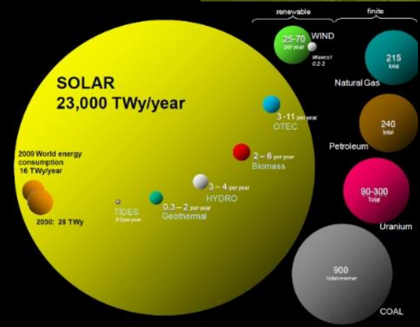


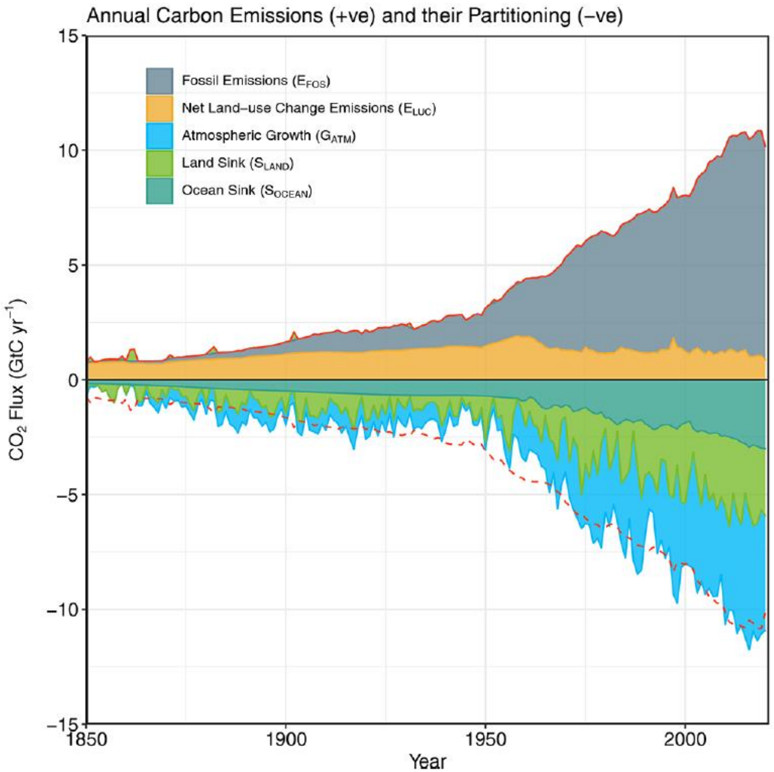
Global solar PV demand projections until 2050 and beyond – why major scenarios differ

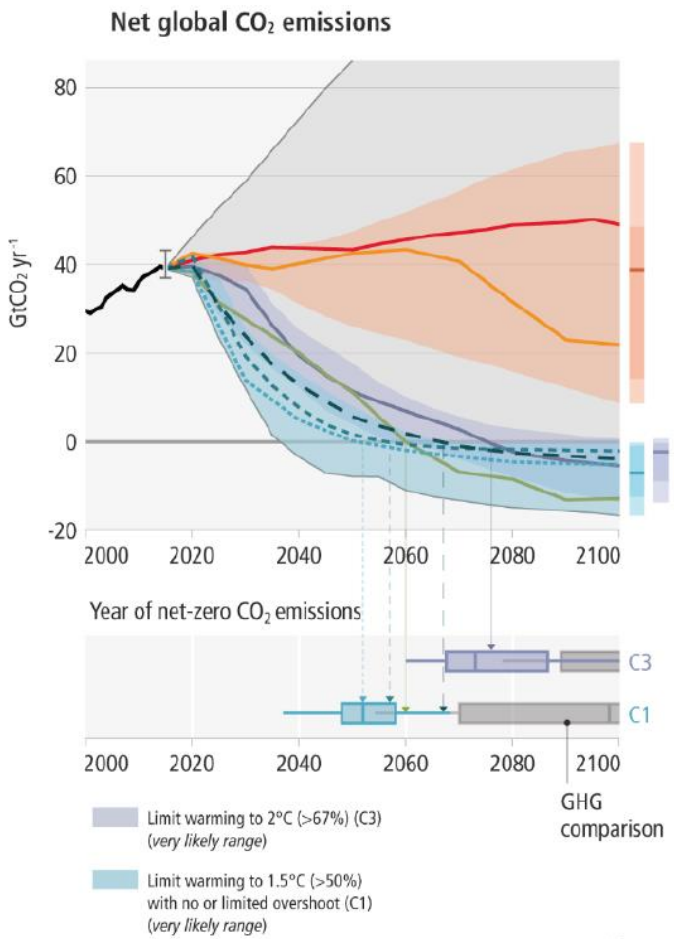
Open your mind. LUT.
Lappeenranta University of Technology

Christian Breyer
LUT University

IEA PVPS Event - PV Scenarios: Now and Then
WCPEC-8
Milan, September 27, 2022

CO_2 Emissions: how it developed, where to go



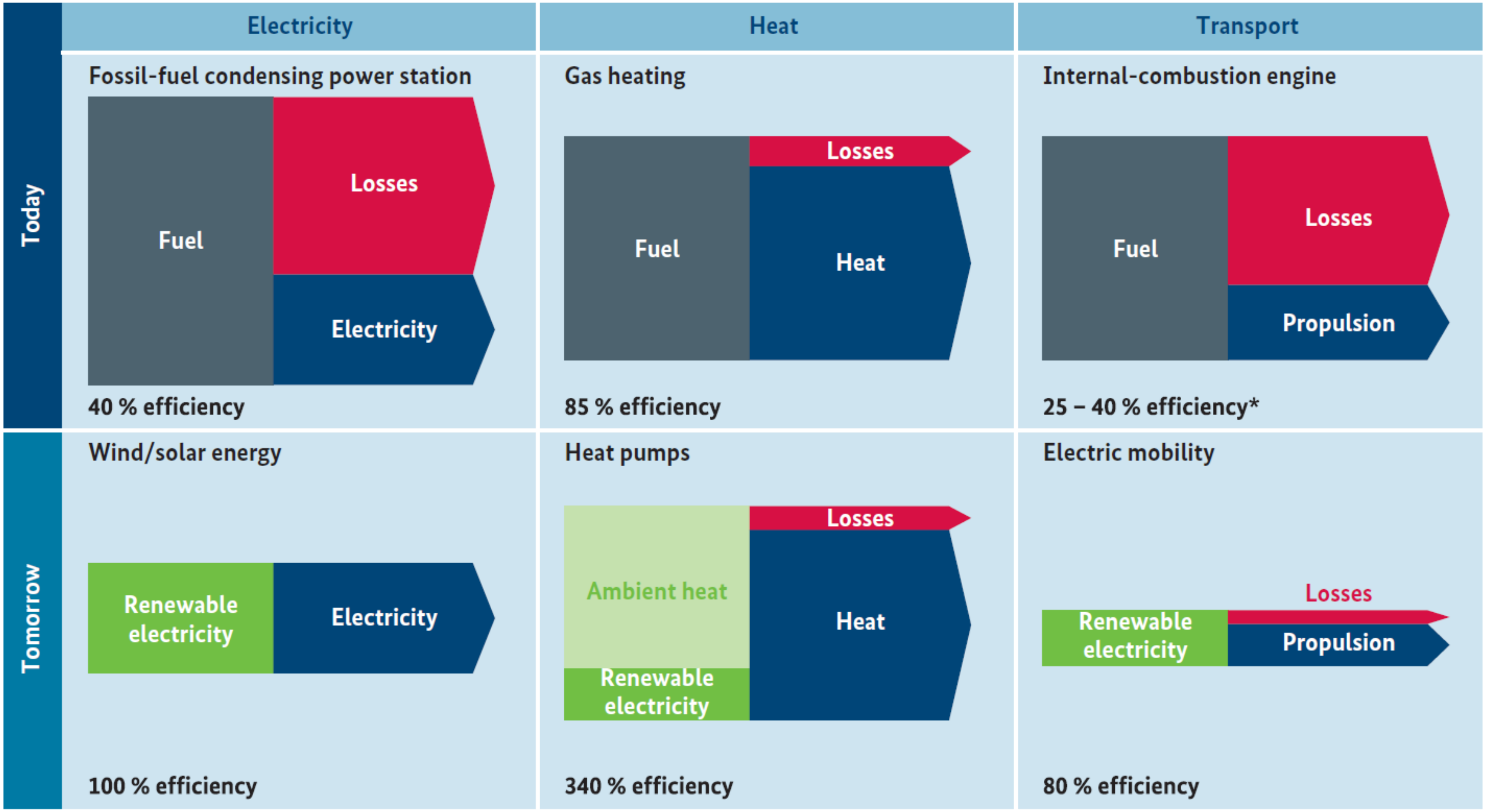


Key insights:

- CO_2 is dominantly form fossil emissions
- We are at the historic record high emissions
- We have to be at zero emissions; carbon budget for 1.5ºC (67%) is used by 2030
- faster transition and net negative CO_2 emissions required

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

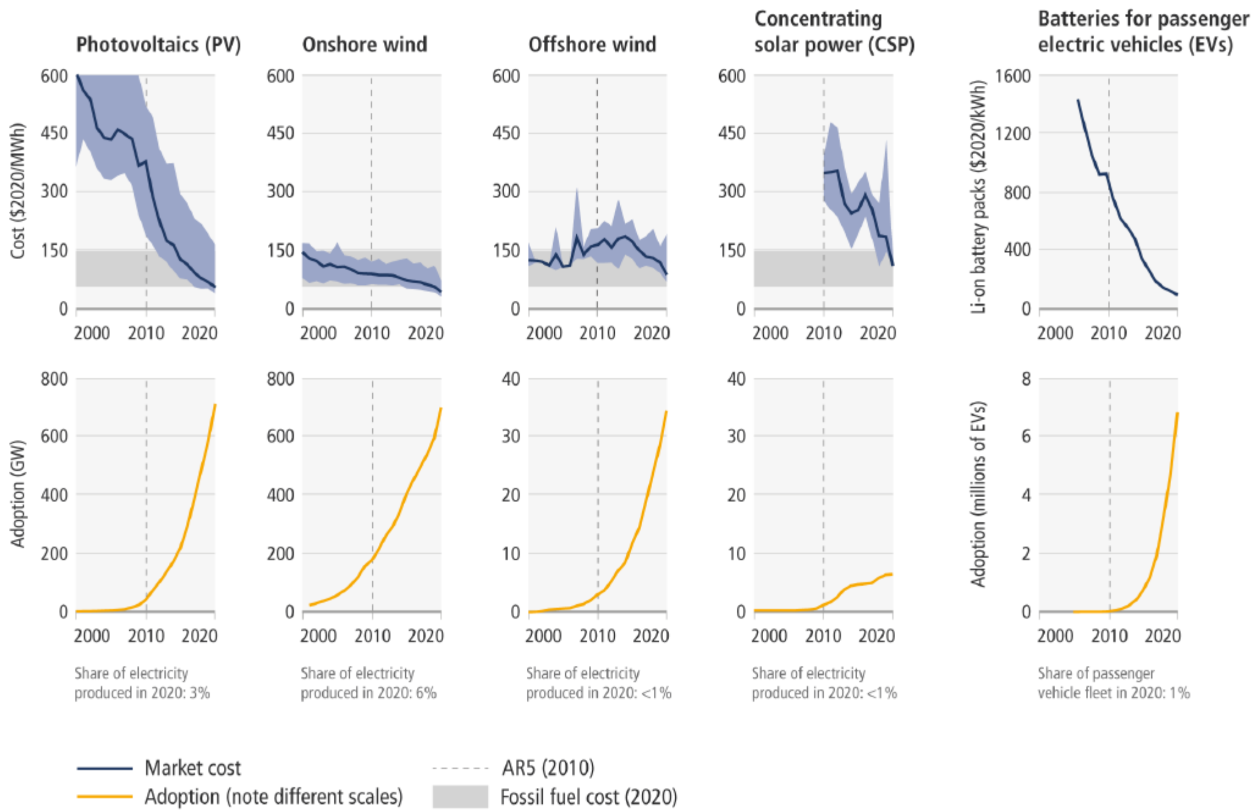
Key Rationale for Electrification: Efficiency



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

source: Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847

Key Driver for Transition: Low-cost Renewables

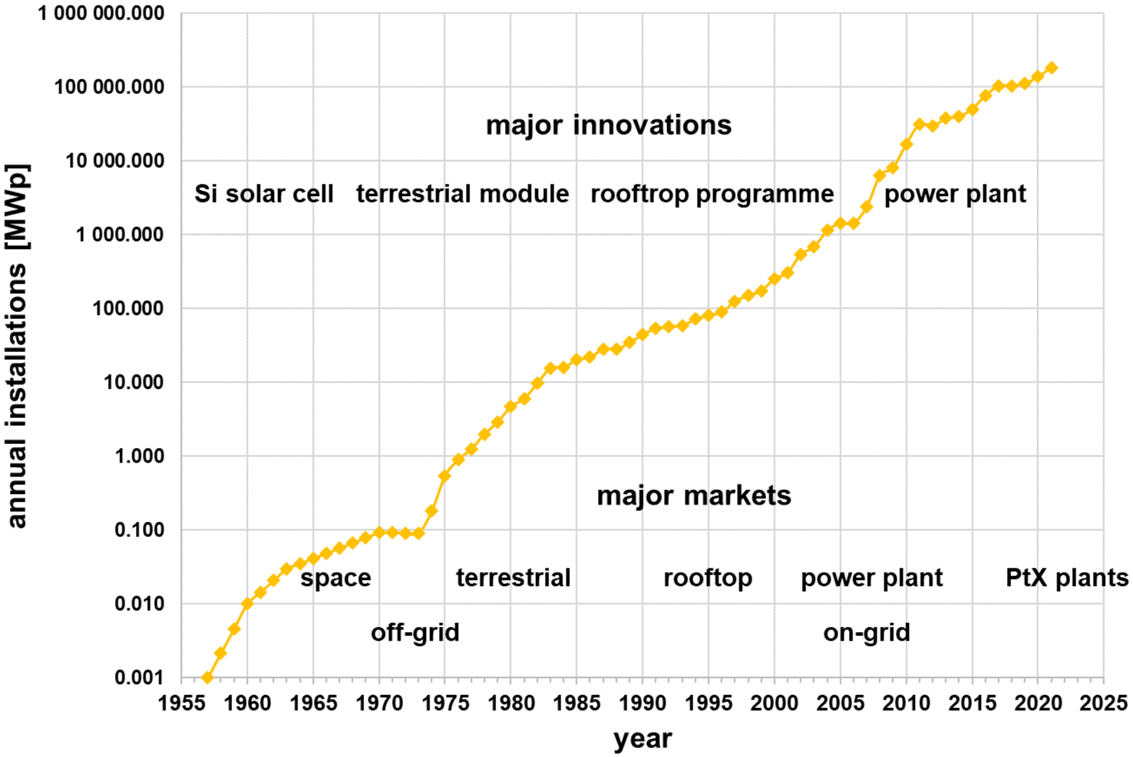


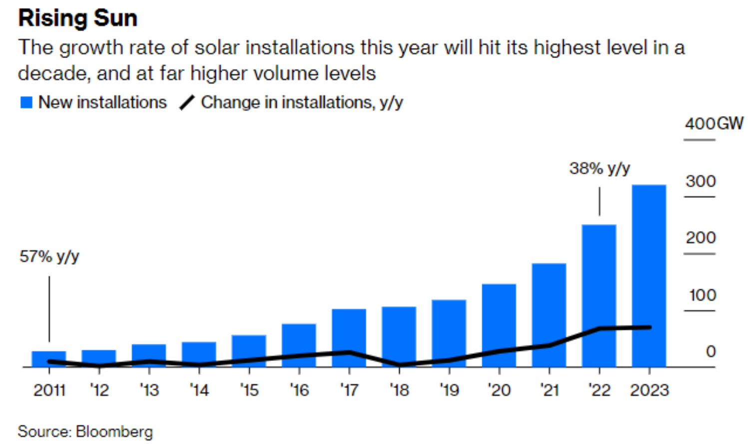
Key insights:

- **Renewables cost declines steeply and continued: solar PV, wind power, batteries, electrolysers, and others**
- **Fossil and nuclear cost go up**
- **Leading economies in the world switch to a renewables energy system, or they will lose competitive edge**
- **Key learning: avoid investments in stranded assets and invest in the required infrastructure, now**

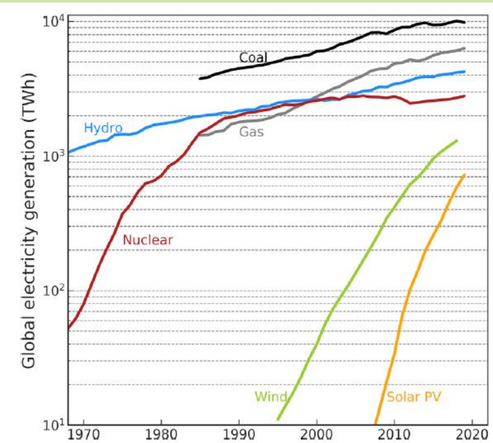
source: IPCC, 2020. 6th Assessment Report WG III

Solar PV Installations: past and near future





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.



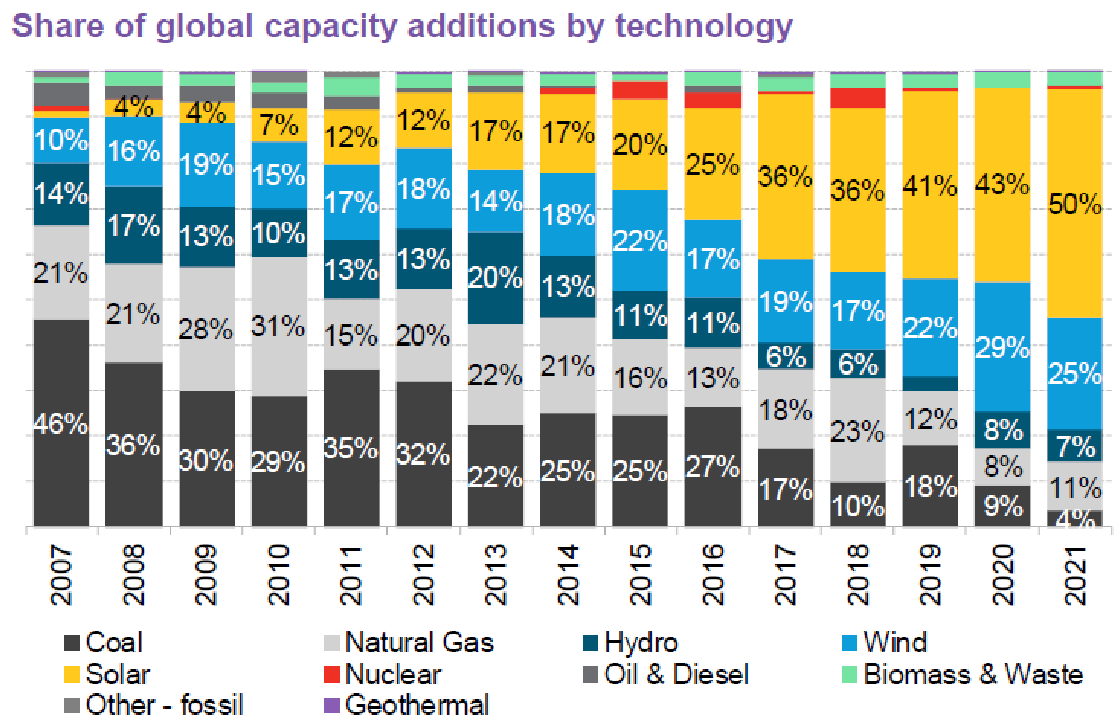
Key insights:

- Low-cost PV dominates one market after another, now Power-to-X plants
- Silicon manufacturing capacity soon around 1 TW/a
- No energy source ever phased in that steeply as PV

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

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

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

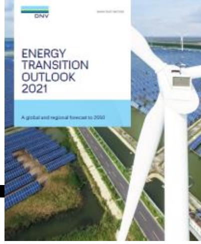
Fossil-nuclear generation will be increasingly irrelevant

Key insights:

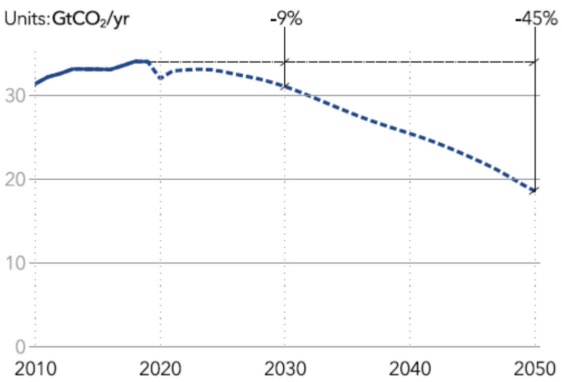
- PV and wind power dominate new installations, with clear growth trends for PV
- Hydropower share declines, a consequence of overall capacity rise, and sustainability limits
- Bioenergy (incl. waste) remain on a constant low share
- New coal plants are close to fade out
- New gas plants decline, with very high gas prices pushing them towards peaking operation
- Nuclear is close to be negligible, the heated debate about nuclear lacks empirical facts

source: BNEF, Power Transition Trends 2022

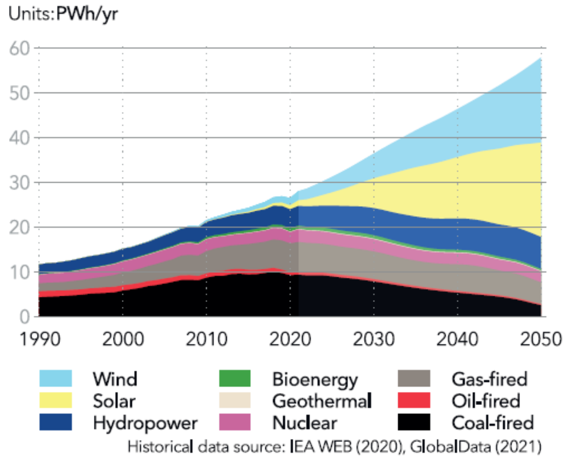
DNV: lack of major transition trends



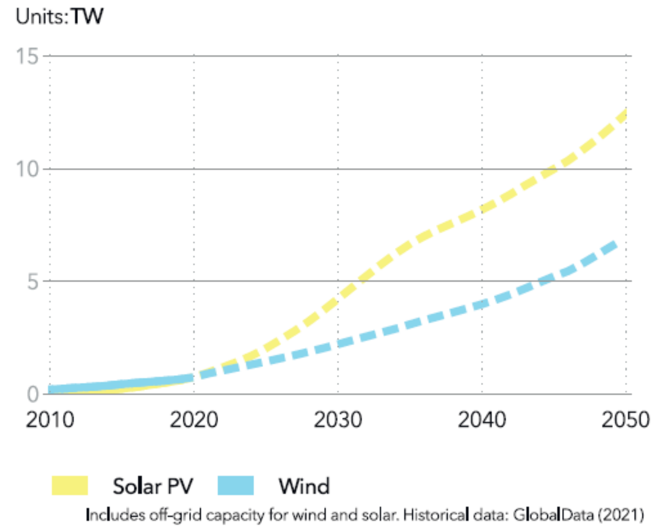
World energy-related CO_2 emissions



World grid-connected electricity generation by power station type



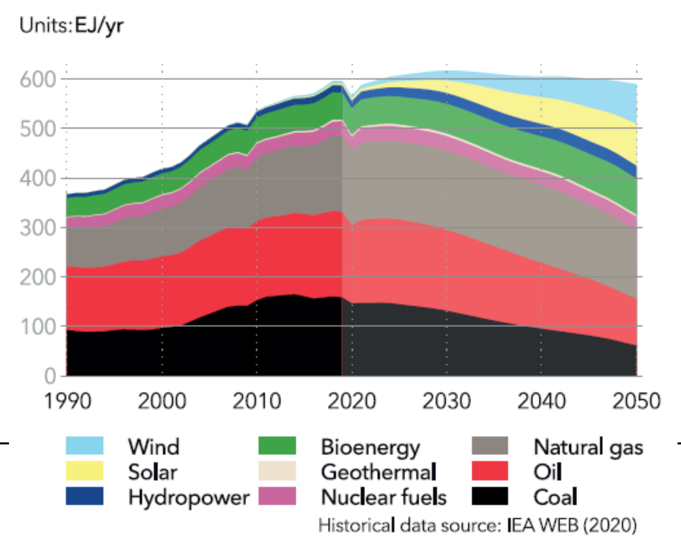
Build-up of solar and wind - global installed capacity



Key insights:

- DNV offers only this single scenario
- Strong violation of the Paris Agreement
- 12.5 TW of PV documents lack of economic insights
- Huge fossil share in primary energy documents massive deficits in electrification
- This scenario seems to be out of the box and may discredit DNV to be taken as a serious consultant

World primary energy supply by source



PV projections of IEA and IRENA

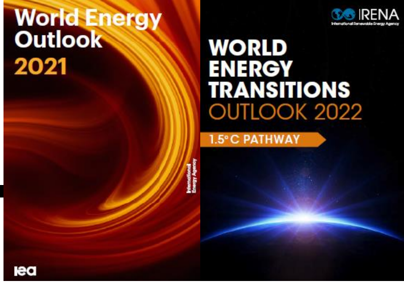


Figure 3.11 ▷ Solar PV and wind installed capacity in the NZE

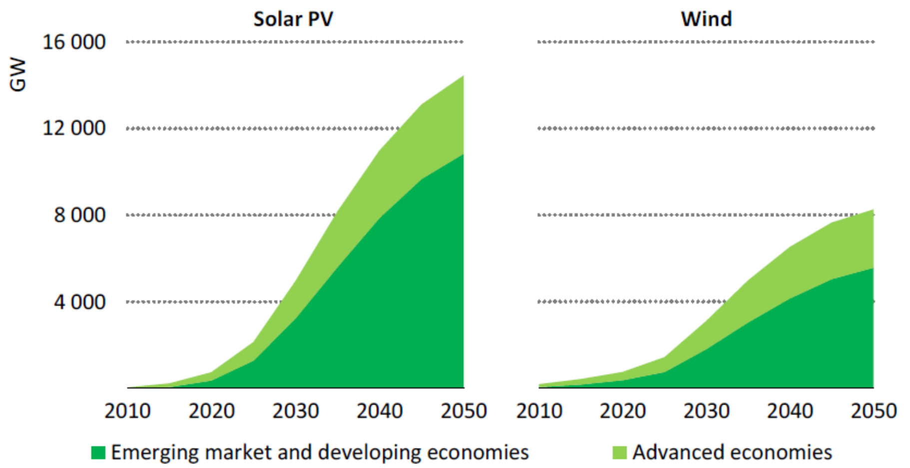
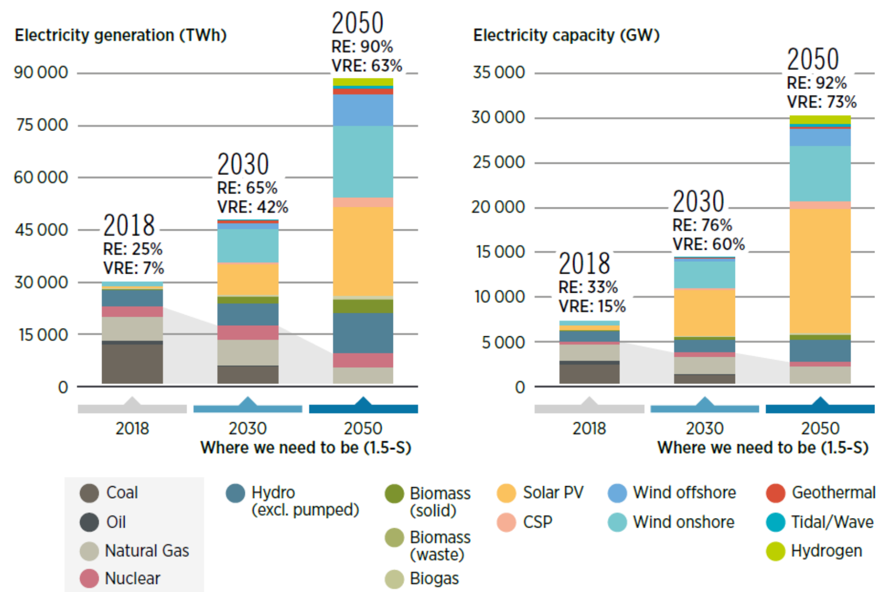


Table 2.6 ▷ Key deployment milestones for renewables

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

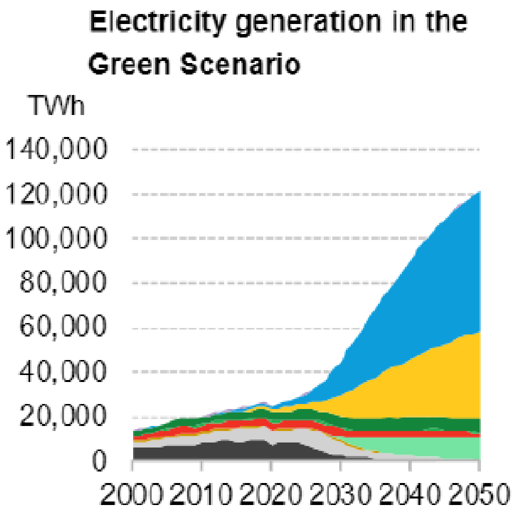
FIGURE 2.3 Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050

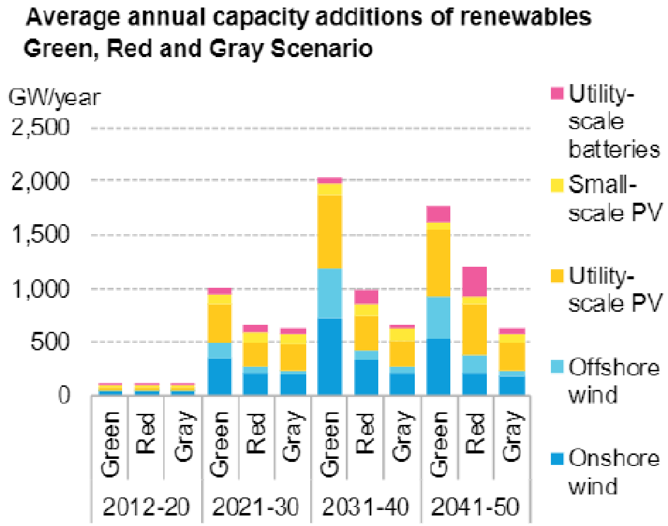


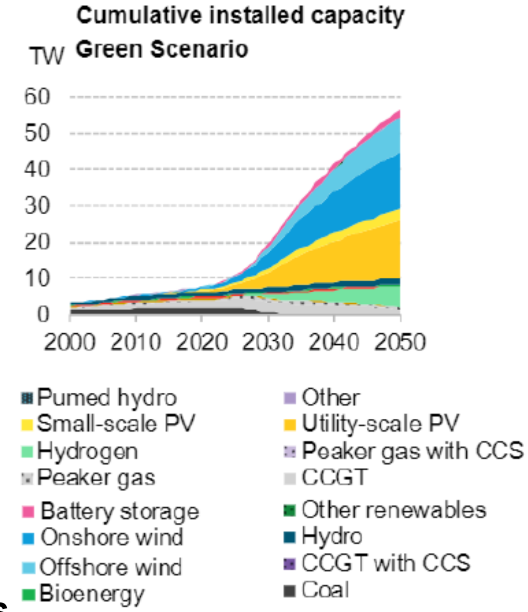
Key insights:

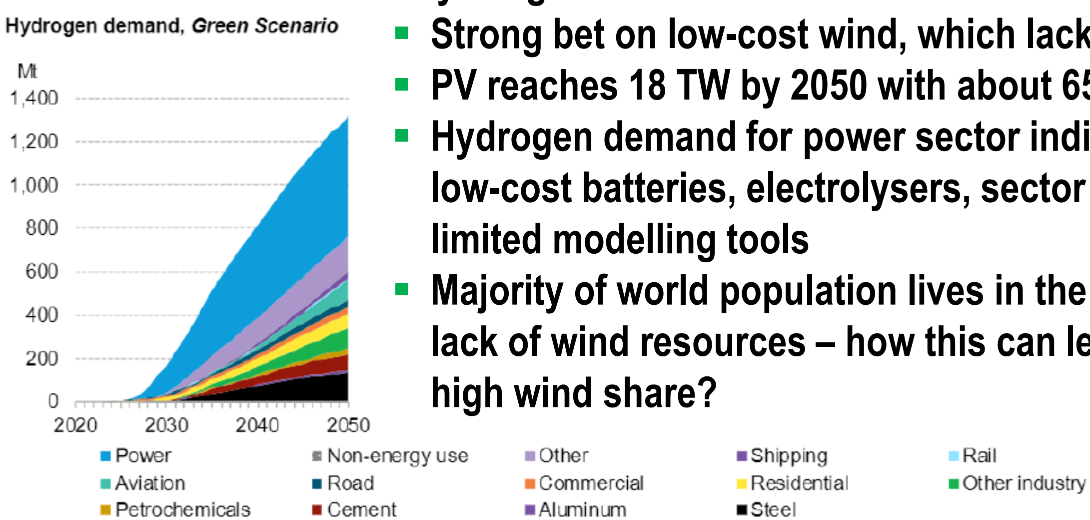
- IEA and IRENA massively underestimated PV in the past
- Not many signals for improvement, as both reach about 14 TW in 2050
- IEA WEO: 630 GW/a in 2030, then zero and negative market growth until 2050 …
- IRENA: 440 GW/a in 2030 to 2050 …
- Both, IEA WEO & IRENA do not seem to have a solid understanding what's required, what's possible, AND what industry is delivering to markets; core deficit: lack of electrification in scenarios

BNEF: strong bet on wind, and high cost PV-battery



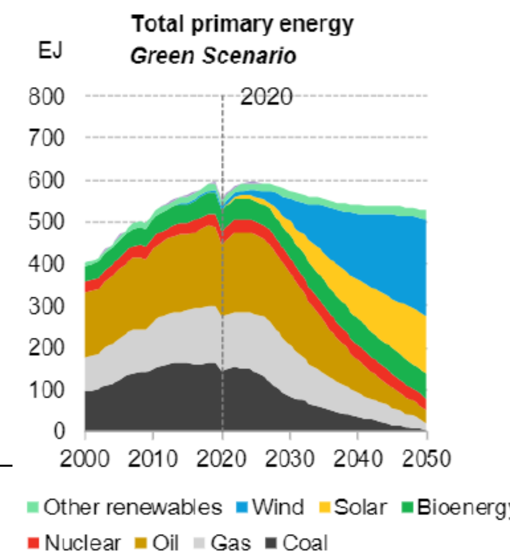






Key insights:

- **Strong bet on low-cost wind, which lacks market trends**
- **PV reaches 18 TW by 2050 with about 650 GW/a in 2040s**
- **Hydrogen demand for power sector indicates lack in low-cost batteries, electrolysers, sector coupling or too limited modelling tools**
- **Majority of world population lives in the sunbelt with lack of wind resources – how this can lead to a very high wind share?**



100% Renewables Energy Systems Research

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 10 June 2022, accepted 19 July 2022, date of publication 25 July 2022, date of current version 29 July 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3193402

TOPICAL REVIEW

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

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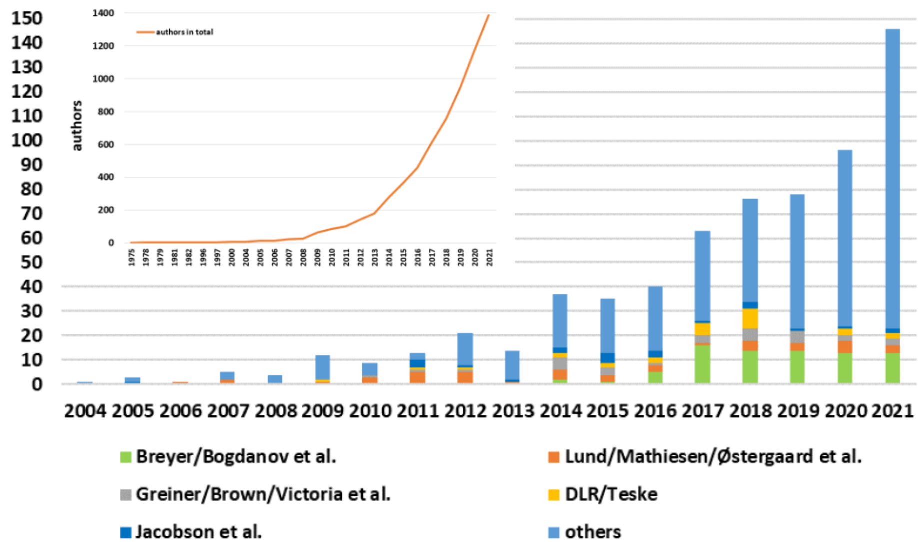
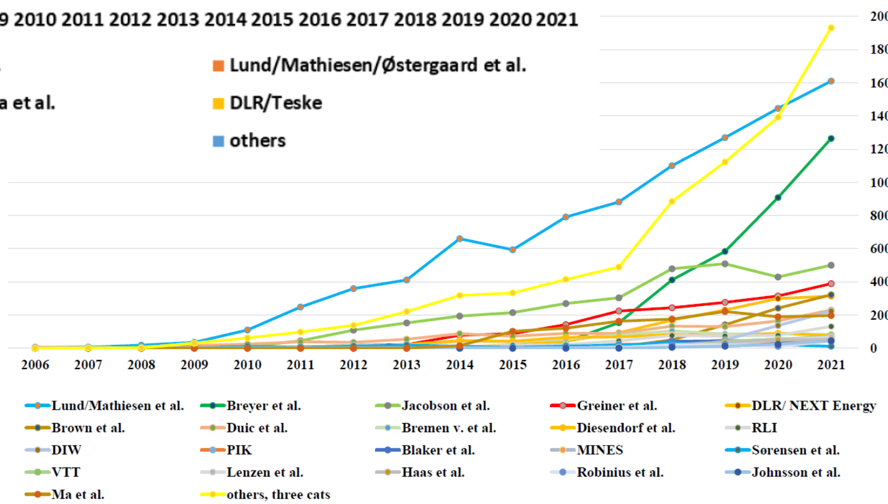
This work was supported in part by Business Finland through the P2XENABLE Project under Grant 8588/31/2019, in part by the Academy of Finland through the Industrial Emissions and CDR Project under Grant 329313, and in part by the LUT University Research Platform "GreenRenew."

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

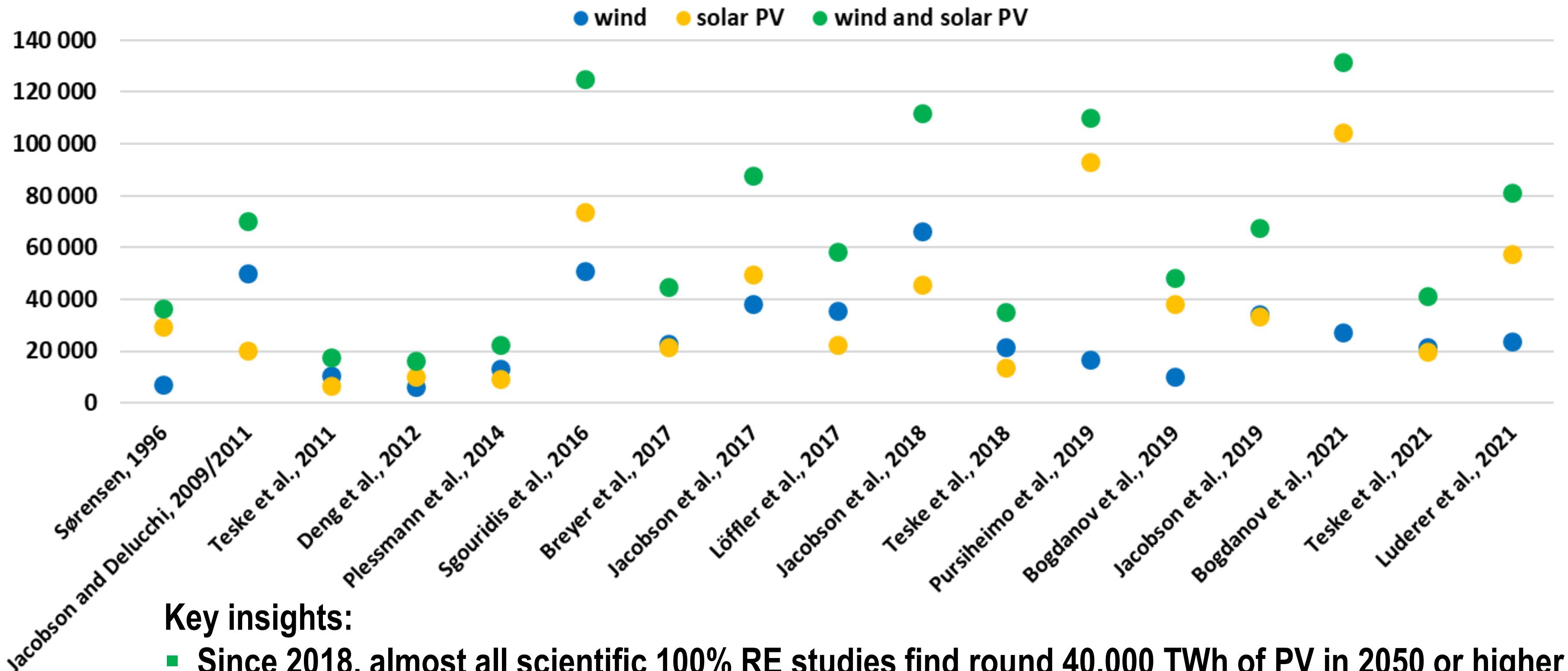


Key insights:

- 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

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

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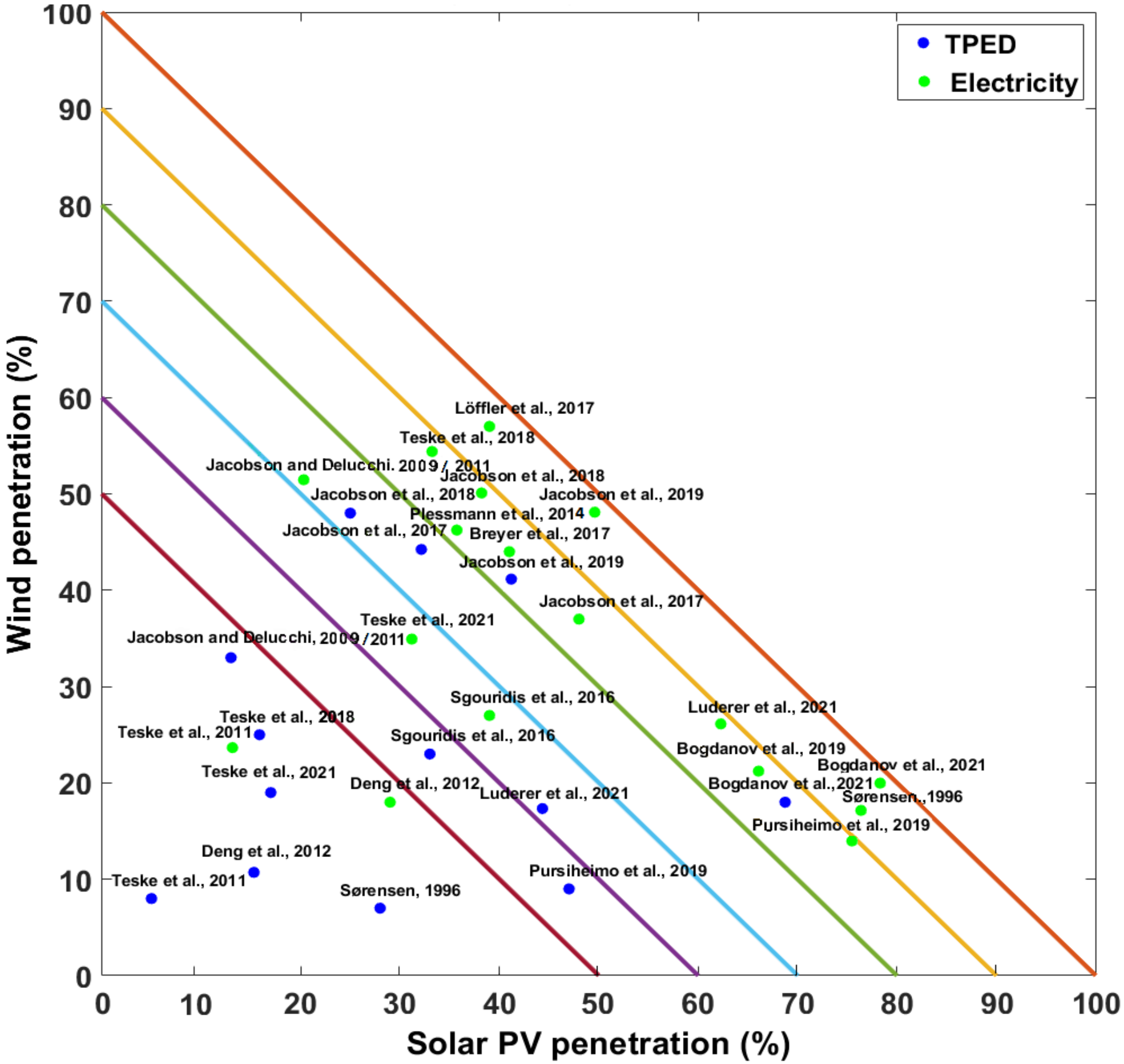
source: Breyer et al., 2022. IEEE Access 10, 78176-78218

Solar PV Share in Global 100% RE studies



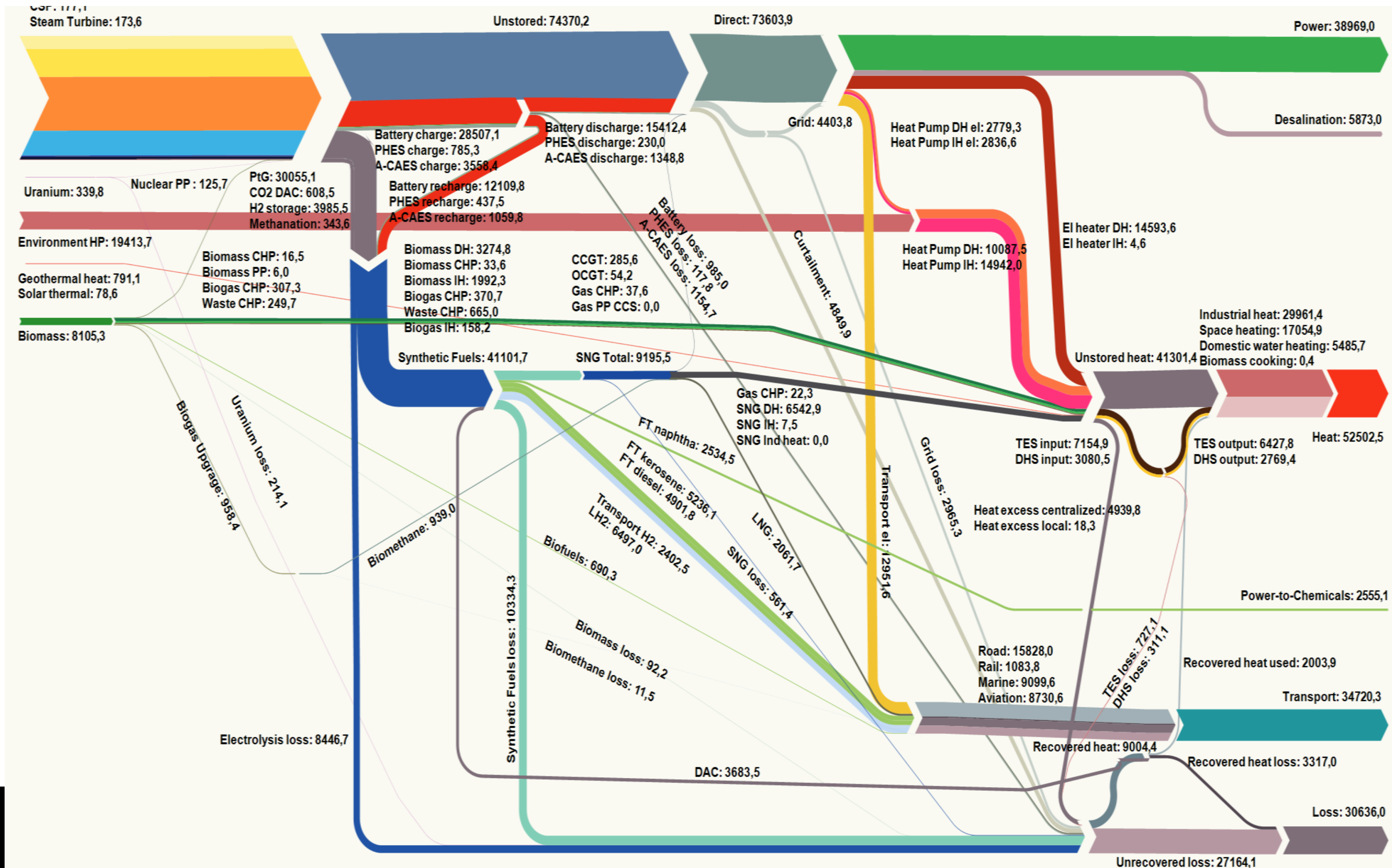
Key insights:

- 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 shares of PV
  - High PV cost assumptions
  - CSP forced in the mix, despite cost
  - Bioenergy forced in the mix, despite biodiversity issues

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

Basis for the 3 TW/a projection: Power-to-X Economy based on Solar PV

- 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 some 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

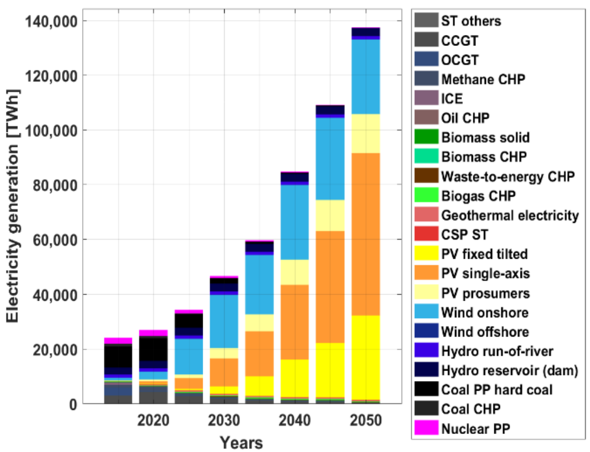


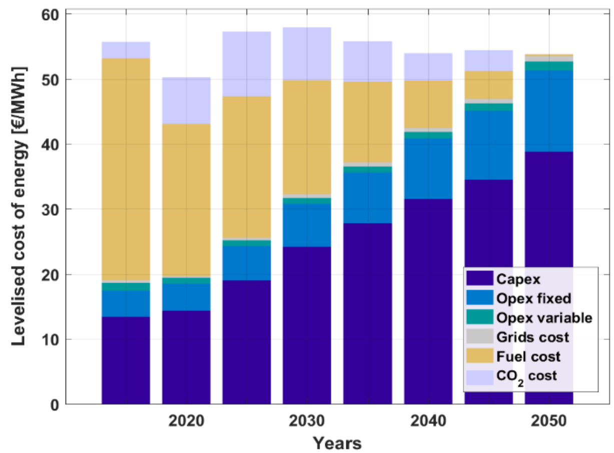
Global

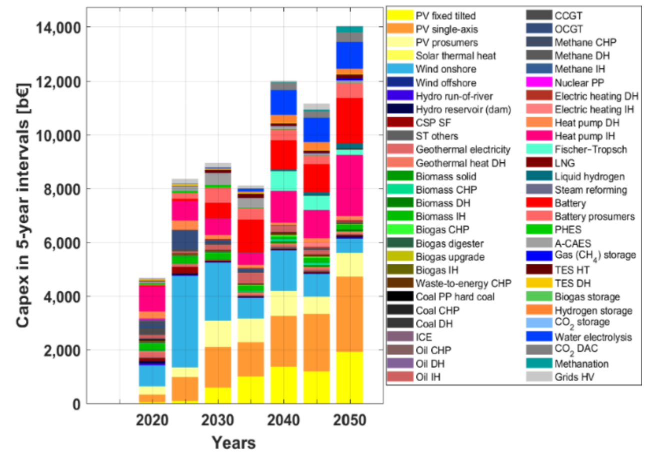
Source: [Bogdanov et al., 2021]

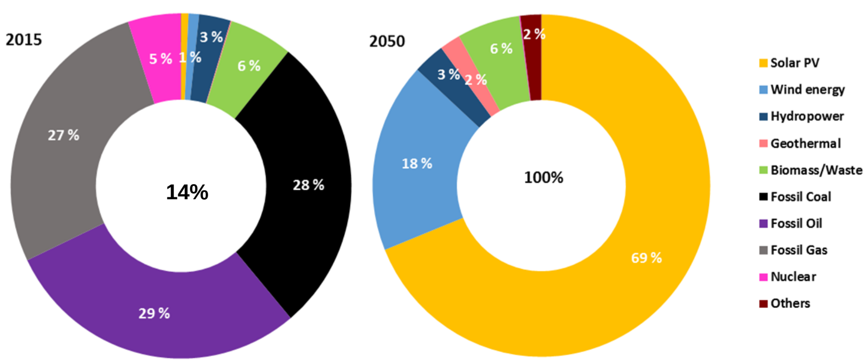
Detailed description of PtX Economy in upcoming WCPEC paper in PIP (if reviewers like it)

100% Renewable Energy System by 2050







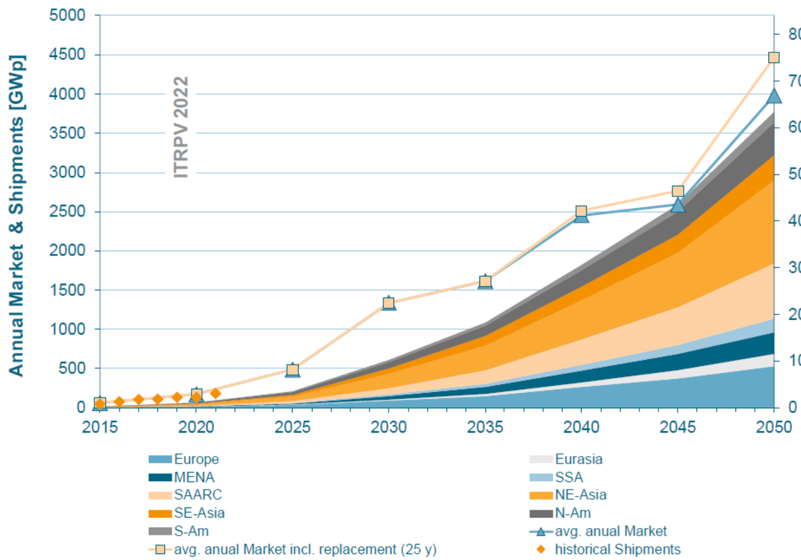


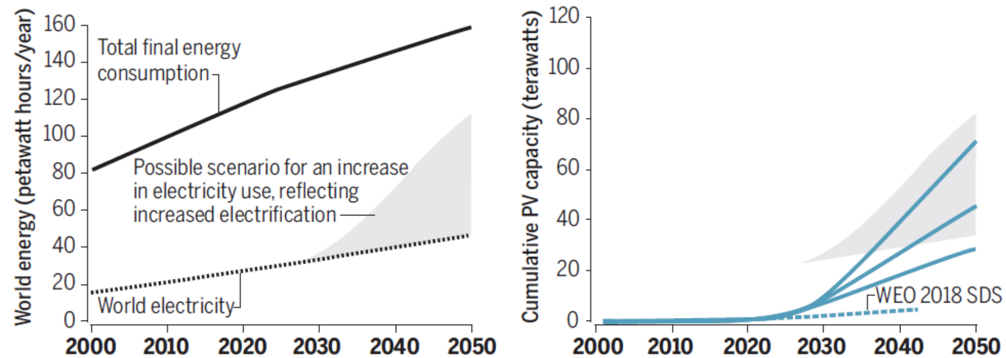
Key insights:

- 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
- 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





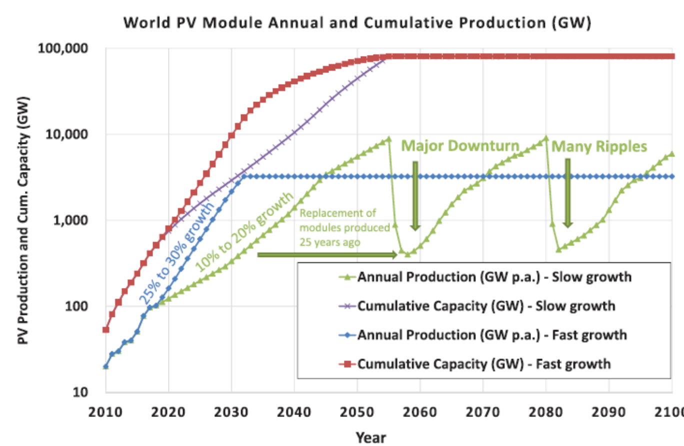


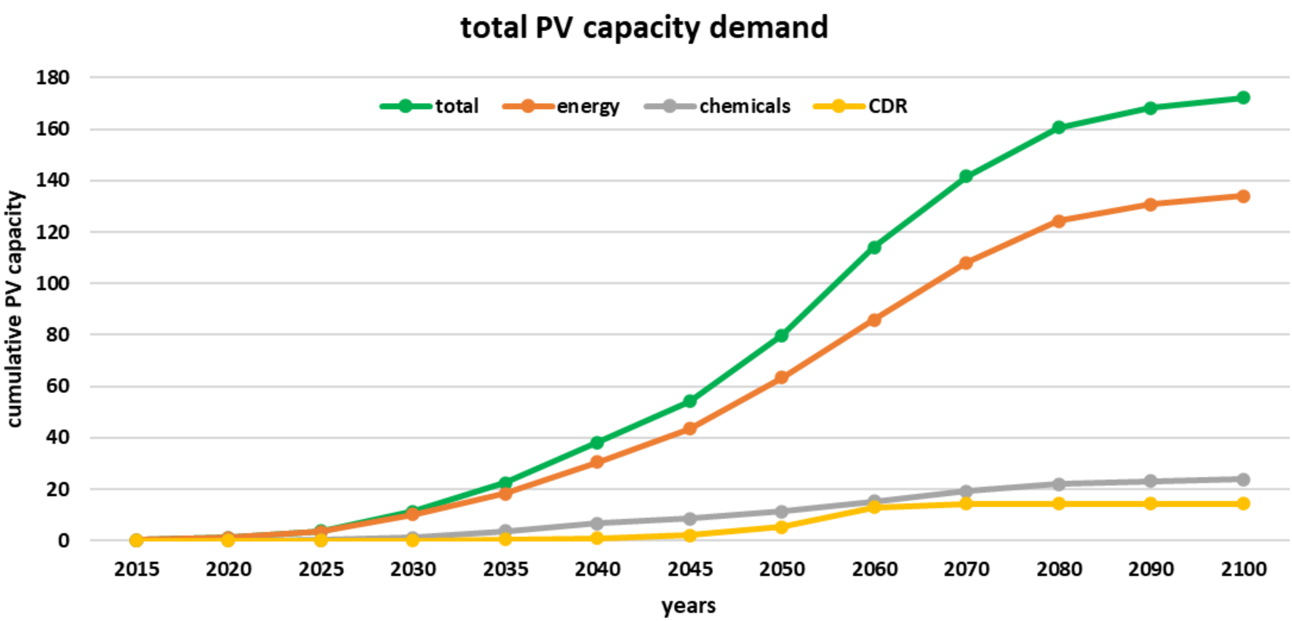
FIG. 4. Slow growth scenario of the PV industry would require increasing the annual production volume to almost 10 GW p.a. with a risk of a major downturn in 2055 and several ripples every 25 years, compared to a fast growth scenario of 25% p.a. minimum, bringing the annual production to a stabilized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

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

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

Is 3 TW/a sufficient?



Assumptions:

- energy-industry-CDR focus
- no one left behind by 2100
- 350 ppm/ 1.0ºC climate target
- based on Bogdanov et al. (2021), Ram et al./ dena (2020), Breyer et al. (2020)

Key insights:

- The 63 TW in 2050 scenario neglects: chemical industry, CO_2 removal and global equity by 2100
- Updated PV target 170 TW by 2100 with an increase to about 80 TW by 2050
  - Energy system: 63 TW, chemicals: 14 TW, CO_2 removal (DACCS): 3 TW
- Installation need (simple calculation): 170 TW and 40 years lifetime means about 4 TW/a
- The 170 TW target was independently suggested by ISE and PIK researchers

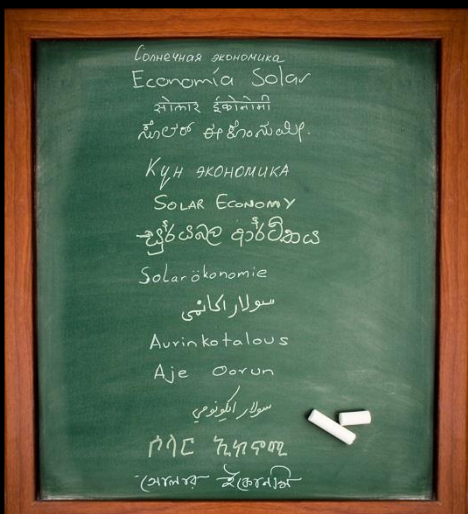
source: Breyer et al., 2021. Solar PV in 100% RE systems. Chapter 14 in Photovoltaics Volume In: Encyclopedia of Sustainability Science and Technology, online

Summary

- Global energy transition reaching zero CO_2 emissions by mid-century is feasible
- Electrification is low-cost and highly efficient
- PV benefits most from the comprehensive electrification (direct, indirect)
- 3 TW/a to be expected in 2040s
- Several key PV stakeholders and experts share the 3 TW/a target
- The Power-to-X Economy is THE major driver for PV demand
- Major stakeholders (international organisations, consultants) lag behind

- Remember Gandhi: laugh, ignore, fight, always known …

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



SCIENTISTS FOR FUTURE

NEO CARBON ENERGY
TRUST IN RENEWABLE.

all publications at: www.scopus.com/authid/detail.uri?authorId=39761029000
new publications also announced via Twitter: @ChristianOnRE

Open your mind. LUT.
Lappeenranta University of Technology

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

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

Basis for the 3 TW/a projection: Power-to-X Economy based on Solar PV

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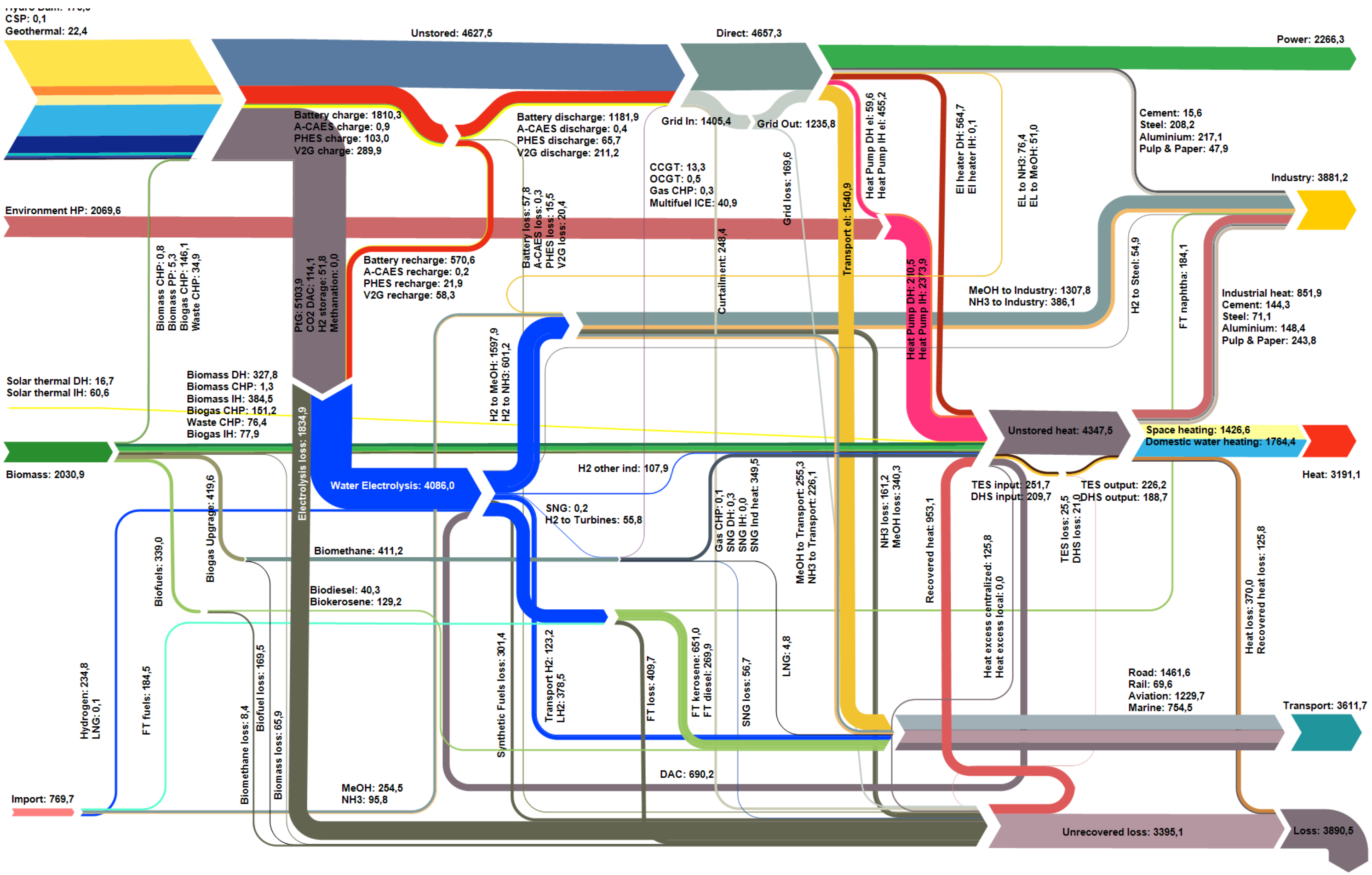
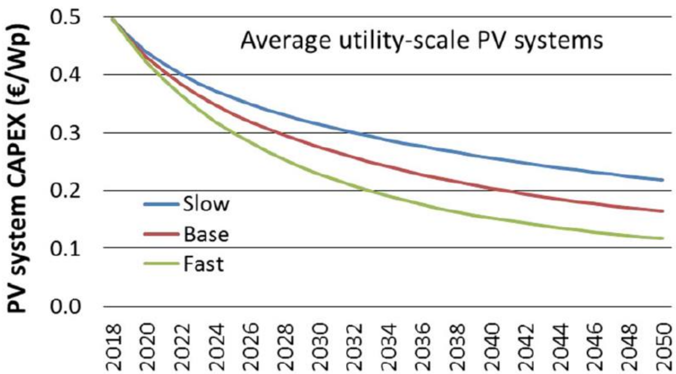
- Core characteristic of energy in future: Power-to-X Economy
  - Primary energy supply from renewable electricity: mainly PV plus some wind power
  - Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
  - Indirect electrification for e-fuels (marine, aviation),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

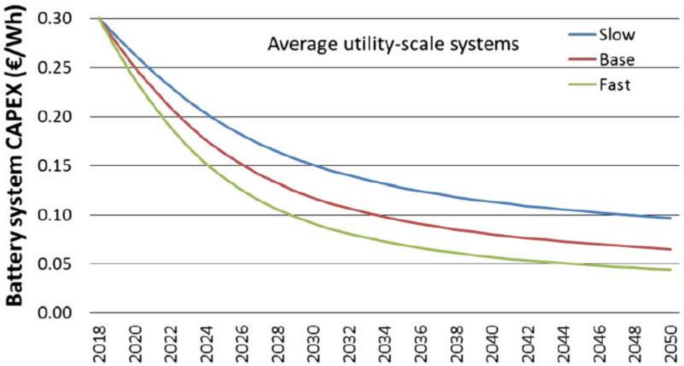


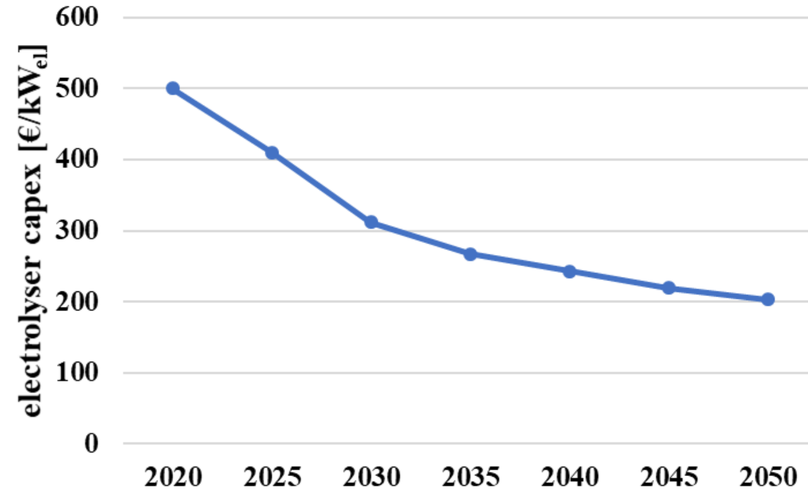
Europe

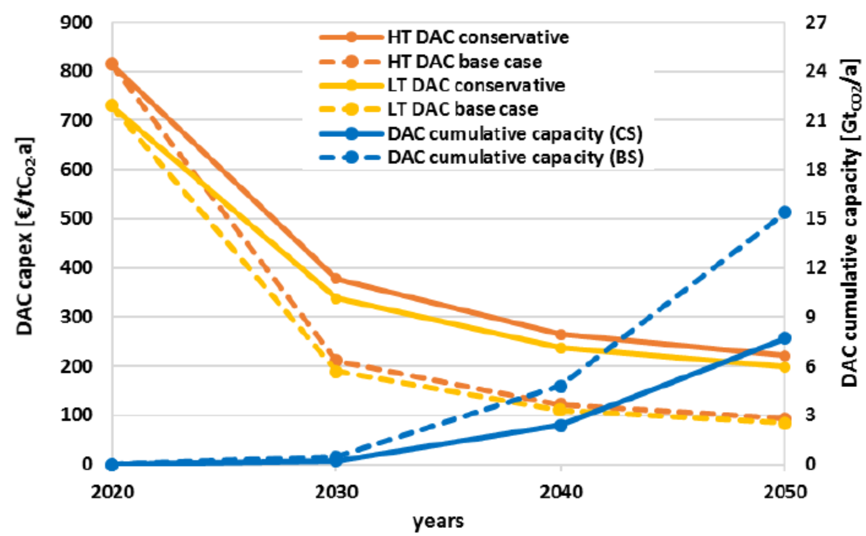
Source: [Greens/EFA, 2022]

Key Diagrams for massive RE induced Change







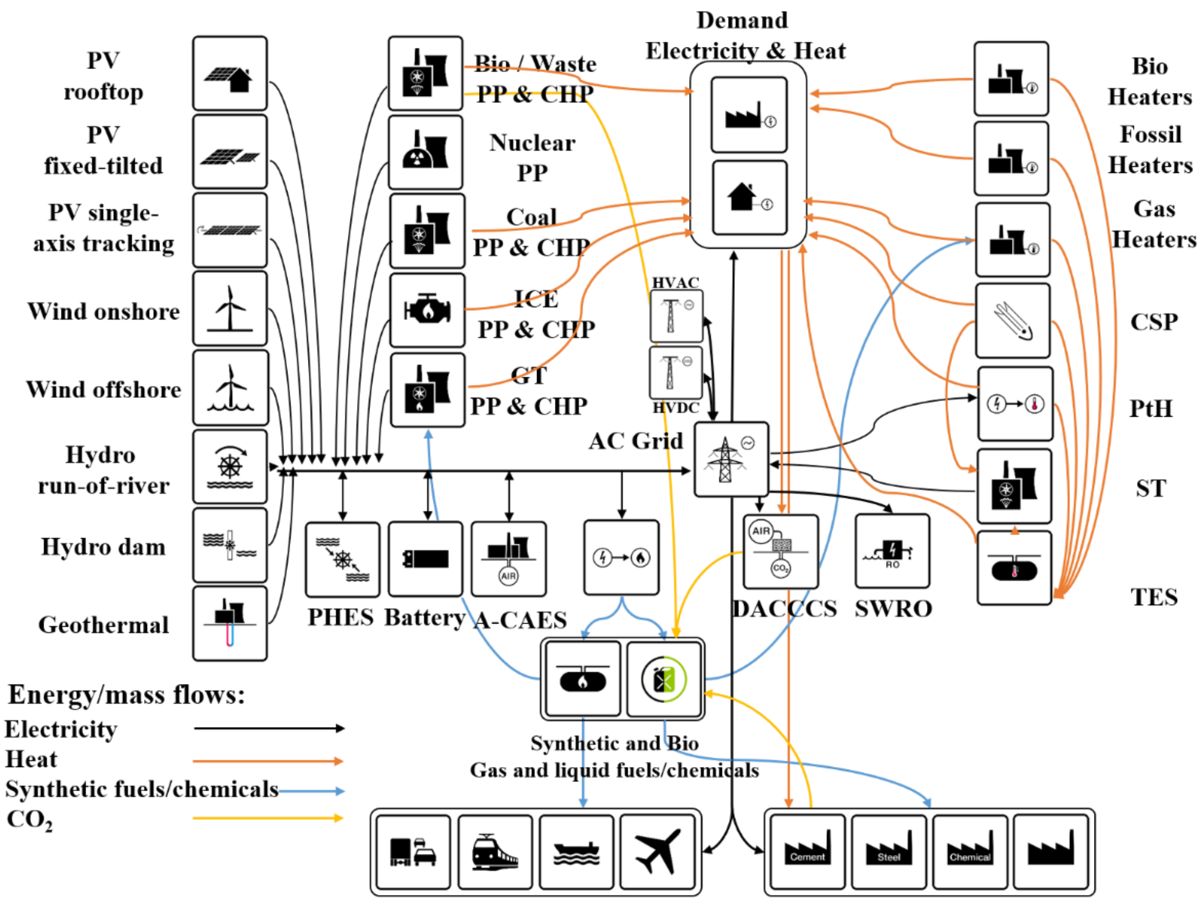


Key insights:

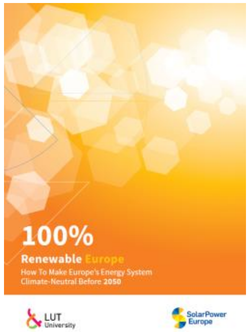
- massive continued cost decline for solar PV, wind, battery, electrolysers, CO_2 DAC
- massive pressure to eliminate all fossil fuels
- massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand

References:
PV, battery: Vartiainen et al., Progress in PV
Electrolyser: LUT model assumptio, Nature
CO_2 DAC: Fasihi et al., J of Cleaner Prod

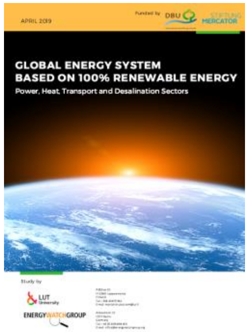
LUT Energy System Transition Model



recent reports



link to report



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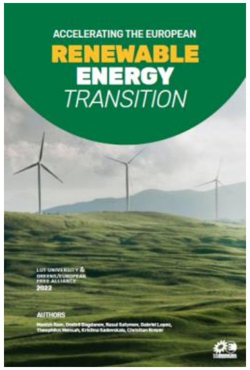

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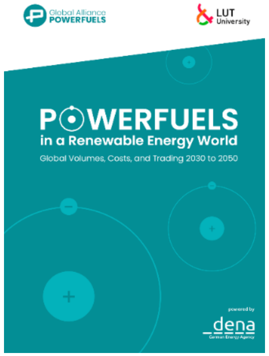


link to report

Key features:

- full hourly resolution, applied in global-local studies, comprising about 120 technologies
- used for several major reports, in about 50 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (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

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

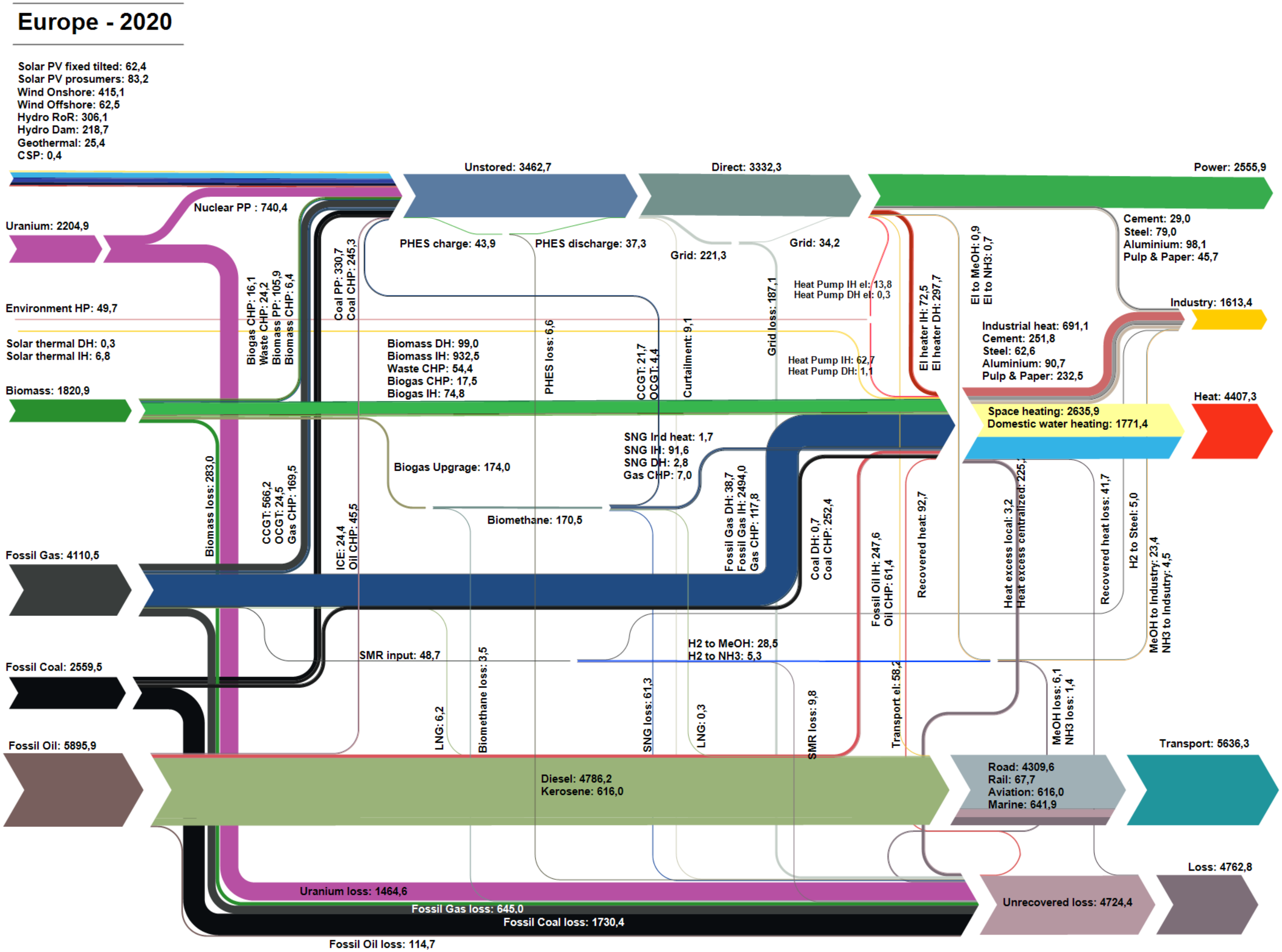
Leading Energy System Models ranked by number of published journal articles. Some selected key functionalities of the leading ESMs are displayed, as they are regarded to be key for further progress in the field of 100% RE system analyses. Selection criterion had been more than five articles detected 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

System Outlook – Energy Flows in 2020



source: published, September 7, Brussels, ordered by a group of parties in the European Parliament

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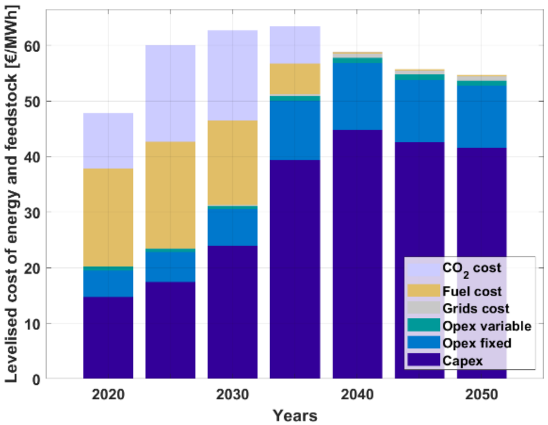
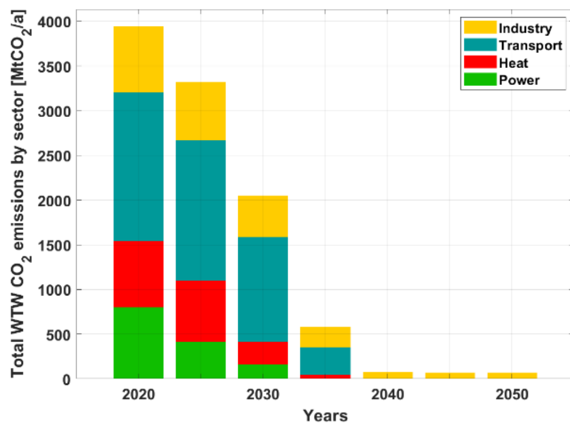
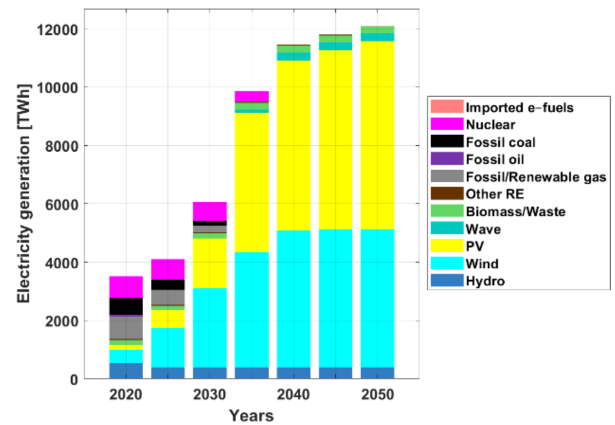
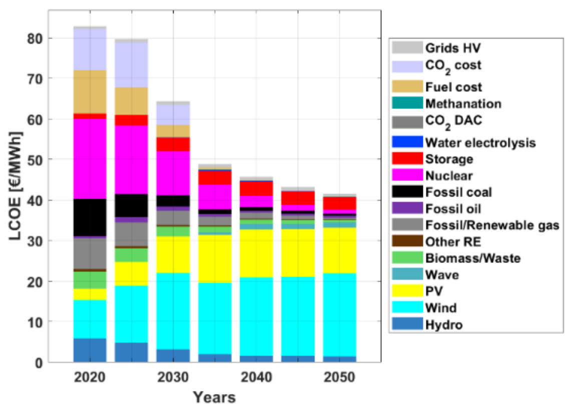
Highly Ambitious Energy-Industry Transition for Europe

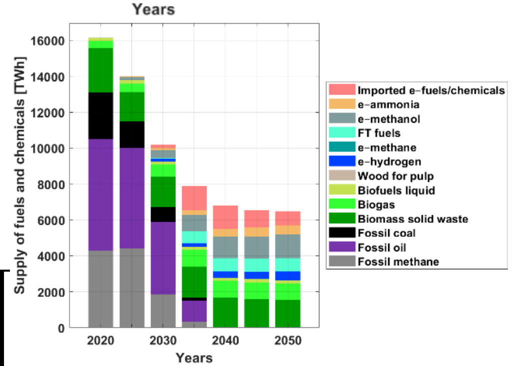
publication in September commissioned by a major group of parties in the European Parliament









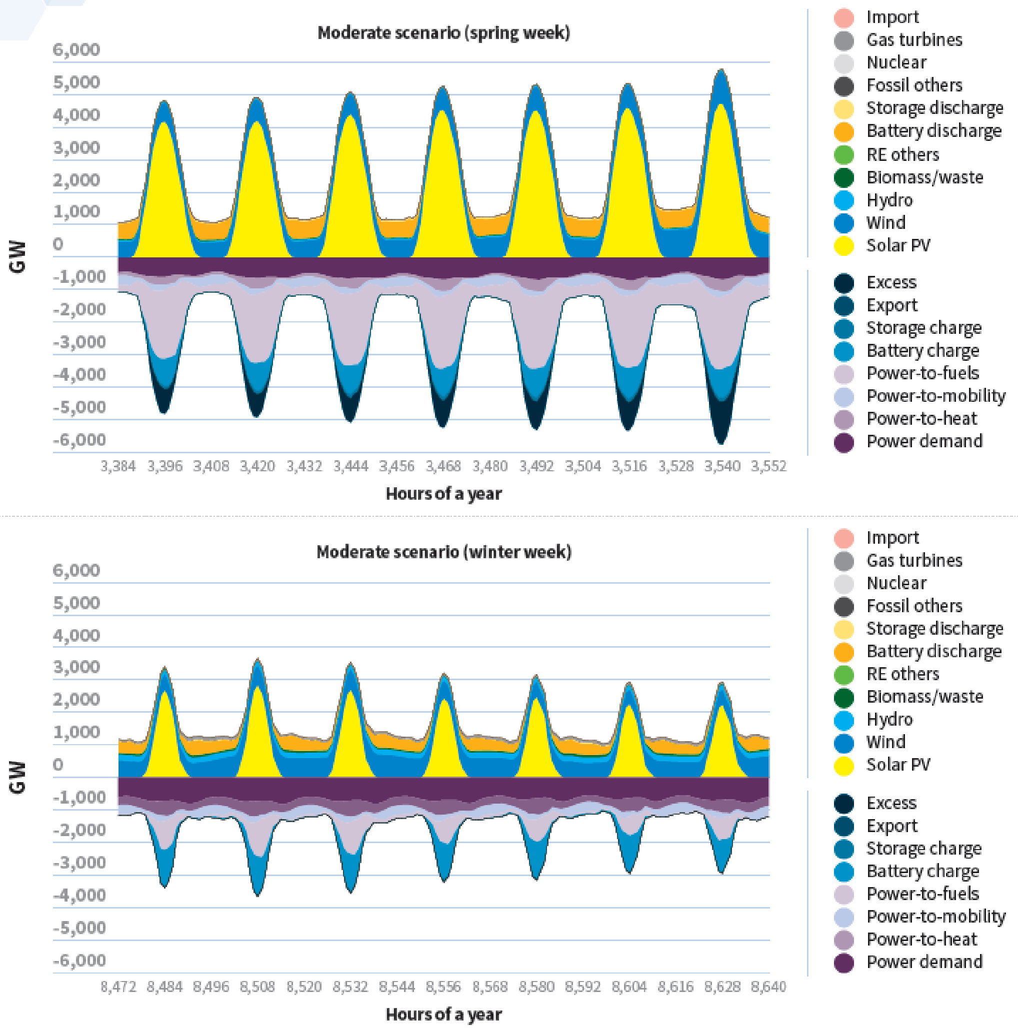


- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: 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
- 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: published, September 7, Brussels, ordered by a group of parties in the European Parliament

Hourly Operation of the Energy System (Europe)

FIGURE 4.8 HOURLY OPERATION OF THE EUROPEAN ENERGY SYSTEM



Key insights:

- Week of least renewables supply (winter) and most renewables supply (spring) 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-fuels) which convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability
- Massive ramp rates in the energy system have to be managed, as well as forecasting errors require balancing
- Collaboration with SolarPower Europe.

Global PV Demand Projections
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source: [SolarPower Europe/ LUT, 2020. 100% Renewable Europe]