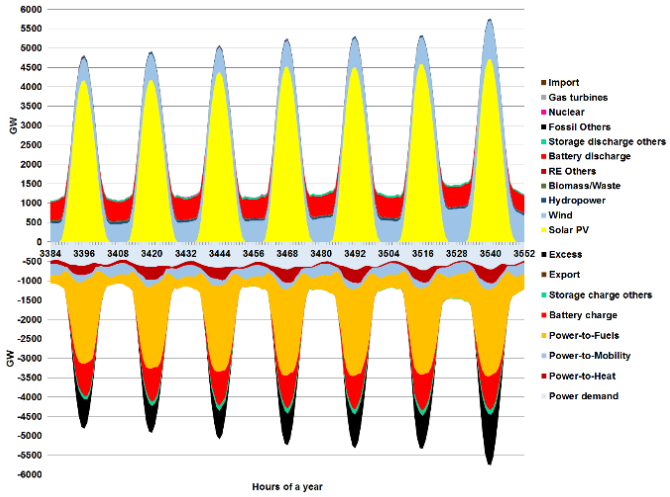
22.8.2024

Curtailment in energy system modelling for 100% renewable energy systems



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PVPMC, Copenhagen, August 22, 2024

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@ChristianOnRE (, Bsky, LinkedIn)

LUT University

Power Market Development: 2008 - 2022

Empiric trends:

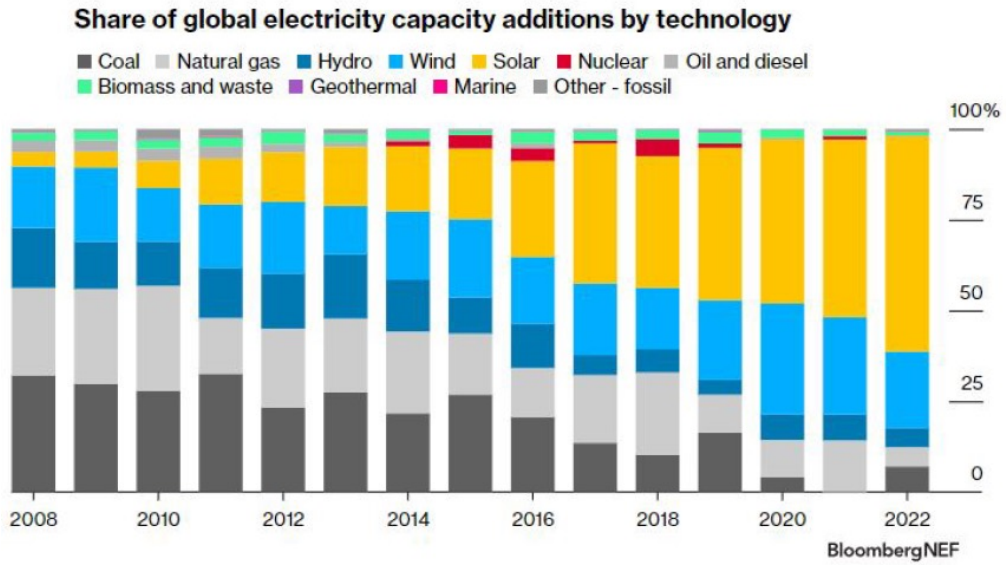
Electricity supply dominated by PV and wind power

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, and +70% YoY in 2023 (note: new PV electricity > wind)

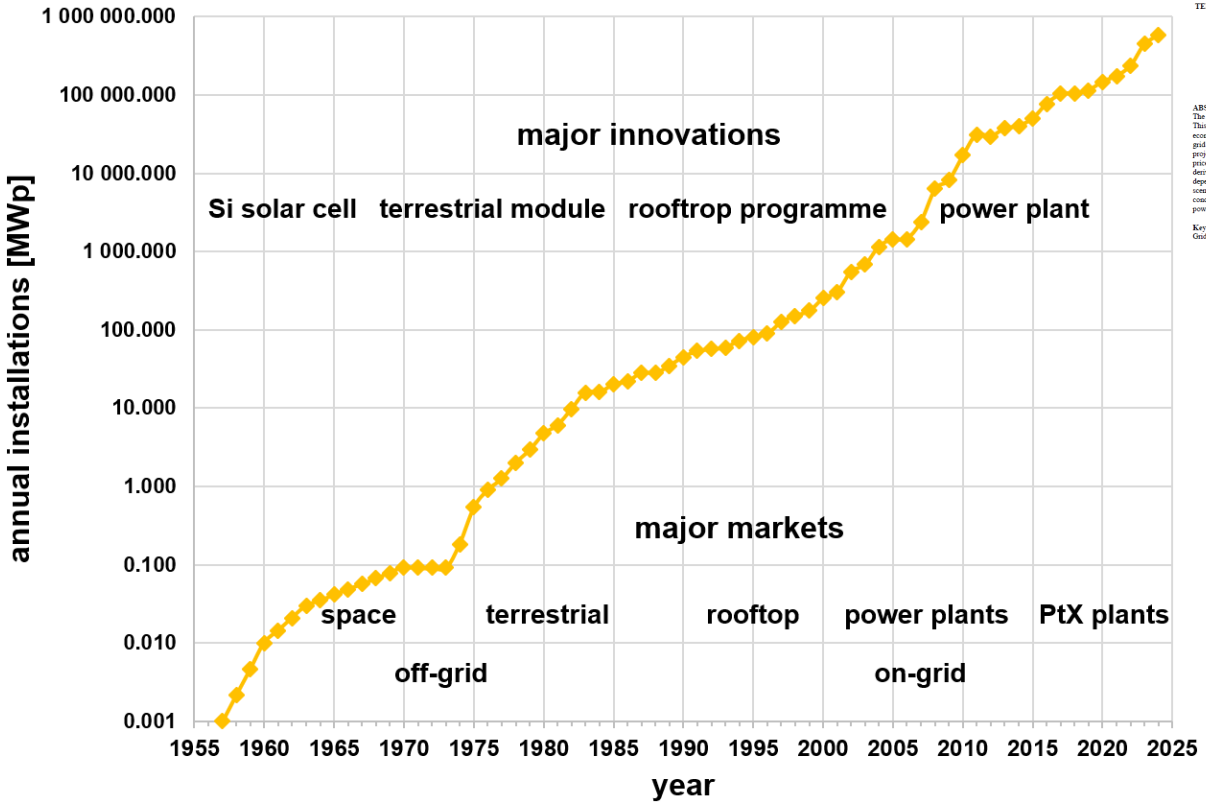
PV is outside any historic experience



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

Solar PV Installations: how it developed





preprint to be published in the proceedings of the
26th European Photovoltaic Solar Energy Conference, 5–9 September 2011, Hamburg, Germany

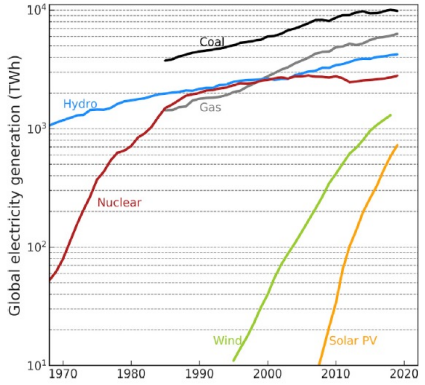
THE PHOTOVOLTAIC REALITY AHEAD:
TERAWATT SCALE MARKET POTENTIAL POWERED BY PICO TO GIGAWATT PV SYSTEMS AND ENABLED BY HIGH LEARNING AND GROWTH RATES

Ch. Breyer[1,2,3]

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[2] Universität Kassel, Wilhelmshöher Allee 73, 34121 Kassel, Germany,
[3] now with: Reiner Lemoine Institut gGmbH, Ostendstraße 25, 12459 Berlin, Germany,
Phone +49 (0) 30 5304 2000, E-mail: christian.breyer@rl-institut.de

ABSTRACT
The photovoltaic (PV) energy technology has the potential to contribute to the global energy supply on a large scale. This potential can only be realised if sustainable and highly competitive PV economics are achieved. An integrated economic PV market potential assessment is presented consisting of grid-parity and fuel-parity analyses for the on-grid markets and an amortization analysis for rural off-grid PV markets. All analyses are mainly driven by cost projections based on the experience curve approach and growth rates for PV systems and electricity and fossil fuel prices for the currently used power supply. A total economic PV market potential of 2,800 GW to 4,300 GW is derived for the year 2020. 600 GW to 1,600 GW of cumulated installed PV capacity is estimated for the year 2020, depending on scenario assumptions. Even the low edge of the expected total installed PV capacity exceeds the scenario assumptions of leading energy organizations, such as IEA, by a factor of more than three to five. In conclusion, PV is on its way to become a highly competitive energy technology. Being complementary to wind power, PV together with wind power might become the backbone of the global energy supply in the coming decades.

Keywords
Grid-Parity, Fuel-Parity, off-grid PV, Hybrid Power Plant, Economic Analysis, Energy Options, PV Markets

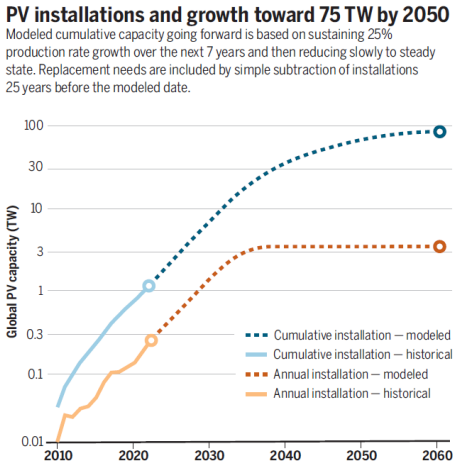


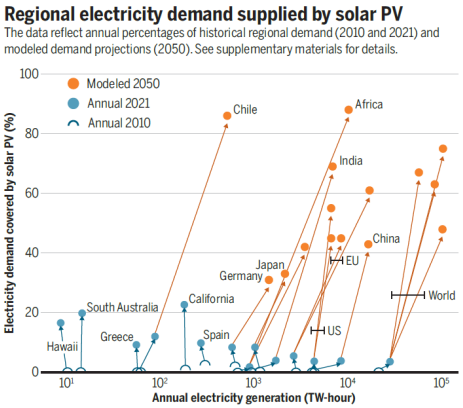
Key insights:

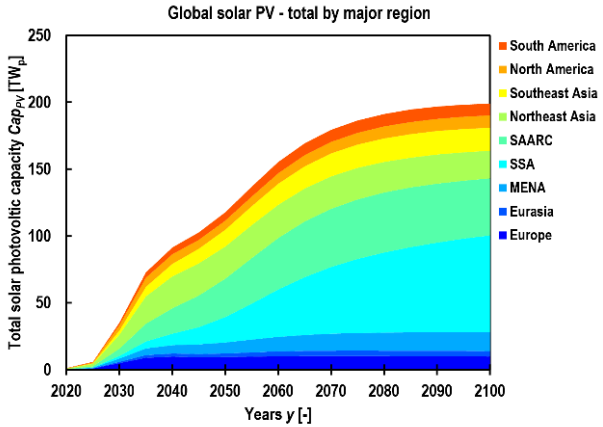
- **low-cost PV dominates one market after another, now Power-to-X plants**
- **solar PV manufacturing capacity soon around 1 TW/a across the entire value chain**
- **no energy source has been ever phased in as steeply as PV**
- **wind power is similar to solar PV, but slightly slower in the phase-in**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

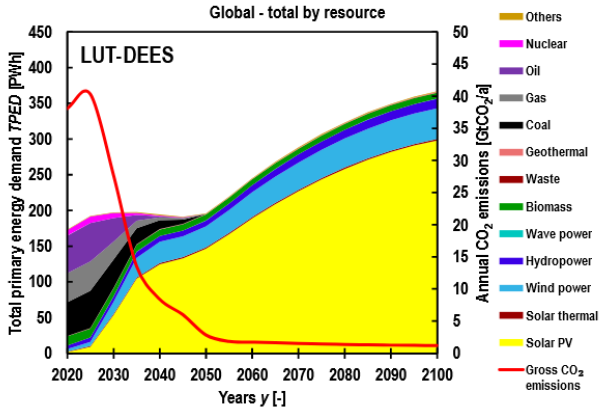
source: Breyer et al., 2021. Solar PV in 100% RE systems. Chapter 14 in Photovoltaics Volume In: Encyclopedia of Sustainability Science and Technology, online
Victoria et al., 2021. Joule 5, 1041-1056
Breyer, 2011. 26th EU PVSEC , 6EP.1.2

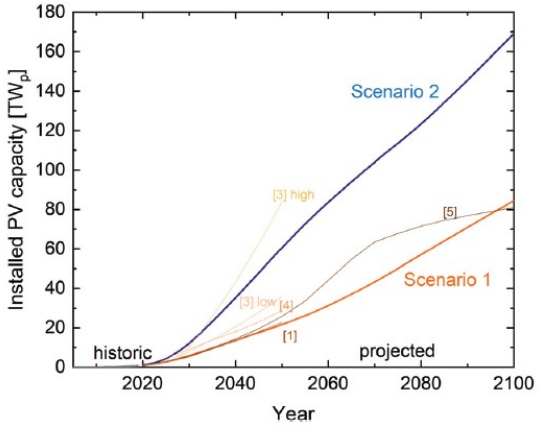
Solar PV Installations: where to go









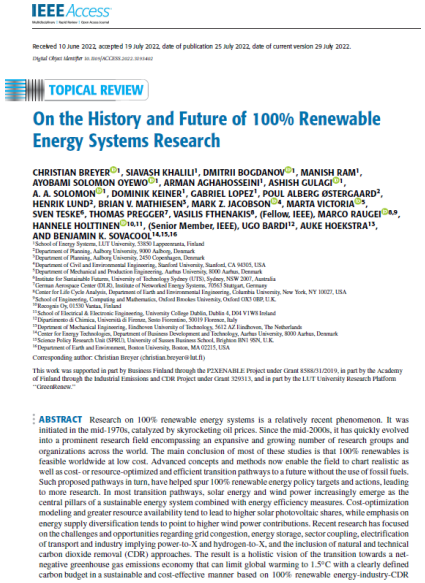


Key insights:

- 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 1.0ºC/ 350 ppm
- Sunbelt regions may reach 60-90% PV supply share
- Americas: US 40-60%, Chile around 80%
- Europe: 50-55%

source: Haegel et al., 2023. Science, 380, 39-42
Goldschmidt et al., 2021. Energy & Environ Science, 14, 5147
Keiner et al., 2023. Energy, 272, 127199

100% Renewable Energy Systems research



IEEE Access

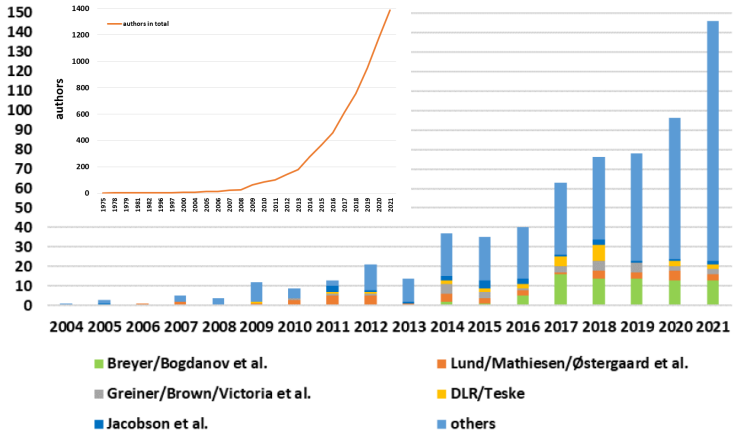
Received 10 June 2022, accepted 19 July 2022, date of publication 25 July 2022, date of current version 29 July 2022.

TOPICAL REVIEW

On the History and Future of 100% Renewable Energy Systems Research

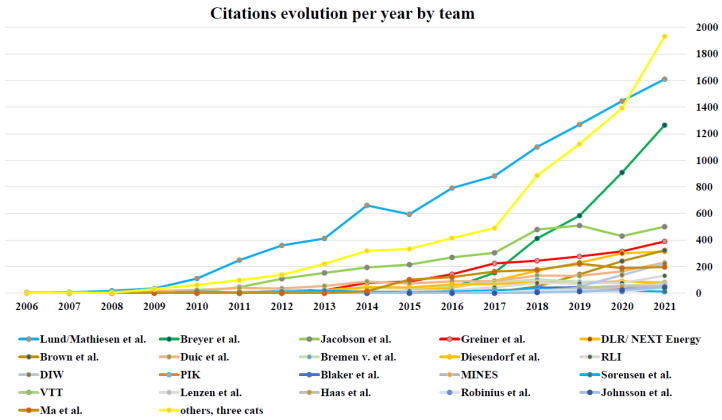
CHRISTIAN BREYER, SIAVASH KHALILI, DMITRII BOGDANOV, MANISH RAM, AYOBAMI SOLOMON OYEWO, ARMAN AGHAHOSSEINI, ASHISH GULAGI, A. A. SOLOMON, DOMINIK KEINER, GABRIEL LOPEZ, POUL ALBERG ØSTERGAARD, HENRIK LUND, BRIAN V. MATHIESEN, MARK Z. JACOBSON, MARTA VICTORIA, SVEN TESKE, THOMAS PREGGER, VASILIS FTHENAKIS, (Fellow, IEEE), MARCO RAUGEI, HANNELE HOLTTINEN, (Senior Member, IEEE), UGO BARDI, AUKE HOEKSTRA, AND BENJAMIN K. SOVACOOL

ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and organizations across the world. The main conclusion of most of these studies is that 100% renewables is feasible worldwide at low cost. Advanced concepts and methods now enable the field to chart realistic as well as cost- or resource-optimized and efficient transition pathways to a future without the use of fossil fuels. Such proposed pathways in turn, have helped spur 100% renewable energy policy targets and actions, leading to more research. In most transition pathways, solar energy and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimization modeling and greater resource availability tend to lead to higher solar photovoltaic shares, while emphasis on energy supply diversification tends to point to higher wind power contributions. Recent research has focused on the challenges and opportunities regarding grid congestion, energy storage, sector coupling, electrification of transport and industry implying power-to-X and hydrogen-to-X, and the inclusion of natural and technical carbon dioxide removal (CDR) approaches. The result is a holistic vision of the transition towards a net-negative greenhouse gas emissions economy that can limit global warming to 1.5°C with a clearly defined carbon budget in a sustainable and cost-effective manner based on 100% renewable energy-industry-CDR



source: Breyer et al., 2022. IEEE Access 10, 78176-78218
Khalili et al., 2022. IEEE Access, 10, 125792-125834

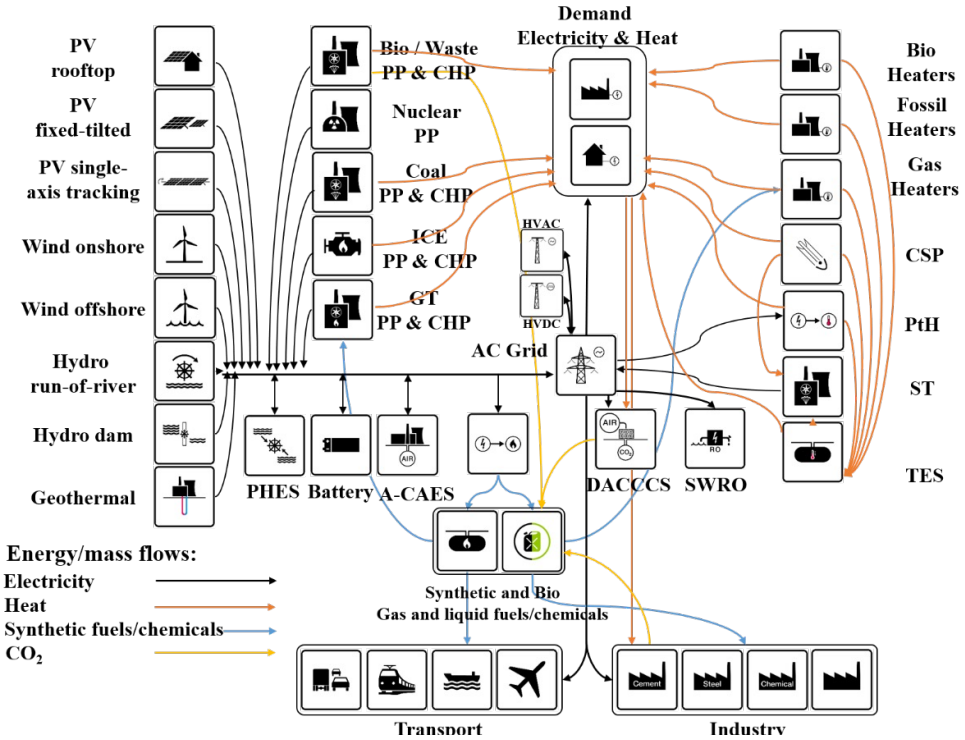
from top to bottom:
development of
- authors in the field
- articles published
- citations received



Key insights:

- research field is growing at high dynamics
- entirely renewable systems research now established
- >1400 individual researchers involved in 100% RE articles
- leading teams (articles, citations): Lund et al. (Aalborg, DK), Breyer et al. (LUT, FI), Jacobson et al. (Stanford, US)
- international organizations are conservative in the adoption of new insights, e.g. IPCC, IEA, World Bank, etc.

LUT Energy System Transition Model (LUT-ESTM)



source:

Bogdanov, Breyer et al., 2021. Applied Energy, 283, 116273

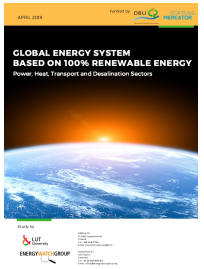
Bogdanov, Breyer et al., 2021, Energy, 227, 120467

Bogdanov, Breyer et al., 2023, Energy, 273, 127213

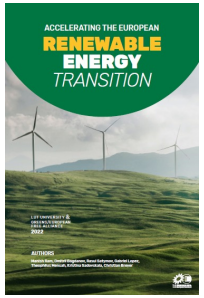
recent reports



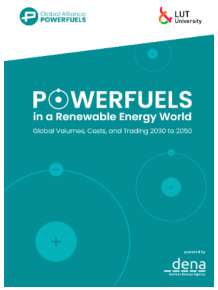
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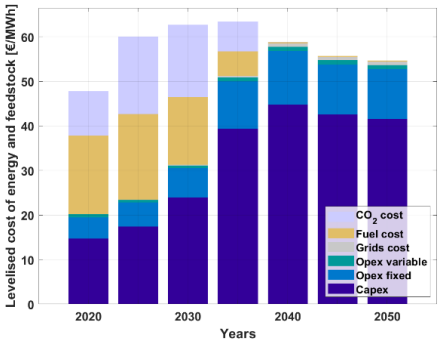


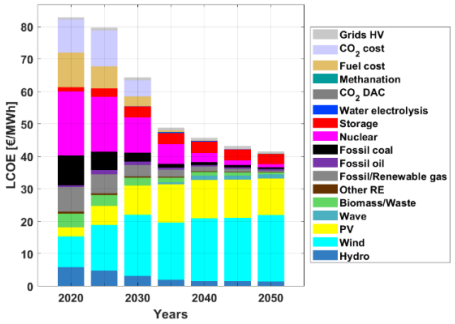
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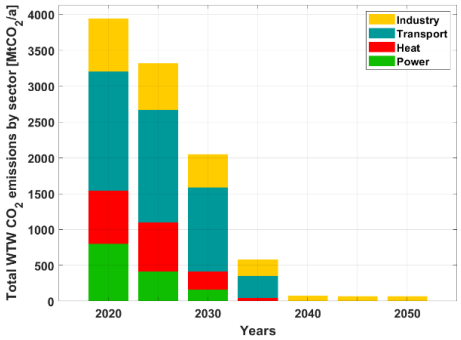
Key features:

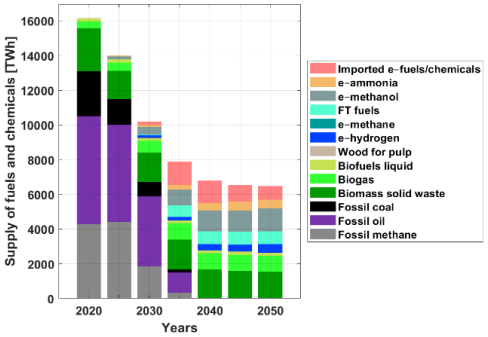
- full hourly resolution, applied in global-local studies, enabling energy-industry-CDR systems, comprising about 150 technologies
- used for several major reports, in 75+ scientific studies, published on all levels
- strong consideration of all kinds of Power-to-X (heat, fuels, chemicals, materials,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

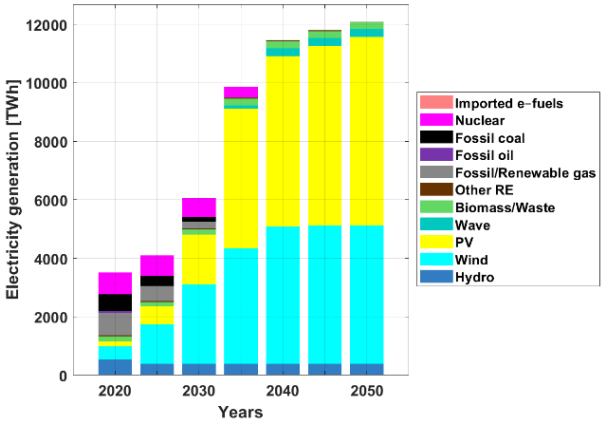
Europe: Highly Ambitious Energy-Industry Transition







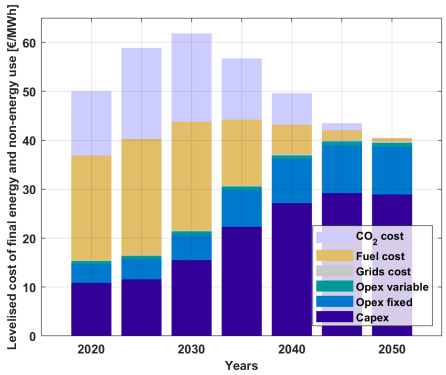


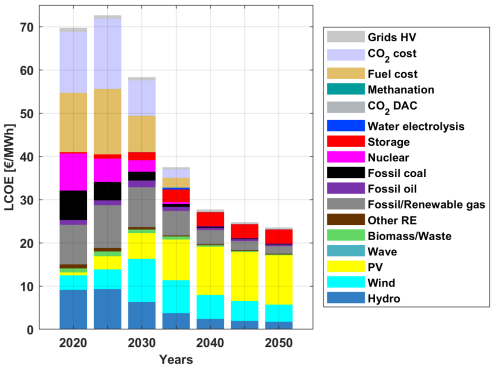


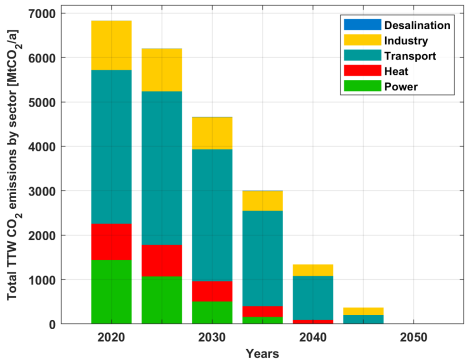
source: Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022

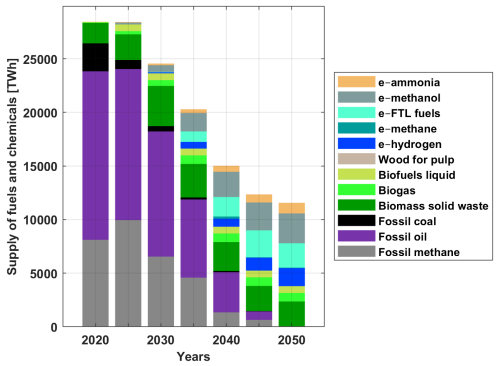
- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: zero CO_2 emissions in 2040
- Massive expansion of electricity would be required, no more than 3.0% curtailment
- 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?

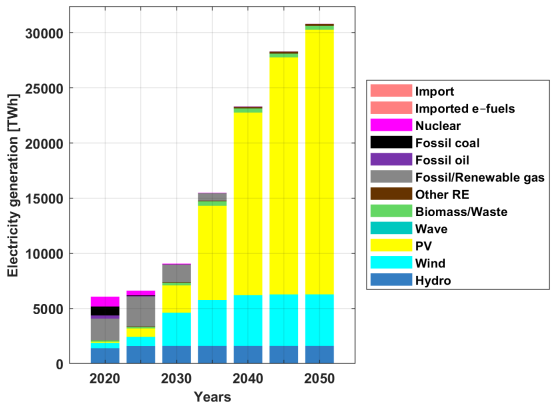
Americas: Highly Ambitious Energy-Industry Transition







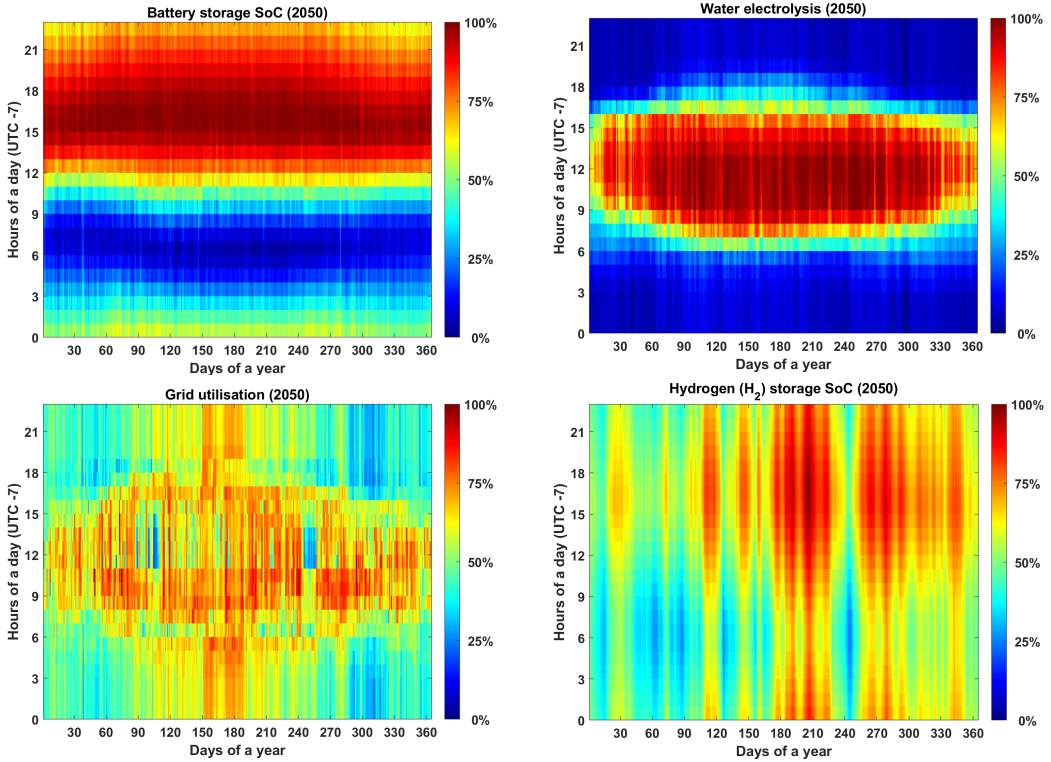




source: Breyer, Lopez et al., 2024. On the Role of Solar PV for the Energy-Industry Transition in the Americas, PVSC-52, Seattle

- Methods: LUT-ESTM, 1-h, 38-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Americas 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 2050
- Massive expansion of electricity would be required , no more than 4.1% curtailment
- e-fuels & e-chemicals ensure stable operation of transport & industry
- Difference to Europe: lower cost (LOCE, LCOFE), higher PV share, 2-2.5x the volumes due to respectively more people
- What's respected:
  - 1.5 ºC target & biodiversity & cost effectiveness & air pollution phase-out
  - renewal of all American energy-industry system & jobs growth
- Why society should not go for such an option?

Operational dynamics (Americas)

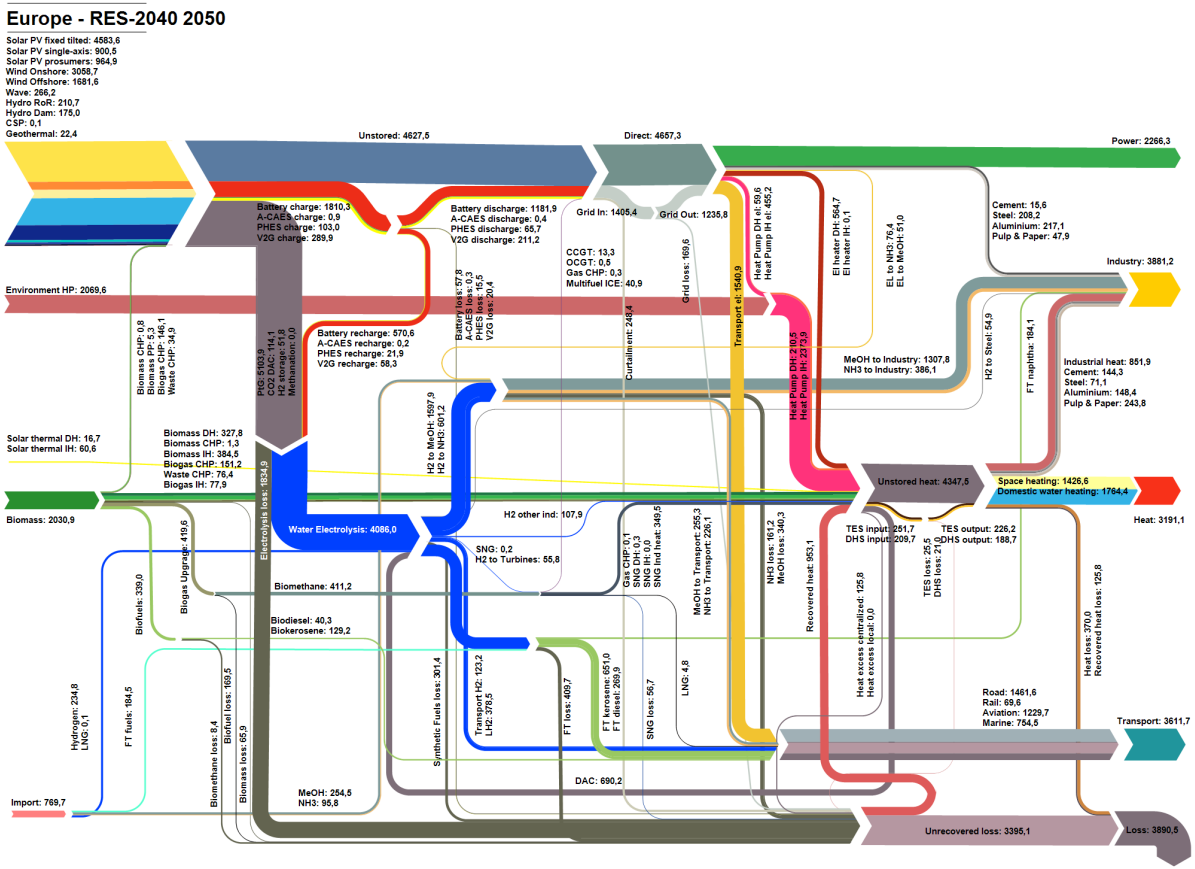


Hourly state-of-charge for utility-scale battery (top left), operation of electrolysers (top right), state-of-charge for hydrogen buffer storage (bottom right), and grids utilization (bottom left) for Americas in 2050.

Dynamics of key energy system components

- 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 and influence of wind pattern
  - optimisation via battery-to-electrolyser discharge in the mornings (38% of all battery discharge) for avoiding **curtailment**
- **Electrolysers:**
  - operation in hours of electricity availability, largely during the daytime, but also in days/weeks of good wind conditions
- **Hydrogen storage:**
  - combination of daily and seasonal characteristics
  - buffering elements in days/weeks of good wind conditions
  - only 0.1% of all electricity demand is hydrogen used in turbines
- **Grids:**
  - solar profile is reflected but also higher demand in mid-year
- **Curtailment:**
  - very well-balanced system with only **4.1%**
  - comment on 'overbuilt': people talking much about overbuilt typically use oversimplified methods for different reasons

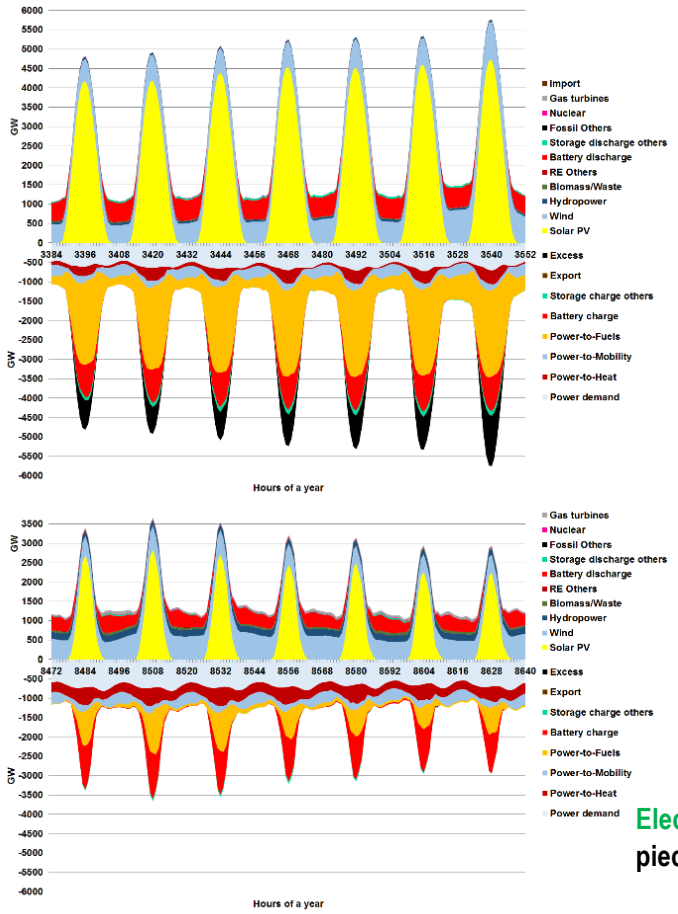
Power-to-X Economy as new characteristic Term



- primary energy is dominated by electricity, complemented by some solar thermal and bioenergy
- the energy flow is described best as Power-to-X Economy, i.e., primary energy dominated by electricity
  - direct electricity use as much as possible, such as electric vehicles, heat pumps, desalination, etc.
  - strong sector coupling
  - indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel
- hydrogen is the second most important energy carrier embedded in power-to-hydrogen-to-X routes
- age of fire phases out … finally we leave the legacy of the campfire and reach a new evolutionary level as a civilisation based on electrons (and photons).

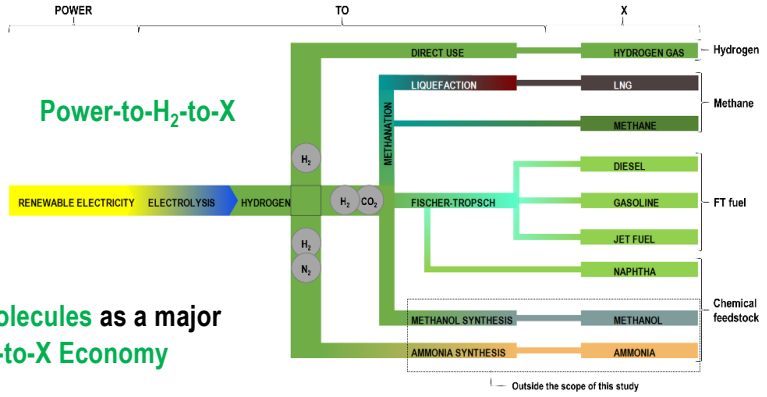
Source:
Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2023, Progress in Photovoltaics
Breyer et al., 2024, International Journal of Hydrogen Energy
Diagram: Greens/EFA, 2022
scenario: RES-2040 for 2050

Hourly Operation and Balancing



Key insights:

- week of most renewables supply (spring) and least renewables supply (winter) is shown
- 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
- 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
- curtailment in this research for entire Europe in 20 regions has been 4.5%

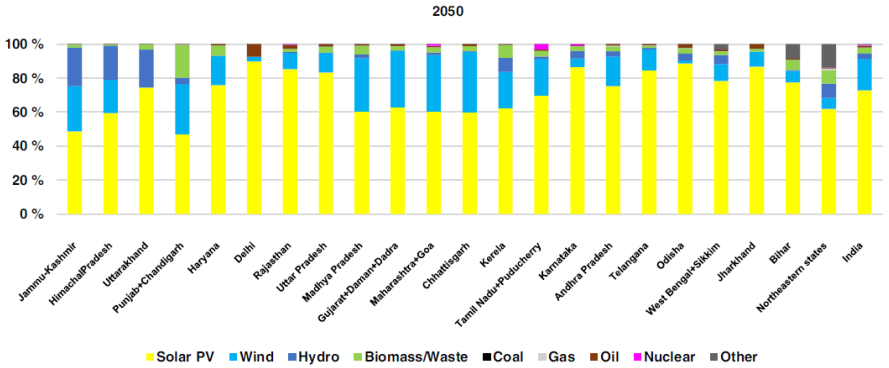


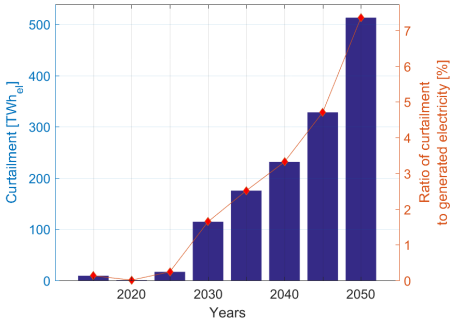
Electrons-to-Molecules as a major piece of Power-to-X Economy

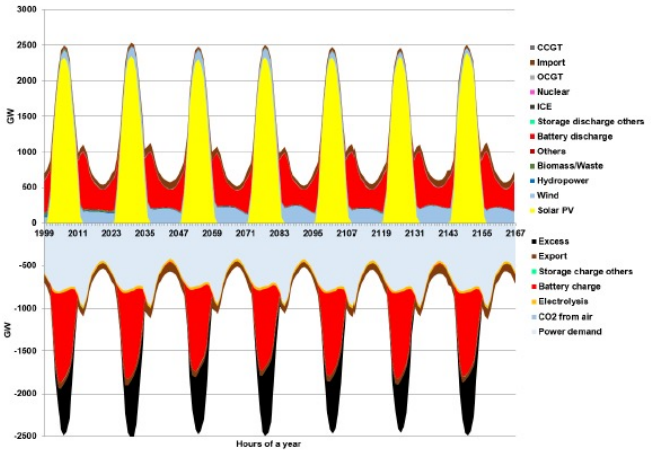
source:
Breyer, Bogdanov, Ram, et al., 2022. Progress in Photovoltaics

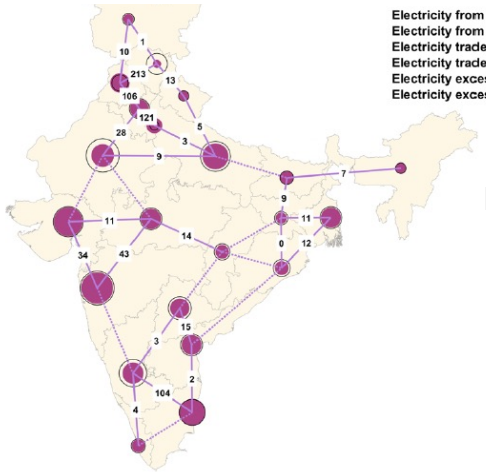


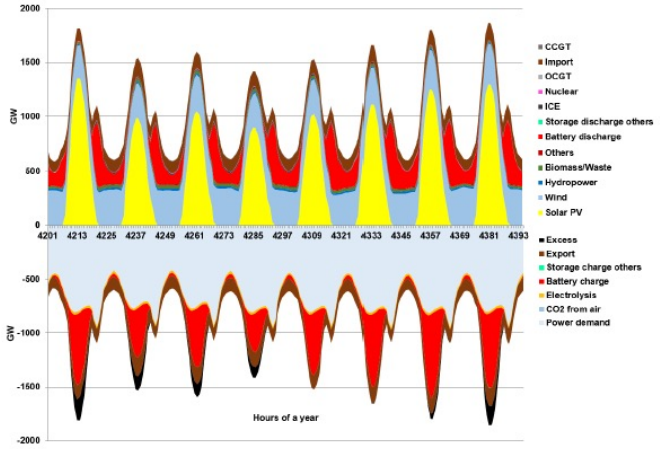
Curtailment in extremer cases: India











Highlights

- most populated country in the world largely supplied by solar PV
- combination of high solar PV share and monsoon leads and limitation of ‘only’ power sector study leads to 7-9% of curtailment
- daily peaks of generation are curtailed, interestingly in the best but also worst supply week of the year

source:
Gulagi et al., 2022. Nature Communications, 13, 5499

Discussion on Curtailment

Some literature find curtailment levels of

- 10% curtailment level: power sector studies with high solar PV shares; all curtailment results up to 10% should be acceptable
- 20% curtailment level: typical only power sector studies without flexibility options in the system solution
- 30% curtailment level: typical highly limited technology portfolio (e.g. only PV & wind & battery), that's not much helpful
- 40% curtailment level: typical renewable energy deniers, often paid by fossil and nuclear money …

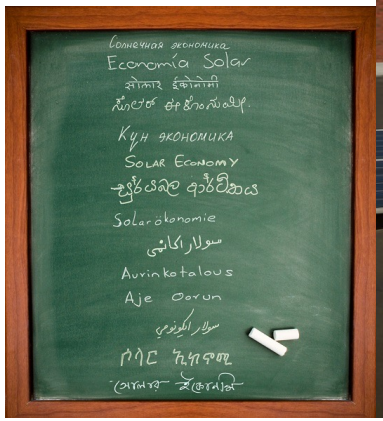
In reality curtailment can be found

- some peak clipping via inverters is standard
- grid limitations may lead to curtailment with 10-20% on annual average, more for peak days, while mitigation is often in planning
- mitigation: grid expansion, battery capacities added, mix of utility-scale and rooftop solutions

How to view on that from energy system modelling view

- academic studies with >10% curtailment may be confronted with questions on proper modelling regarding technology portfolio diversity, sector coupling, or funding backgrounds in extreme cases
- flexibility is most important for low curtailment, based on grids, storage, demand response (EVs, power-to-heat, electrolyers), and overall e-fuels, e-chemicals, e-materials (typically via electrolyers coupled to hydrogen storage)
- curtailment is always part of a least cost solution but may not be higher than 10% on a regional basis as annual average

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







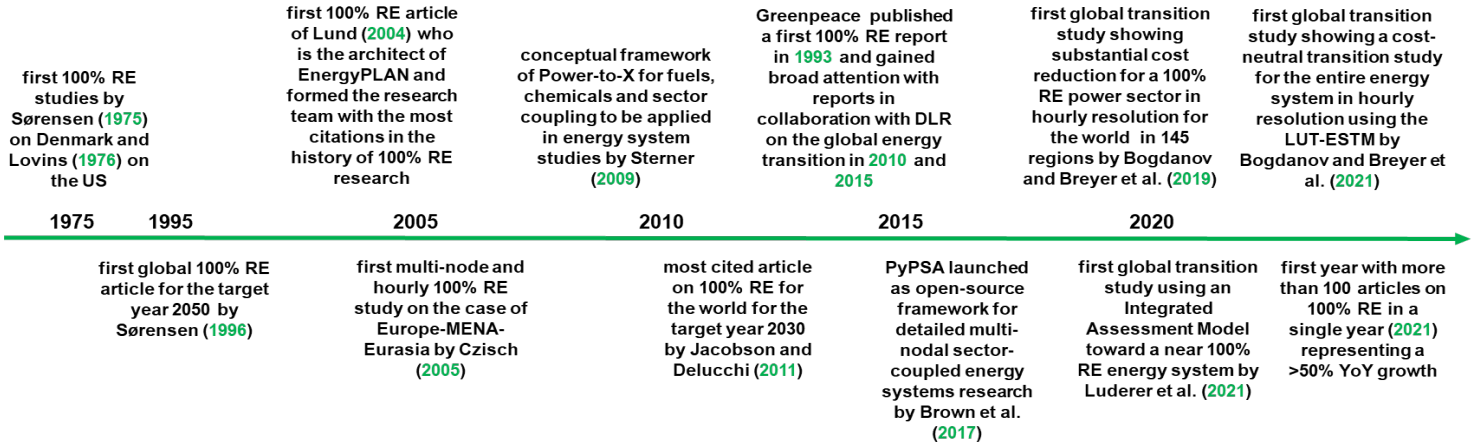
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On the History of 100% RE Systems Research



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

- the first 100% RE system analysis was published in 1975 by Sørensen on the case of Denmark
- in 1976, Lovins published the second article on 100% RE on the United States: ”the soft energy path”
- the first global analysis for a 100% RE system published in 1996 in a journal by Sørensen
- the first multi-node, hourly and large region 100% RE analysis in 2005 by Czisch
- Power-to-X concept for e-fuels, e-chemicals & sector coupling on energy systems emerged in 2009 by Sterner
- the most cited article in the filed published in 2011 by Jacobson and Delucchi
- LUT established 100% RE systems in 145 regions for the world in hourly resolution and cost optimization as energy transition pathway
- 1200+ articles have been published in which 100% RE system analysis have been taken into consideration