




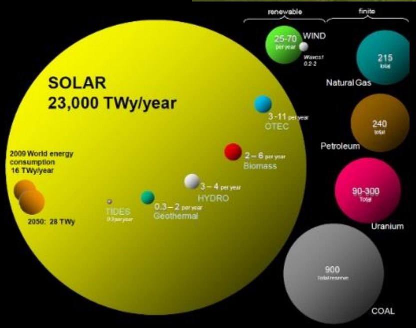

Global Energy Transition
Power-to-X Economy will be built on renewable electricity and green hydrogen

Open your mind. LUT.
Lappeenranta University of Technology

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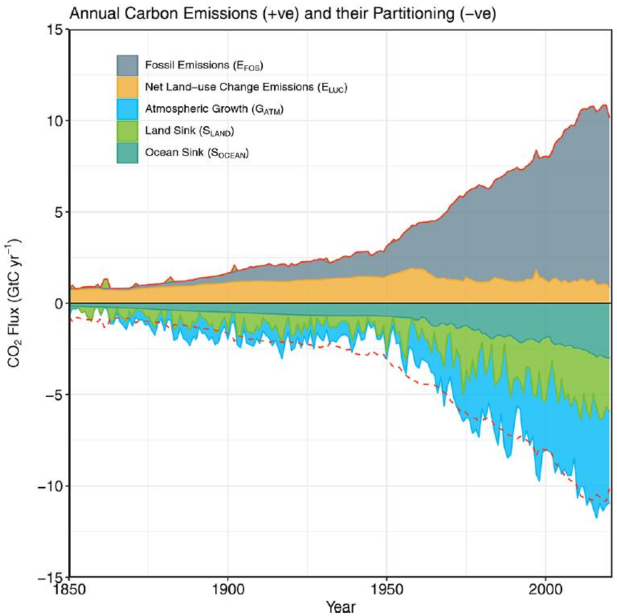
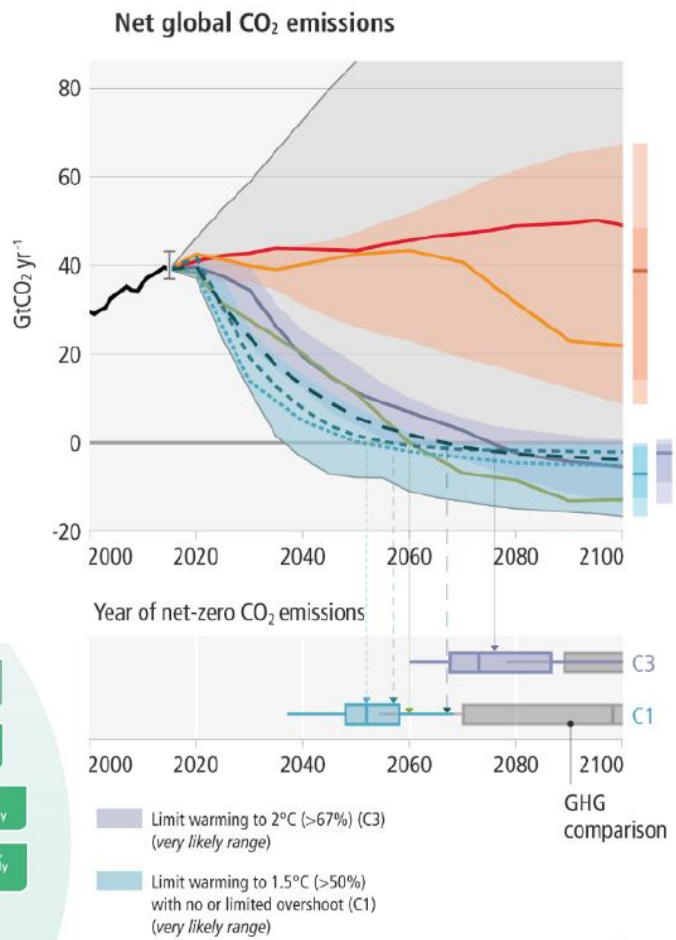
Professor for Solar Economy

2nd Seminar in Hydrogen Research Forum Finland
Lappeenranta, August 8, 2023

CO_2 Emissions: how it developed, where to go



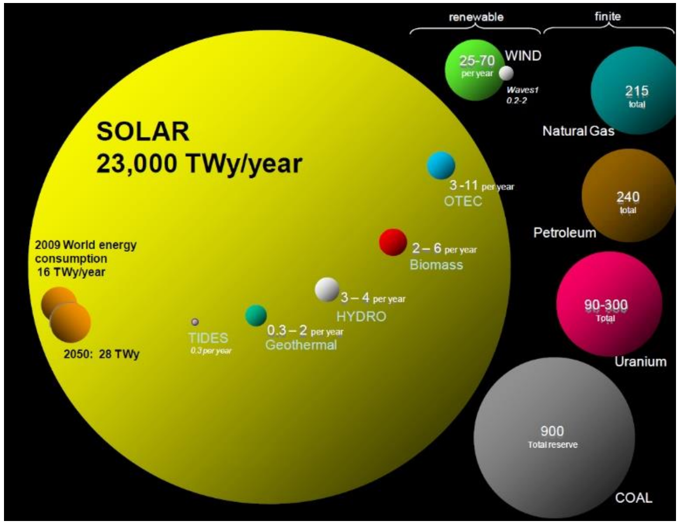


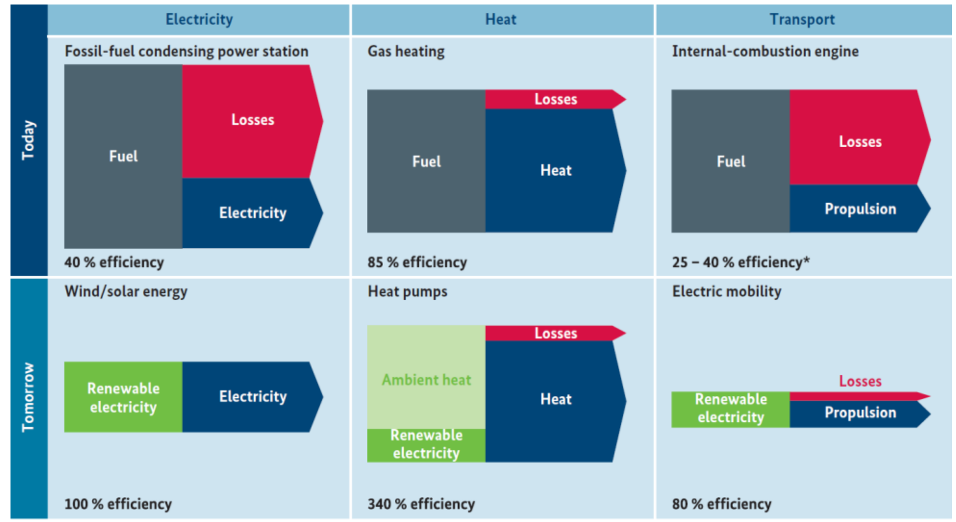
Key insights:

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

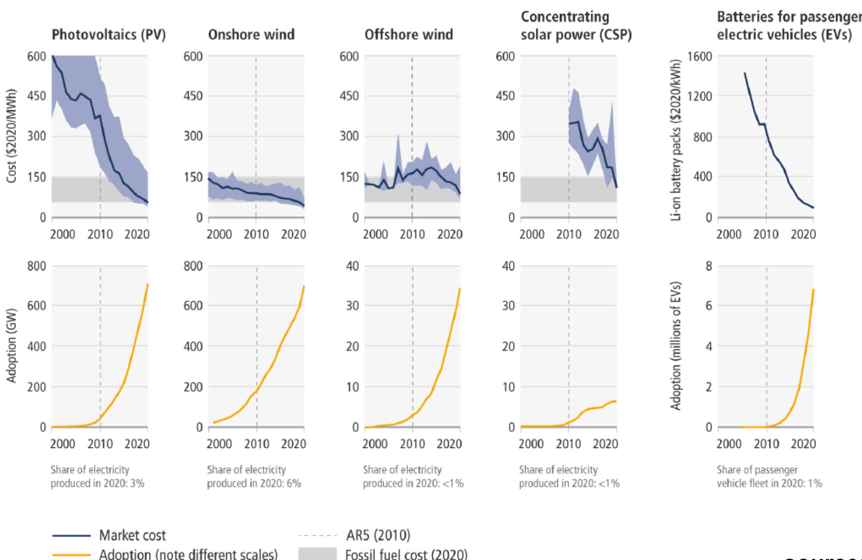
source: IPCC, 2020. 6th Assessment Report WG III

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 %.



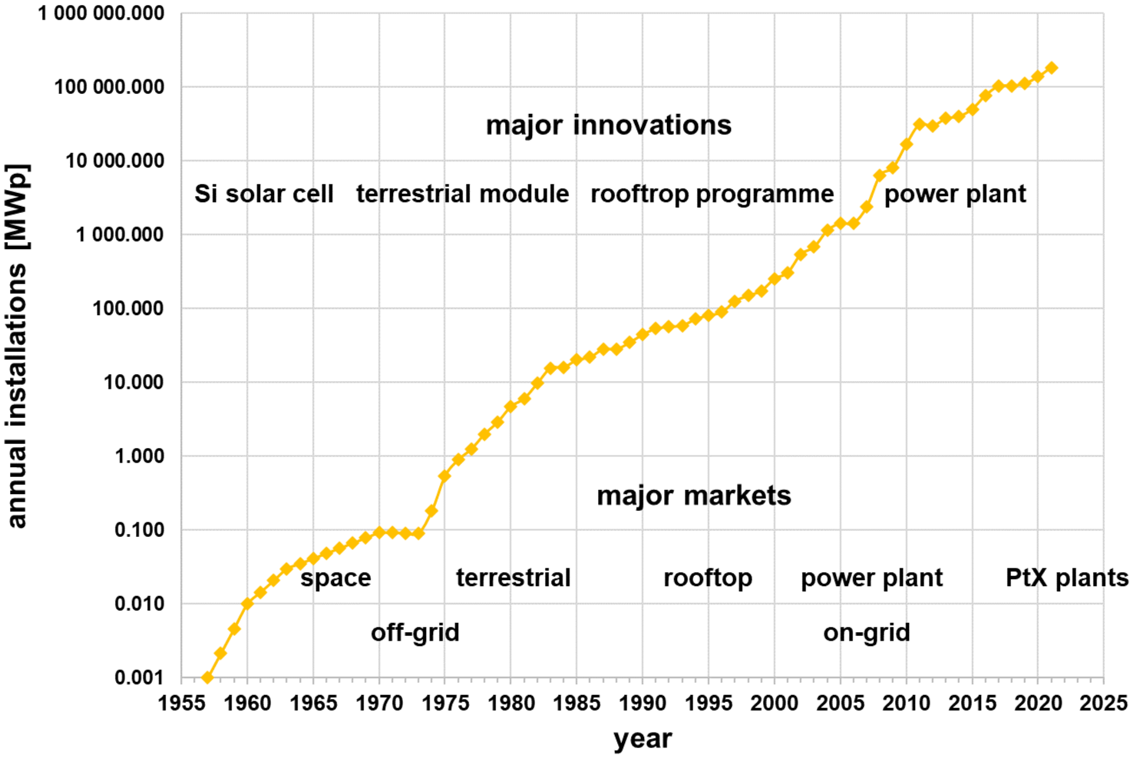
Key insights:

- 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:

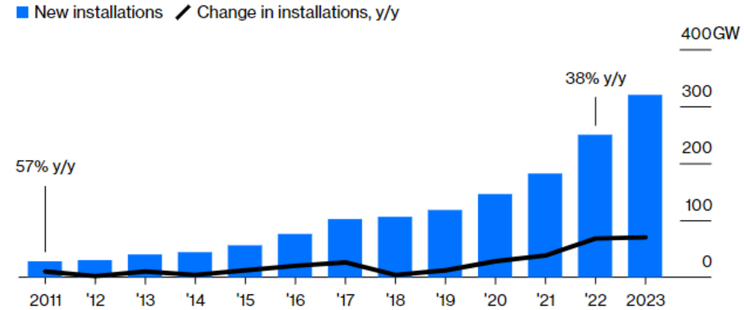
Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50
Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847
IPCC, 2020. 6th Assessment Report WG III

Solar PV Installations: past and near Future



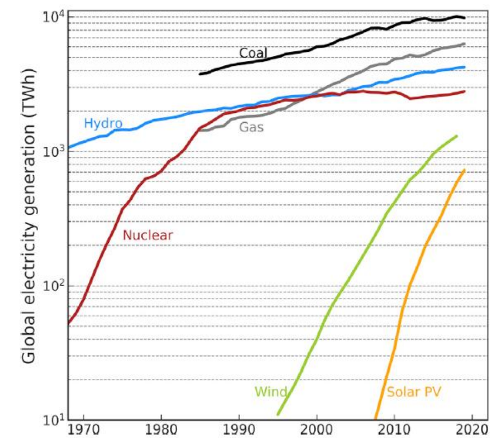
Rising Sun

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
- Solar PV shows the fastest phase-in in history (+30% annual installs in 2022)

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:

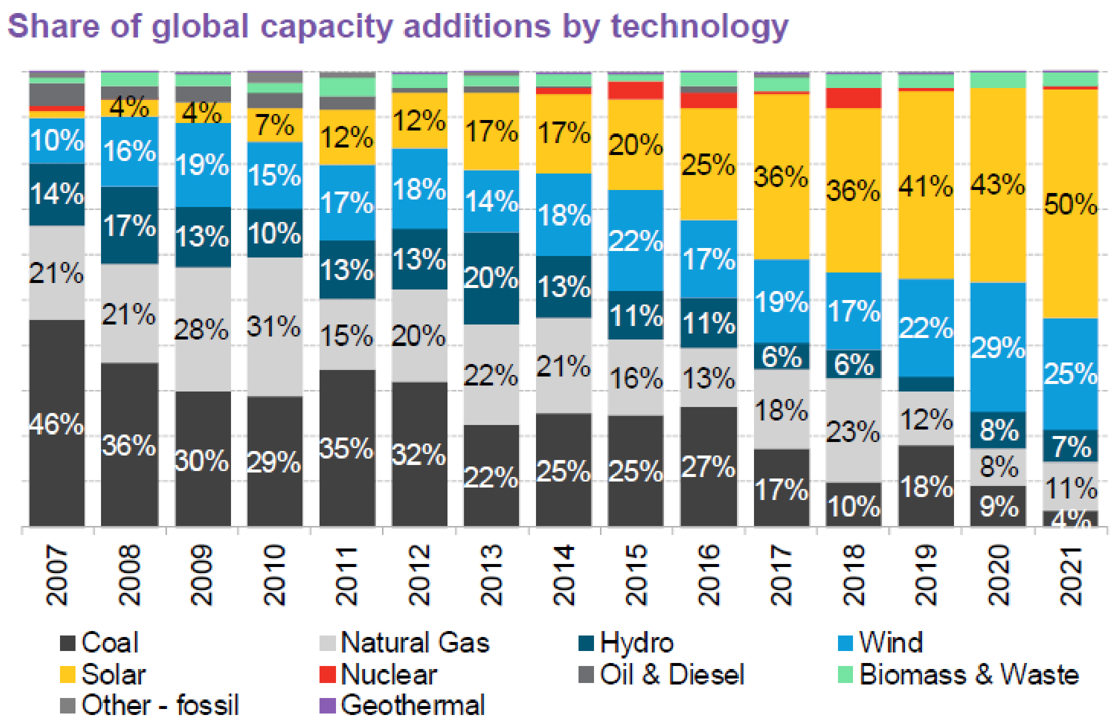
Electricity supply dominated by PV and wind power

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

Fossil-nuclear generation will be increasingly irrelevant

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

PV is outside any historic experience

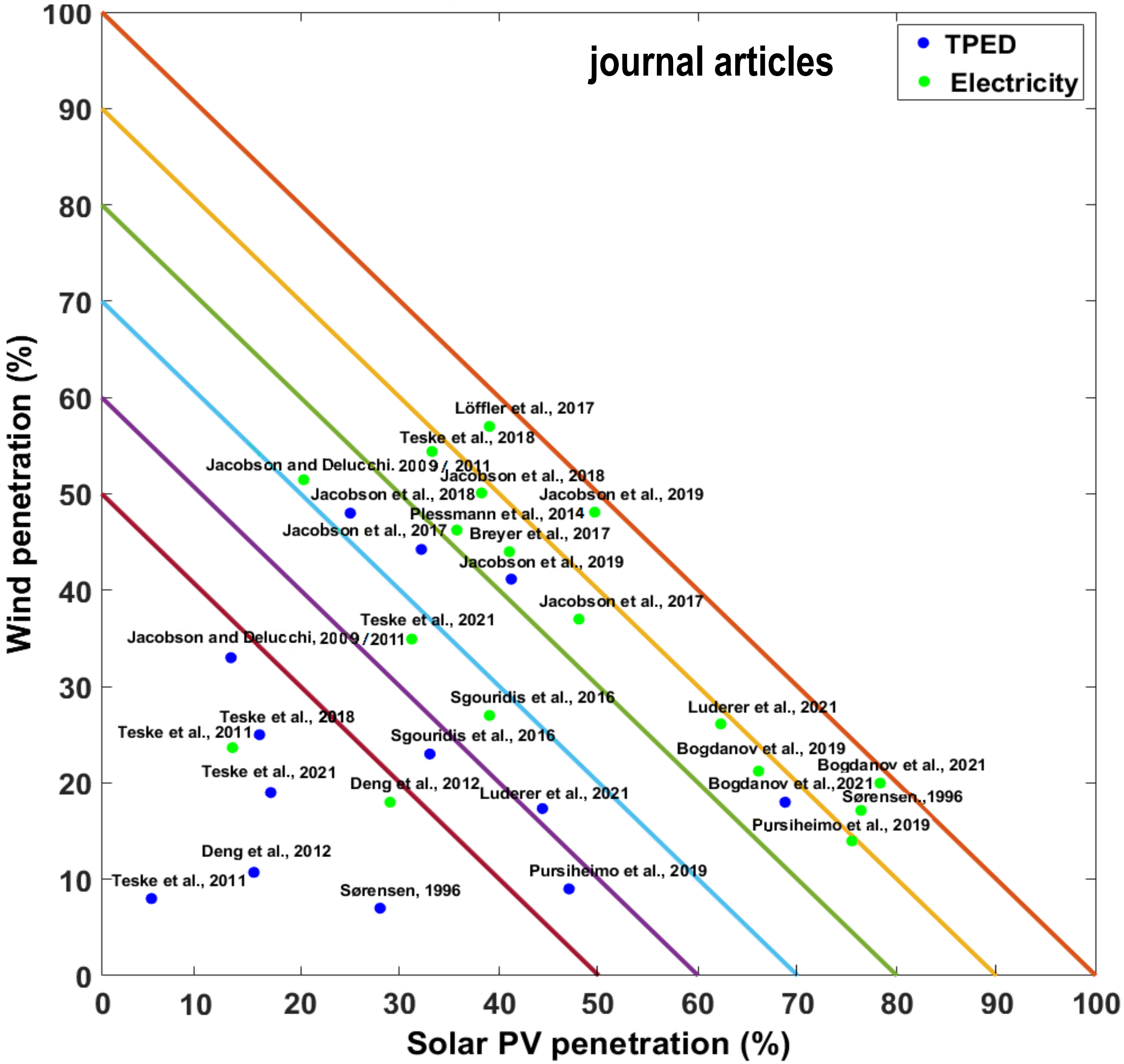


Source: BloombergNEF

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

Global: PV and Wind Share in 100% RE Studies

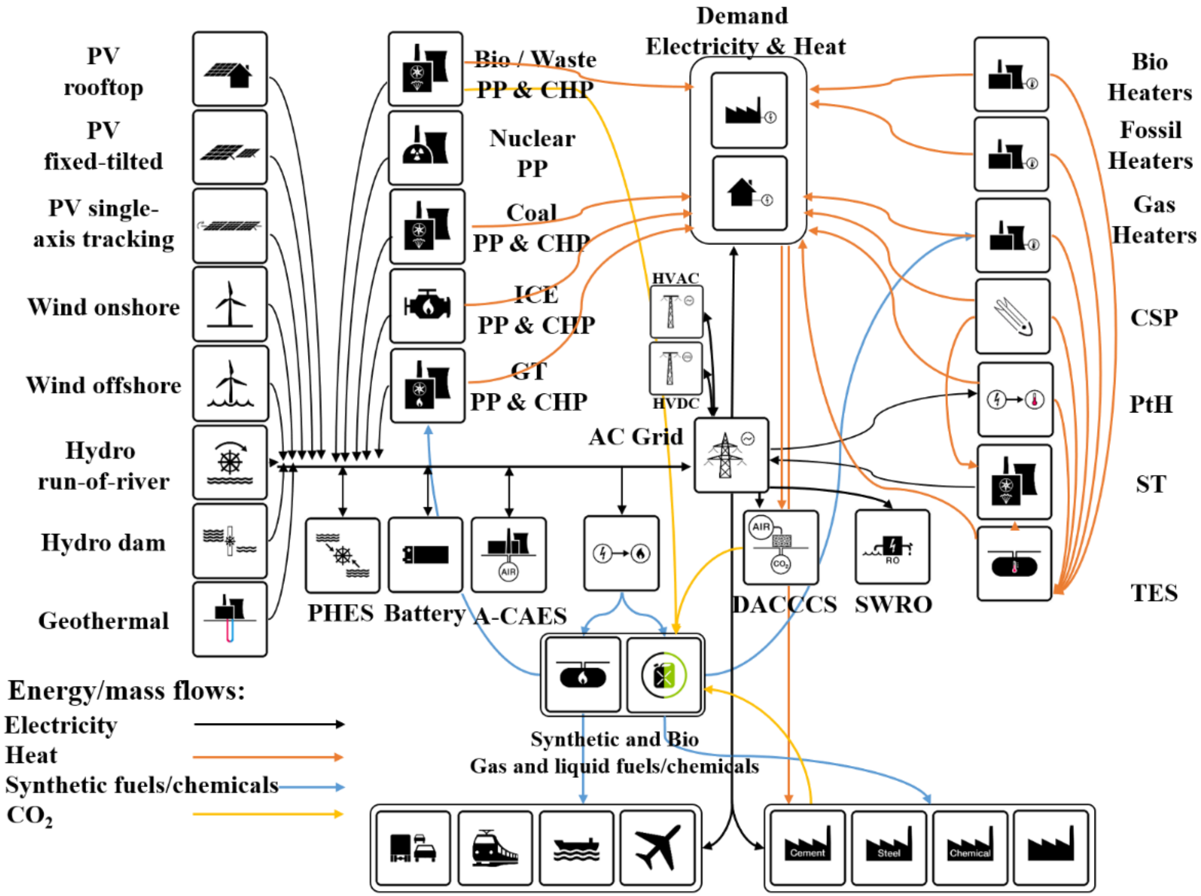


Key insights:

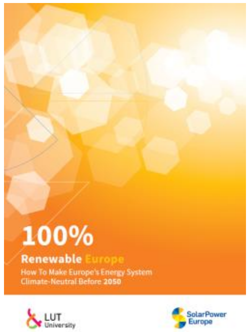
- 3 main groups:
  - High PV & wind: more PV
  - High PV & wind: more wind
  - Lower PV & wind
- PV share of around 50% by 2050 is standard
- Group of studies with high PV shares (70-80%) have all in common that they anticipate continued PV cost decline
- PV strongly benefits from electrification, low-cost 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

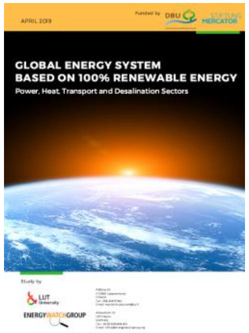
source: Breyer et al., 2022. IEEE Access 10, 78176-78218

LUT Energy System Transition Model (LUT-ESTM)



recent reports





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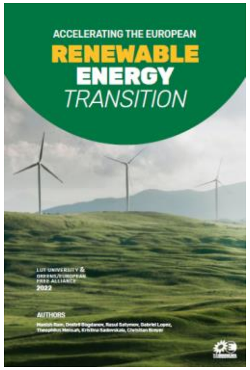

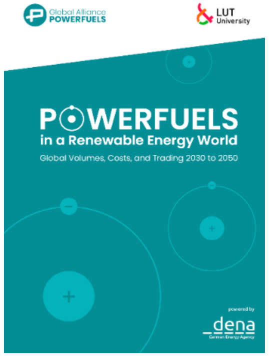

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Key features:

- 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 (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

What’s the role of electricity and hydrogen?

Guiding questions:

- What types of energy services demands can be directly electrified?
- What types of energy services demands cannot be electrified (directly, indirectly) at all?
- For all types of energy services demands which cannot be directly electrified, what’s the role of hydrogen?
- For what types of energy services demands hydrogen is needed directly?

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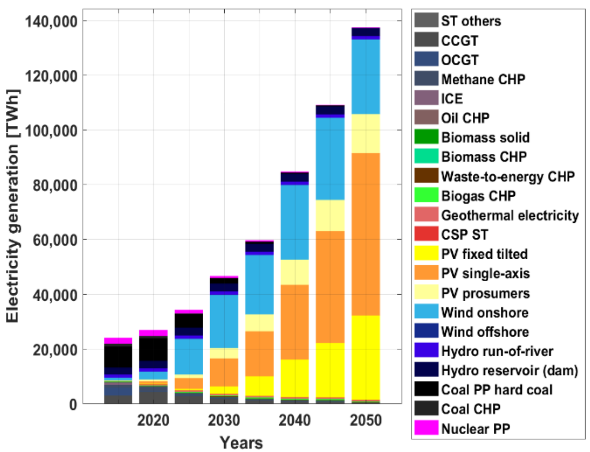
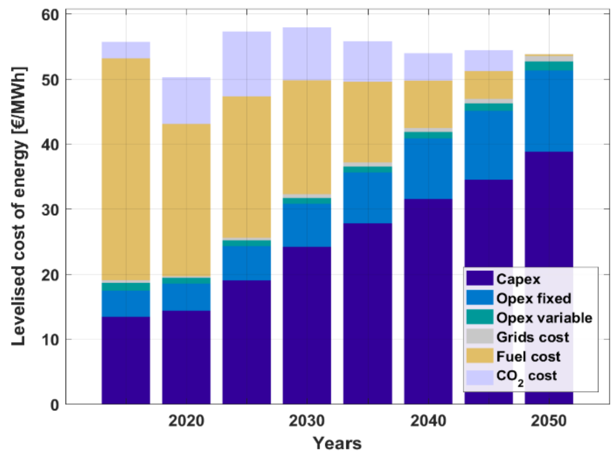
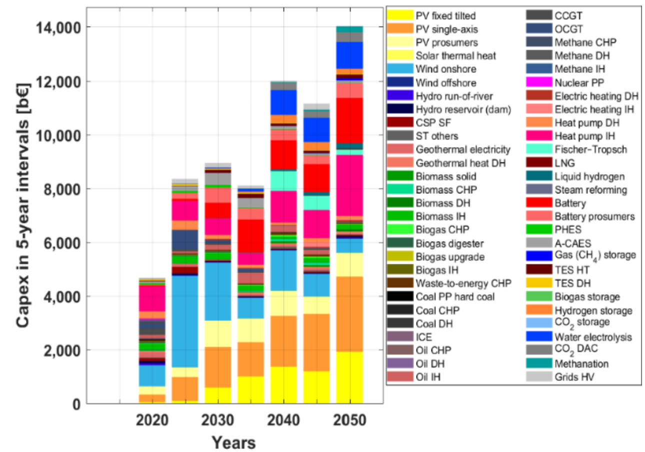
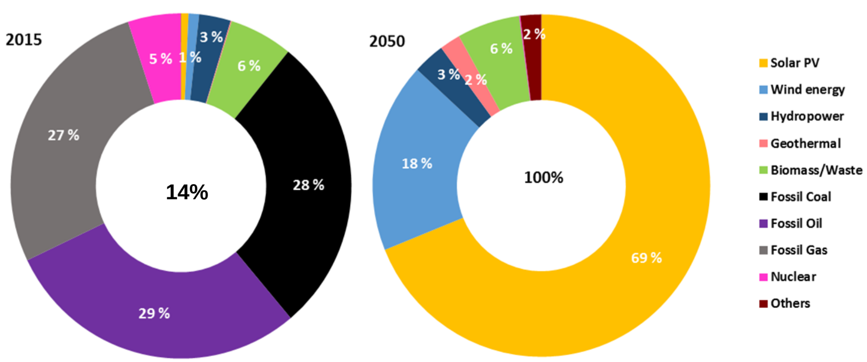
Global: 100% Renewable Energy System by 2050







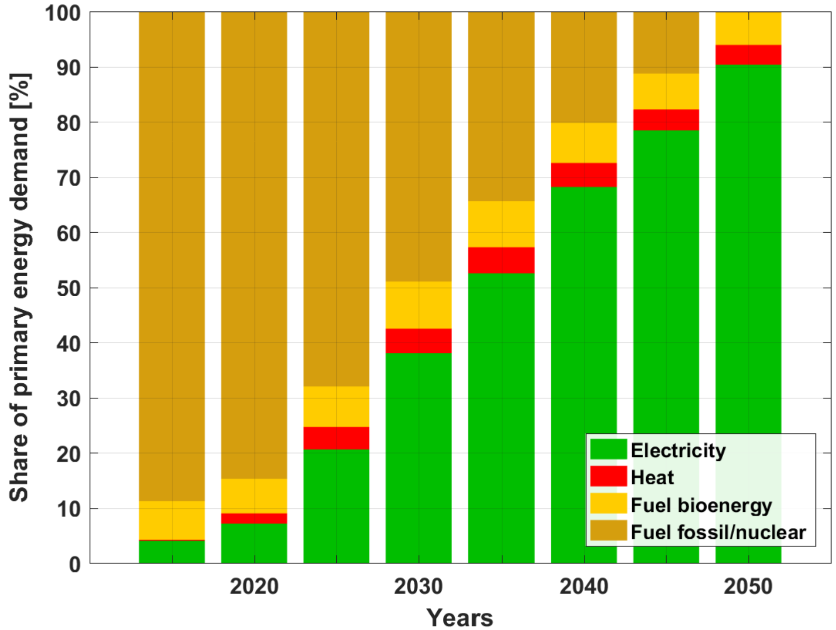


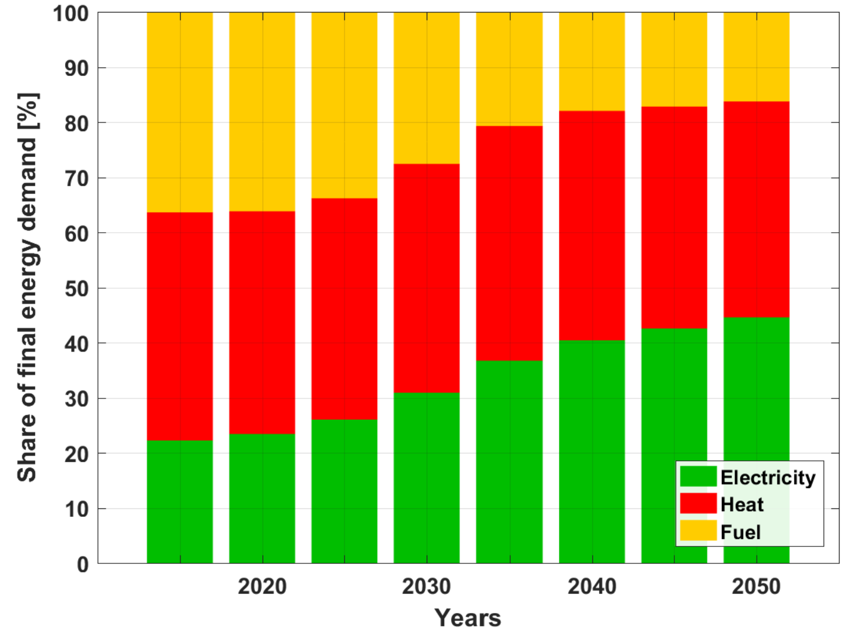
Key insights:

- 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



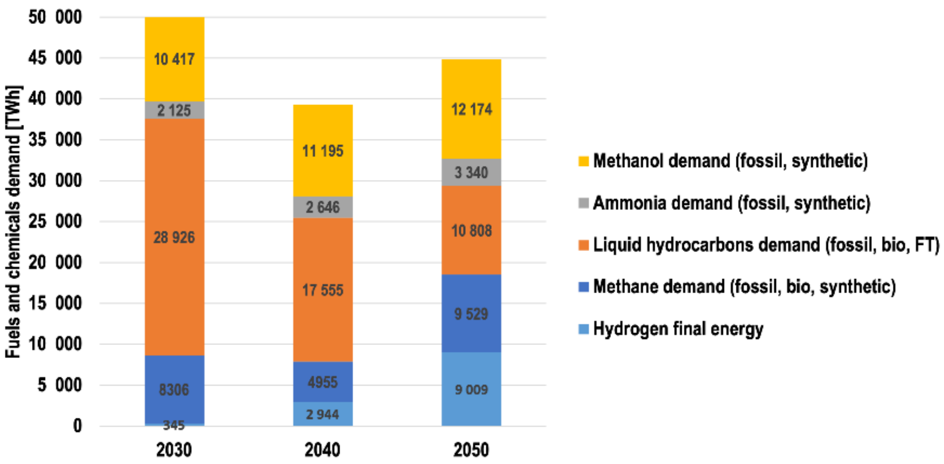


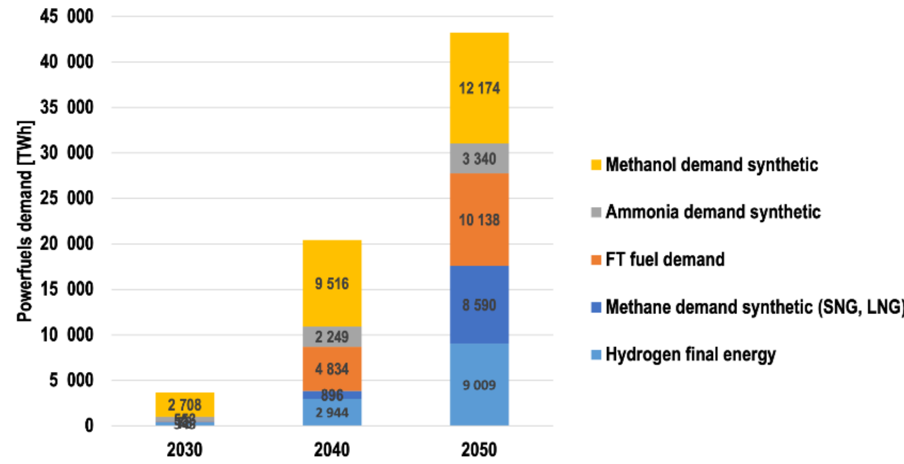
Key insights:

- 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

Global demand for e-fuels and e-chemicals





Fuels and Chemicals in general:

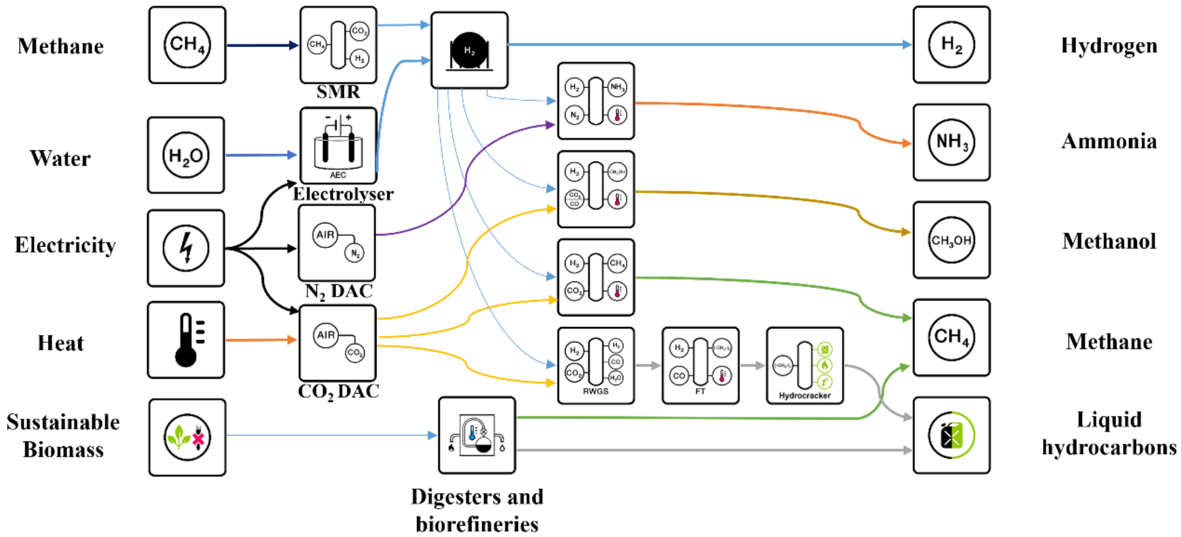
- steady growth of chemicals
- methanol represents non-ammonia chemicals
- liquid hydrocarbons are in steady decline, mainly due to electrification of road transportation
- methane demand in decline until 2040 with increase till 2050, with uncertainty for hydrogen substitution

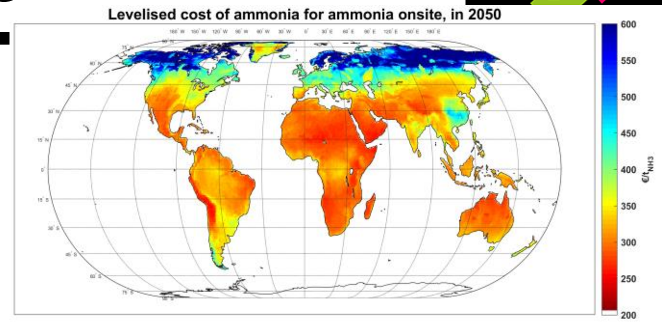
e-fuels and e-chemicals:

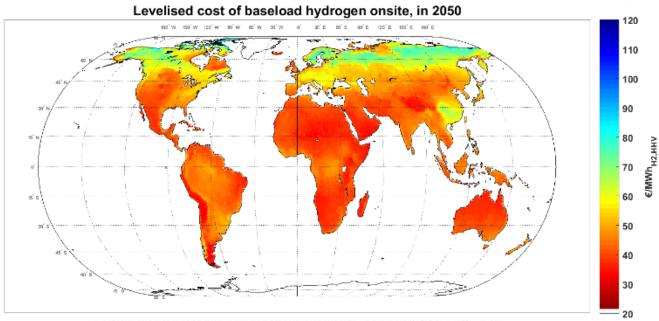
- first markets during 2020s by 2030
- strong growth over the decades reaching a volume of more than 40,000 TWh
- less uncertainty for e-chemicals
- highest uncertainty for e-methane demand due to substitution by e-hydrogen, e-ammonia, e-methanol

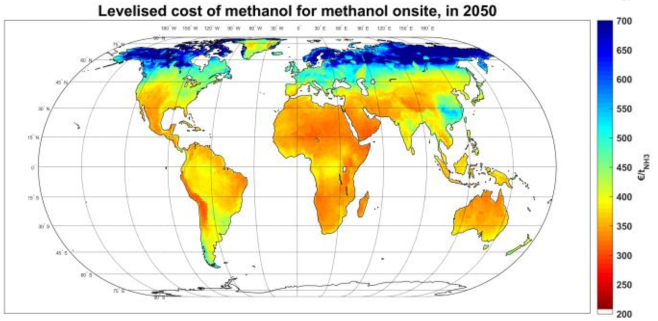
source: [Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, RSER]

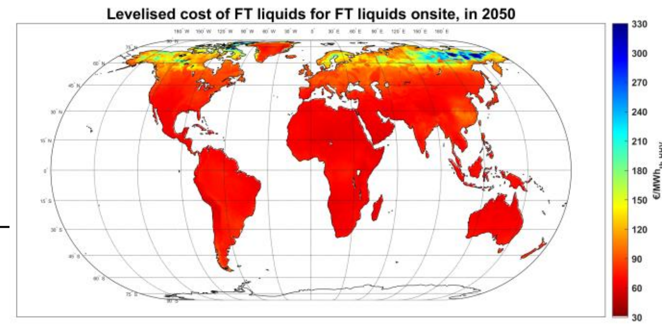
Sustainable e-fuels and e-chemcials









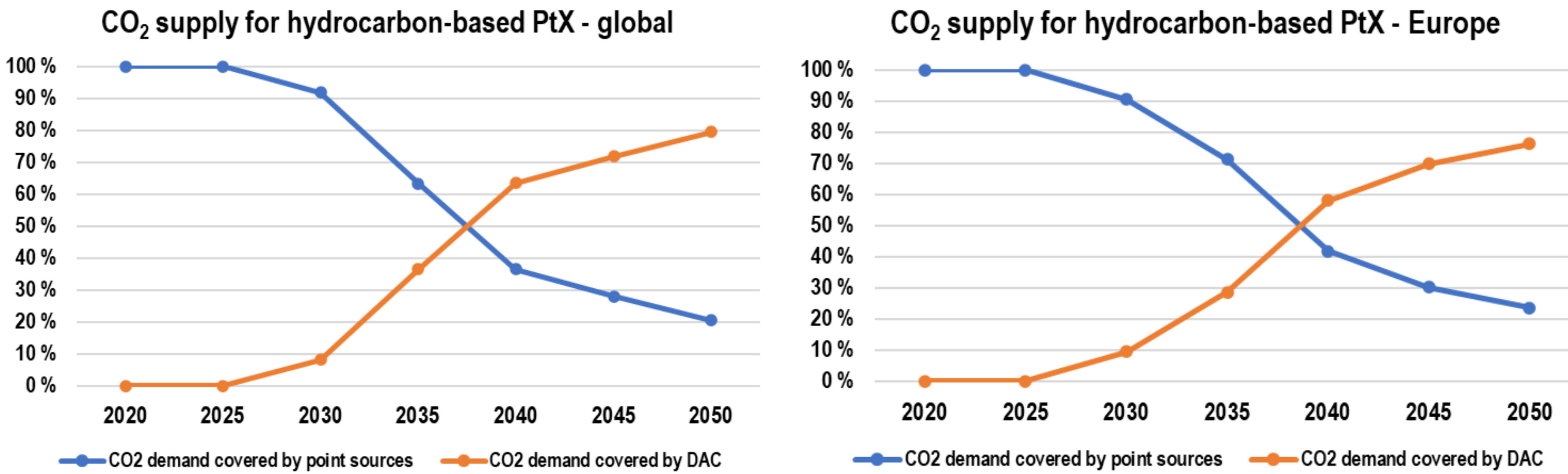


Key insights:

- **Sustainable biomass is highly limited, since energy crops shall be limited to zero due to food supply and biodiversity restrictions**
- **All fuels can be produced based on electricity, water and air**
- **All e-fuels production routes are technically available on high TRL**
- **Methane is still listed by may not be required, as technically not necessary, relatively high cost, AND high GWP due to leakage**
- **Major challenge ahead: domestic self-supply in Europe or imports of e-fuels?**

source: Fasihi et al., PtL; Fasihi et al., PtA; Fasihi et al., PtH2; Fasihi et al., PtCH4;

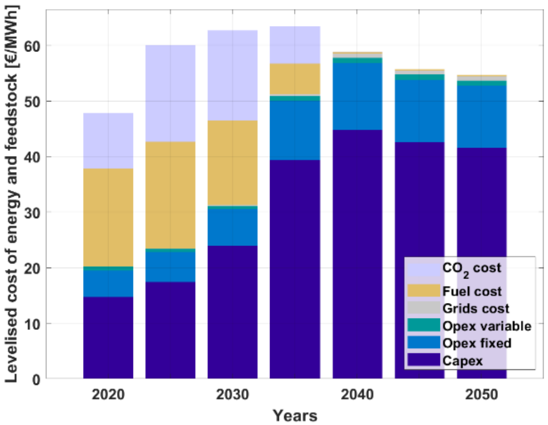
CO_2 as raw material for e-fuels and e-chemicals

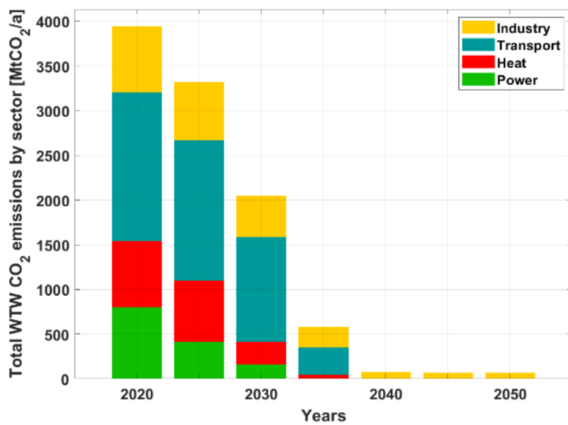


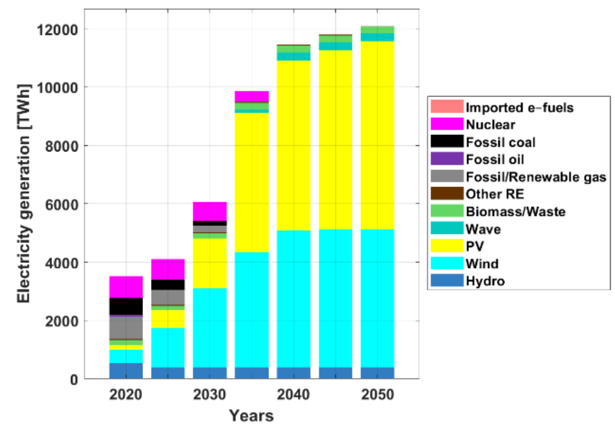
- Finally, 80% of global CO_2 raw material demand needs to be covered by direct air capture (DAC), while the DAC demand in Europe is slightly lower at 76%
- Industrial phase-in of DAC is critical in 2020s, as point sources are available, while DAC requires a first market ramp-up for massive scaling in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

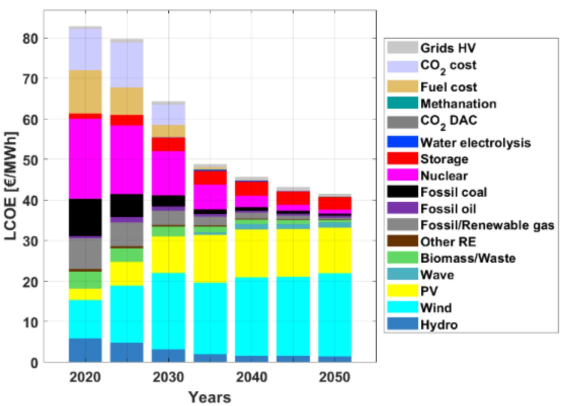
source: [Galimova et al., 2022. Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals, Journal of Cleaner Production, 373, 133920]

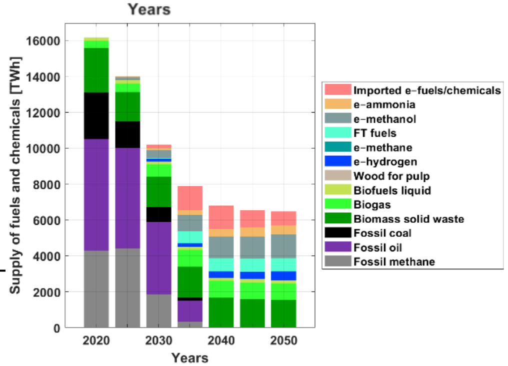
Europe: Highly Ambitious Energy-Industry Transition







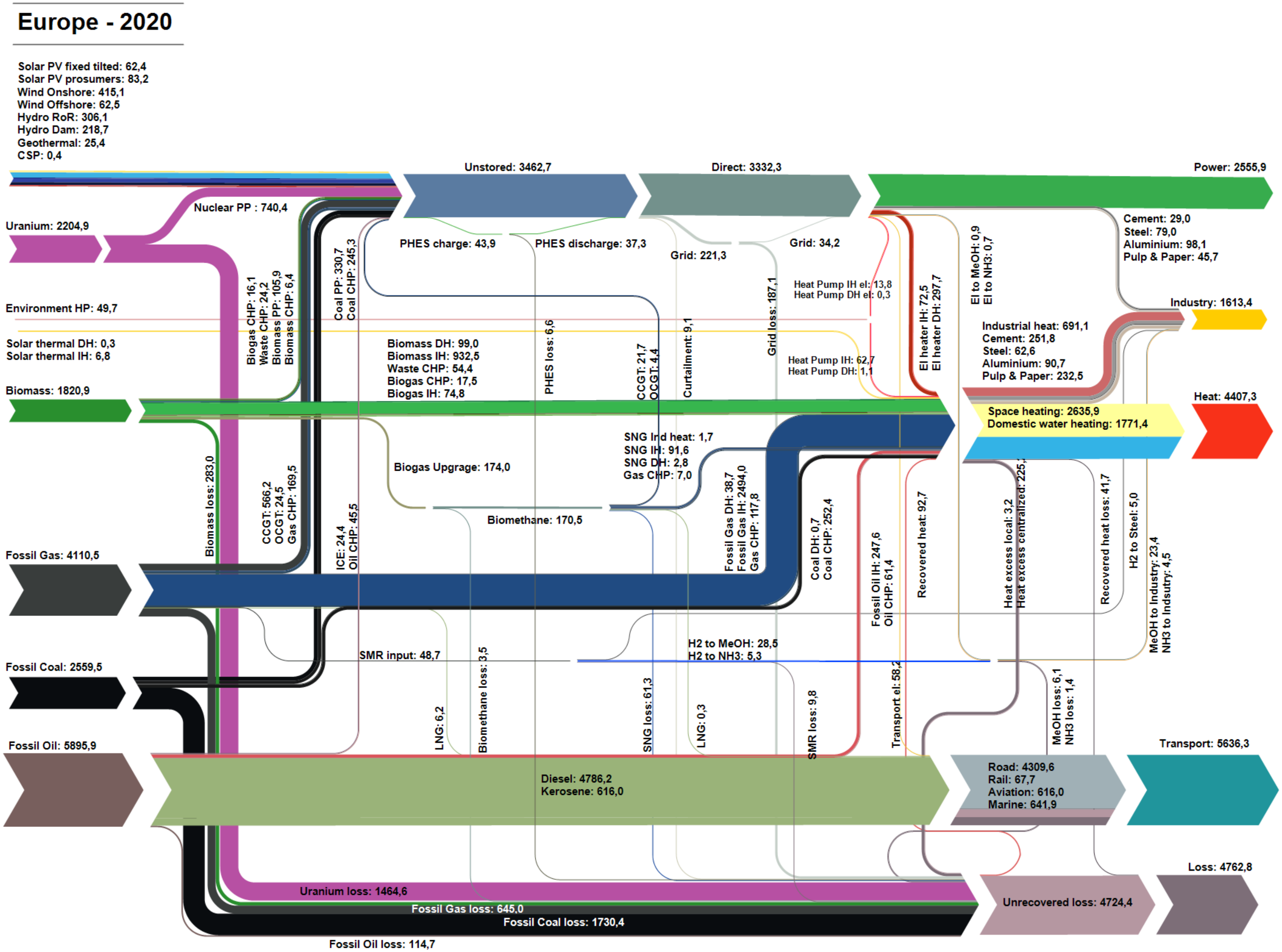




- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: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

System Outlook – Energy Flows in 2020

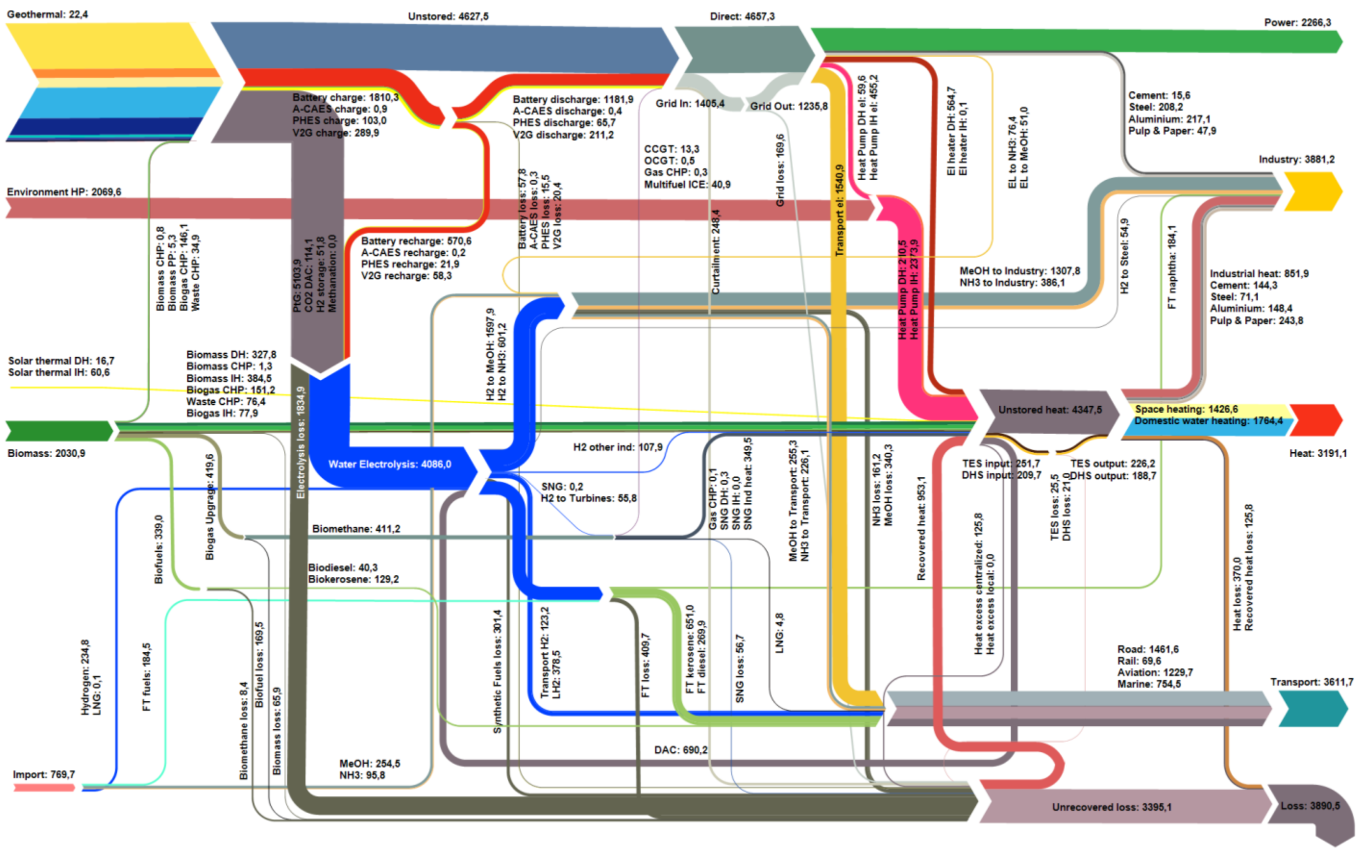


SERENDIPV

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
  - Hydrogen is a subset of the PtX Economy
  - Main demand: e-fuels (marine, aviation), e-chemicals, e-steel – ammonia, methanol kerosene jet fuel

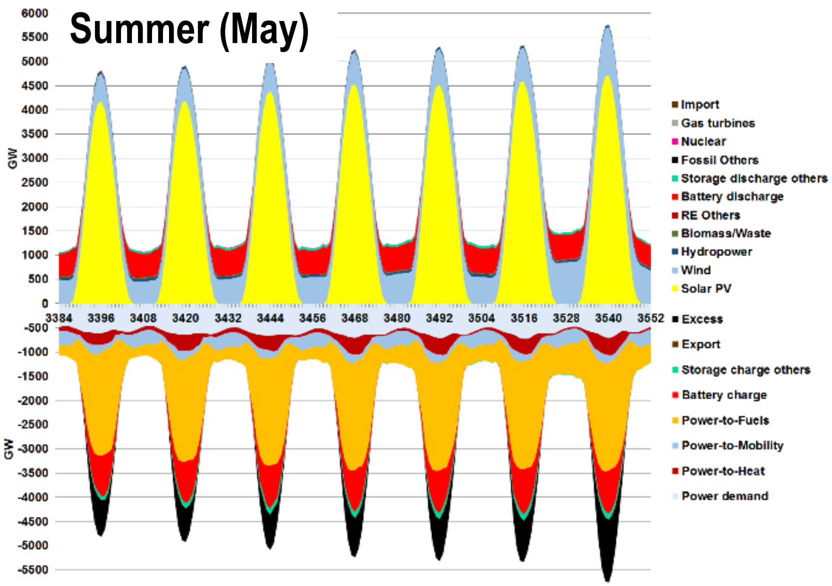


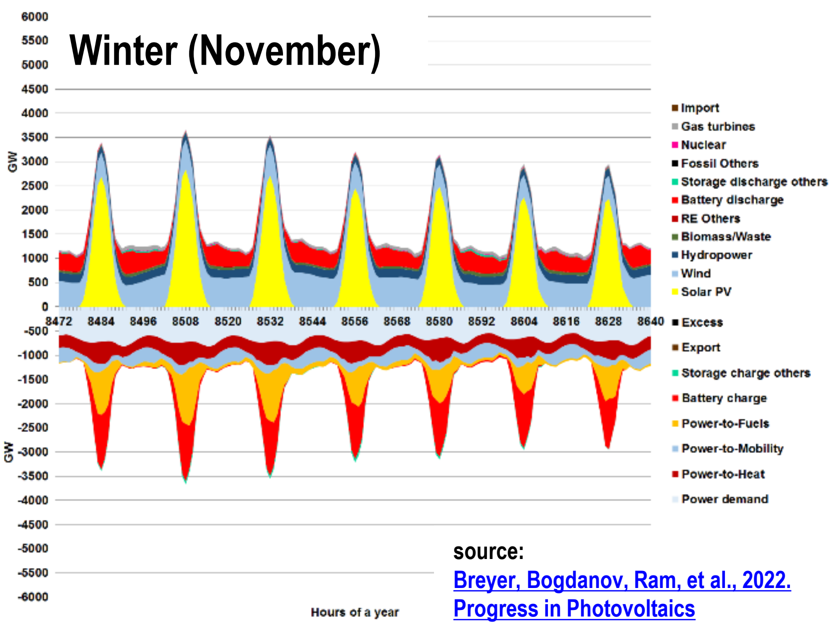
Source:
Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2022. Progress in Photovoltaics

Breyer et al., 2023. The role of electricity-based hydrogen in the emerging Power-to-X Economy, submitted

Diagram: Greens/EFA, 2022

Hourly Operation and Balancing



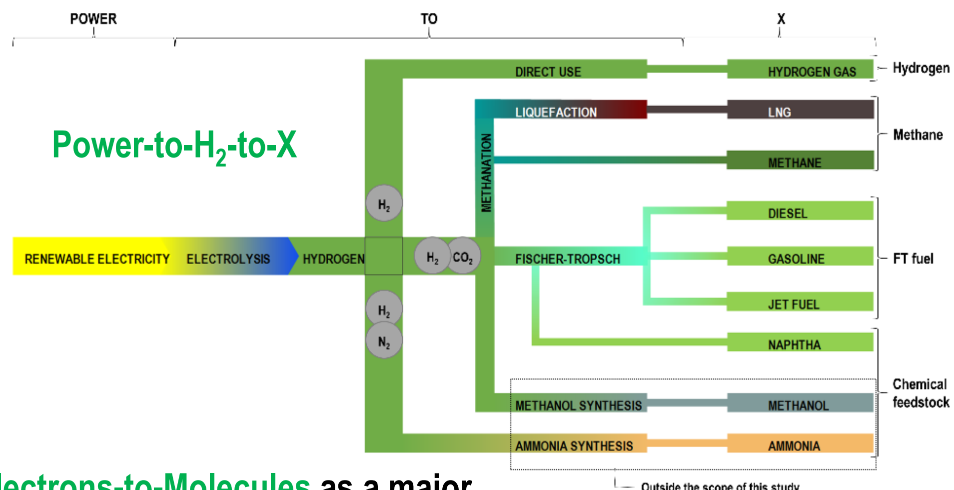


source:
Breyer, Bogdanov, Ram, et al., 2022. Progress in Photovoltaics

Key insights:

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

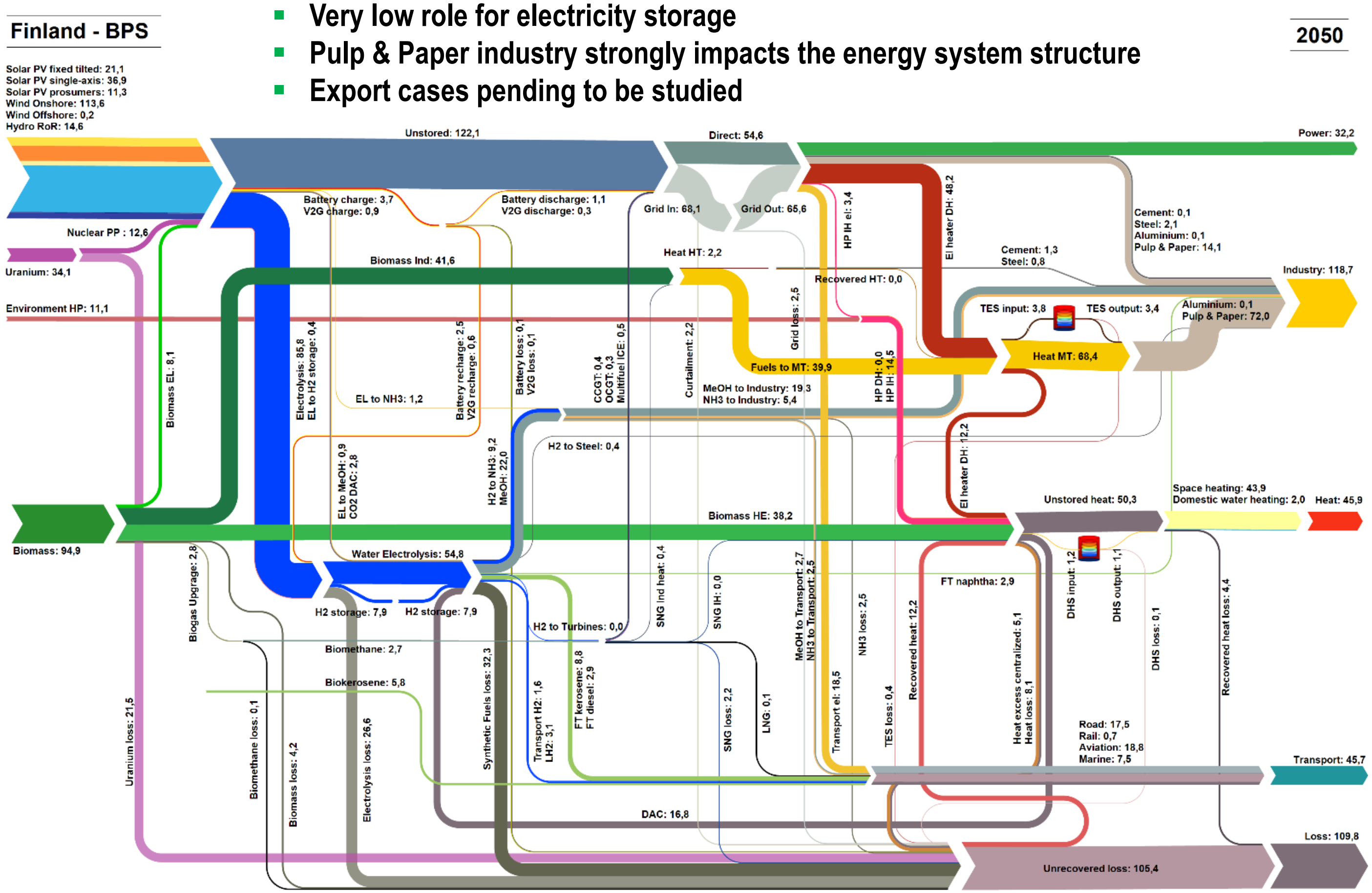
Power-to-H_2-to-X



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

Energy flow Finland in future

- Case: self-supply of energy needs in Finland (except uranium supply)
- Energy supply based on wind power, bioenergy, solar PV
- Bioenergy largely for heat
- Very high electrification (direct, indirect)
- Very low role for electricity storage
- Pulp & Paper industry strongly impacts the energy system structure
- Export cases pending to be studied



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 et al., 2023. The role of electricity-based hydrogen in the emerging Power-to-X Economy, submitted
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-CDR 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
- CO_2 removal is essential for a safe climate and a sustainable civilisation

Role of hydrogen:

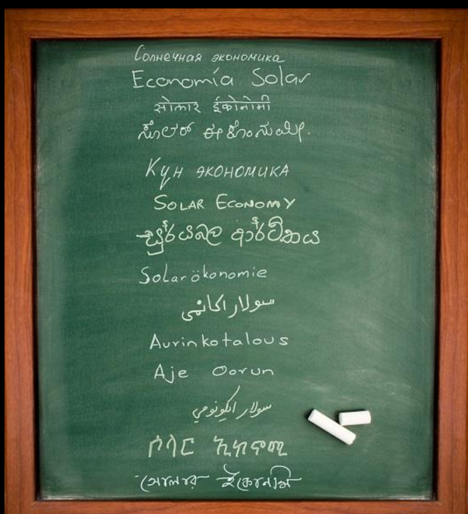
- Provide solutions when direct electrification is not possible, since the latter is typically more efficient and lower in cost
- Main demand for hydrogen: e-fuels & e-chemicals (e-ammonia, e-methanol, e-kerosene jet fuel, e-methane, e-hydrogen), e-materials (e-steel, e-carbon fibre)
- Hydrogen as an essential intermediate energy carrier in power-to-H_2-to-X routes as a subset of the Power-to-X Economy
- Up to 61,000 TWh_{H2} demand by mid-century with up to 88,000 TWh_{el} demand

CO_2 evolves from an emission to a raw material to the core element for active climate regulation

- CO_2-to-X in CCU approaches requires about 10 $GtCO_2$ as raw material
- CO_2-to-X in CDR approaches requires about 40 $GtCO_2$ as input for climate regulation in a broad CDR portfolio

Times are amazing, as the global energy-industry system of the present is comprehensively restructured, while almost all core components are now roughly understood & already in the roll-out or ready for roll-out

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



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Comparing Scenarios of varying Ambitions


Applied Energy
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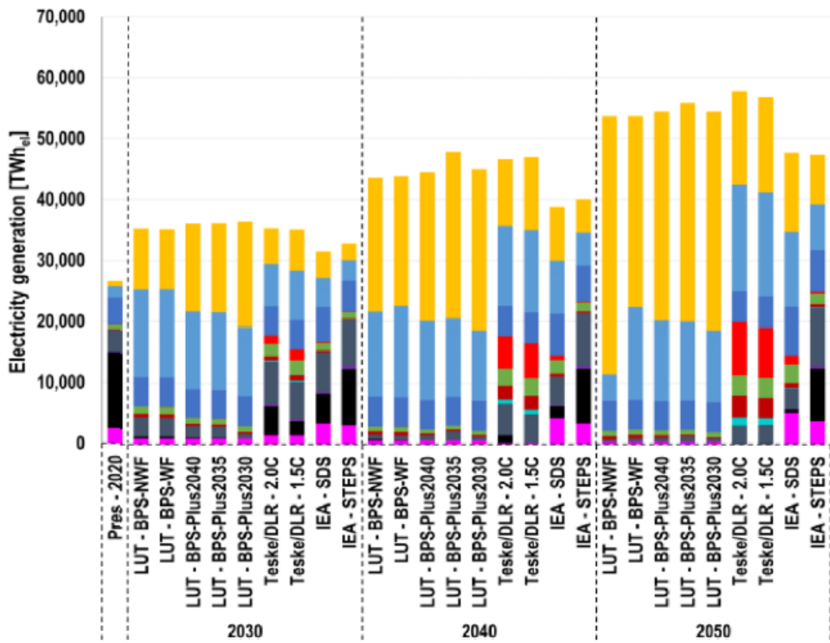
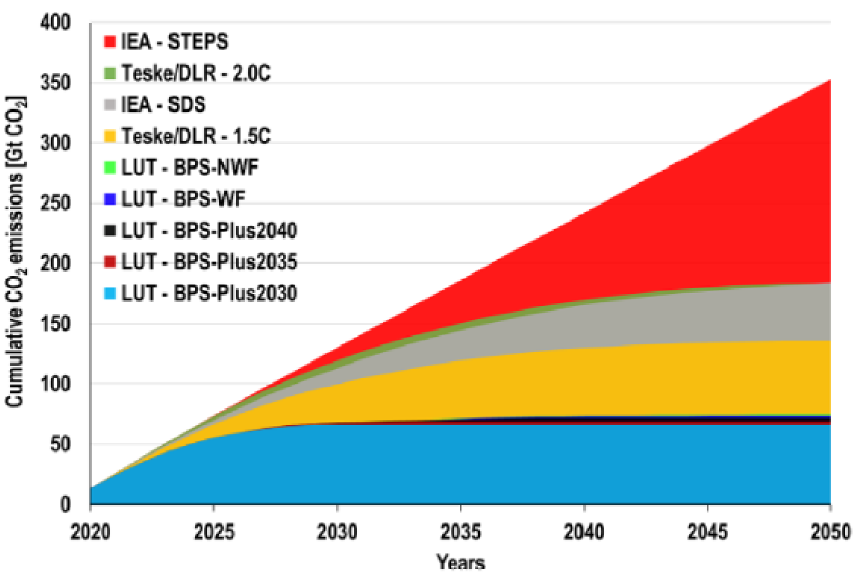
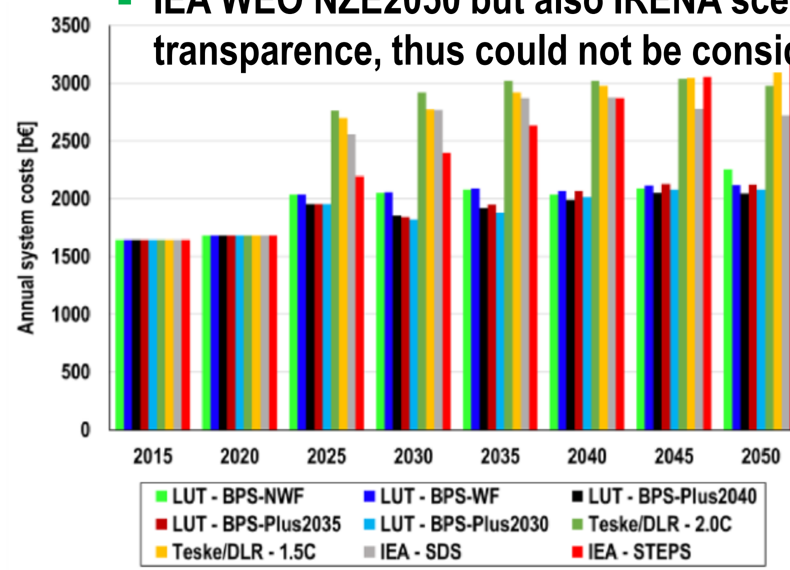
Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness



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]

Power-to-X Economy vs Hydrogen Economy

Power-to-X Economy:

- 90% of the entire energy-industry will be finally based on electricity as the dominating source of energy
- Electricity can be converted in all forms of energy
- Electricity as final energy carrier is most attractive due to high efficiency
- Power-to-X conversion can be found in all energy sectors in various forms

Hydrogen Economy:

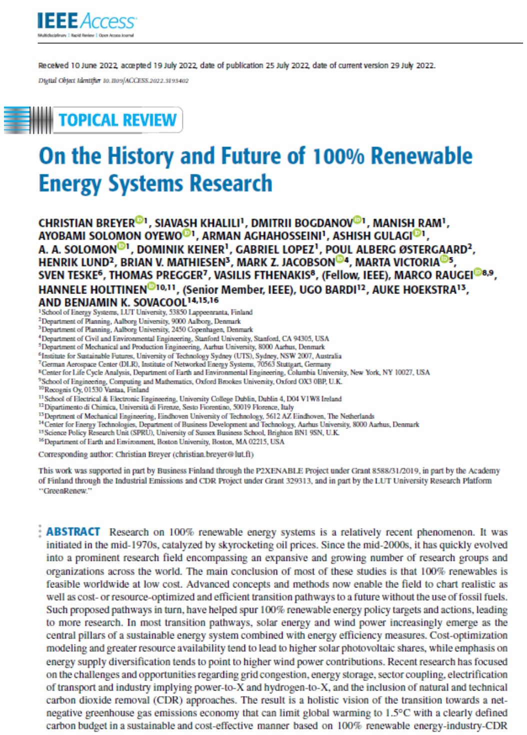
- Hydrogen is a very important element of the arising energy system
- Hydrogen is typically NOT attractive as a final energy carrier
- Hydrogen is serves mainly as intermediate energy carrier
- Sources other than renewable electricity seem to be not much relevant (cost, emissions, limits)

Power-to-X Economy vs Hydrogen Economy:

- The arising energy system represents substantially more features of a Power-to-X Economy than of hydrogen related features

- Power-to-X Economy is the more inclusive & comprehensive description of the arising energy system

100% Renewables Energy Systems Research



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TOPICAL REVIEW

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

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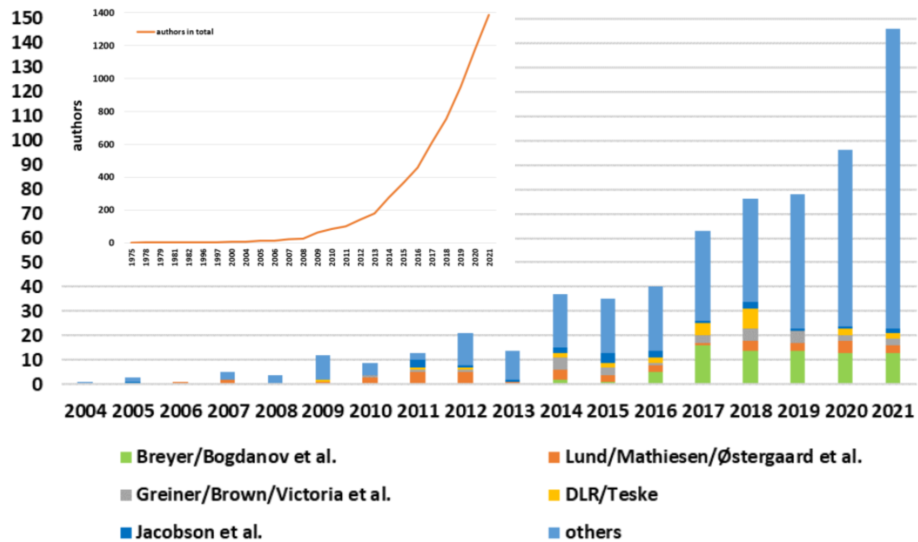
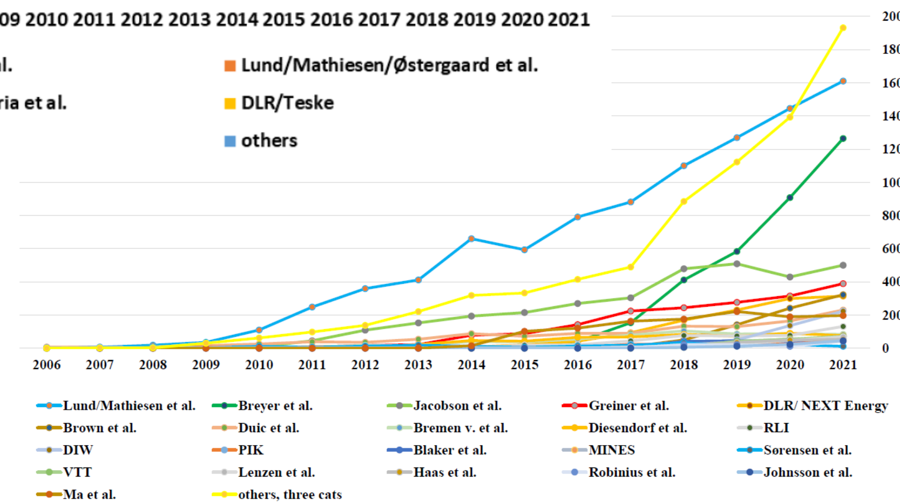
ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and 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
- >1400 individual researchers involved in 100% RE articles
- 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 et al., 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.

		citations		model used for 100% RE											
Model	articles	total	2021	earliest	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**

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

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, RSER