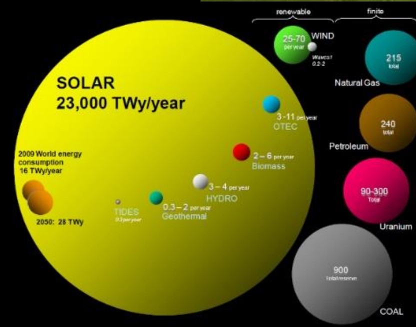




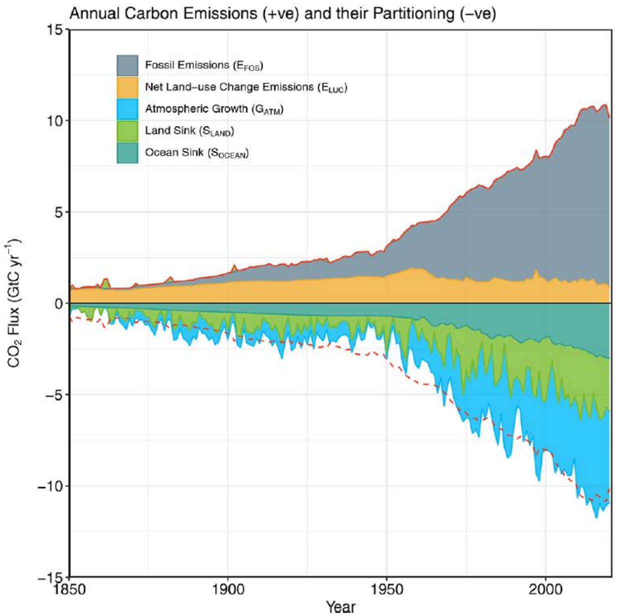



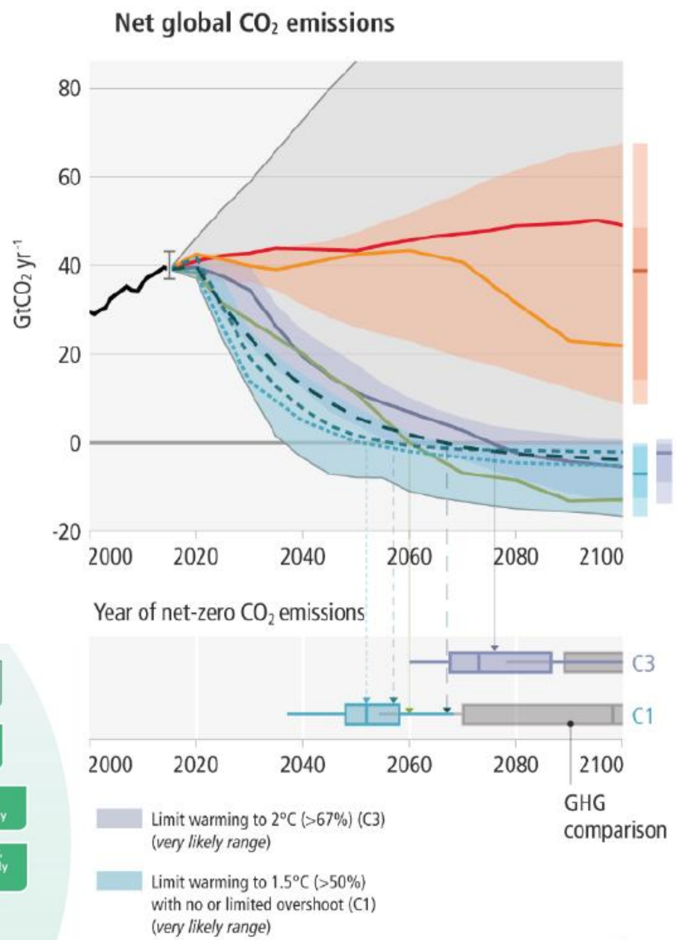
100% renewable electricity for ambitious energy and industry transitions by mid-century

Open your mind. LUT.
Lappeenranta University of Technology

Christian Breyer
LUT University, Finland
Long-Term Energy Scenarios
Session 4: Role of 100% renewable electricity for the energy system transition in scenarios
Bonn, December 7-9, 2022

CO_2 Emissions: how it developed, where to go



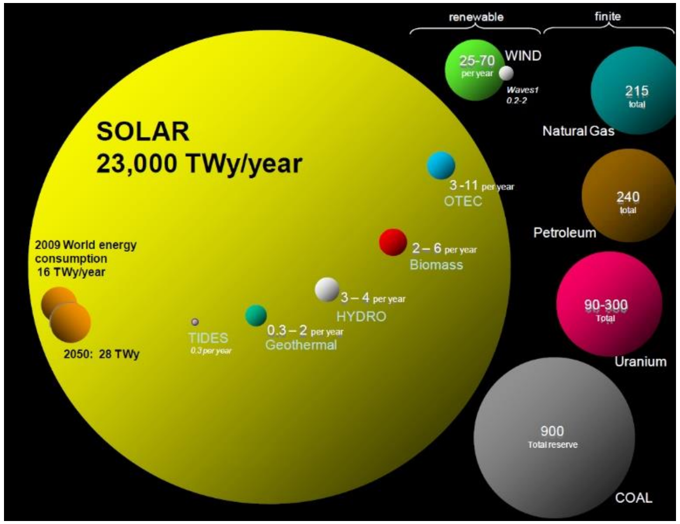


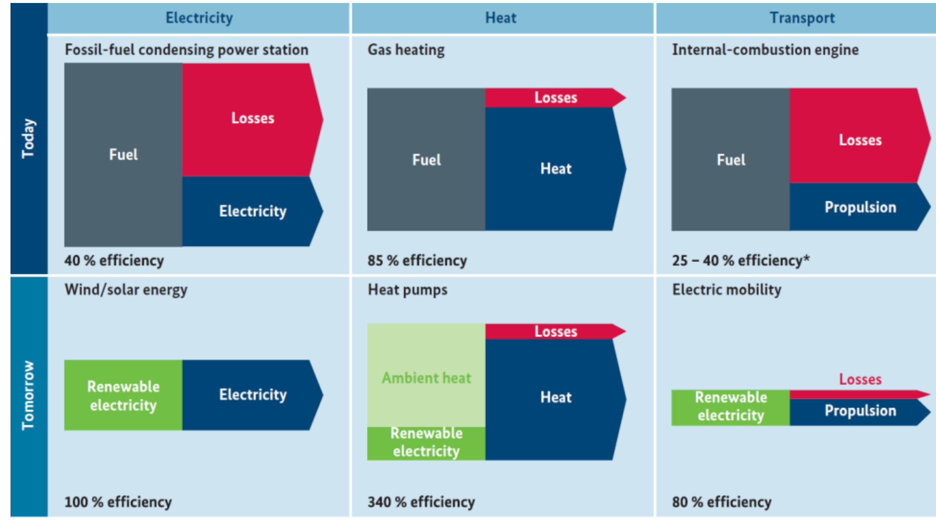
Key insights:

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

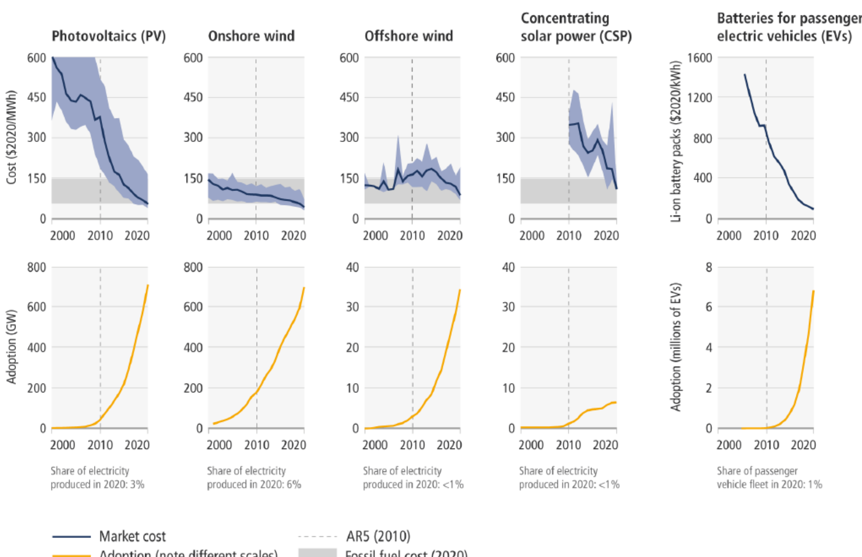
source: IPCC, 2020. 6th Assessment Report WG III

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 %.

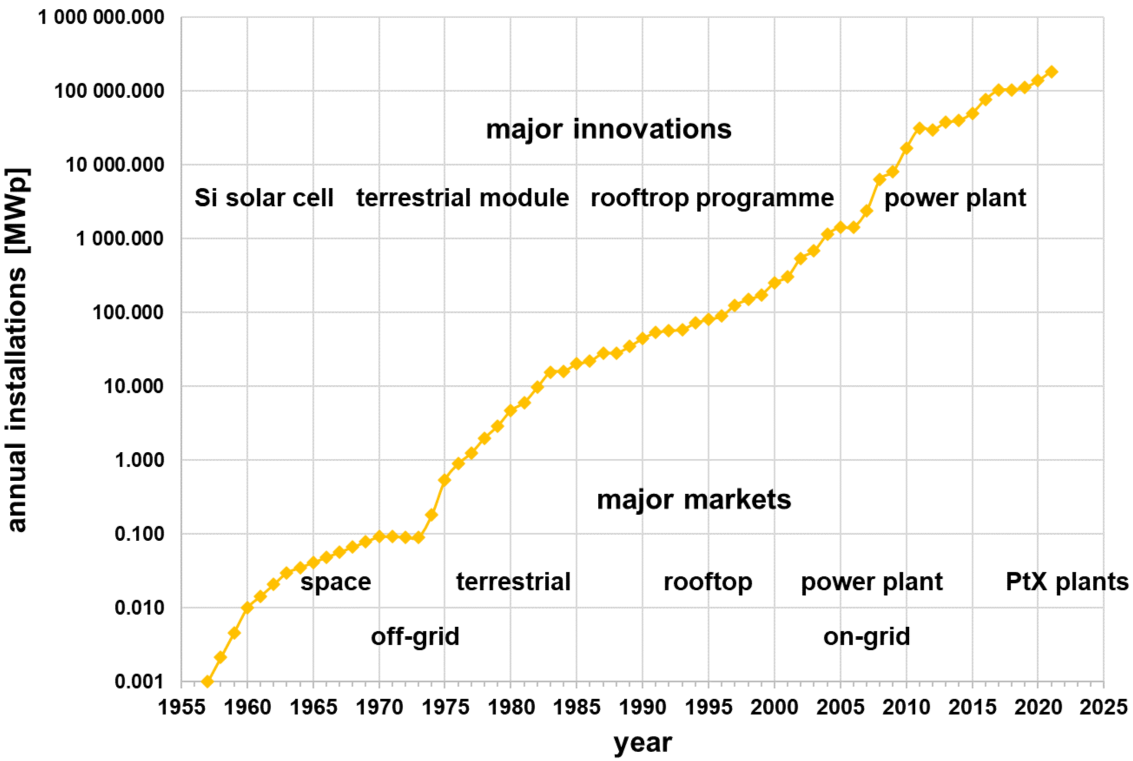


Key insights:

- **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**

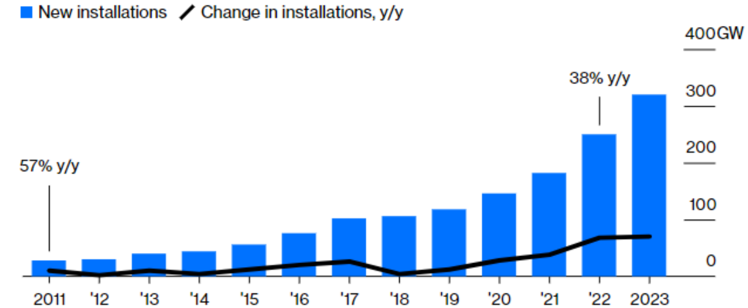
source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50
Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847
IPCC, 2020. 6th Assessment Report WG III

Solar PV Installations: past and near Future



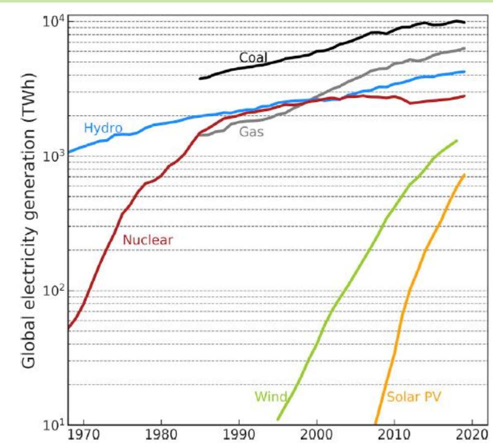
Rising Sun

The growth rate of solar installations this year will hit its highest level in a decade, and at far higher volume levels



Source: Bloomberg

Solar polysilicon – the semiconductor from which photovoltaic panels are made – is growing even faster. Existing and planned manufacturing capacity will amount to about 2.5 million metric tons by 2025, according to research last week from BloombergNEF's Yali Jiang. That's sufficient to build *940 gigawatts* of panels every year.



Key insights:

- Low-cost PV dominates one market after another, now Power-to-X plants
- Silicon manufacturing capacity soon around 1 TW/a
- 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

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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

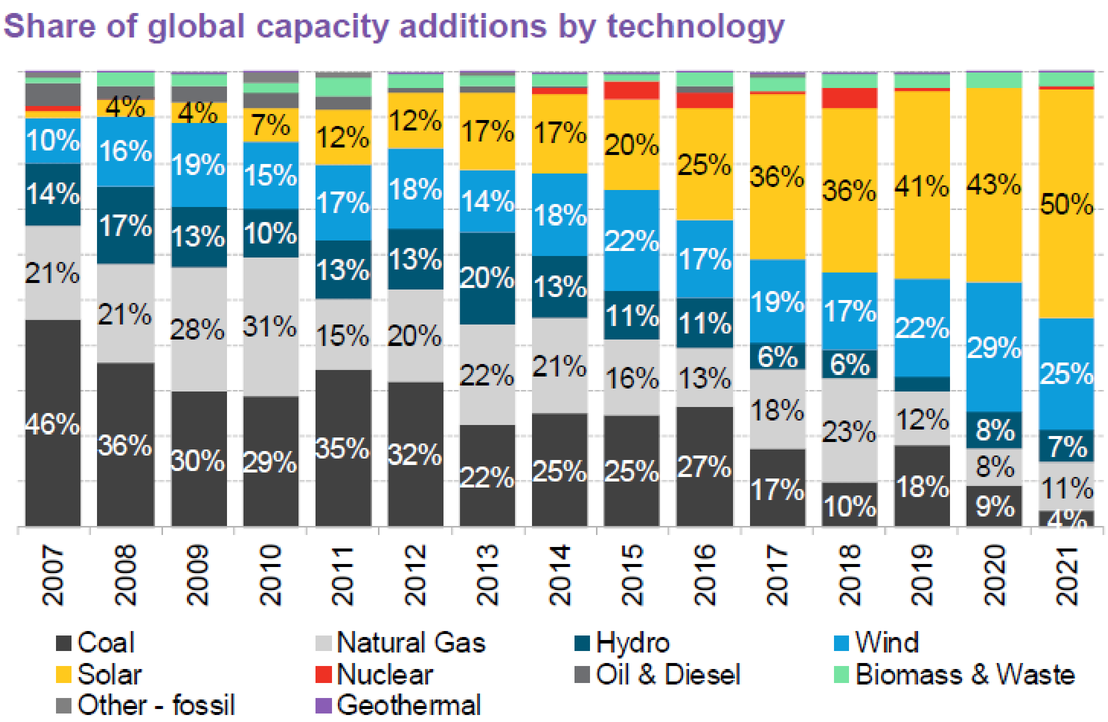
Power Market Development: 2007 - 2021

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



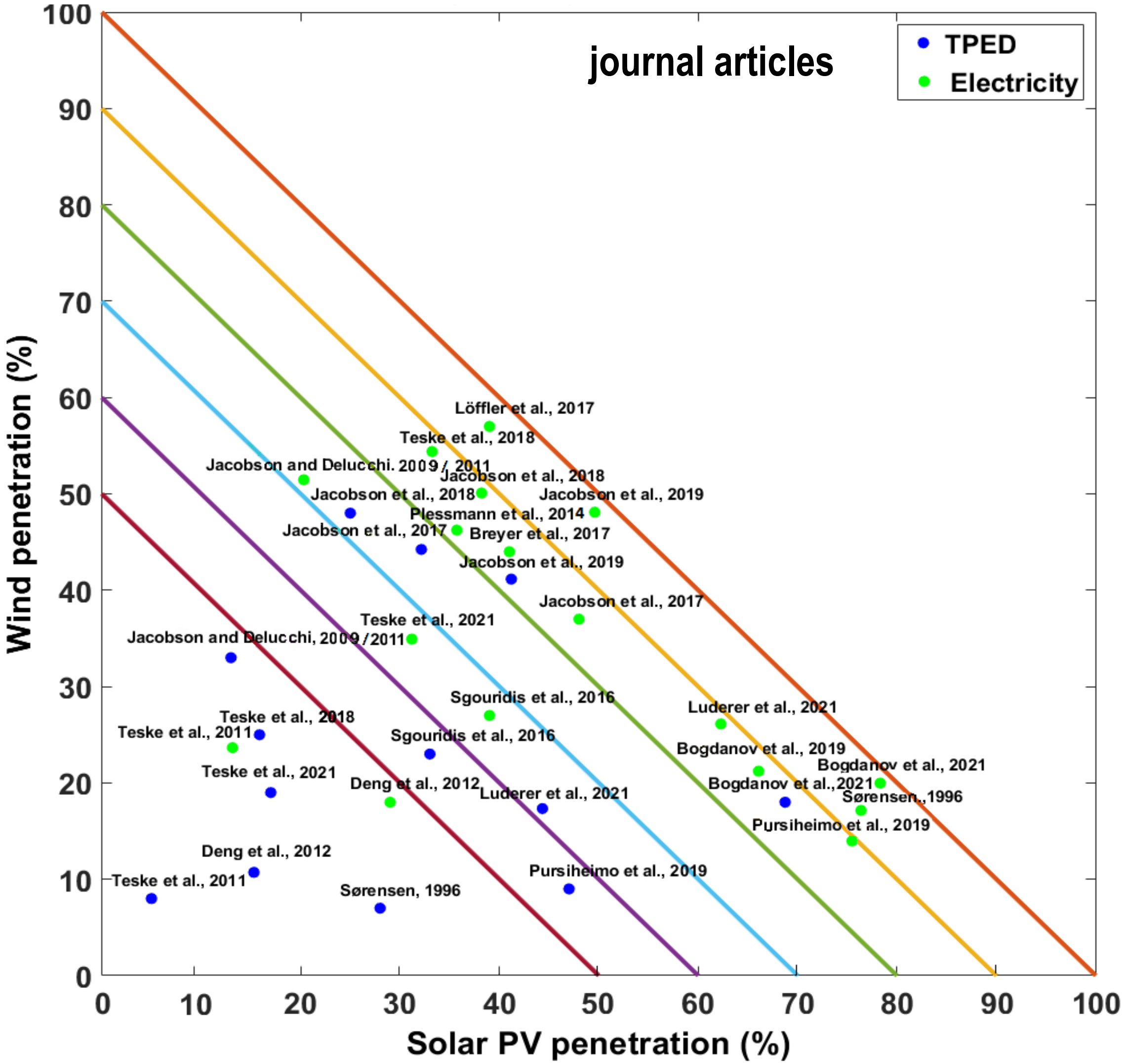
Source: BloombergNEF

Key insights:

- 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 and 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

On the History of 100% RE Systems Research

1975 – first 100% RE studies by Sørensen (1975) on Denmark and Lovins (1976) on the US

1995 – first global 100% RE article for the target year 2050 by Sørensen (1996)

first 100% RE article of Lund (2004) who is the architect of EnergyPLAN and formed the research team with the most citations in the history of 100% RE research

2005 – first multi-node and hourly 100% RE study on the case of Europe-MENA-Eurasia by Czisch (2005)

conceptual framework of Power-to-X for fuels, chemicals and sector coupling to be applied in energy system studies by Sterner (2009)

2010 – most cited article on 100% RE for the world for the target year 2030 by Jacobson and Delucchi (2011)

Greenpeace published a first 100% RE report in 1993 and gained broad attention with reports in collaboration with DLR on the global energy transition in 2010 and 2015

2015 – PyPSA launched as open-source framework for detailed multi-nodal sector-coupled energy systems research by Brown et al. (2017)

first global transition study showing substantial cost reduction for a 100% RE power sector in hourly resolution for the world in 145 regions by Bogdanov and Breyer et al. (2019)

2020 – first global transition study using an Integrated Assessment Model toward a near 100% RE energy system by Luderer et al. (2021)

first global transition study showing a cost-neutral transition study for the entire energy system in hourly resolution using the LUT-ESTM by Bogdanov and Breyer et al. (2021)

first year with more than 100 articles on 100% RE in a single year (2021) representing a >50% YoY growth

- The first 100% RE system analysis was published in 1975 by Sørensen, on Denmark
- Lovins published in 1976 the second article on 100% RE, on the United States: ”the soft energy path”
- Stockholm Environment Institute & Greenpeace published the first report in 1993 for the target year 2100
- The first global analysis for a 100% RE system published in 1996 in a journal, by Sørensen
- Power-to-X concept for fuels, chemicals & sector coupling on energy systems emerged in 2009 by Sterner
- LUT established a state-of-the-art for 100% RE systems in 145 regions for the world in hourly resolution and cost optimisation as energy transition pathway
- 950+ articles have been published in which 100% RE system analysis have been taken into consideration

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

100% Renewables Energy Systems Research

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

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TOPICAL REVIEW

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

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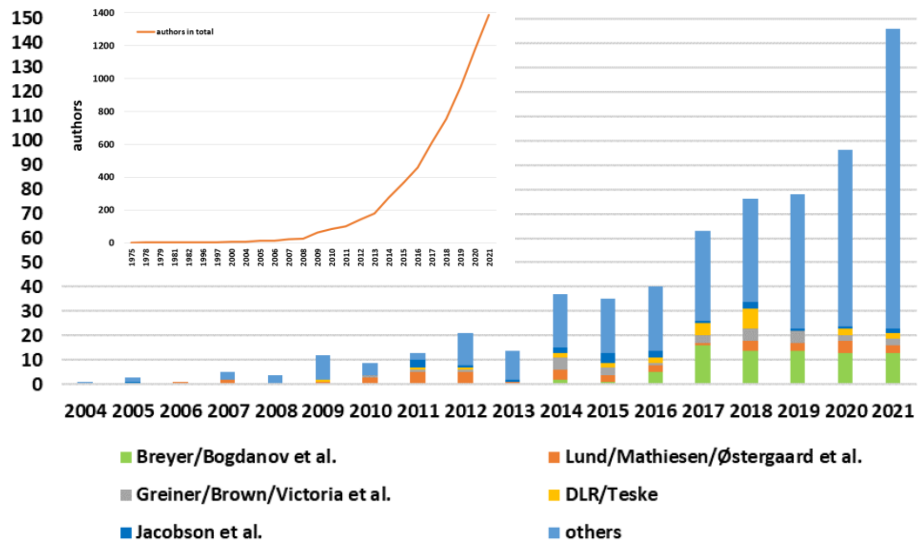
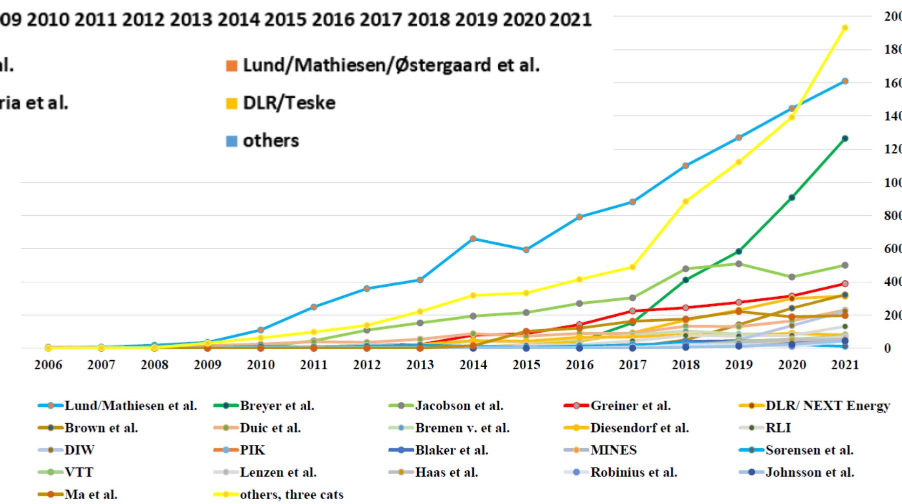
ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and 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



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
- Three leading teams: Lund et al. (Aalborg, DK), Breyer et al. (LUT, FI), Jacobson et al. (Stanford, US)
- International organisations are conservative in adoption of new insights, e.g. IPCC, IEA, World Bank, etc.

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

Leading Energy System Models used in the Field

Table 2. Energy system models used for 100% RE systems analyses. All models used at least five times for 100% RE systems analyses are listed and ranked to the number of published articles applying the model. Some key features of the leading ESMs are indicated. Citations for the 550 category one articles are allocated to the models used as of mid-2022.

Model	articles	citations total	citations 2021	model used for 100% RE earliest	model used for 100% RE latest	inter-connected multi-node	full hourly	multi-sector	detailed industry	relevant CDR	optimi-sation	simu-lation	transi-tion	over-night	off-grid integration
EnergyPLAN	74	7797	1293	2006	2021	yes	yes	yes	no	no	no	yes	no	yes	no
LUT-ESTM	63	2833	939	2015	2021	yes	yes	yes	yes	no	yes	yes	yes	yes	no
HOMER	22	1298	310	2007	2021	no	yes	no	no	no	yes	yes	no	yes	no
TIMES	19	745	134	2011	2021	no	no	yes	yes	no	yes	yes	yes	yes	no
AU model	16	1313	134	2010	2018	yes	yes	no	no	no	yes	yes	no	yes	no
PyPSA	16	704	274	2017	2021	yes	yes	yes	no	no	yes	no	no	yes	no
LOADMATCH	10	1188	302	2015	2021	no	yes	yes	no	no	no	yes	yes	yes	no
REMix	10	604	147	2016	2021	yes	yes	yes	no	no	yes	yes	no	yes	no
GENeSYS-MOD	10	226	90	2017	2021	yes	no	yes	no	no	yes	no	yes	no	no
ISA model	9	183	62	2016	2021	no	yes	yes	no	no	yes	no	no	yes	no
NEMO	7	647	84	2012	2017	yes	yes	no	no	no	yes	no	no	yes	no
H_2RES	6	715	84	2004	2011	no	yes	yes	no	no	no	yes	no	yes	no
MESAP/PlaNet	6	270	51	2009	2021	no	no	yes	no	no	no	yes	yes	yes	no
others	282	11709	2362												
total	550	30232	6226												

- Two leading energy system models for 100% RE system studies are EnergyPLAN and LUT-ESTM
- PyPSA to join the group of leading models
- Not a single model analysed CO_2 direct removal (CDR) and off-grid electrification integration
- Industry sector inclusion only by two models: LUT-ESTM & TIMES, while PyPSA joined in the meantime

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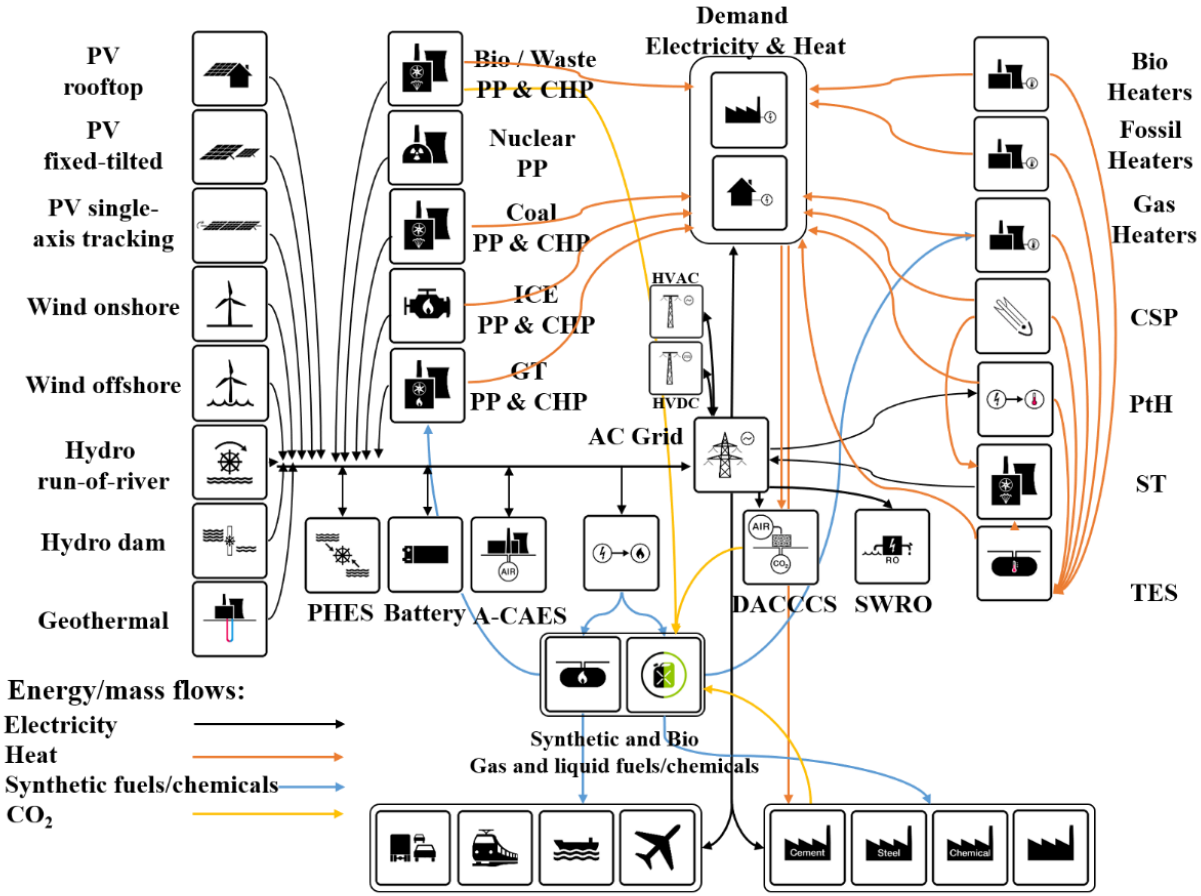
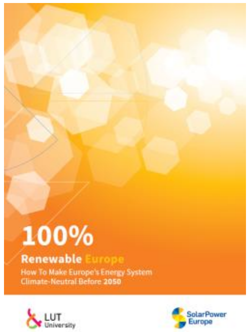
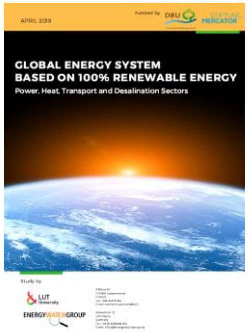
source: Khalili and Breyer, 2022. IEEE Access, 10, 125792-125834

LUT Energy System Transition Model



recent reports





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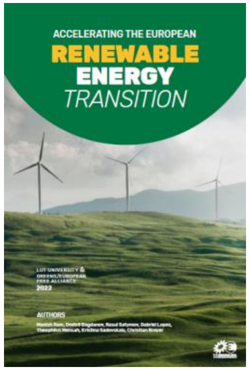

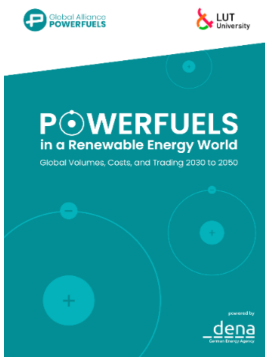

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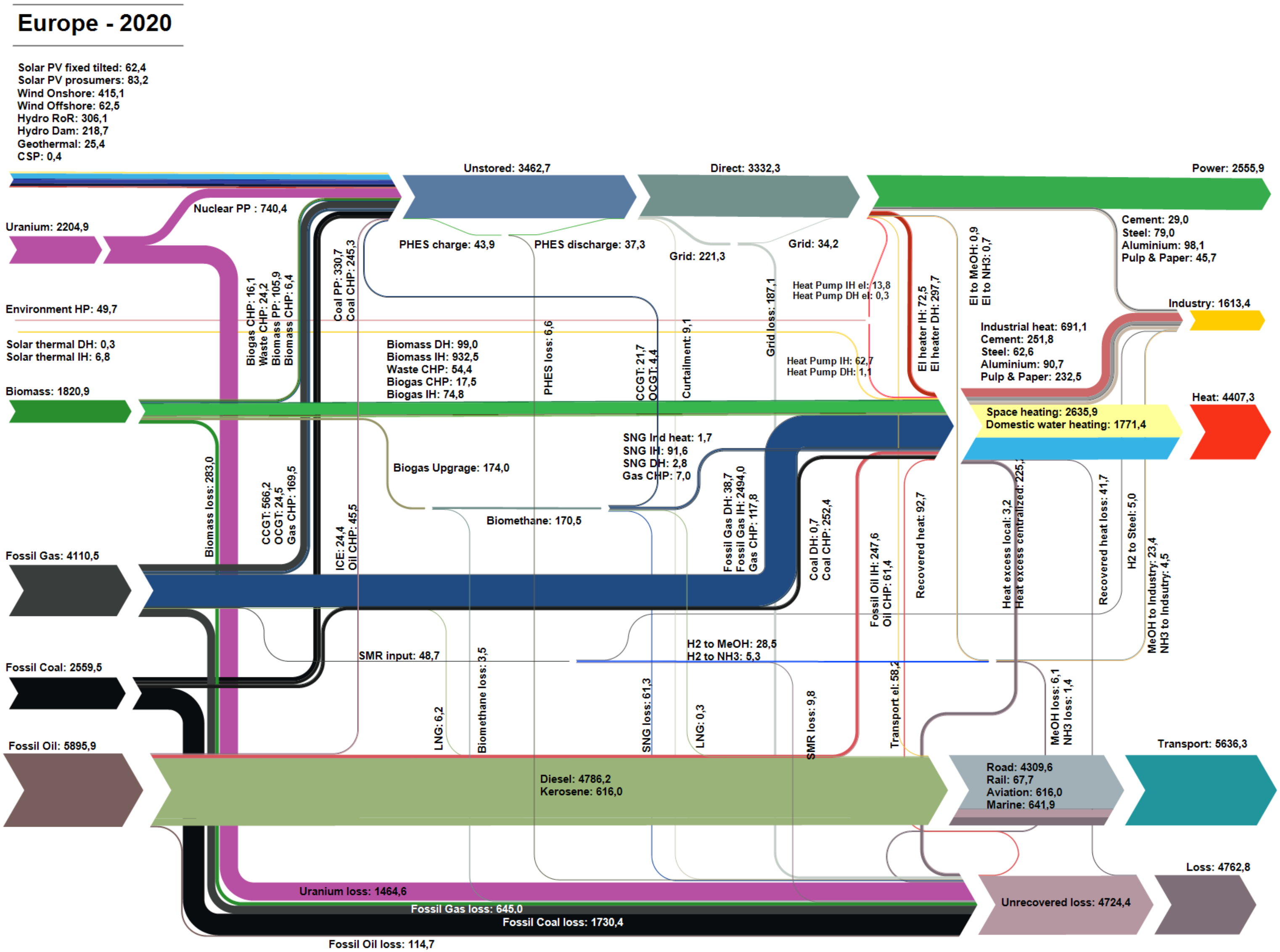
Key features:

- 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 (mobility, heat, fuels, chemicals, desalinated water, CO_2)

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

Europe: System Outlook – Energy Flows in 2020



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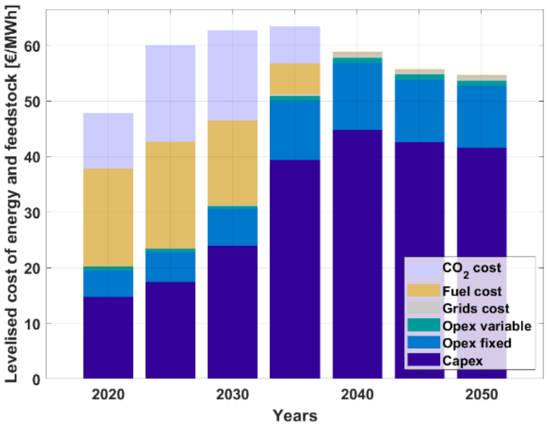
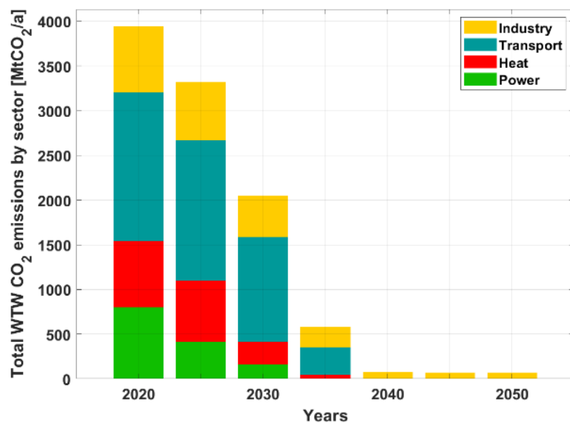
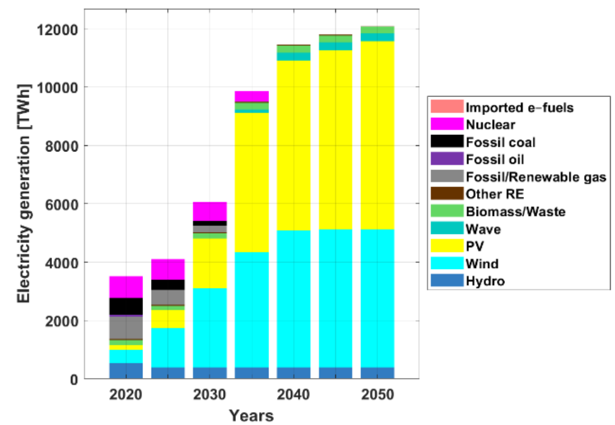
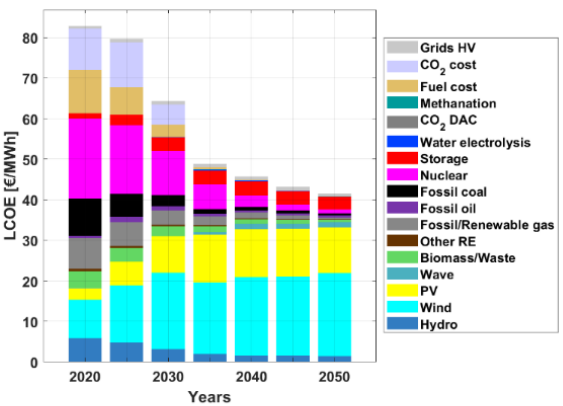
source: [Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022]

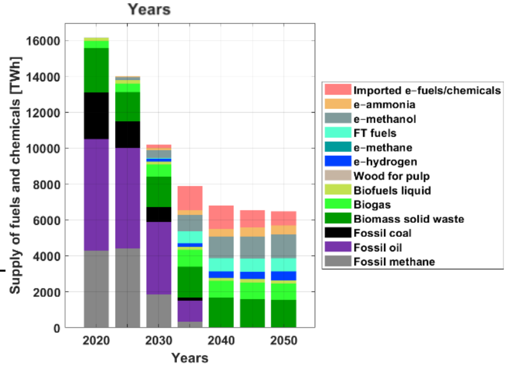
Europe: Highly Ambitious Energy-Industry Transition









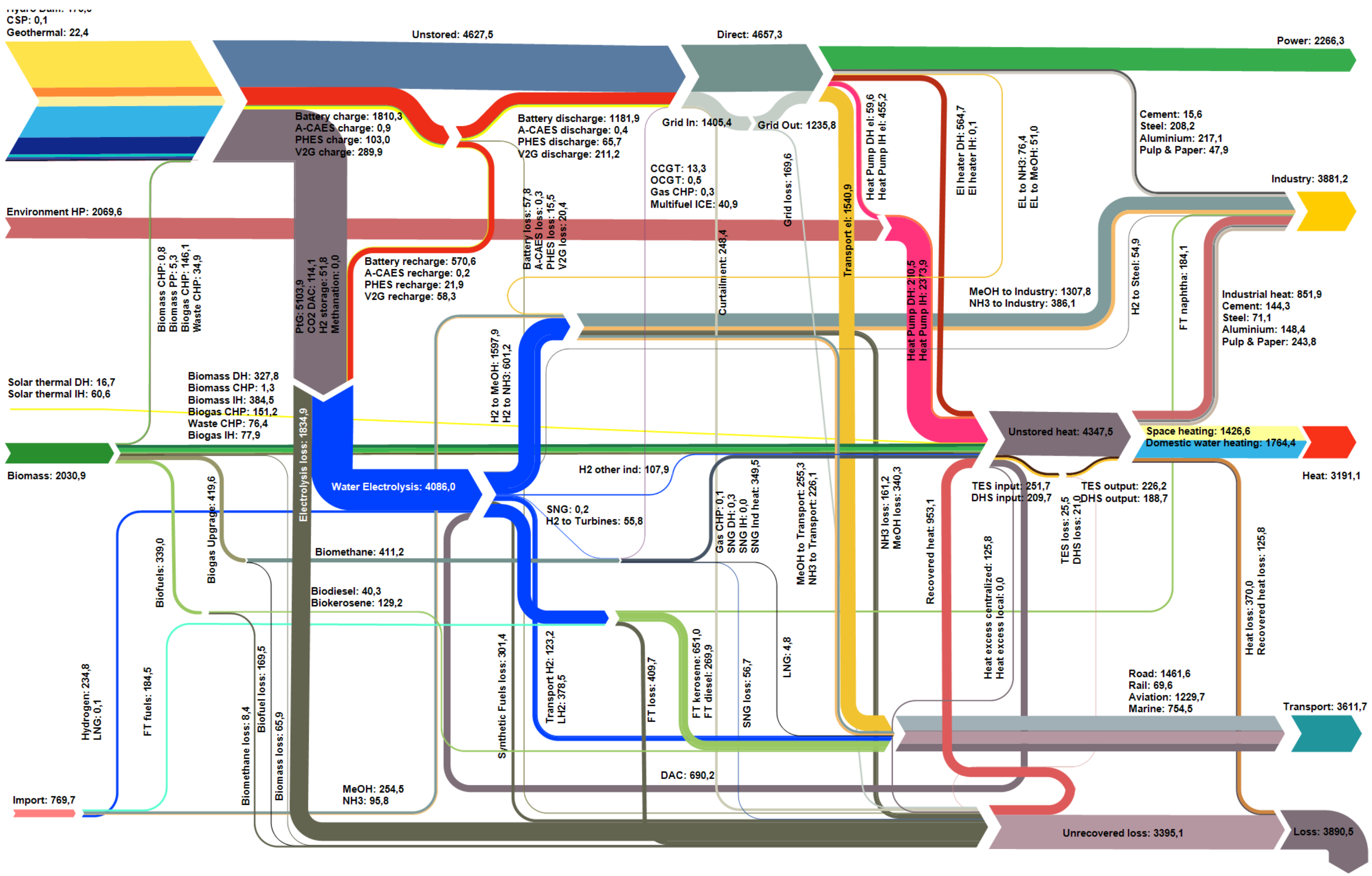


- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: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

Power-to-X Economy as new characteristic Term

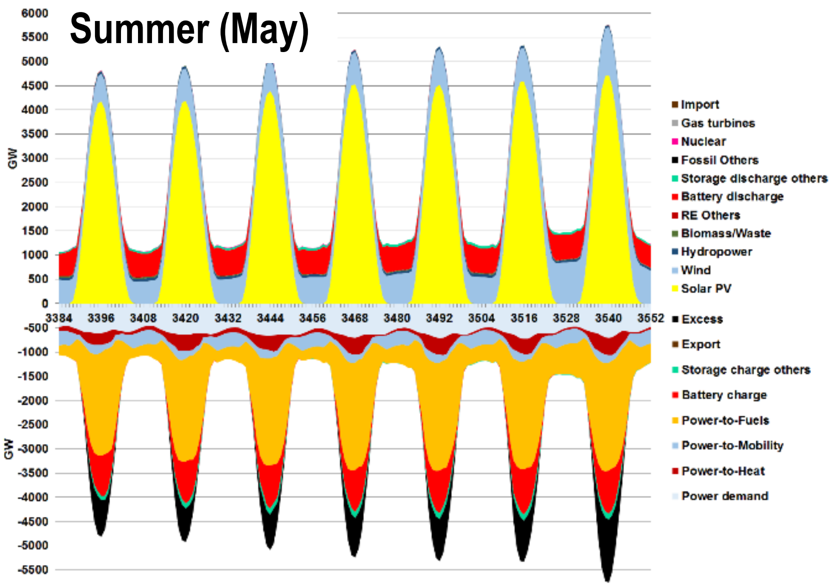
- Zero CO_2 emission low-cost energy system is based on electricity
- Core characteristic of energy in future: Power-to-X Economy
  - Primary energy supply from renewable electricity: mainly PV plus wind power
  - Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
  - Indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel; power-to-hydrogen-to-X

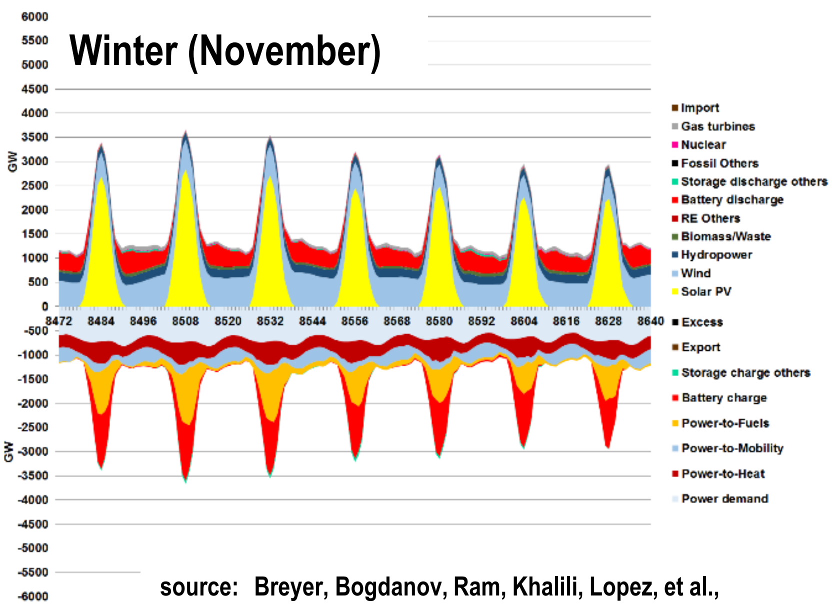


Source:
Power-to-X economy:
Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2023.
Progress in Photovoltaics, in press

Diagram: Greens/EFA, 2022

Hourly Operation and Balancing

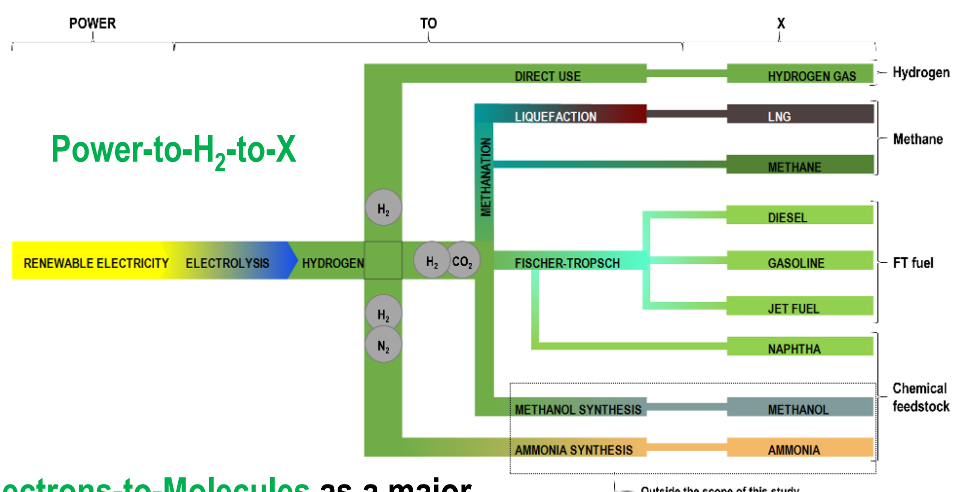




source: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2023. Progress in Photovoltaics, in press

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

Research on e-fuels demand in global studies

Table 1. Global 100% renewable energy system analyses. A threshold of minimum 95% renewables share in at least the electricity supply was considered for inclusion in the table. This criterion was applied to include the near-100% RE system analyses, but also to ensure appearance of fossil energy-free solution structures. Abbreviation: simulation (Sim), optimisation (Opt), power sector (P), all sectors (A), transition (T), overnight (O), e-hydrogen (e-H_2), e-methane (e-CH_4), power-to-liquids (PtL), CO_2 via electricity-based direct air capture (e-CO_2), total primary energy demand (TPED).

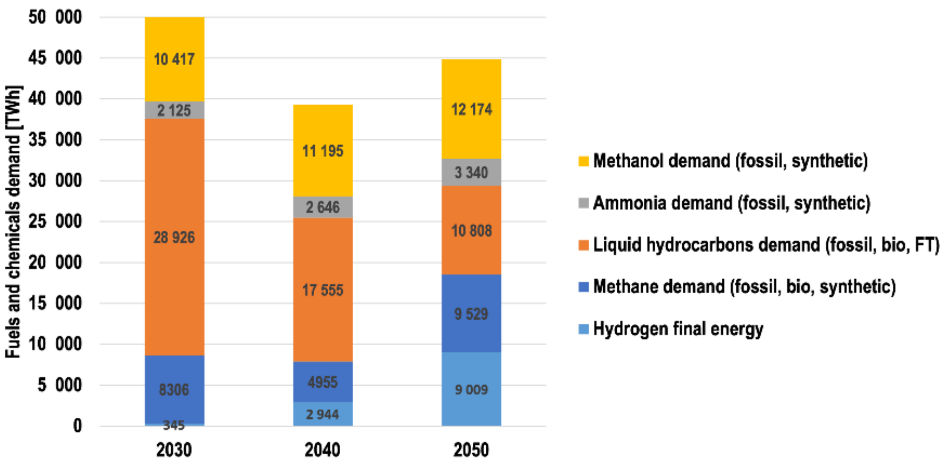
	Model	Type	Temporal resolution	Sectors	Path	e-H_2 [TWh]	H_2-to-fuel [TWh]	e-CH_4 [TWh]	e-PtL [TWh]	e-CO_2 [MtCO_2]	e-fuels total [TWh]	share in TPED [%]
Luderer et al. (2021) [62]	REMIND-MAgPIE	Opt	annual	A	T	10,833	0	-	-	-	10,833	7.9%
Teske et al. (2021) [44]	Mesap/PlaNet (DLR-EM), TRAEM, [R]E 24/7, [R]E-SPACE	Sim	hourly/ annual	A	T	10,349	0	-	1750	-	12,099	10.6%
Bogdanov et al. (2021) [29]	LUT-ESTM	Opt	hourly	A	T	40,153	31,253	8590	12,672	3,334	30,162	20.1
Jacobson et al. (2019) [63]	LOADMATCH, GATOR-GCMOM	Sim	30-seconds	A	O	2585	0	-	-	-	2585	3.1%
Bogdanov et al. (2019) [72]	LUT-ESTM	Opt	hourly	P	T	1238	1238	932	-	-	932	1.6%
Pursiheimo et al. (2019) [28]	VTT-TIMES	Opt	time slices	A	T	19,062	0	11,814	-	-	30,876	15.8%
Teske et al. (2018) [74]	Mesap/PlaNet (DLR-EM)	Sim	annual	A	T	6868	0	-	1,496	-	8364	9,6%
Jacobson et al. (2018) [84]	LOADMATCH, GATOR-GCMOM	Sim	30-seconds	A	O	4528	0	-	-	-	4528	3.2%
Löffler et al. (2017) [65]	GENeSYS-MOD	Opt	time slices	A	T	X	0	-	-	-	n/a	n/a
Jacobson et al. (2017) [85]	GATOR-GCMOM	Sim	annual	A	O	4517	0	-	-	-	4517	3.8%
Breyer et al. (2017) [73]	LUT-ESM	Opt	hourly	P	O	963	963	725	-	-	725	n/a
Sgouridis et al. (2016) [86]	NETSET	Sim	annual	A	T	n/a	n/a	-	-	-	n/a	n/a
Plessmann et al. (2014) [71]	MRESOM	Opt	hourly	P	O	n/a	n/a	1,960	-	-	1960	n/a
Deng et al. (2012) [67]	Ecofys	Sim	annual	A	T	1875	0	-	-	-	1875	2.6
Teske et al. (2011) [87]	Mesap/PlaNet (DLR-EM)	Sim	annual	A	T	1996	0	-	-	-	1996	1.5
Jacobson and Delucchi (2009) [88], (2011) [69], [89]	GATOR-GCMOM	Sim	annual	A	O	29,619	0	-	-	-	29,619	19.7%
Sørensen (1996) [90]	unspecified	Sim	annual	A	O	4380	0	-	-	-	4380	4.1%

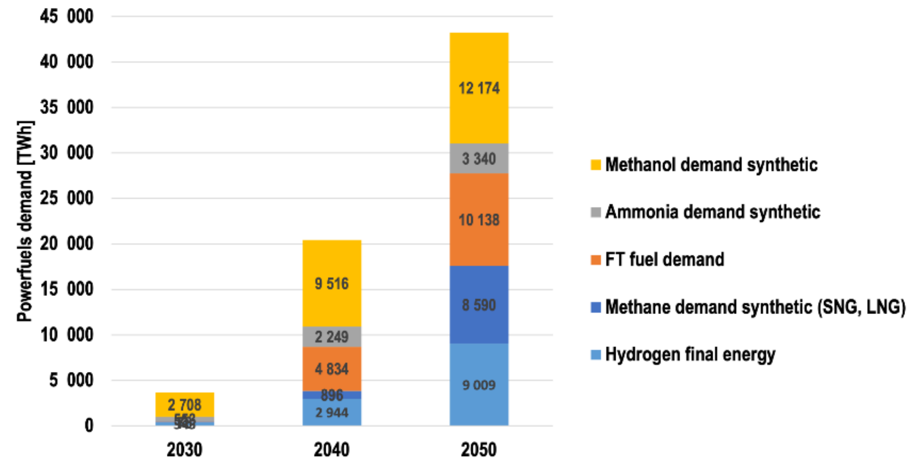
Key insights :

- **All following insights are for global energy system studies**
- **All energy system studies are limited**
- **Not a single energy system study exists with all five major e-fuels/chemicals**
- **Integrated Assessment Models for IPCC lack any insights beyond hydrogen**
- **Only two teams model e-liquids**
- **Only two teams model e-methane**
- **e-hydrogen is a standard feature**
- **Only one team uses e-CO_2**
- **Highest e-fuels demand around 30,000 TWh – but e-chemicals are missing**
- **Highest e-hydrogen demand around 40,000 TWh w/o chemicals**
- **Low results for e-fuels/chemicals due to outdated PV cost and high biofuel assumptions**

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

Global demand for e-fuels



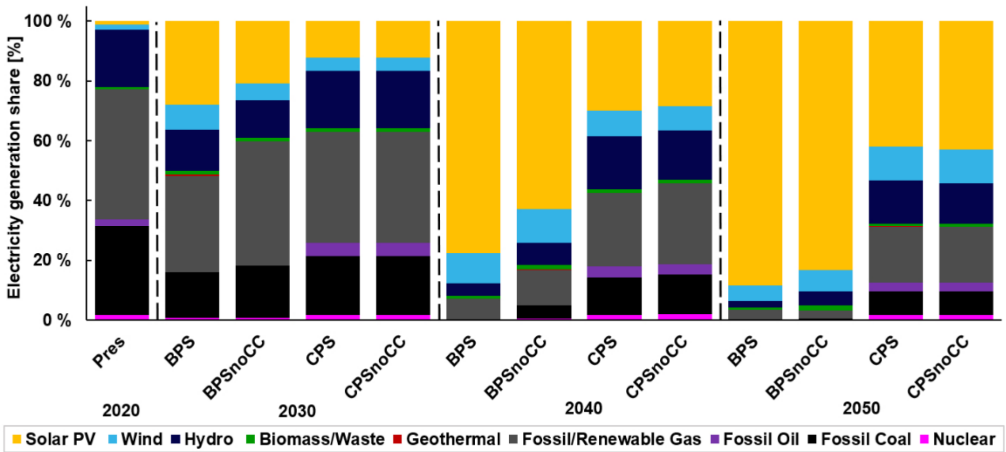


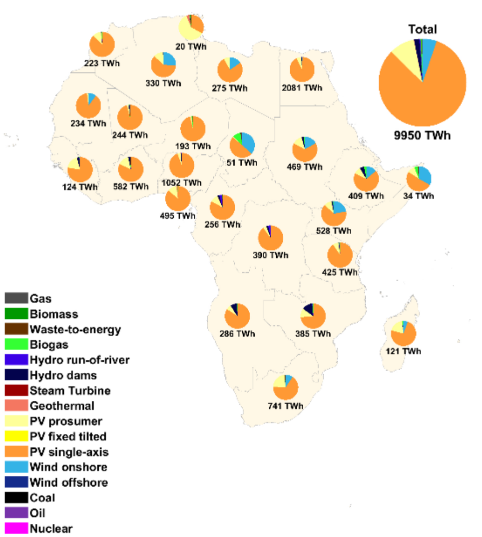
Fuels and Chemicals in general:
- steady growth of chemicals
- methanol represents non-ammonia chemicals
- liquid hydrocarbons are in steady decline, mainly due to electrification of road transportation
- methane demand in decline until 2040 with increase till 2050, with uncertainty for hydrogen substitution

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

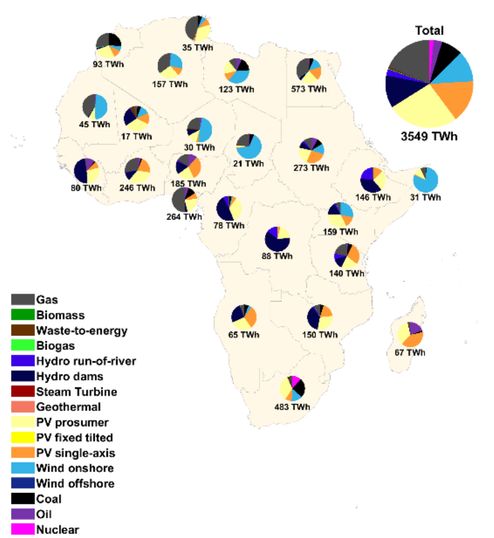
source: Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, under review

Africa: Electricity the Basis for all Energy





Regional electricity generation in 2050 – BPS



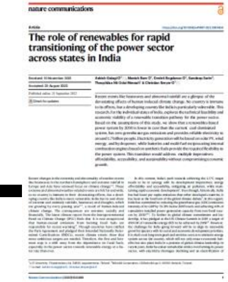
Regional electricity generation in 2050 – CPS

Highlights

- The generation mix across the scenarios is dominated by solar PV by 2050, representing 42 – 88% of the total electricity supply
- In the BPS, the regional electricity supply mix is dominated by solar PV single-axis tracking in most of the regions due to excellent solar conditions and continuous cost reduction in PV technologies.
- Wind power and hydropower contribution remains important; however, these resources are not evenly distributed across the continent.
- Wind generation to be around 340 – 520 TWh in 2050, supplied mainly by countries around the Sahara Desert, Horn of Africa, and some parts of Southern Africa.
- In 2050, hydropower generation will be around 230 – 510 TWh, mainly supplied by countries in Central and East Africa.

source: Oyewo et al. 2022. Contextualizing the scope, scale, and speed of energy pathways toward sustainable development in Africa. iScience, 25, 104965

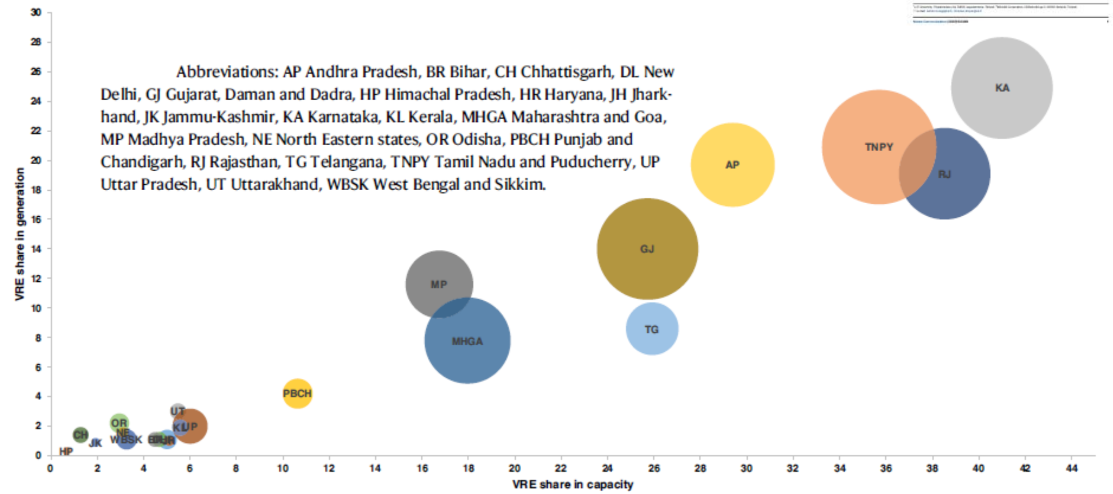
India: Solar and Wind Deployment

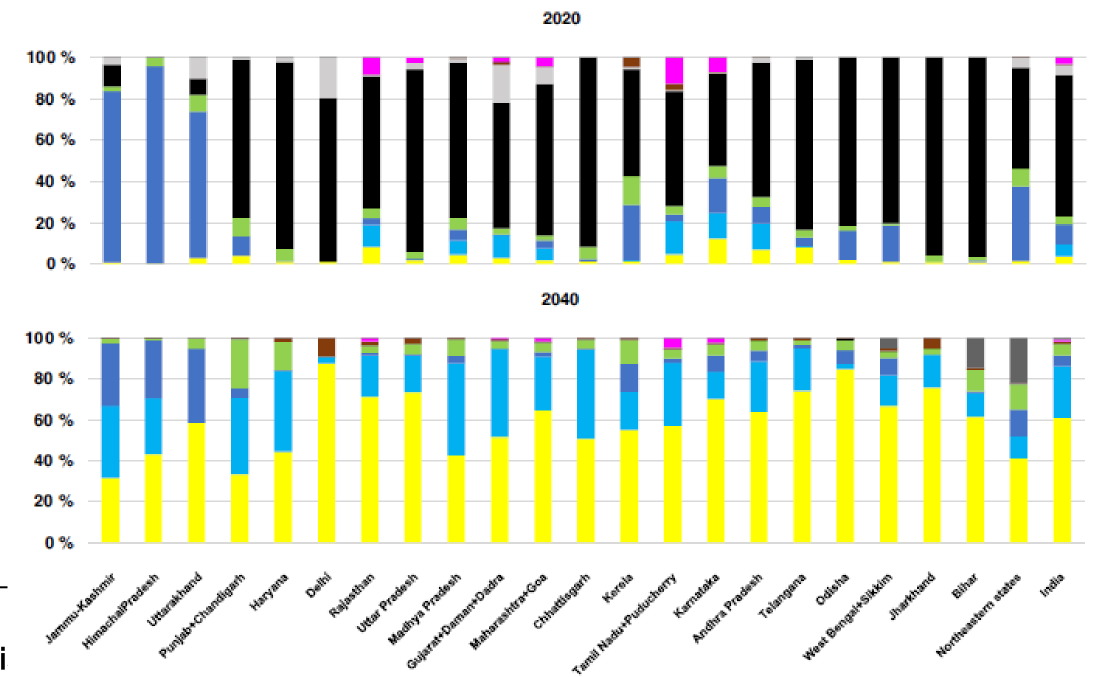


Highlights

- Several states of India have passed 20% PV & wind shares in electricity generation
- Some states remain strong in hydropower, many keep wind power as a substantial source of power, and all benefit from high solar PV shares
- By 2040 the energy transition in electricity generation in India could be largely done

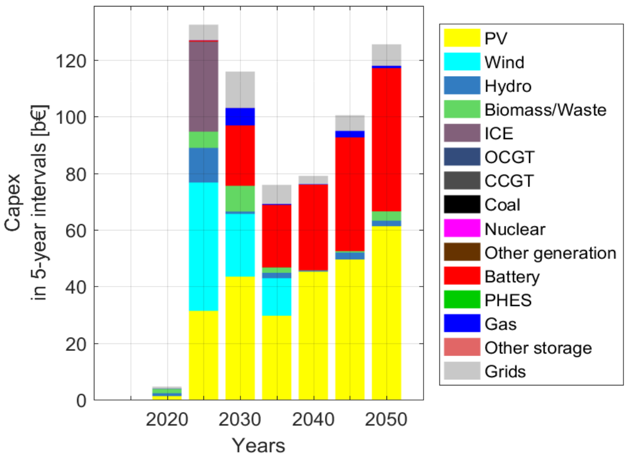
- Not shown:
  - solar PV share would be higher for all energy demand via Power-to-X applications and very good scalability
  - Monsoon: strong grids, complementarity with wind and hydropower, and Power-to-X helps to manage the monsoon season

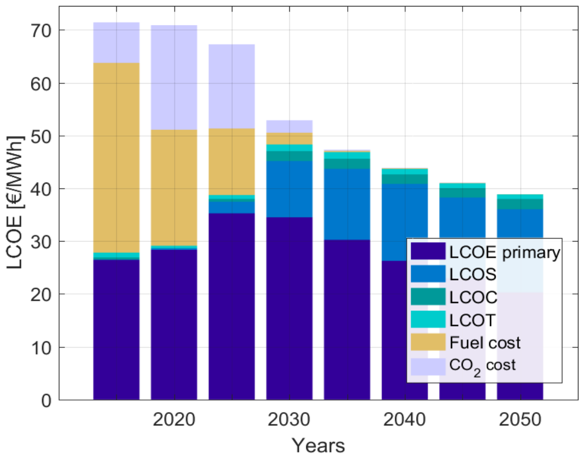


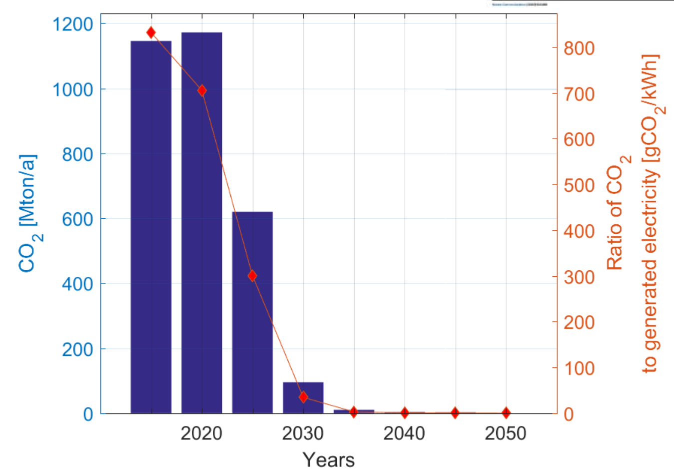


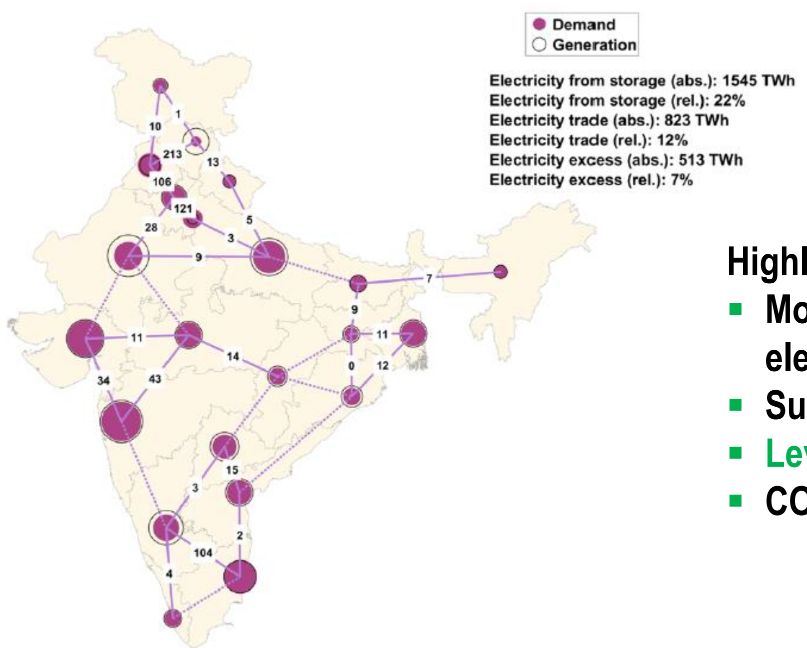
source: Gulagi et al., 2022. Nature Communications, 13, 5499

India: Capex, LCOE, CO_2, Storage, Grids









Highlights

- Most electricity is generated in states of demand, less than 25% of electricity demand needs to be stored, curtailment is low
- Substantial investments required: solar PV, wind power, batteries, grids
- Levelised cost of electricity (LCOE) can decline by 40%
- CO_2 emissions in power generation can be almost stopped by 2040

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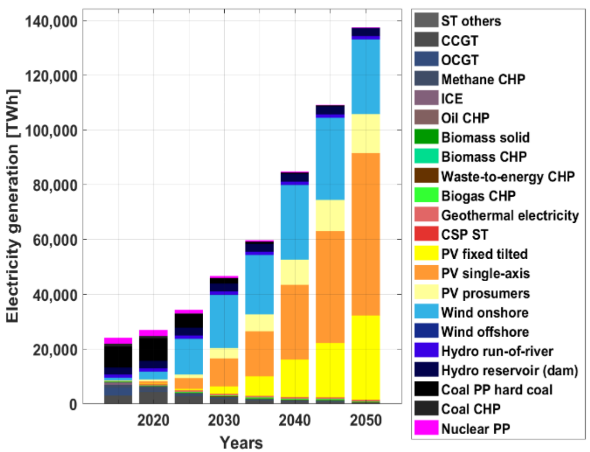
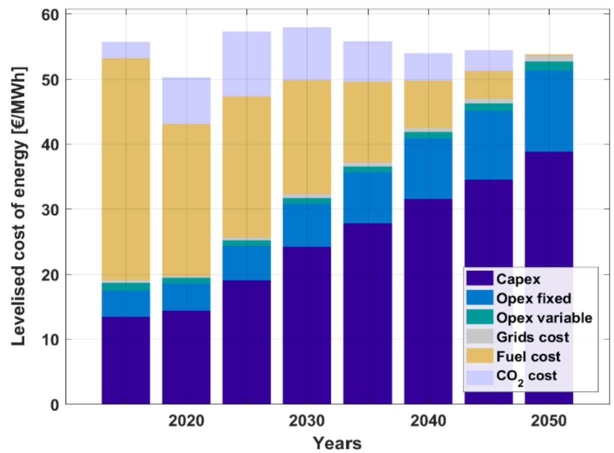
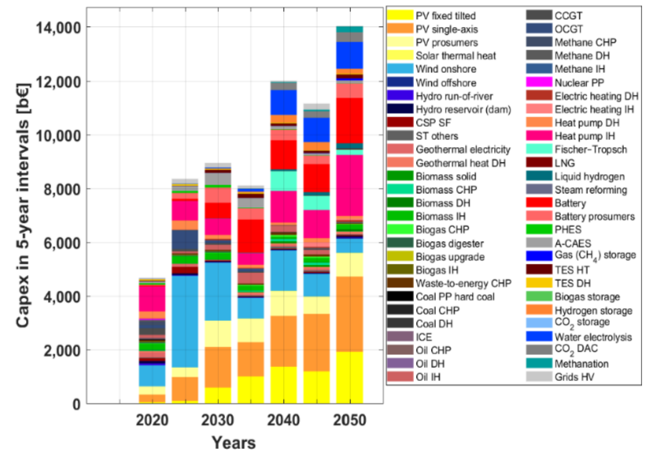
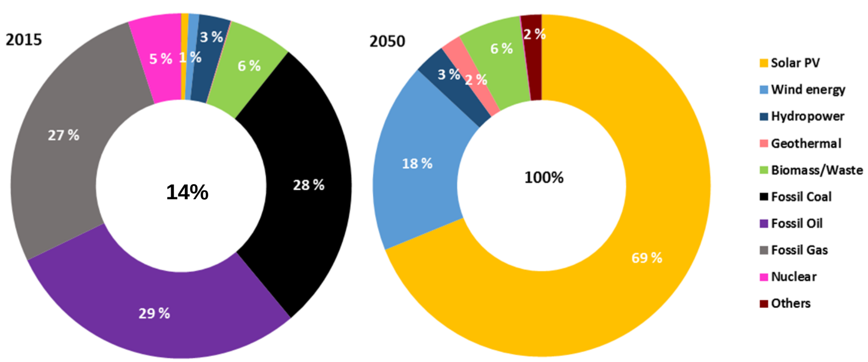
source: Gulagi et al., 2022. Nature Communications, 13, 5499

Global: 100% Renewable Energy System by 2050







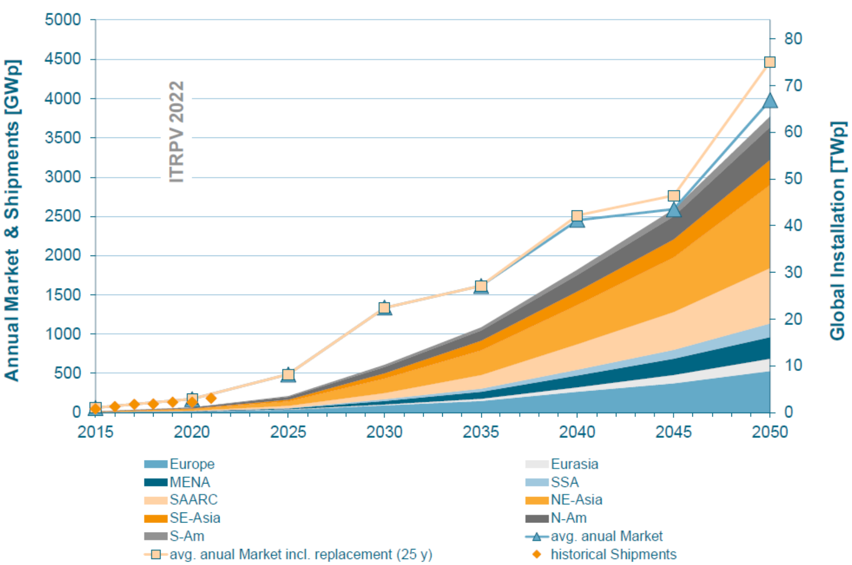


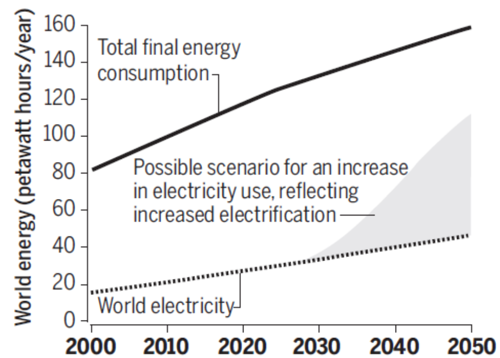
Key insights:

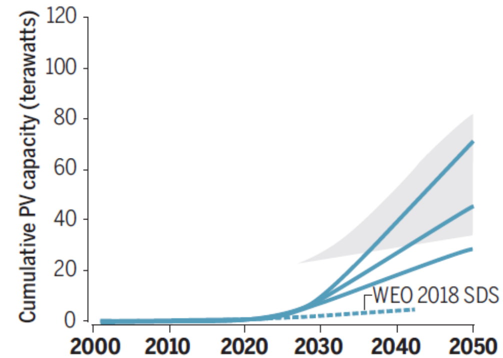
- Low-cost **PV-wind-battery-electrolyser-DAC** leads to a **cost-neutral energy transition** towards 2050
- This implies about 63 TW of PV, 74 TWh_{cap} of battery, 13 TW_{el} of electrolysers by 2050 for the energy system
- This leads to about 3 TW/a of PV, 850 GW_{el} of electrolyser installations 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

100% Renewable Energy System by 2050







Key insights:

- Low-cost PV leads to a cost-neutral energy transition towards 2050
- This implies about 63 TW of PV by 2050 for the energy system
- This leads to about 3 TW/a of PV installations in 2040s
- This view is now common sense among PV experts
  - ITRPV uses this scenario as the most progressive scenario
  - ISE & NREL & AIST et al. use this scenario
  - Pierre Verlinden based the manufacturing ramping on it

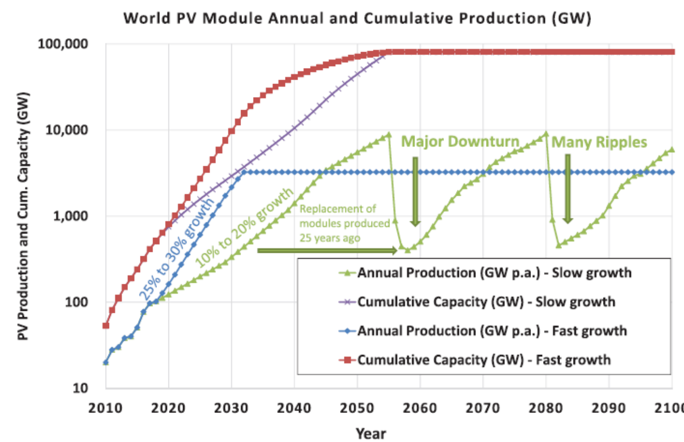
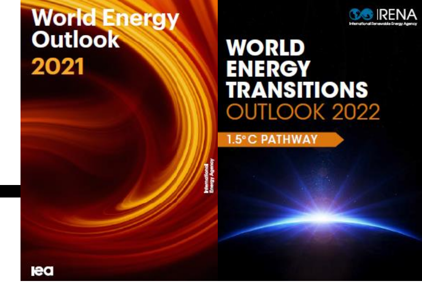


FIG. 4. Slow growth scenario of the PV industry would require increasing the annual production volume to almost 10 GW p.a. with a risk of a major downturn in 2055 and several ripples every 25 years, compared to a fast growth scenario of 25% p.a. minimum, bringing the annual production to a stabilized level of about 3 GW p.a.

Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

source: VDMA, 2022. ITRPV
Haegel et al., 2019. Science
Verlinden, 2020. J Renew Sustain Energy



PV Projections of IEA and IRENA

Figure 3.11 ▷ Solar PV and wind installed capacity in the NZE

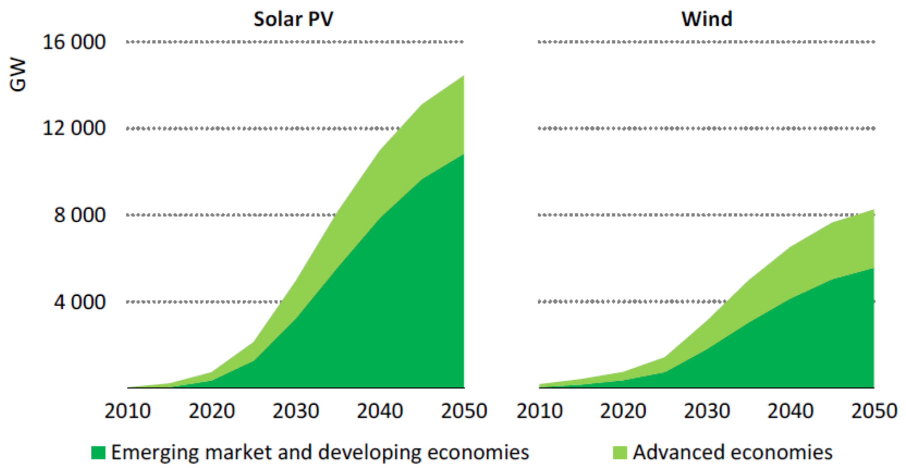
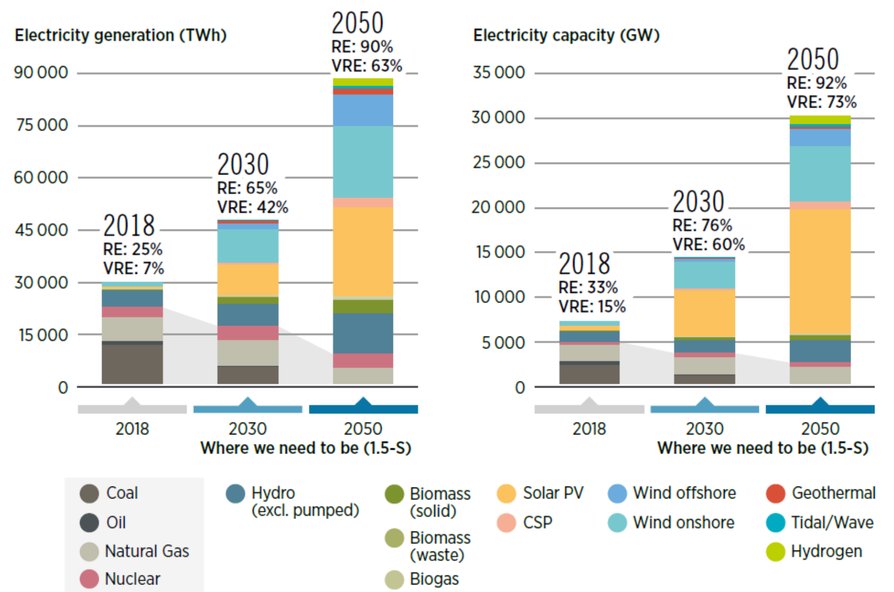


Table 2.6 ▷ Key deployment milestones for renewables

Sector		2020	2030	2050
Electricity sector				
Renewables share in generation		29%	61%	88%
Annual capacity additions (GW):	Total solar PV	134	630	630
	Total wind	114	390	350
	– of which: Offshore wind	5	80	70
	Dispatchable renewables	31	120	90

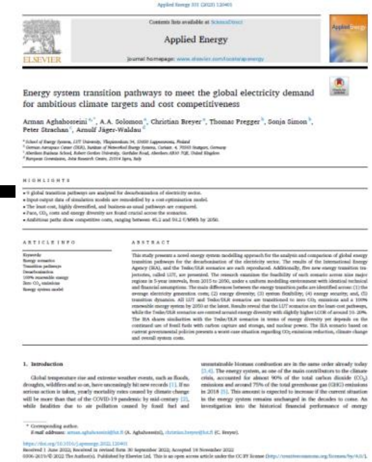
FIGURE 2.3 Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050

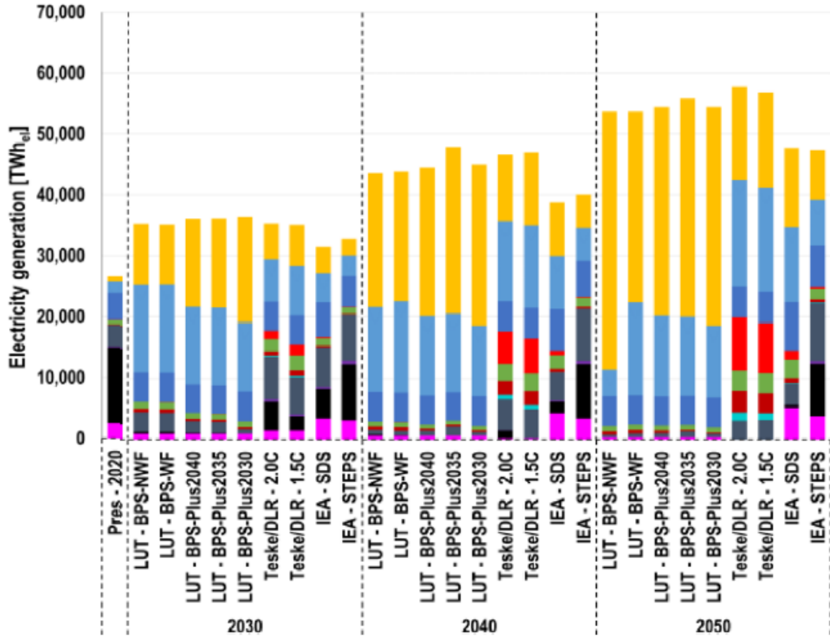


Key insights:

- IEA massively underestimated PV in the past
- Not many signals for improvement, IEA & IRENA reach about 14 TW in 2050
- IEA WEO: 630 GW/a in 2030, then zero and negative market growth until 2050 …
- IRENA: 440 GW/a in 2030 to 2050 …
- Both, IEA WEO & IRENA seem to require more scientific support for techno-economic possible paths and business support what industry is delivering to markets; core deficit: lack of electrification in scenarios

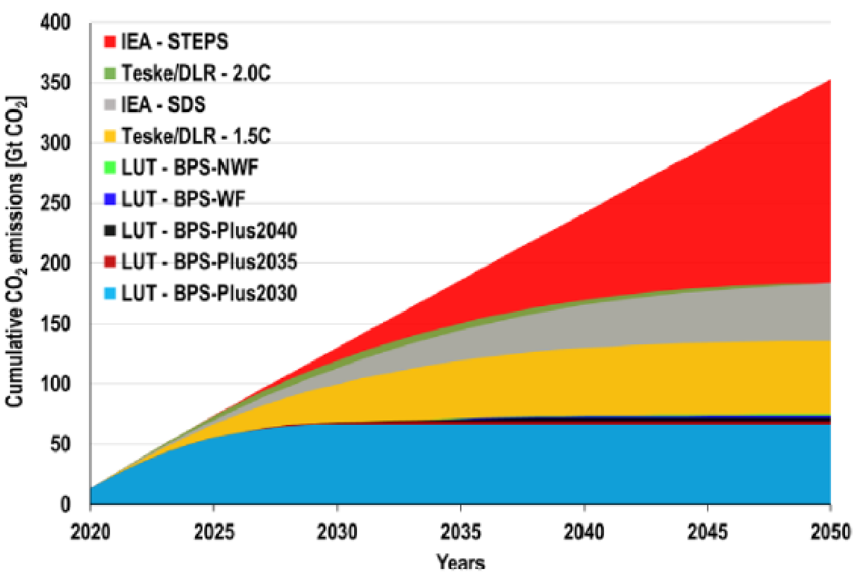
Comparing Scenarios of varying Ambitions

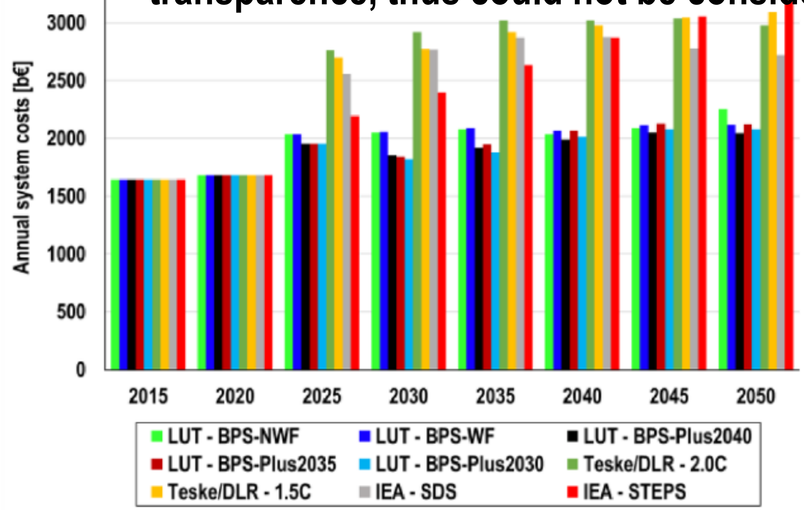




Background and insights:

- Power sector analysed
- World in 9 regions studied
- Hourly resolution used
- Transition till 2050 compared
- IEA WEO, Teske/DLR, LUT scenarios considered
- IEA WEO scenarios represent worst case: high cost and lowest CO_2 reduction performance, also due to higher cost of fossil CCS and nuclear
- 100% RE is doable for different paths: least cost with higher PV share vs higher diversity for higher cost
- Least cost power sector for 100% RE in 2030s
- IEA WEO NZE2050 but also IRENA scenarios lack transparence, thus could not be considered





Source: Aghahosseini et al., 2023. Applied Energy, 331, 120401

Do we have enough Raw Materials?

Key insights:

- This is ongoing research; almost no one linked materials demand to highly ambitious scenarios
- Solar PV
  - Silicon and glass should be fine, also aluminium if required
  - Silver will be not enough, but can be substituted by copper or aluminium
- Wind power
  - Cement, steel and copper should be fine
  - Neodymium and dysprosium for PMG limited, but not necessarily required
- Batteries
  - Cobalt-free Li-ion batteries may be soon the standard also in electric vehicles
  - Lithium is at the edge, even if reserves may be enough, then ramping extraction may be limited
  - Lithium from desalination brines and also oceans may be an ultimate solution
  - Batteries based on Mg, Al, Na, etc. may tackle the challenge
- Electrolysers
  - PEM is limited due to iridium need (15-50 GW/a)
  - AEL seems not to be limited
- CO_2 direct air capture
  - No limitation known so for

- more investigation required, but seems to be doable; AND, circular economy is a MUST

source: Breyer et al., 2022. IEEE Access 10, 78176-78218
Greim et al., 2020. Nature Communications, 11, 4570
Junne et al., 2020. Energy, 211, 118532

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Critiques and Responses on 100% RE Systems

Critique	Response
PV & wind are no firm capacity for baseload	Hourly resolution is standard for real weather years, real demand profiles and detailed system representation
100% RE would be not affordable	100% RE systems for same or less costs than systems with substantial fossil CCS or nuclear shares
Transition would require fossil fuels for building renewable systems thus more CO_2 emissions	Energy pay back time of PV around 1 year, wind < 1 year and operation of 30 years; 100% RE system energy return on energy invested table between 10-15, while fossil EROI decline
Lack of materials for energy transition	Substantial materials supply ramping required, while the only really limiting material seems to be lithium, thus massive research for alternative chemistries required (e.g. Na, Al, Mg based batteries)
Degrowth and declining demand required	100% RE systems are scalable and support a prosperous economy, while circular economy is a must, powered by low-cost PV & wind & battery & electrolysers & DAC

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

Summary

- Energy transition reaching zero CO_2 emissions by mid-century is feasible
- Faster transition is required for true leaders, absolute zero by 2040 is possible
- Electrification is low-cost and highly efficient
- PV benefits most from comprehensive electrification (direct and indirect)
- Power-to-X Economy is THE characteristic structure of the arising energy system
- Common insights: 100% RE is doable, electrification is key, PtX for hard-to-abate
- Conflicts: role of PV vs wind, sustainability of bioenergy, hydrogen-to-X, CO_2-to-X
- Blind sports: Global South analyses, critical materials, true global-local view
- Learnings for policy makers: new investments matter, talk to progressive scientists
- Main constraint: clear legally binding targets and willingness to execute the paths
- Awareness required that international organisations (and consultants) lag behind

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

LUT model in Comparison

We have been ranked as one of the more advanced energy models among all available energy models, which is capable of handling long-term energy transitions with high time resolution, high geospatial spread and importantly built-in sector coupling.

Among models used for highly renewable energy systems we are in lead together with EnergyPLAN.

Bottom-up long-term models	*Foresight approach*	*Resolution*				*Transparency*
		In time	*In space*	*In techno-economic detail*	*In sector coupling*	
LEAP [120]	Perfect foresight	Low	Low	Low	High	Medium
MARKAL/TIMES [101,102]	Perfect foresight	Low	Medium	Low	High	Low
OSeMOSYS [104,105]	Perfect foresight	Low	Medium	Low	High	High
Temoa [107,108]	Perfect foresight	Low	Medium	Low	High	High
MESSAGE [110]	Perfect foresight	Low	Medium	Low	High	Low
Balmorel [112]	Perfect foresight	High	High	Medium	Low	High
eMix [121]	Perfect foresight	Medium	Medium	High	Low	Low
EPLANoptTP [119]	Perfect foresight	High	Low	Low	High	Medium
Mahbub et al. [118]	Myopic	High	Low	Low	High	Medium
LUT [114,117]	Myopic	High	High	Medium	High	Medium

source: [Prina et al., 2020. Renew Sustain Energy Rev, 129, 109917](#)

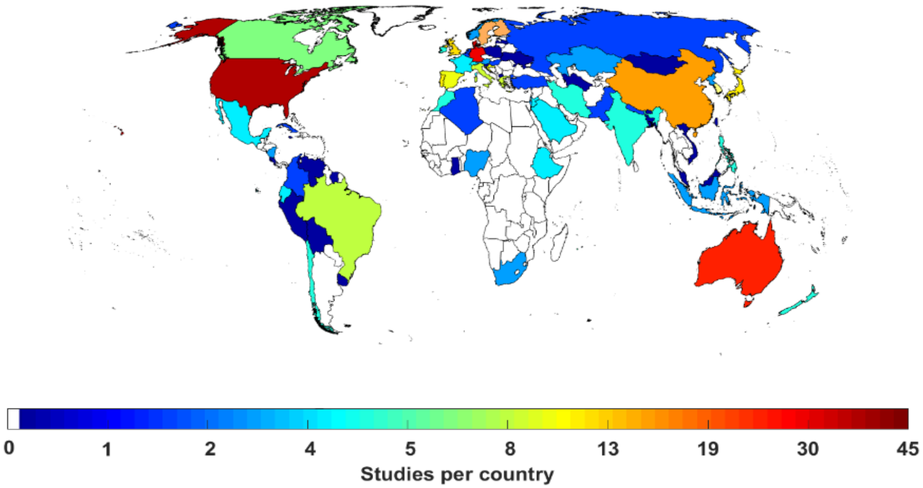
Leading Energy System Models ranked by number of published journal articles. Some selected key functionalities of the leading ESMs are displayed, as they are regarded to be key for further progress in the field of 100% RE system analyses. Selection criterion had been more than five articles detected for 100% RE system analyses. Citations comprise the Scopus recordings until early July 2021 for the total and the annual value for 2020.

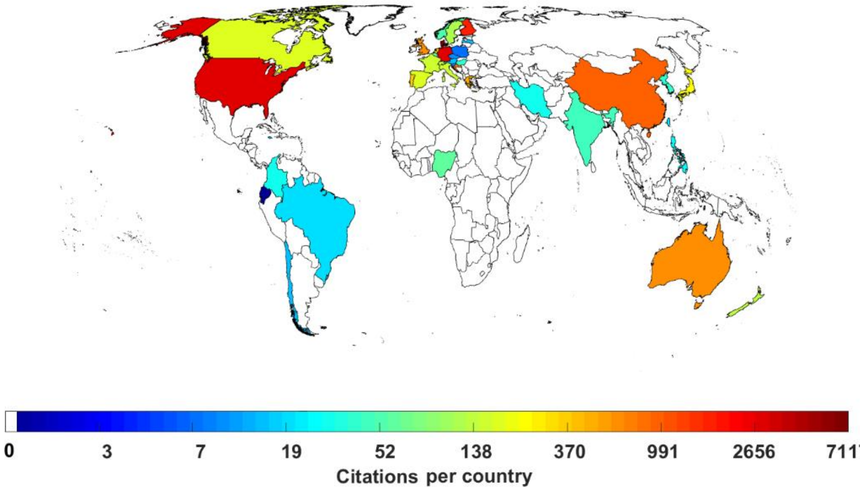
Model	articles	citations		model used for 100% RE		inter-connected multi-node	Full hourly	multi-sector	Detailed industry	relevant CDR	optimi-sation	simu-lation	transi-tion	over-night
		total	2020	earliest	latest									
EnergyPLAN	73	6670	1081	2006	2021	yes	yes	yes	no	no	no[a]	yes	no	yes
LUT model	63	1983	649	2015	2021	yes	yes	yes	Yes	no	yes	yes	yes	yes
HOMER	22	1044	228	2007	2021	no	yes	no	no	no	yes	yes	no	yes
TIMES	19	601	137	2011	2021	no	no	yes	yes	no	yes	yes	yes	yes
AU model	16	1188	145	2010	2018	yes	yes	no	no	no	yes	yes	no	yes
PyPSA	16	440	169	2017	2021	yes	yes	yes	no	no	yes	no	yes	yes
GENeSYS-MOD	10	141	57	2017	2021	yes	no	yes	no	no	yes	no	yes	no
LOADMATCH	10	925	240	2015	2021	no	yes	yes	no	no	no	yes	yes	no
REMix	10	439	118	2016	2018	yes	yes	yes	no	no	yes	yes	no	yes
ISA model	9	126	43	2016	2020	no	yes	yes	no	no	yes	no	no	yes
NEMO	7	566	82	2012	2017	yes	yes	no	no	no	yes	no	no	yes
H_2RES	6	674	47	2004	2011	no	yes	yes	no	no	no	yes	no	yes
MESAP/PlaNet	6	207	48	2009	2021	no	no	yes	no	no	no	yes	yes	yes
others	292	9204	1694											
total	550	24,600	4800											

[a] EnergyPLAN itself is not able for optimisation, however, the EPLANopt [45] derivative allows optimisations

source: [Lopez, Breyer et al., 2022. Renew Sustain Energy Rev, 164, 112452](#)

Studies and Citations per Country

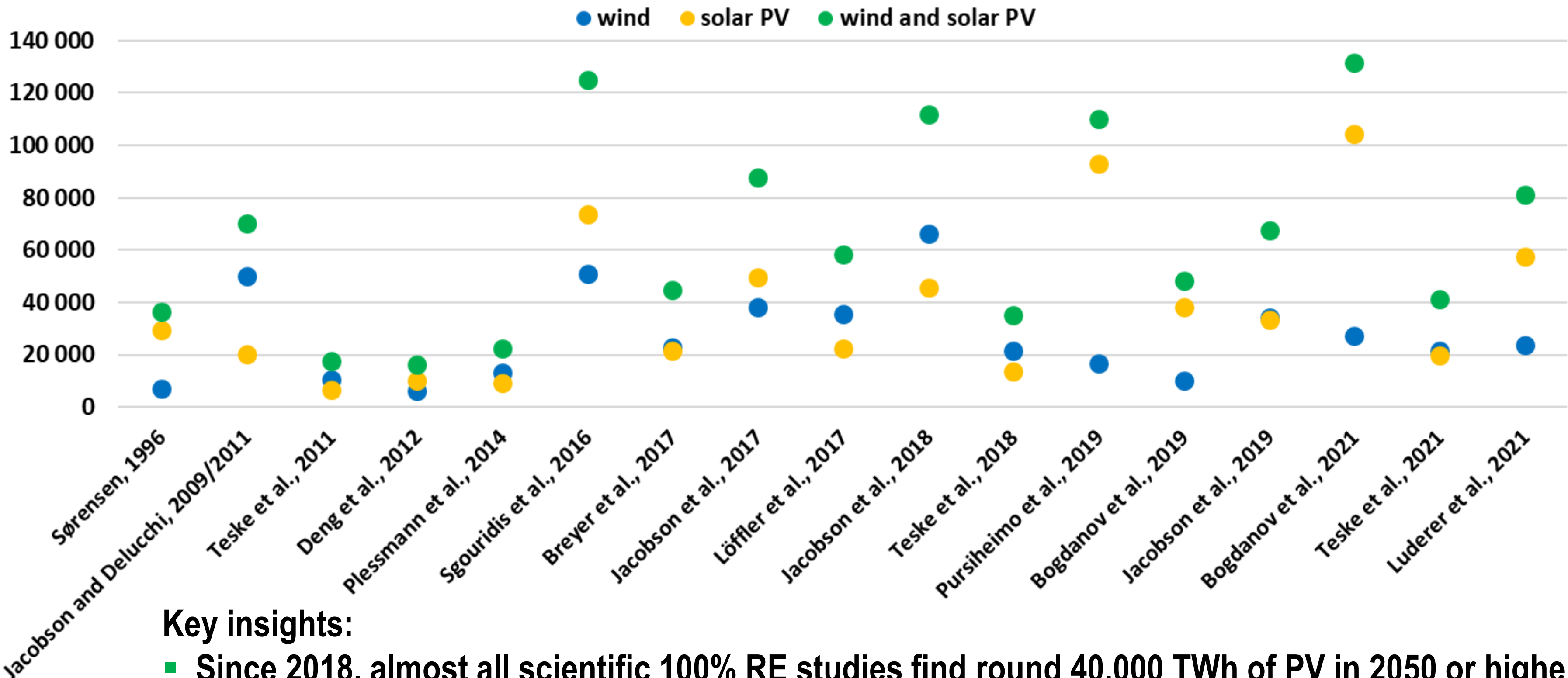




- The US is the country for which the most country studies have been performed (45 studies in total)
- Europe leads with 181 studies in total: DK with 39 studies, DE with 35, all others below 15
- AU has been analysed with 30 studies
- Huge research gaps for sunbelt countries, in particular in Africa, South Asia and Southeast Asia
- Citations analysis of first author affiliation documents a high aggregation of 100% RE research in a few countries (DK, DE, US, FI), often also for countries without own 100% RE research, but with researchers from these countries

source: [Khalili and Breyer, 2022. IEEE Access, 10, 125792-125834]

Scientific studies on PV demand

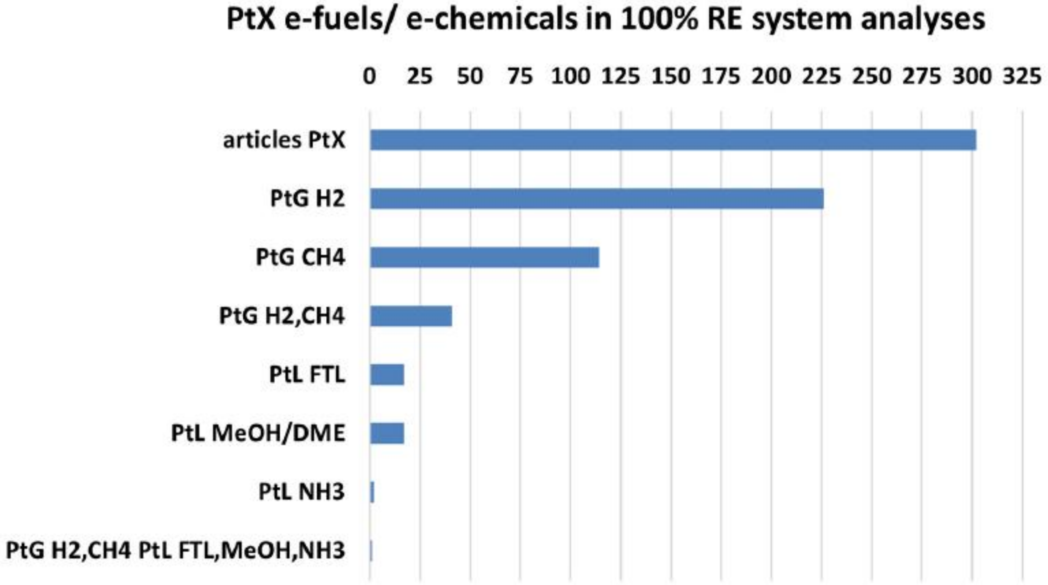


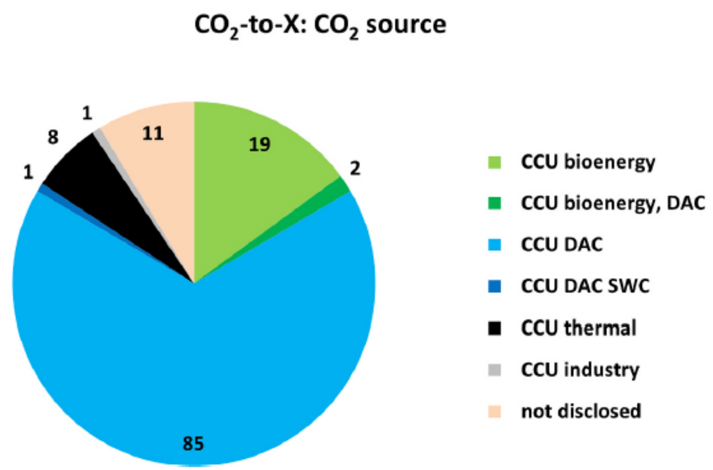
Key insights:

- Since 2018, almost all scientific 100% RE studies find round 40,000 TWh of PV in 2050 or higher (exception is Teske/DLR et al. who strongly bet on CSP which leads to higher cost)
- Two studies find around 100,000 TWh of PV in 2050 (Pursiheimo et al., Bogdanov/Breyer et al.)
- Related capacities are around 22-27 TW for 40 PWh and 49-63 TW for 100 PWh
- Energy-climate researchers started to notice PV with 58 PWh in 2050
- Contribution of wind power is declining since years, a consequence of low-cost PV/ batteries/ electrolysers

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

e-fuels in 100% RE Systems Studies

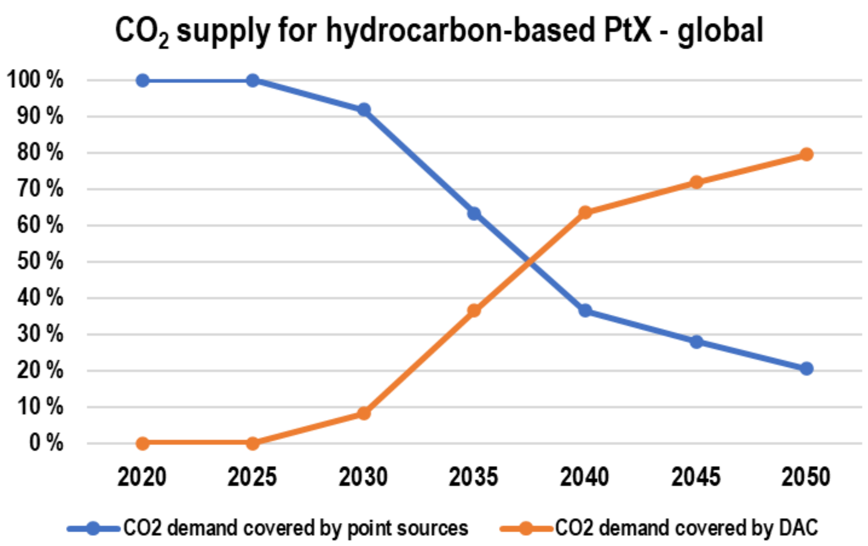


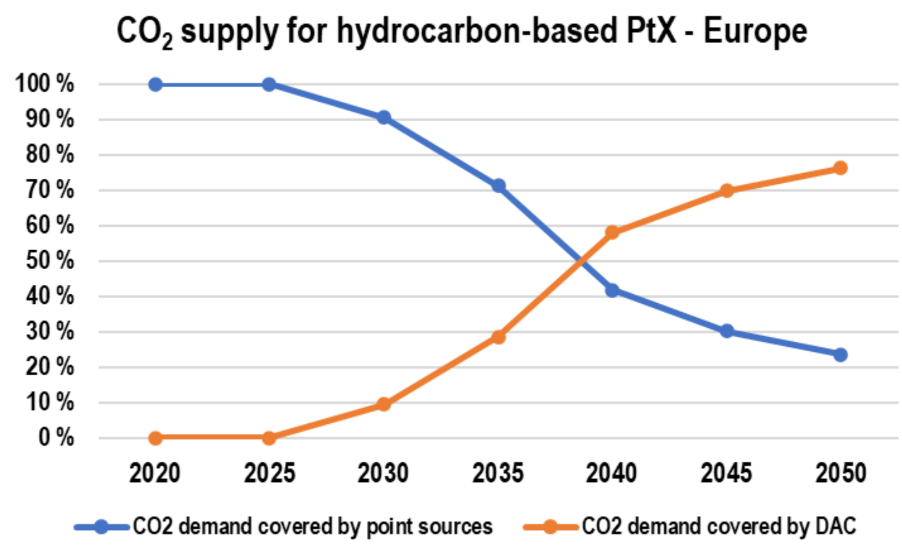


- review basis: 550 articles on 100% RE system analyses (as for the bibliometric analysis)
- 45% of all 100% RE articles do NOT comprise e-fuels
- e-fuels/chemical beyond H_2/CH_4 are practically not used
- 1 single article covers the five main e-fuels/ chemicals
- CO_2 source dominated by DAC, then bioenergy, no industry
- 48% of all CO_2-to-X articles from LUT
- gaps e-fuels: multiple gaps for all e-fuels/ chemicals; huge gaps beyond H_2/CH_4
- gaps CO_2-to-X: models/modlers do not cover this; bio-CO_2 and industrial CCU lacking

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

CO_2 as raw material for e-fuels and e-chemicals

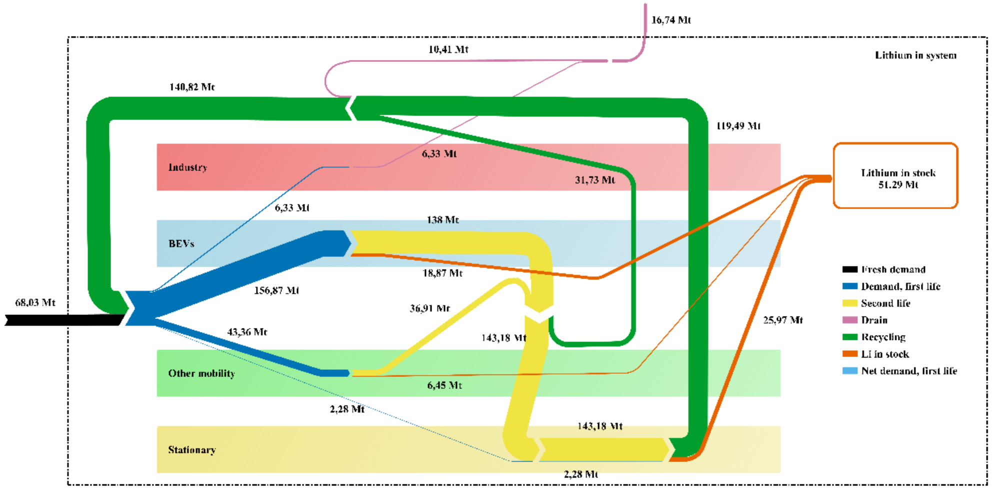


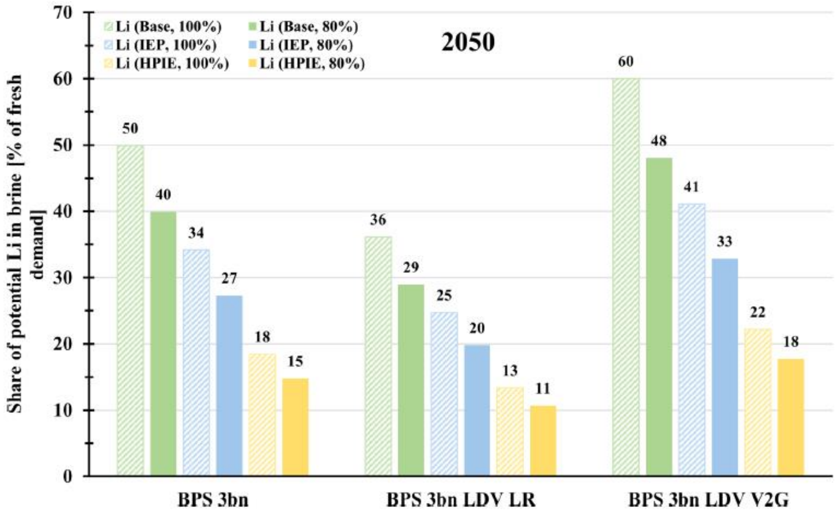


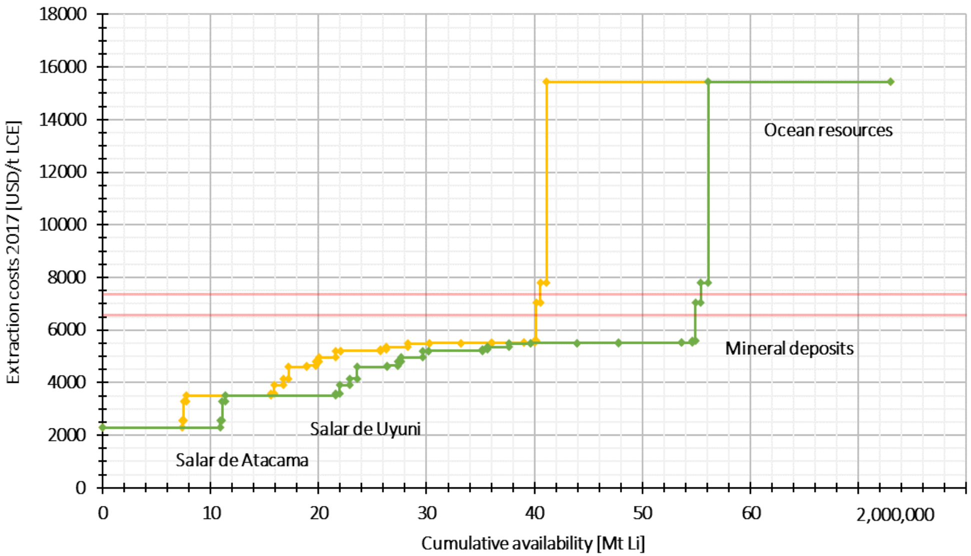
- **Finally, 80% of global CO_2 raw material demand needs to be covered by direct air capture (DAC), while the DAC demand in Europe is slightly lower at 76%**
- **Industrial phase-in of DAC is critical in 2020s, as point sources are available, while DAC requires a first market ramp-up for massive scaling 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)**

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

Lithium – a potentially limiting raw Material







Key insights:

- No consensus on the Lithium availability
- Matching various supply and demand scenarios almost always leads to supply shortage (total resource in 2060s/2070s, annual supply earlier)
- Circular economy is a must for Lithium
- Lithium based batteries can carry the energy transition far, but not fully
- Alternative battery concepts needed, such on Aluminium or Magnesium basis
- Extraction of Lithium from desalination brines may contribute in addition 15-50% of Lithium demand

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source: Greim, Solomon, Breyer et al., 2020. Nature Communications, 11, 4570
Lundaev, Solomon, Caldera, Breyer, 2022. Minerals Engineering, 185, 107652