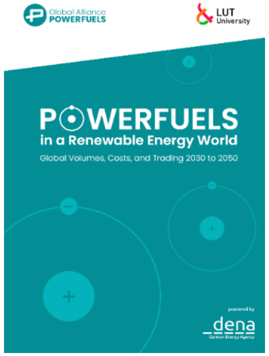
Power, Heat, Transport and Desalination Sectors

LUT University ENERGYWATCHGROUP

[link to report](#)


ACCELERATING THE EUROPEAN RENEWABLE ENERGY TRANSITION

[link to report](#)


Global Alliance POWERFUELS LUT University

POWERFUELS in a Renewable Energy World

Global Volumes, Costs, and Trading 2030 to 2050

dena

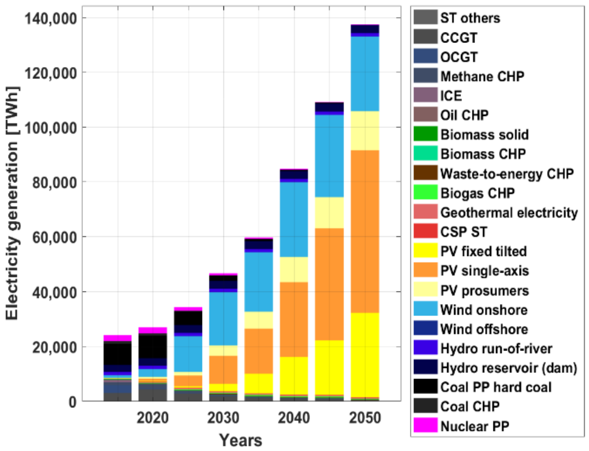
[link to report](#)

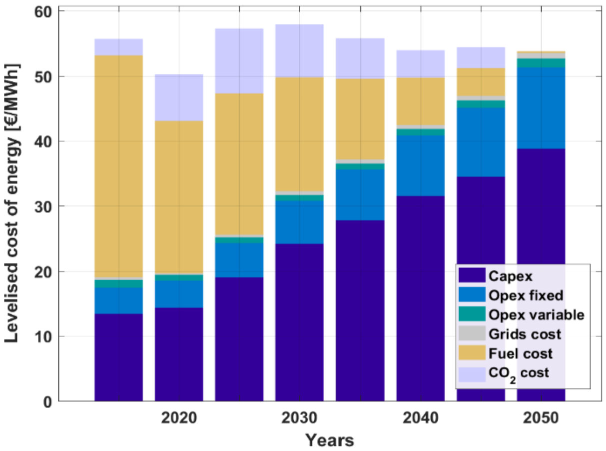
Key features:

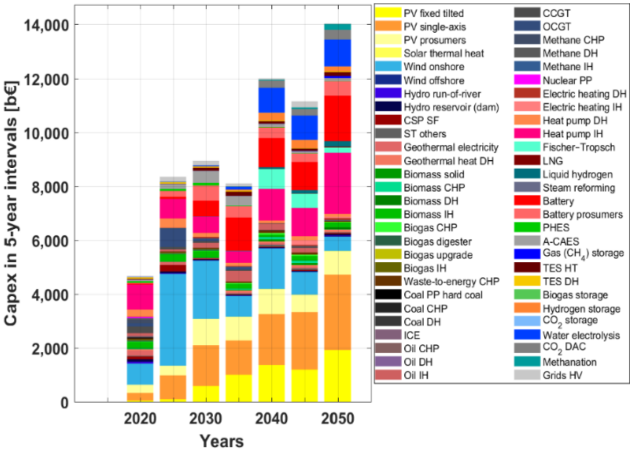
- full hourly resolution, applied in global-local studies, comprising about 120 technologies
- used for several major reports, in about 50 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (heat, fuels, chemicals, materials, freshwater, CO_2, CDR, forests)

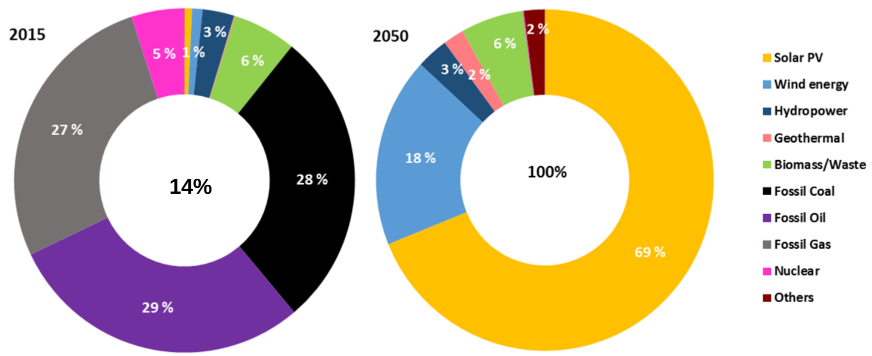
source: [Bogdanov, Breyer et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, 283, 116273](#)

Global: 100% Renewable Energy System by 2050







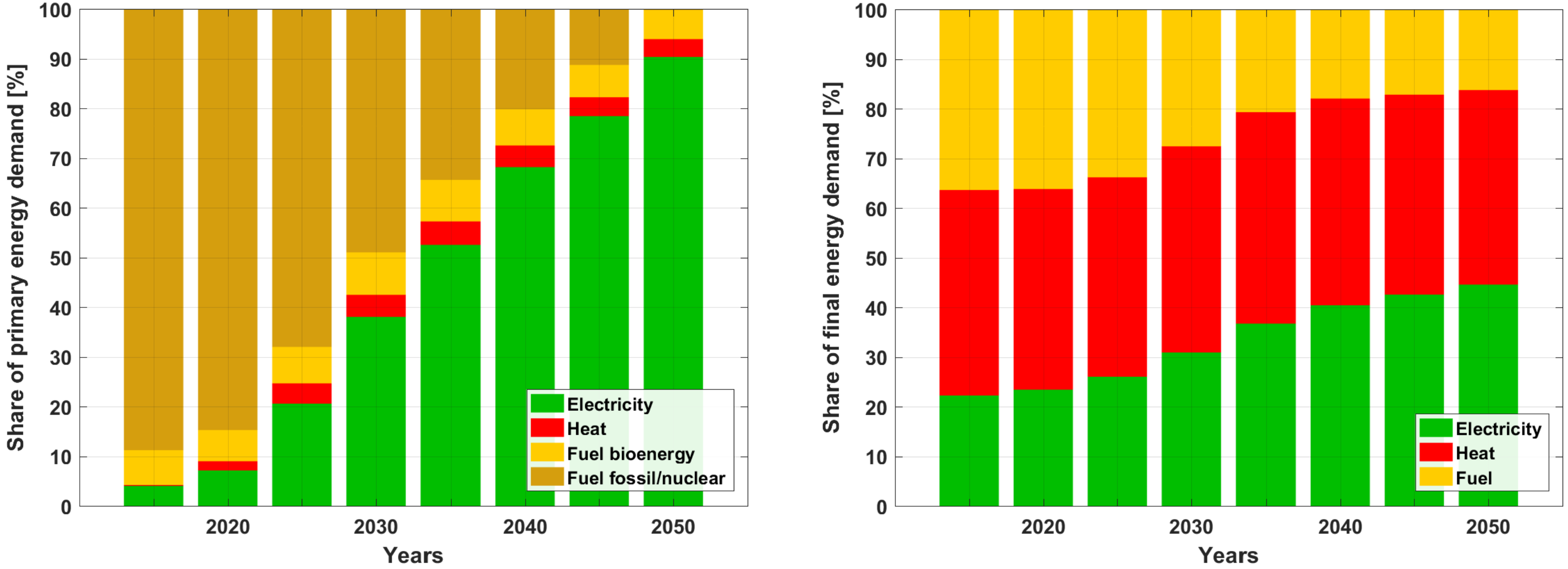


Key insights:

- 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

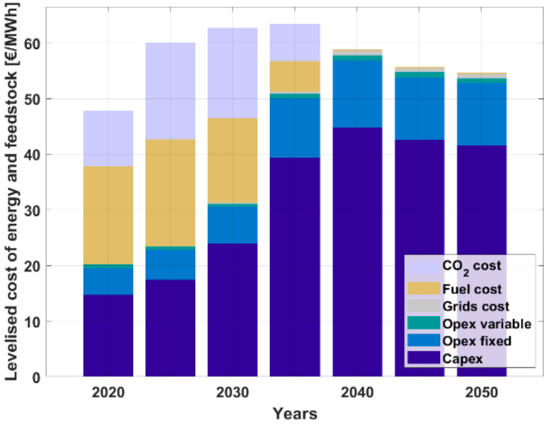


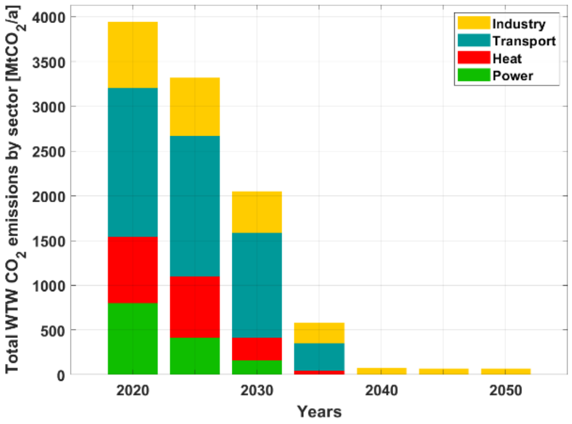
Key insights:

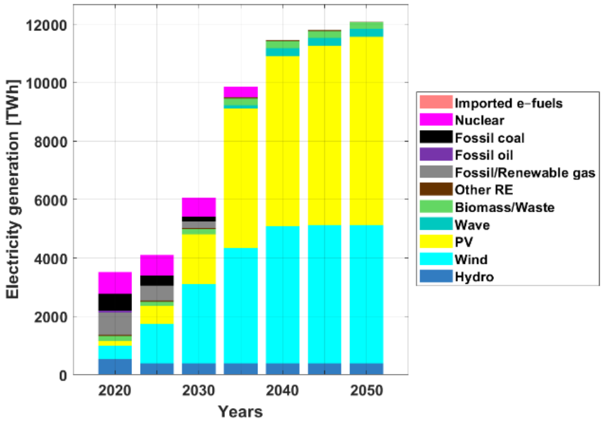
- Electricity emerges to the dominant primary energy source (<5% ► 90%), driven by low-cost and efficiency
- Electricity share in final energy is not structurally changing (22% ► 45%)
- Transition from combustion-based to electron-based society is the fundamental driver, due to efficiency and low-cost
- 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

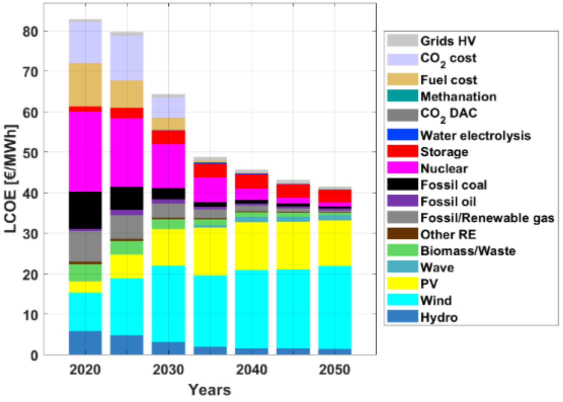
source: Bogdanov et al., 2021. Energy, 227, 120467
EWG/LUT, 2019. Global Energy System based on 100% RE

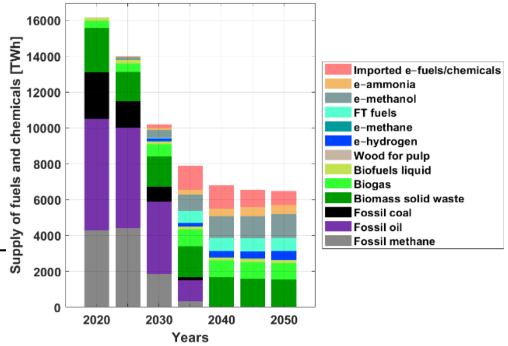
Europe: Highly Ambitious Energy-Industry Transition











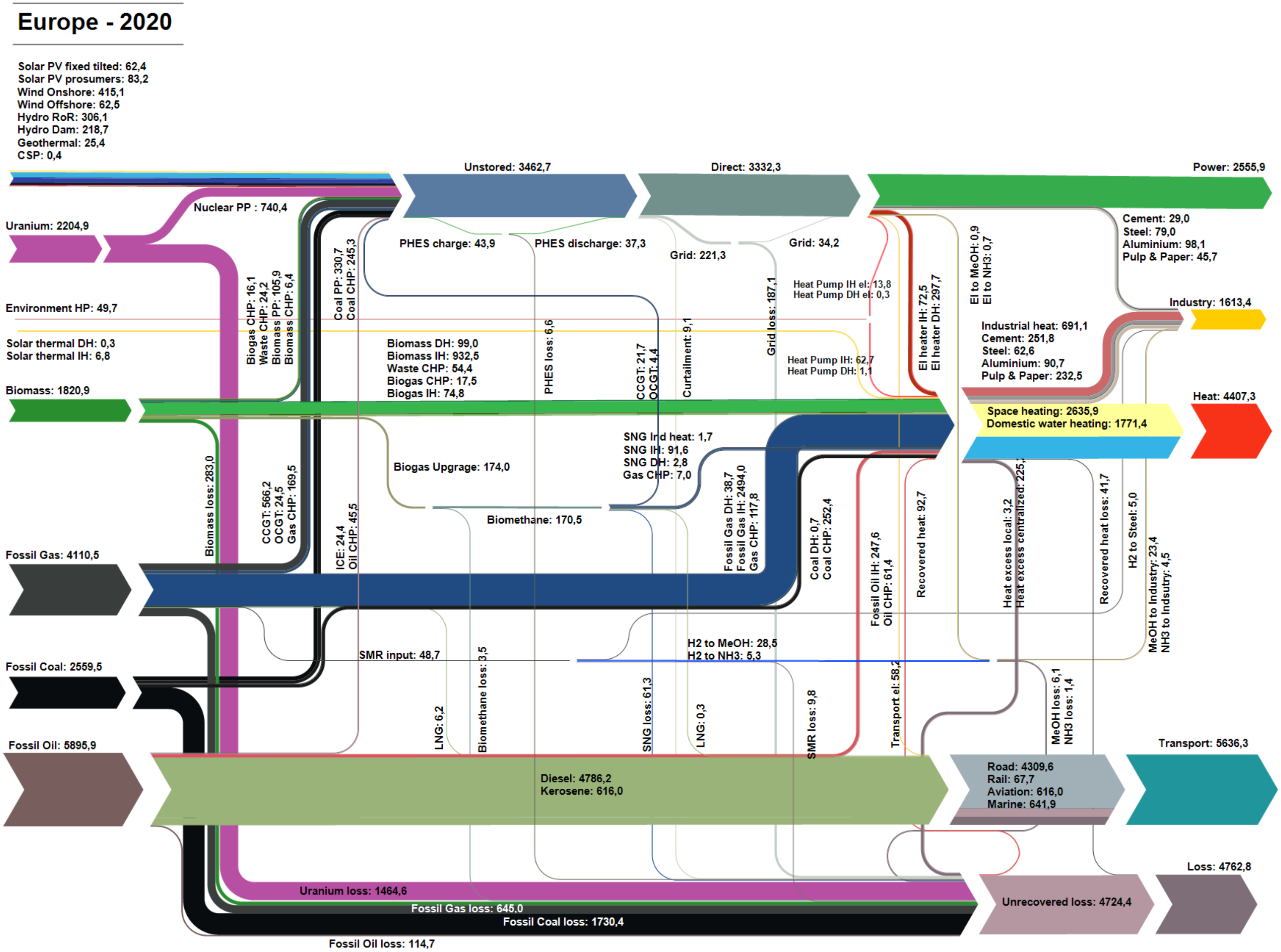
- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: 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?

@ChristianOnRE

SERENDIPV

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

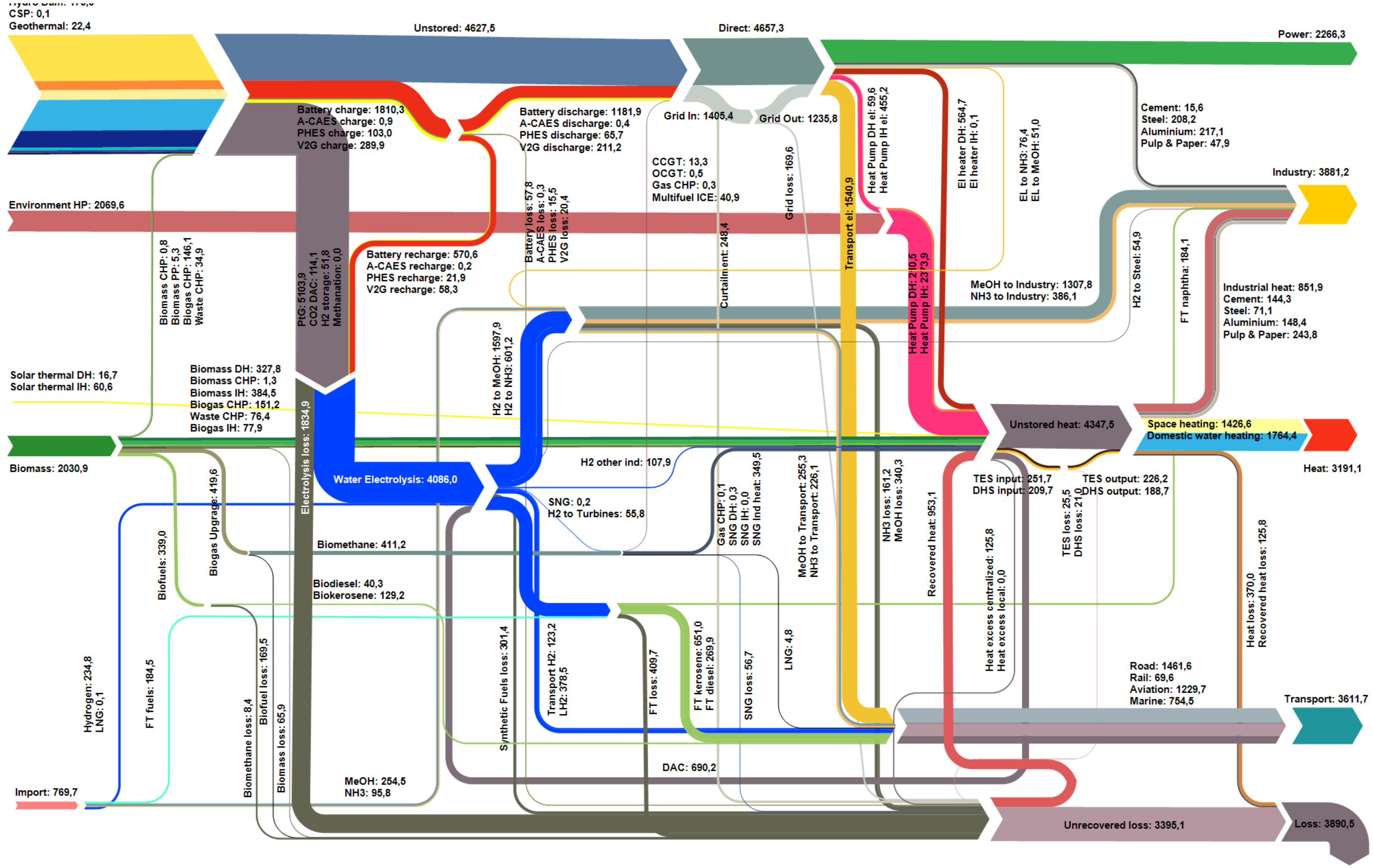
System Outlook – Energy Flows in 2020



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

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

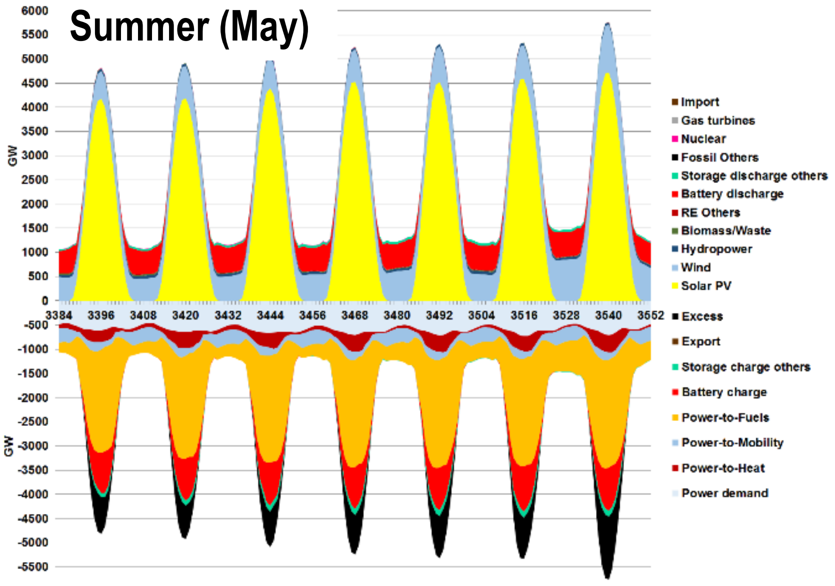


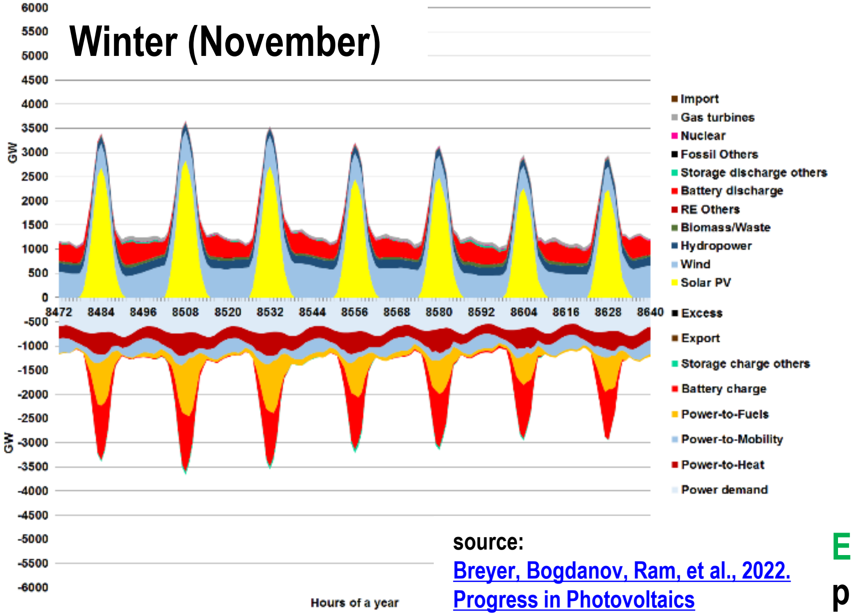
Source:
Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2022. Progress in Photovoltaics

Breyer et al., 2023. International Journal of Hydrogen Energy

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

Hourly Operation and Balancing

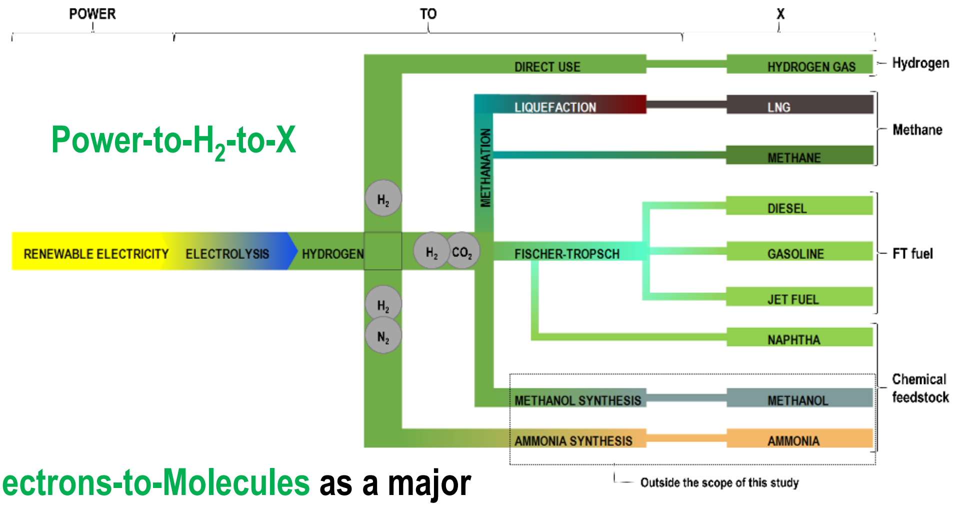




source:
[Breyer, Bogdanov, Ram, et al., 2022. Progress in Photovoltaics]

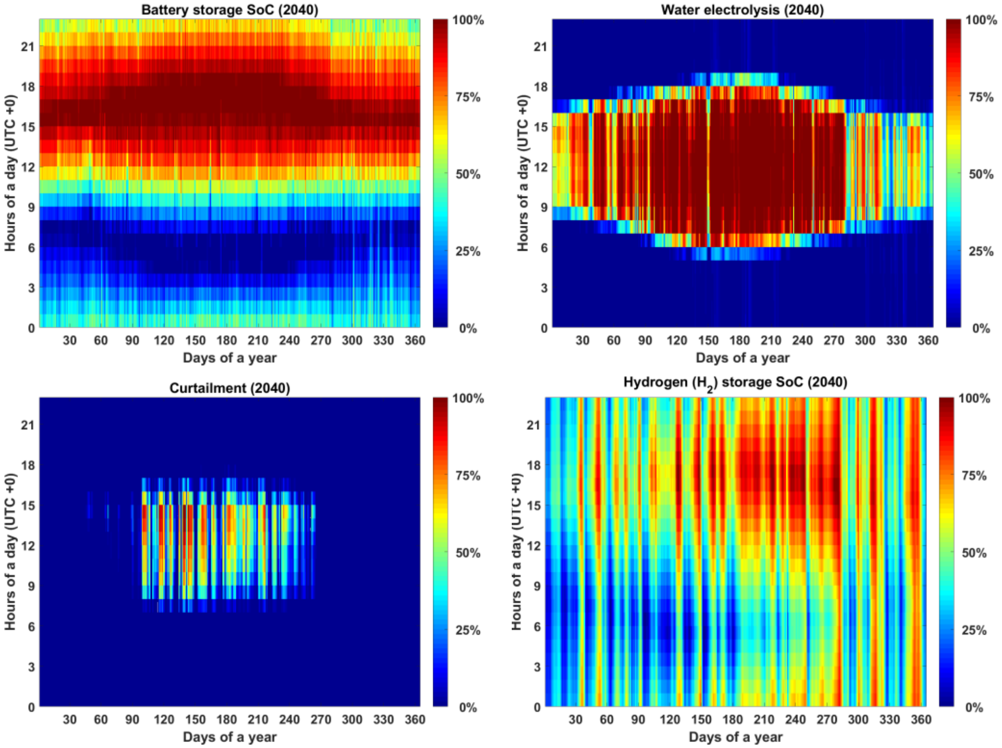
Key insights:

- 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



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

Case Iberia

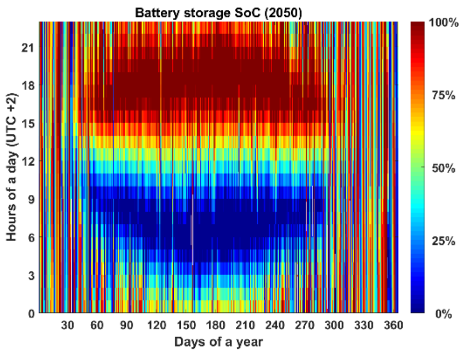


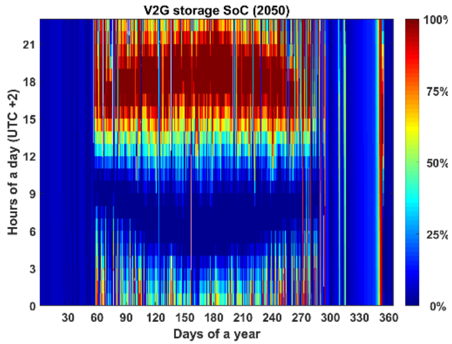
Hourly state-of-charge for utility-scale battery (top left), operation of electrolysers (top right), state-of-charge for hydrogen buffer storage (bottom right), and curtailment (bottom left).

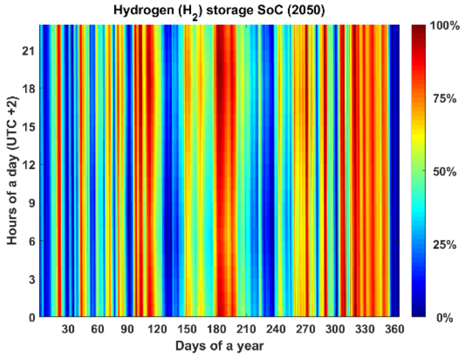
- Energy systems with very high shares of variable renewables (PV, wind) require flexibility: supply complementarity, demand response, sector coupling, grids, and storage
- Battery storage:
  - Charging during the daytime and discharging in the afternoon/night
  - Slight seasonal variation
- Electrolysers:
  - Operation in hours of electricity availability, largely during the sunshine hours, and in the summer months with high solar energy yield
- Hydrogen storage:
  - Operation mainly as a weekly buffer, but also with diurnal elements for optimal supply of baseload H_2-to-X synthesis
- Curtailment:
  - Well balanced system with 8.4% electricity curtailment during peak solar production months as least cost solution

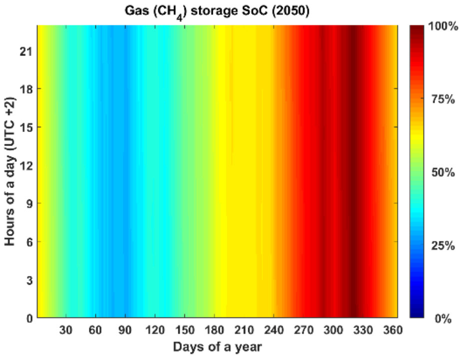
source: ElSayed et al., 2023. 2023, On the full potential and role of different solar photovoltaic system technologies in the Iberian energy transition, EU PVSEC, Lisbon

Case Finland

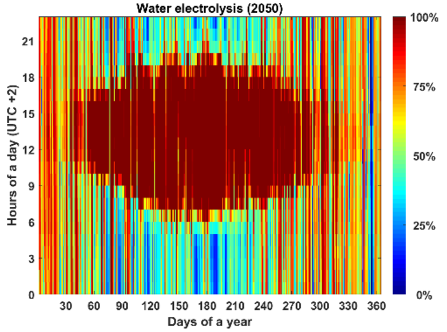


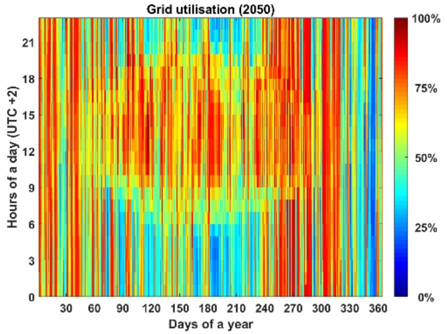


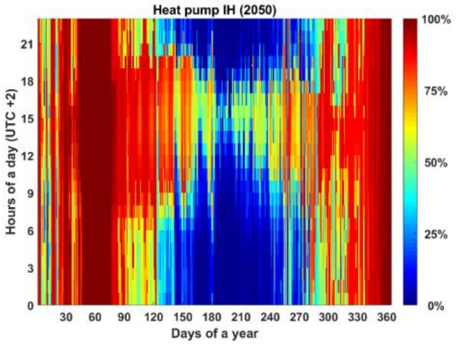


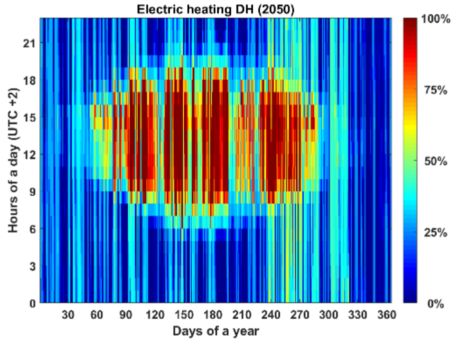


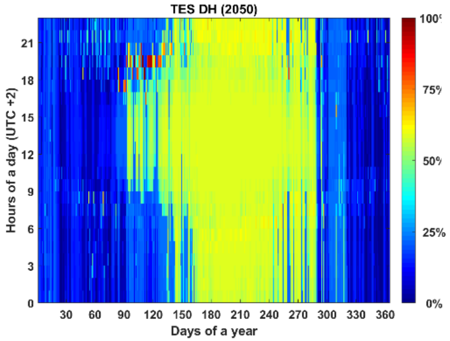
- Operation in hourly resolution shows day-night **battery** dispatch & wind support
- **Hydrogen** storage as classical buffer storage for H_2-to-X, mainly for synthesis
- **Methane** storage is used as seasonal storage
- **Electrolysers** use wind and PV electricity, and much of the latter
- **Grid** utilisation reflects wind and solar supply, high use in winter, PtX in summer (more details on a following slide)
- **Heat pumps** in full operation in the winter, supported by direct electric heating, while direct operation seems favourable with **TES** rather in the summer





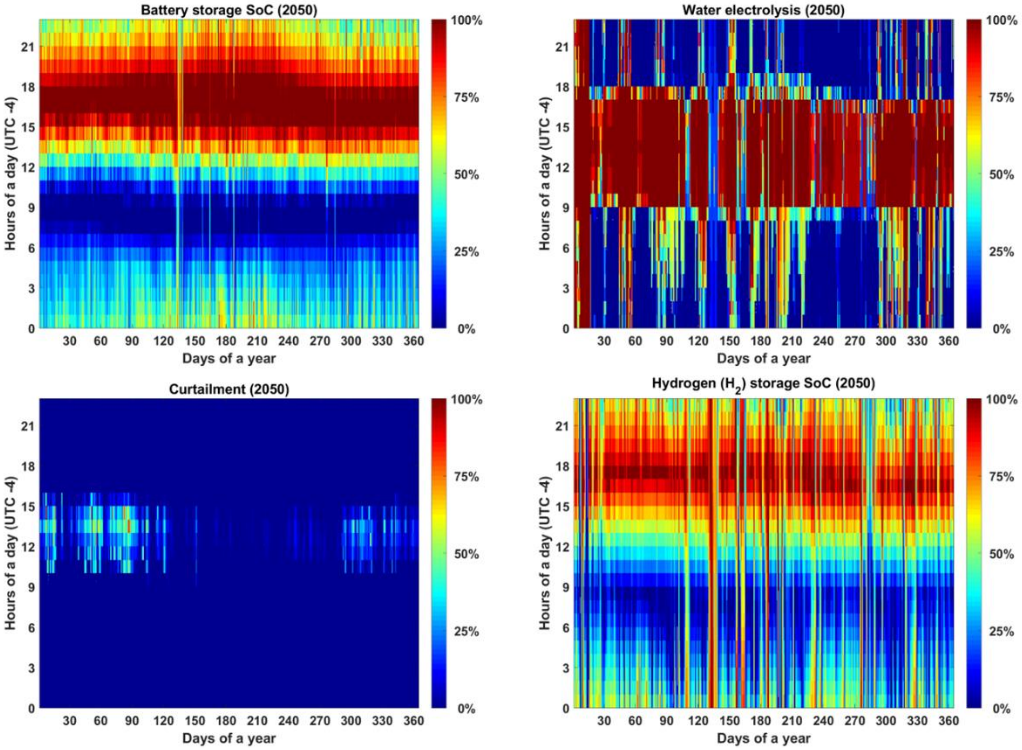






source:
Satymov et al., 2023. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, submitted

Case Puerto Rico

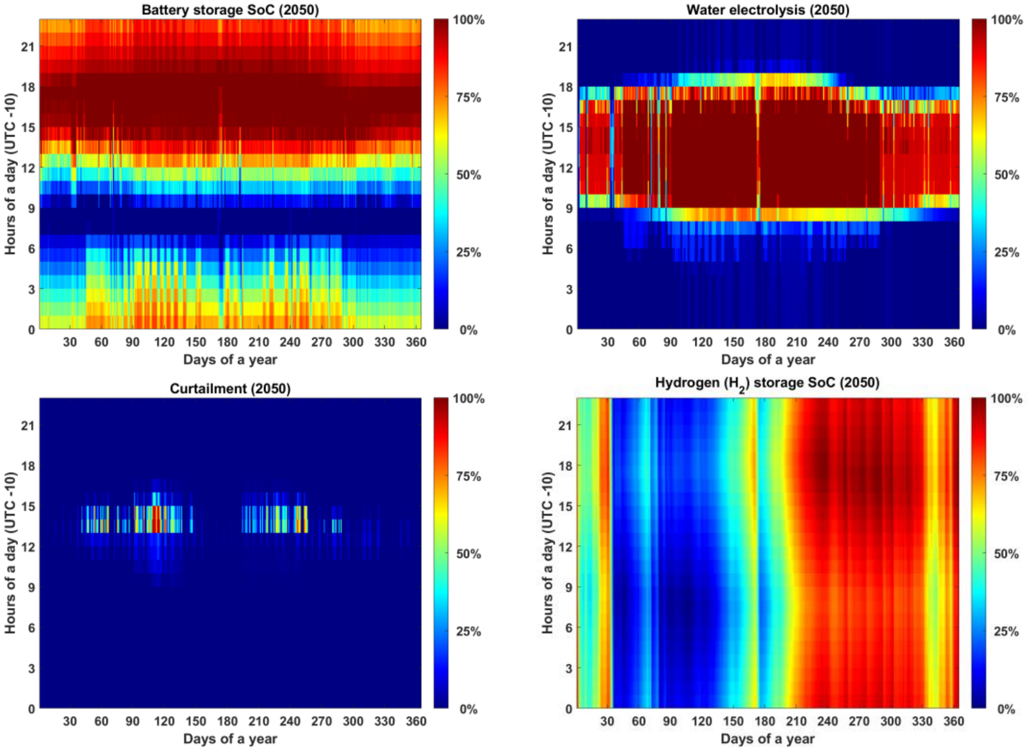


Hourly state-of-charge for utility-scale battery (top left), operation of electrolysers (top right), state-of-charge for hydrogen buffer storage (bottom right), and curtailment (bottom left) for Puerto Rico in 2050.

- Energy systems with very high shares of variable renewables (PV, wind) require flexibility: supply complementarity, demand response, sector coupling, grids, and storage
- Battery storage:
  - Charging during the daytime and discharging in the afternoon/night
  - Slight seasonal variation
  - Slight influence of wind pattern on batteries
  - optimisation via battery-to-electrolyser discharge in the mornings (16% of all battery discharge)
- Electrolysers:
  - Operation in hours of electricity availability, largely during the daytime, but also in days/weeks of good wind conditions
- Hydrogen storage:
  - Operation different to many regions in the world
  - Hydrogen storage similar to battery, but with more buffering elements as shown in days/weeks of good wind conditions
  - Only 4.3% of all electricity demand is hydrogen used in turbines
- Curtailment:
  - Very well balanced system with only 3.4%

source: 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

Case Hawaii



Hourly state-of-charge for battery storage (top left), operation of electrolysers (top right), state-of-charge for hydrogen buffer storage (bottom right), and curtailment (bottom left) in 2050.

- Energy systems with very high shares of variable renewables (PV, wind) require flexibility: supply complementarity, demand response, sector coupling, grids, and storage
- Battery storage:
  - Charging during the daytime and discharging in the evening/night
  - Slight seasonal variation
  - Small influence of wind pattern on batteries
  - Significant usage of stored electricity for electrolysis (60% of all battery discharge)
- Electrolysers:
  - Operation in hours of electricity availability, almost exclusively during the daytime
- Hydrogen storage:
  - Operation mainly as a seasonal storage to achieve an optimal supply of baseload H_2-to-X synthesis
- Curtailment:
  - Only 0.5% of all generated electricity is curtailed Low curtailment possible due to flexible electrolysis operating during peak solar production

source: Lopez et al., 2023. Role of Storage in the Power-to-X Economy: The Case of Hawaii, 17th IRES, Aachen

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

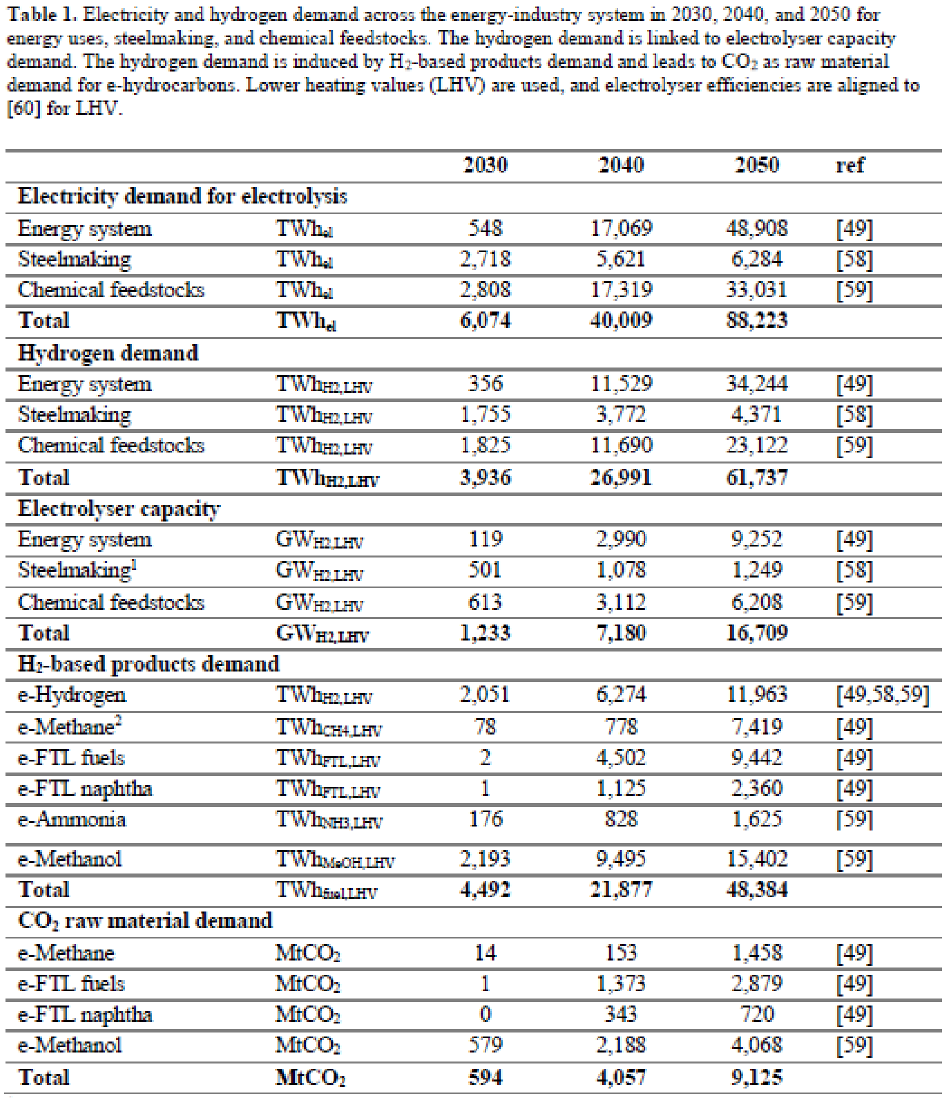


Table 1. Electricity and hydrogen demand across the energy-industry system in 2030, 2040, and 2050 for energy uses, steelmaking, and chemical feedstocks. The hydrogen demand is linked to electrolyser capacity demand. The hydrogen demand is induced by H_2-based products demand and leads to CO_2 as raw 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., 2023. 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

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

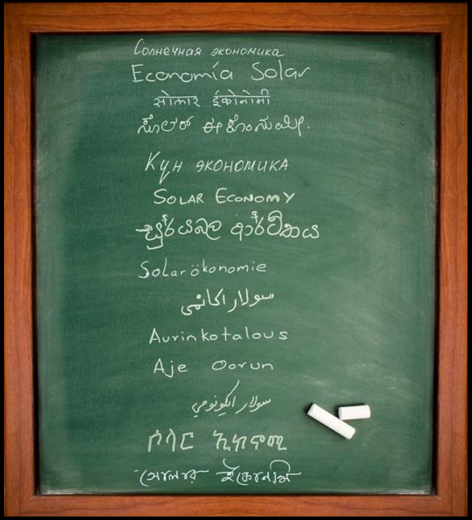
Role of storage:

- 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
- Batteries: >90% of all electricity storage goes through batteries (prosumers, utility, V2G)
- 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
- Thermal energy storage: adaptation to heat loads and heat supply

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!



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