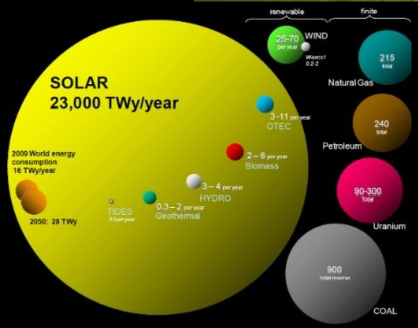

Insights from Long-Term Energy Scenarios: The 100% Renewable Energy Opportunity

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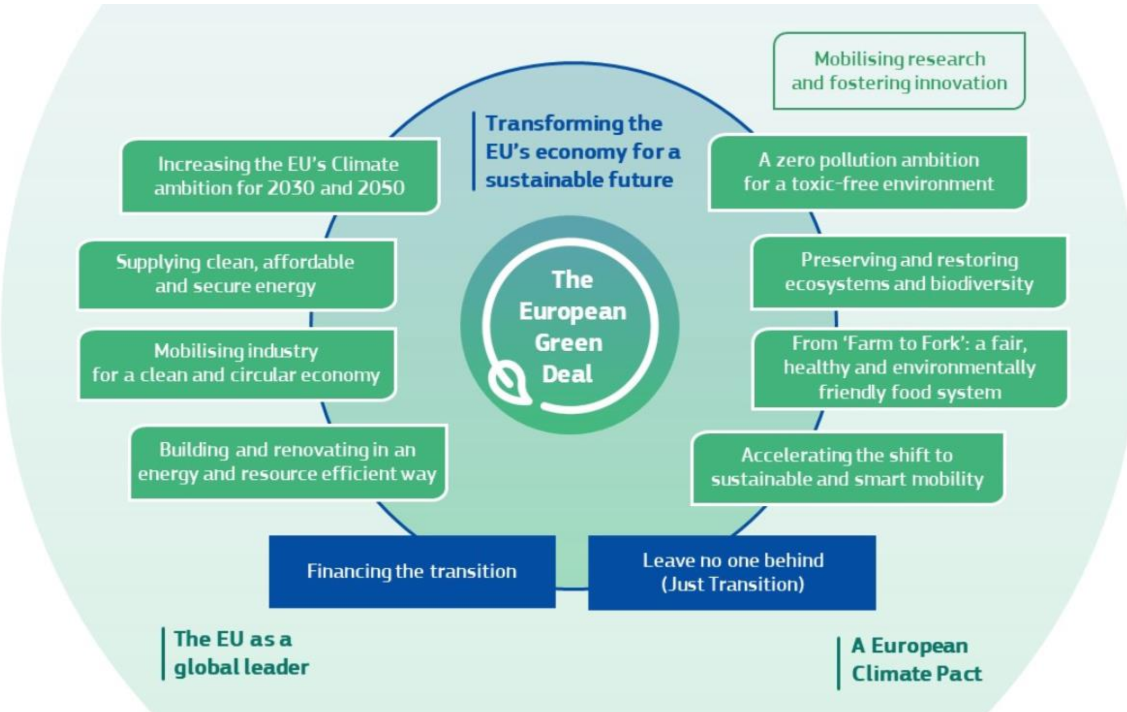
Lappeenranta University of Technology

Christian Breyer
LUT University, Finland
IAEE webinar
November 23, 2020

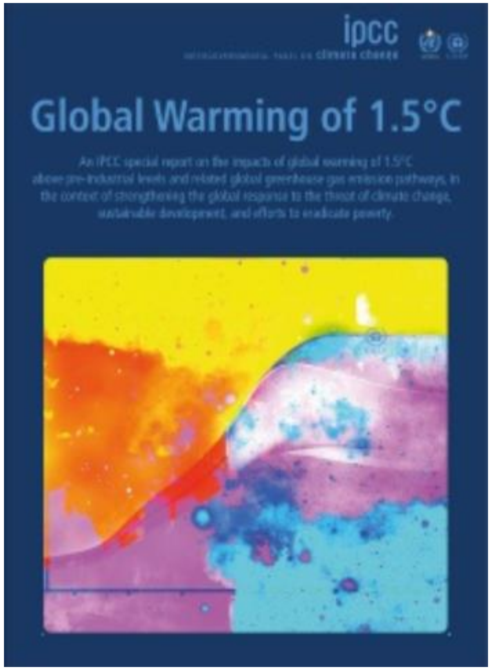
Background

European Green Deal



Paris Agreement

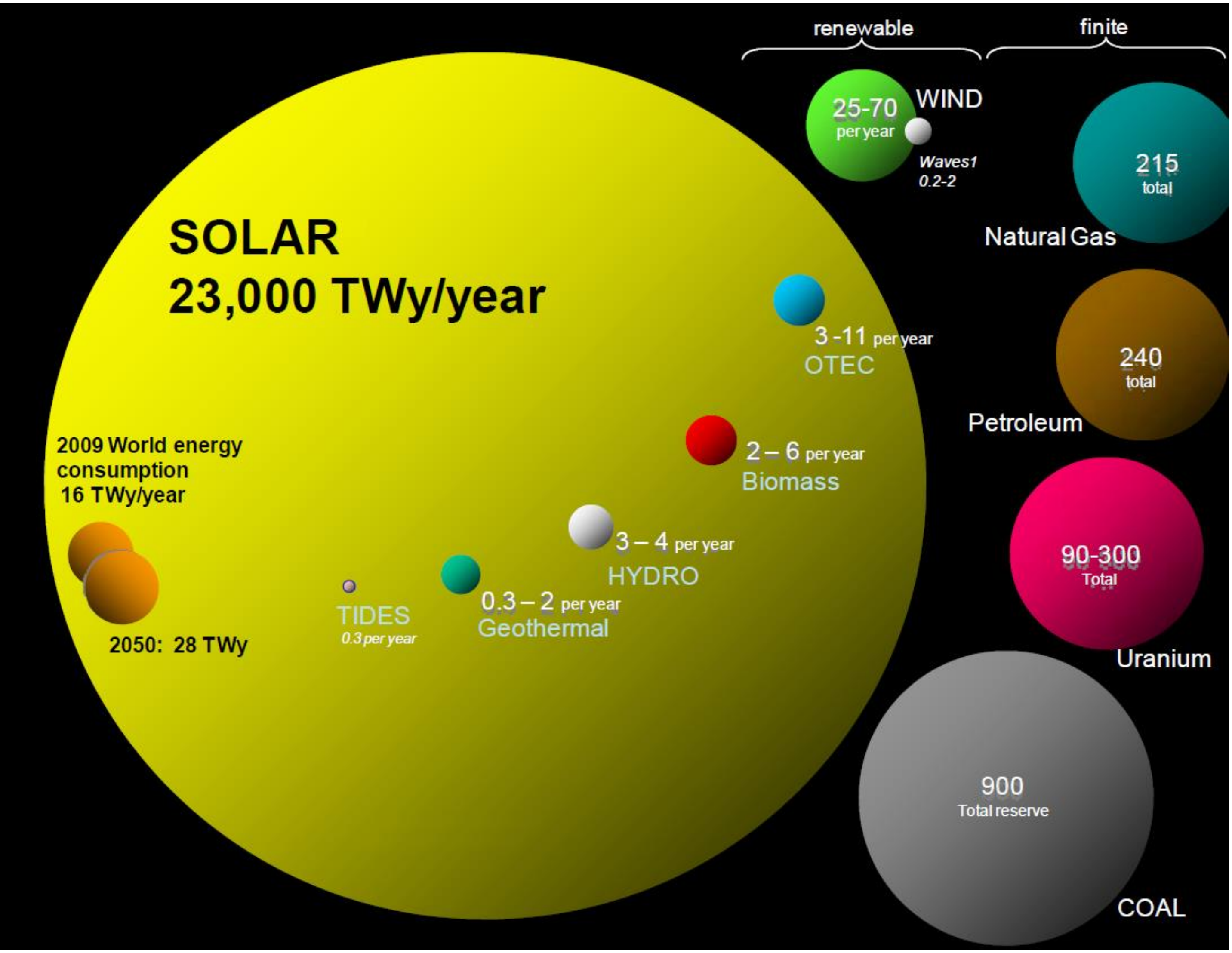
("well below 2ºC")



What does it mean?

- (net) zero greenhouse gas (GHG) emissions by 2050 are mandatory
- negative GHG emissions are costly, risky, with unclear responsibilities
- thus zero GHG emissions is the real target for the energy system

Resources and Energy Demand



Key insights:

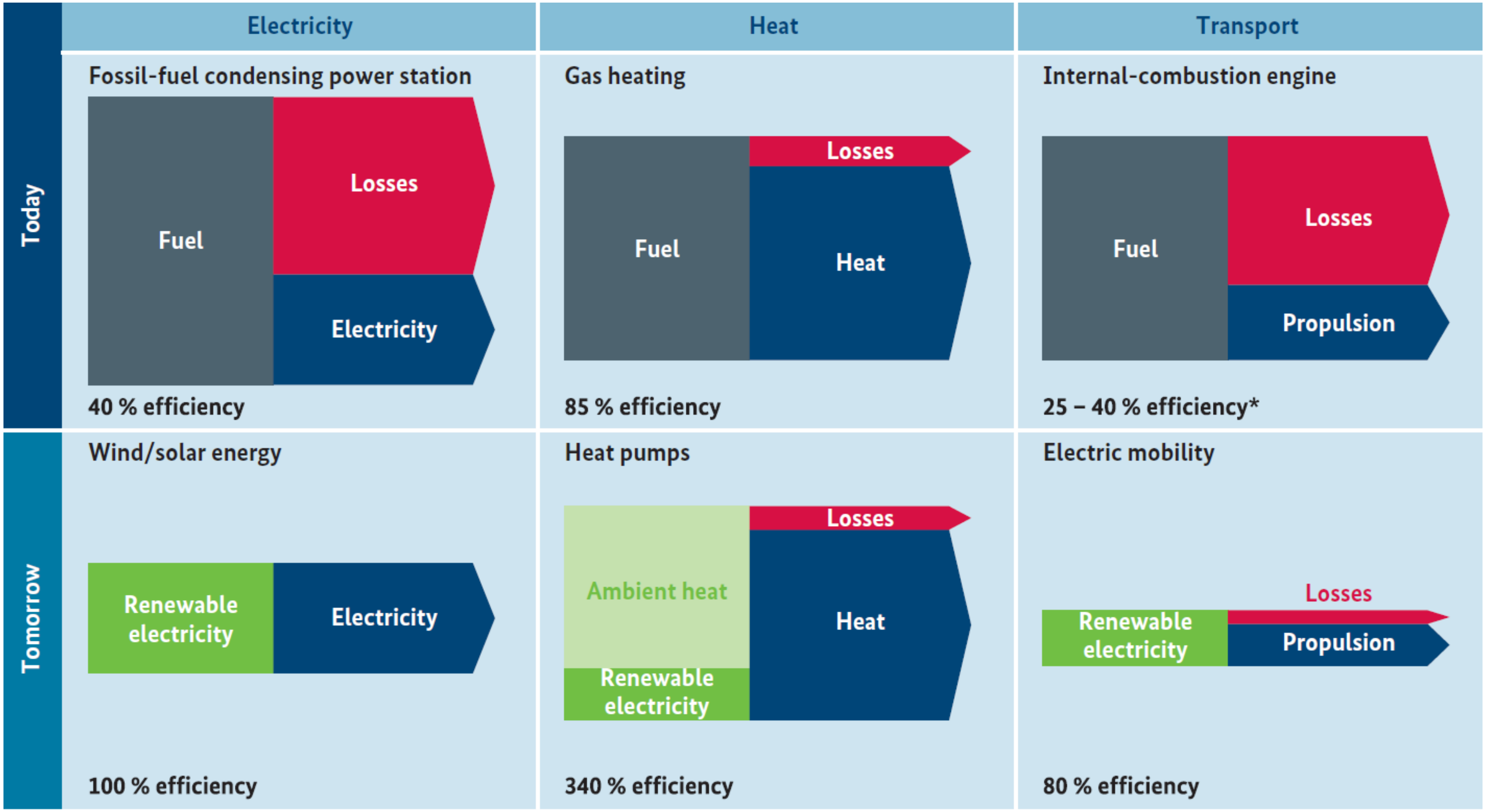
- no lack of energy resouces
- limited conventional resources
- solar and wind resources need to be the major pillars of a sustainable energy supply

Remark:

- conventional resources might be lower than depicted by Perez

source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50

Key Rationale for Electrification: Efficiency

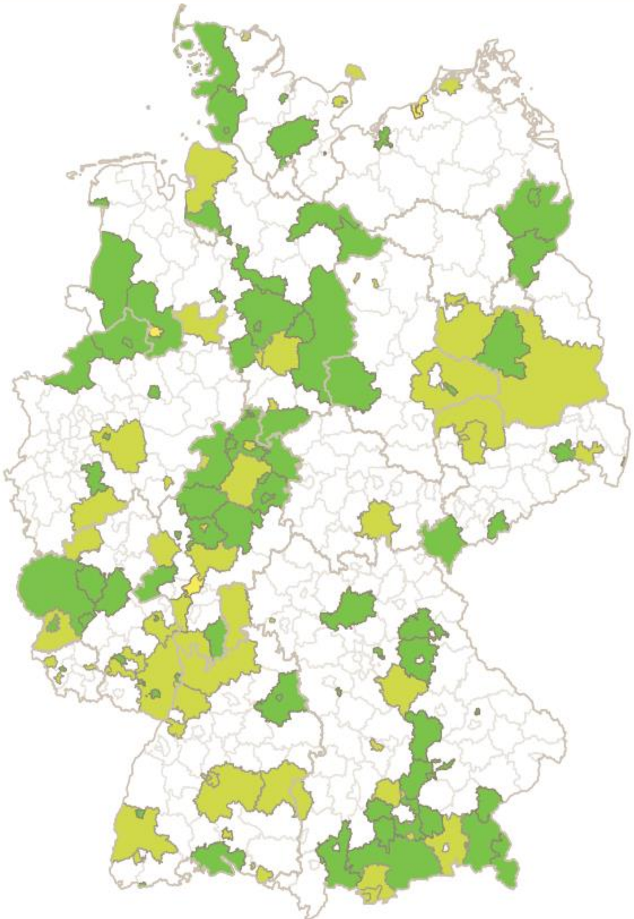


* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

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

100% RENEWABLES

www.go100re.net



www.100-ee.de/

Nov 2016, COP-22, Marrakech:
48 countries (Climate Vulnerable Forum) decided for a 100% RE target

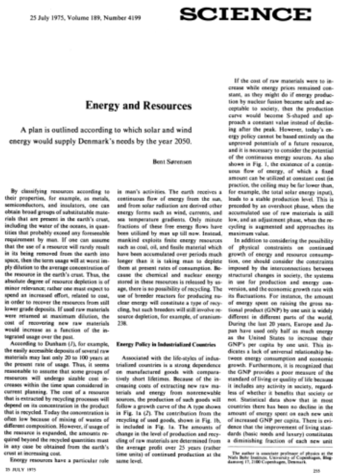
More Countries and States set 100% targets, e.g.:
Denmark, Sweden, **California**, Spain, Hawaii, …

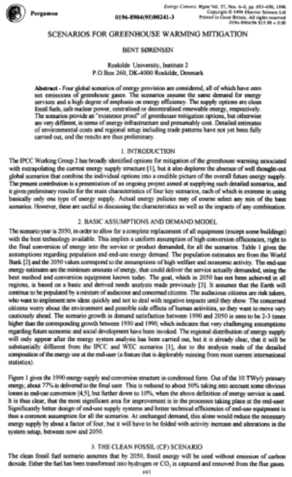
Some Countries are already around 100%, e.g.:
Norway, Costa Rica, Uruguay, Iceland, …

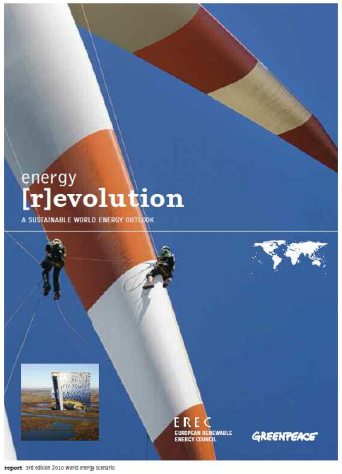
Cities with 100% RE targets, e.g.:
Barcelona, Masdar City, Munich, Masheireb, Downtown, Doha, Vancouver, San Francisco, Copenhagen, Sydney, …

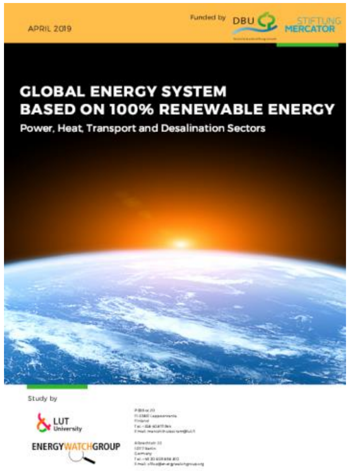
Companies with 100% RE targets, e.g.:
Google, Microsoft, Coca-Cola, IKEA, Wärtsilä, Walmart, …

Major Milestones on 100% RE Research



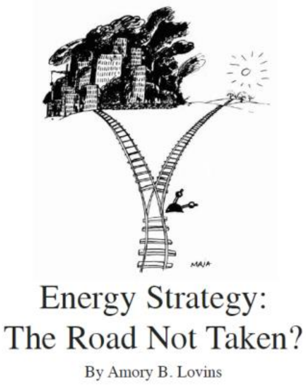


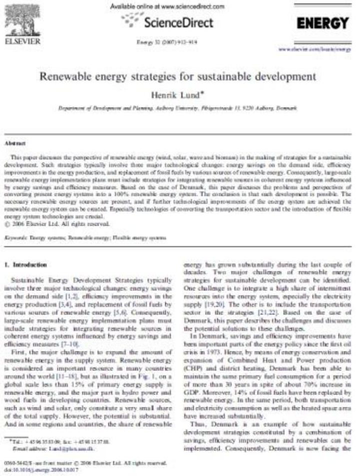


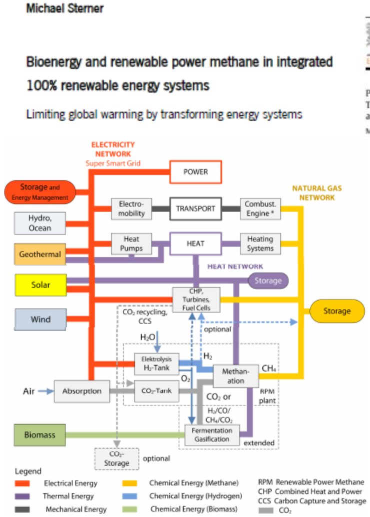


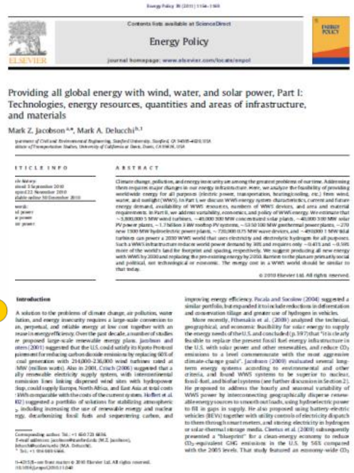
[Sørensen, 1975](#) | [Sørensen, 1996](#) | [Czisch, 2005](#) | [Greenpeace, 2010](#) | [LUT/EWG, 2019](#)

[Lovins, 1976](#) | [Lund, 2007](#) | [Sterner, 2009](#) | [Jacobson, 2011](#) | [Bogdanov et al. 2019](#)

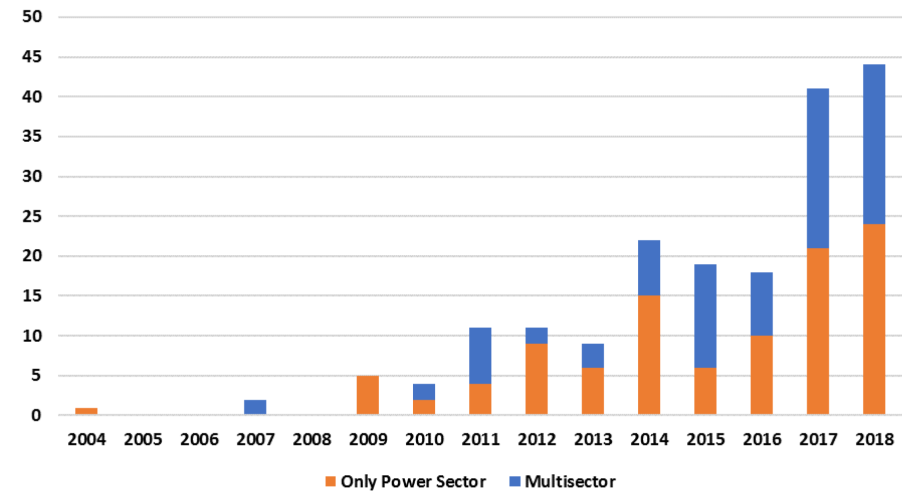


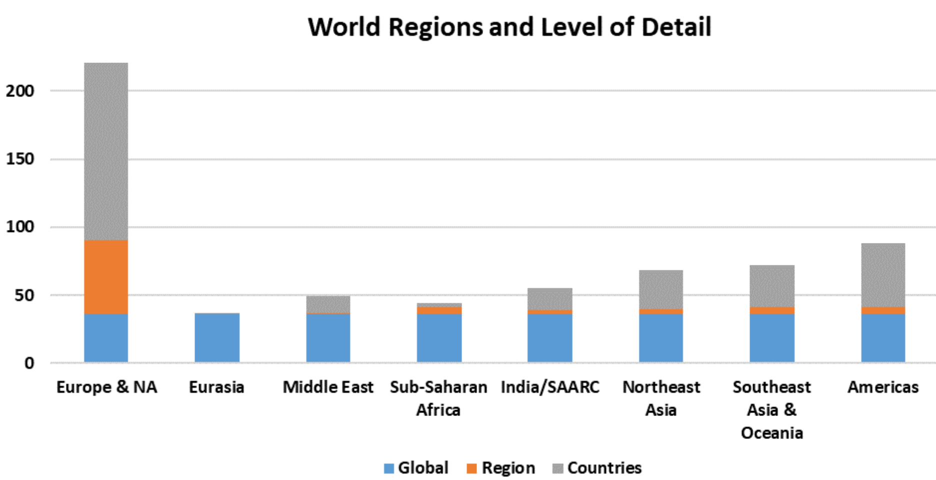


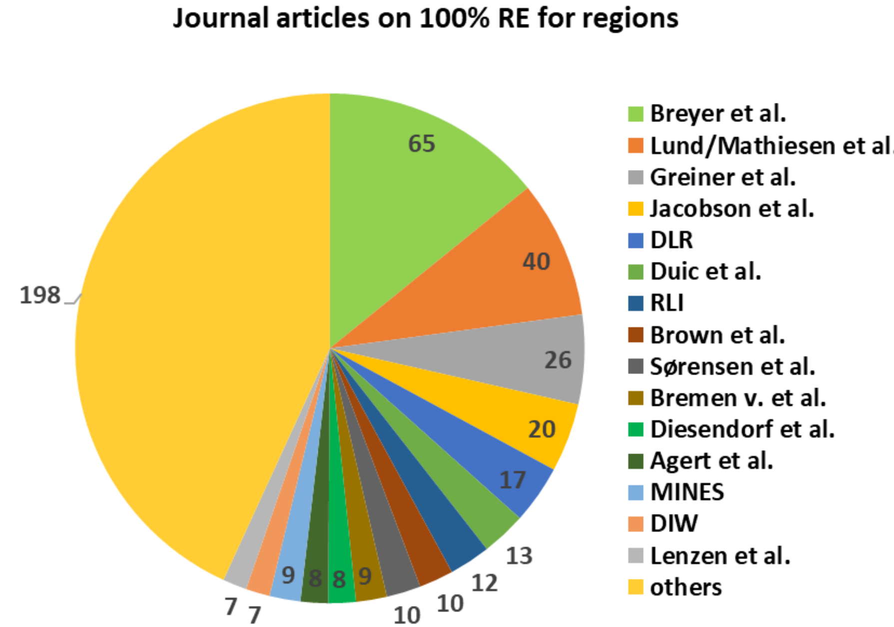




100% RE Articles in recent Years





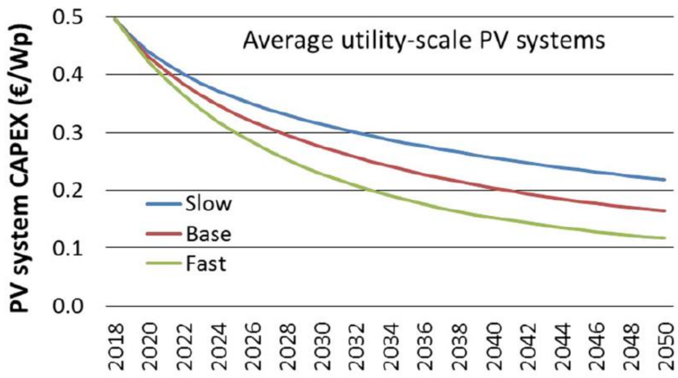


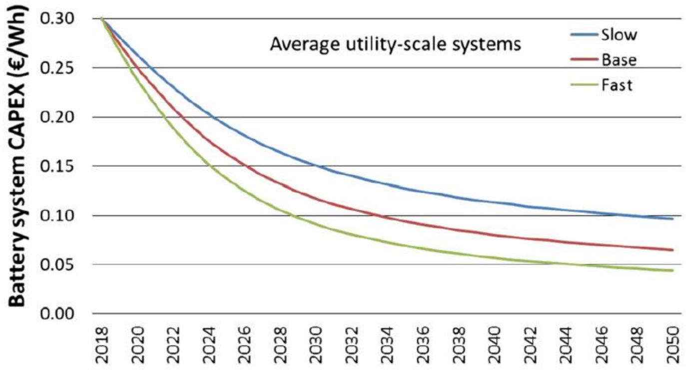
source: Hansen, Breyer, Lund H., 2019. Energy, 175, 471-480

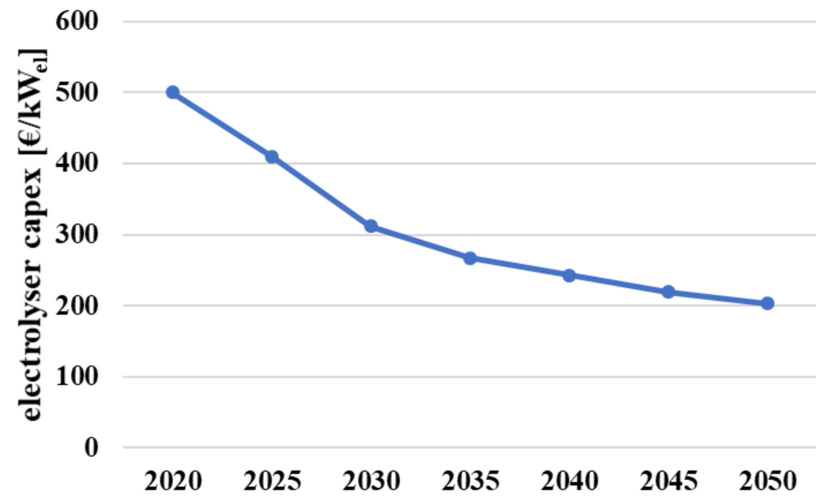
Key insights:

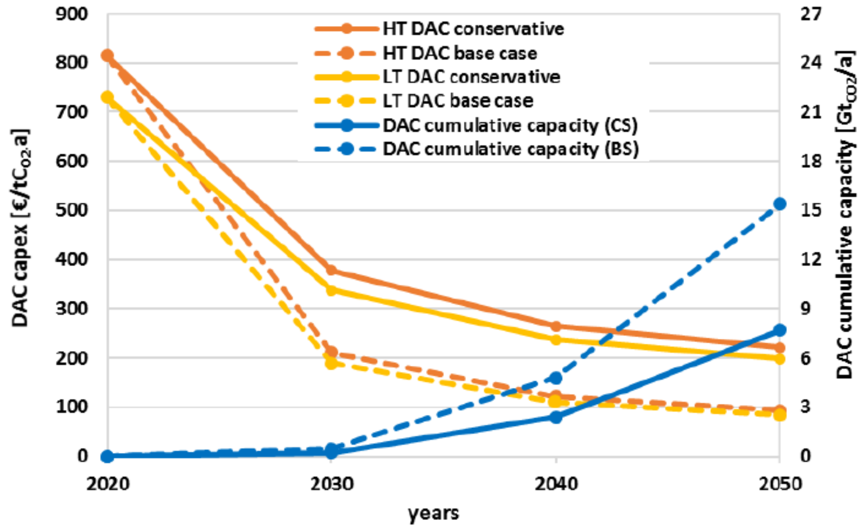
- Research field exists since about 10 years
- Most publications are in hourly resolution
- More multisector publications
- Europe (FI, DK, DE) is hot spot of 100% RE research
- Gaps are in regional coverage and sectoral coverage (industry, NETs), temporal range (21st century)
- Community starts to get impact on neighbouring fields (e.g. IAMs, IPCC), but still ignored for major reports (IEA, IRENA, most governments)

Key Diagrams for massive PV induced Change







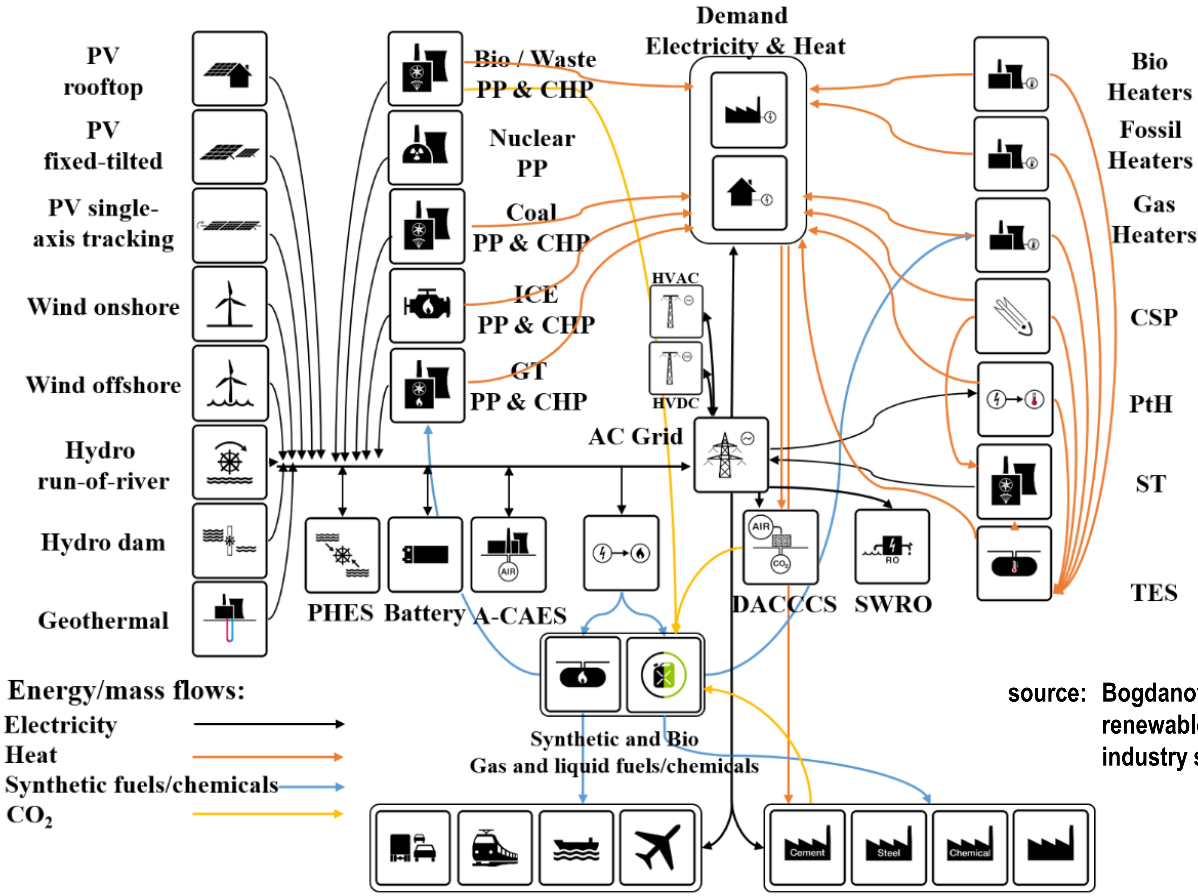


Key insights:

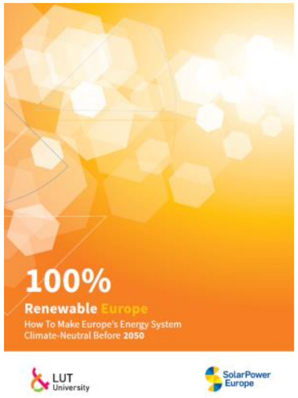
- massive continued cost decline for solar PV, wind, battery, electrolysers, CO_2 DAC
- massive pressure to eliminate all fossil fuels
- massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand

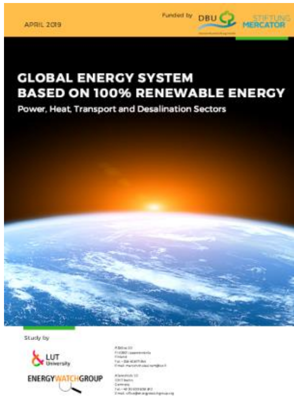
References:
PV, battery: Vartiainen et al., Progress in PV
Electrolyser: LUT model assumptio, Nature
CO_2 DAC: Fasihi et al., J of Cleaner Prod

LUT Energy System Transition Model



recent reports





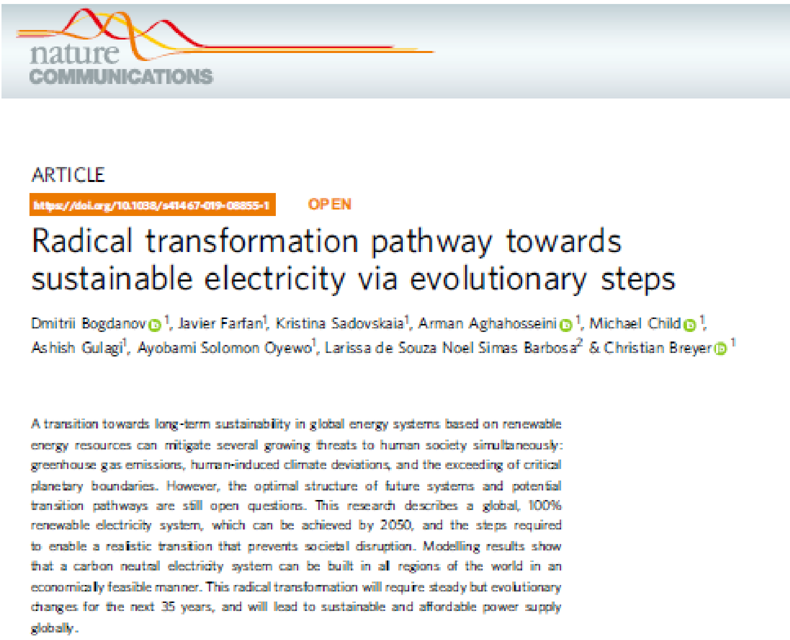
link to report | link to report

source: Bogdanov et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, accepted

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)

Renewables for the Power Sector


nature COMMUNICATIONS

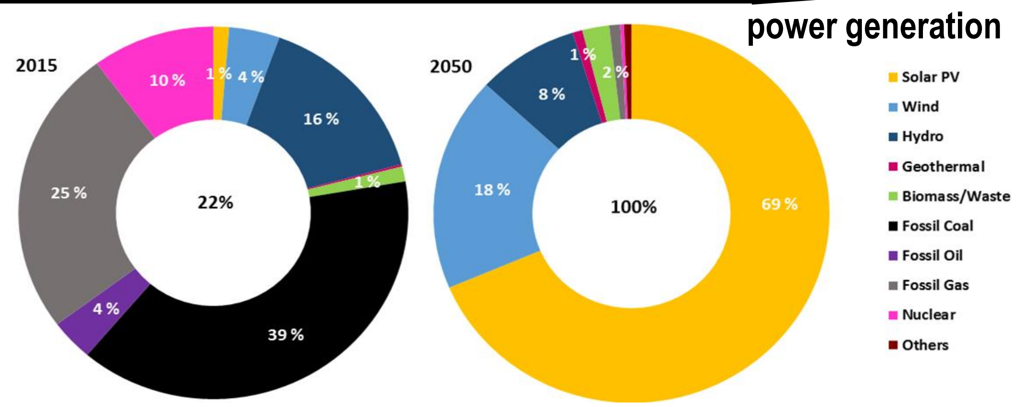
ARTICLE

https://doi.org/10.1038/s41467-019-08855-1 OPEN

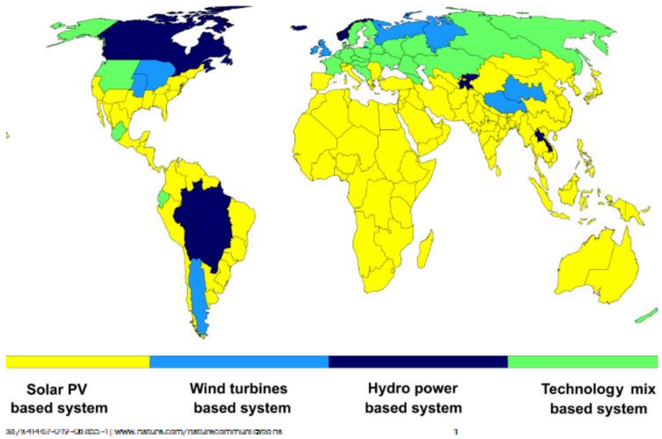
Radical transformation pathway towards sustainable electricity via evolutionary steps

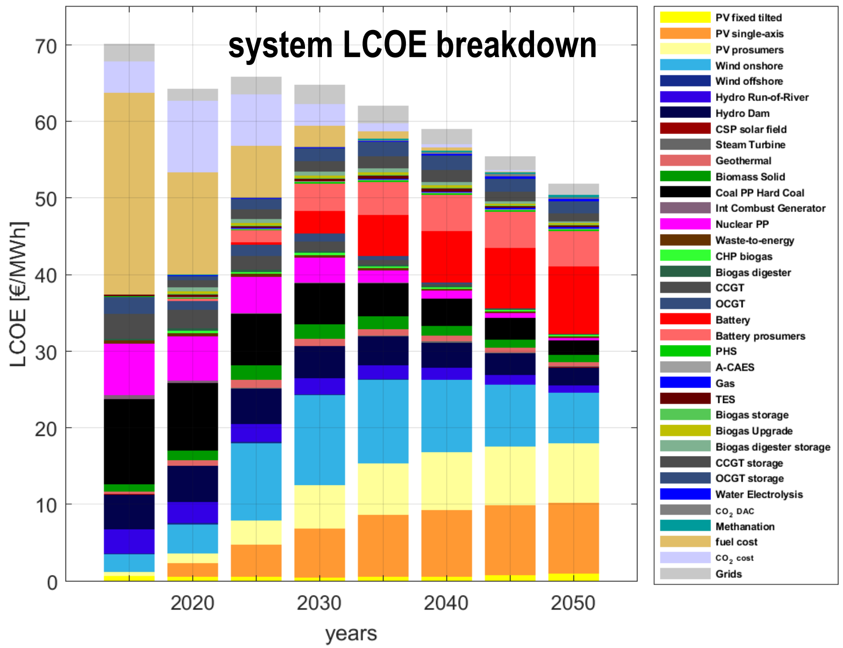
Dmitrii Bogdanov[1], Javier Farfan[1], Kristina Sadovskaia[1], Arman Aghahosseini[1], Michael Child[1], Ashish Gulagi[1], Ayobami Solomon Oyewo[1], Larissa de Souza Noel Simas Barbosa[2] & Christian Breyer[1]

A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: greenhouse gas emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the optimal structure of future systems and potential transition pathways are still open questions. This research describes a global, 100% renewable electricity system, which can be achieved by 2050, and the steps required to enable a realistic transition that prevents societal disruption. Modelling results show that a carbon neutral electricity system can be built in all regions of the world in an economically feasible manner. This radical transformation will require steady but evolutionary changes for the next 35 years, and will lead to sustainable and affordable power supply globally.



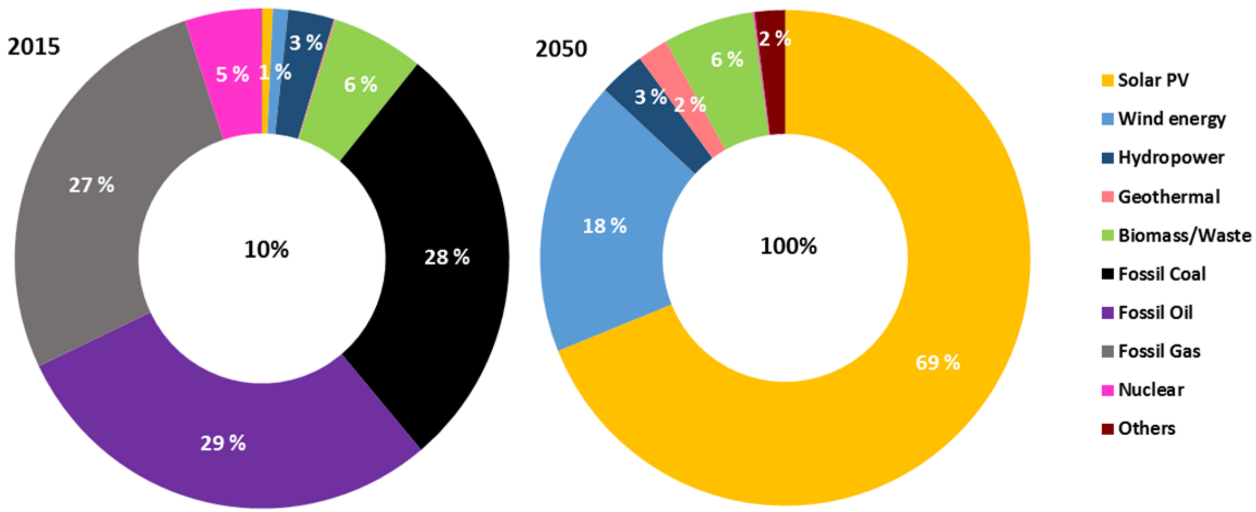
Area demand:
- **Wind: 4% max per region; 0.3% of land area used**
- **Solar PV rooftop is zero impact area; ground-mounted is 0.14% of total global land area**

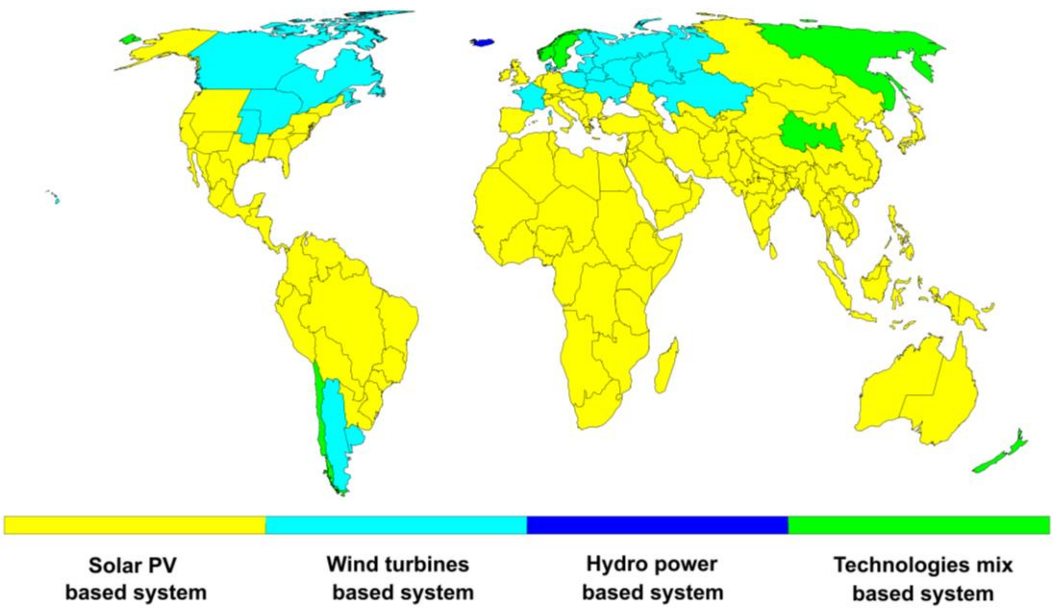




source: Breyer et al., 2018., PIP 26, 505-523; Bogdanov et al., 2019. Nature Comms, 10, 1077

Renewables for ALL energy demand (TPED)





Key insights:

- TPED shifts from being dominated by coal, oil and gas in 2015 towards solar PV and wind energy by 2050
- Renewable sources of energy contribute less than 20% of TPED in 2015, while in 2050 they supply 100% of TPED
- Solar PV drastically shifts from less than 1% in 2015 to around 69% of primary energy supply by 2050, as it becomes the least cost energy supply source across the world
- Solar PV capacity demand
  - 63 TW energy system
  - 13 TW chemical industry

source: EWG/LUT, 2019. Global Energy System based on 100% RE

Global: Energy System Cost

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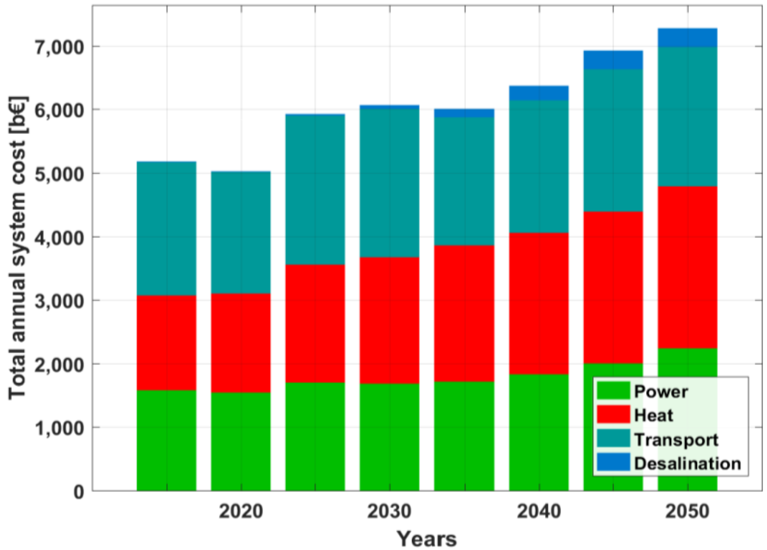

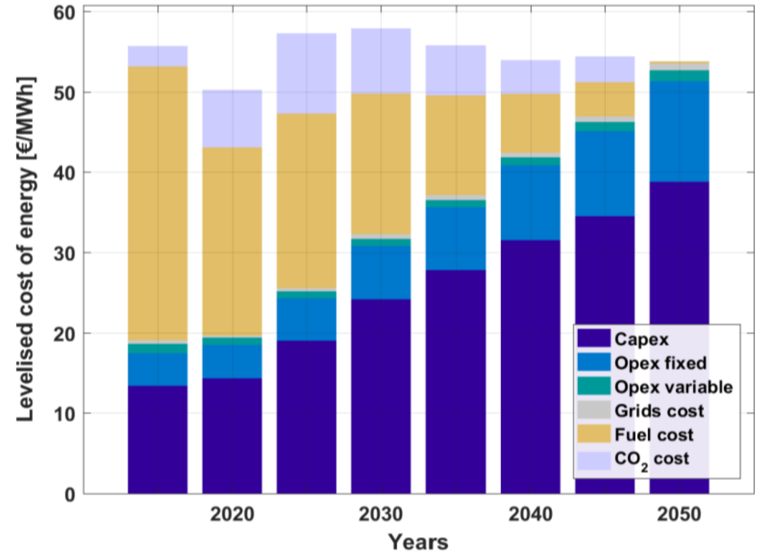

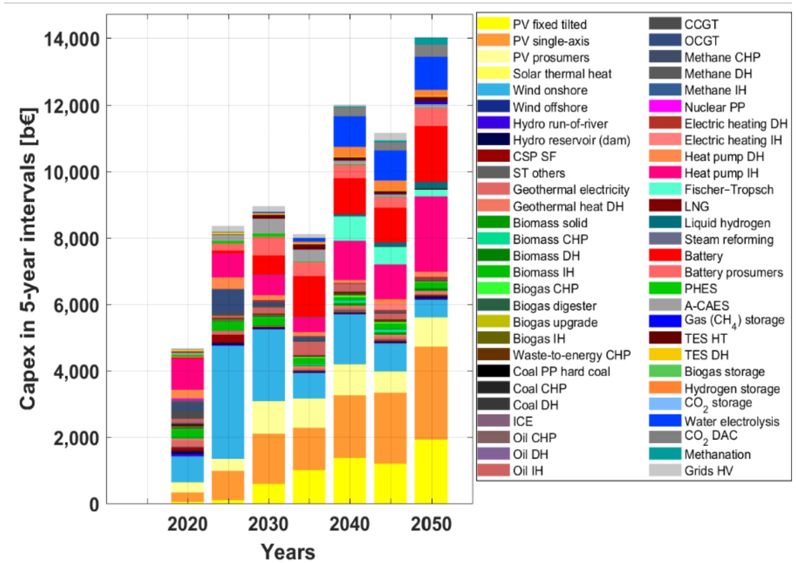

Key insights:

- The total annual costs are in the range of 5100-7200 b€ through the transition period and well distributed across the 3 major sectors of Power, Heat and Transport
- Levelised cost of energy remains around 50-57 €/MWh and is increasingly dominated by capital costs as fuel costs lose importance through the transition period, which could mean increased self-reliance by 2050
- Costs are well spread across a range of technologies with major investments for PV, wind, batteries, heat pumps and synthetic fuel conversion up to 2050
- The cumulative investment costs are about 67,200 b€

source: EWG/LUT, 2019. Global Energy System based on 100% RE

Global: Energy Demand and Electrification

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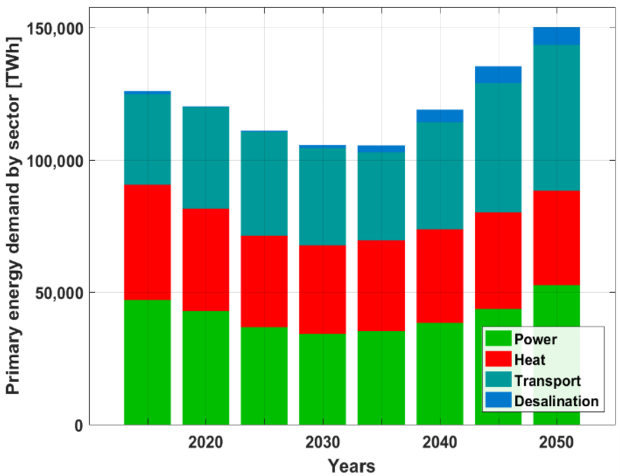
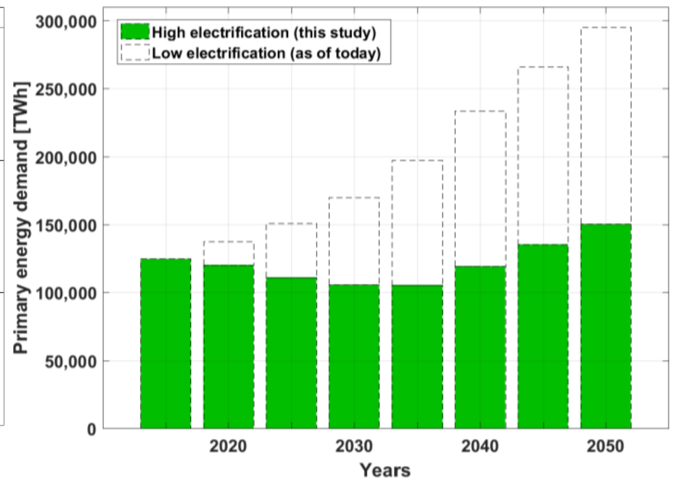
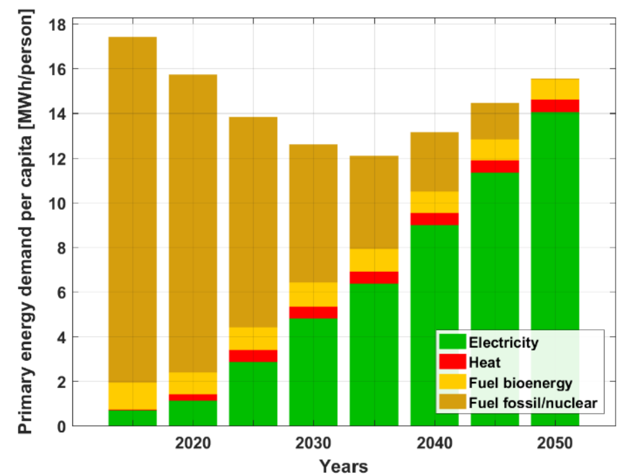




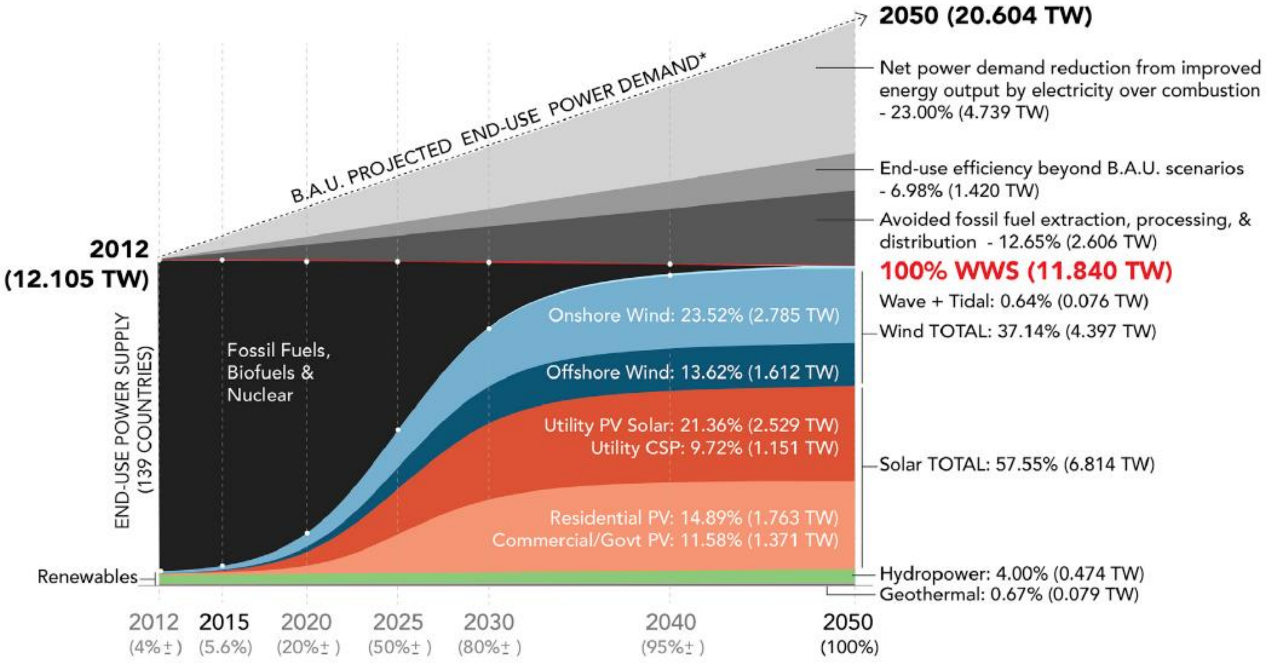


Key insights:

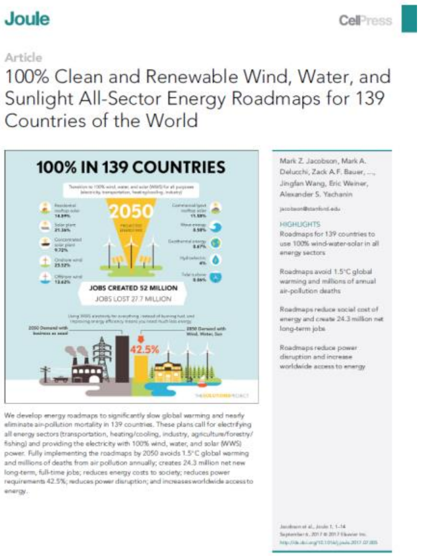
- A global compound average annual growth rate of about 1.0% in final energy demand drives the transition. This is composed by final energy demand growth for power and heat, desalinated water demand and transportation demand linked to powertrain assumptions. This leads to a comprehensive electrification, which massively increases overall energy efficiency, to an even higher growth rate in provided energy services.
- This results in an average annual growth rate of about 0.5% in total primary energy demand (TPED).
- World population is expected to grow from 7.2 to 9.7 billion, while the average per capita PED decreases from around 17 MWh/person in 2015 to 12 MWh/person by 2035 and increases up to around 15 MWh/person by 2050.
- In comparison, current practices (low electrification) would result in a TPED of nearly 300,000 TWh by 2050.
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 90% in 2050, saving nearly 150,000 TWh compared to the continuation of current practices (low electrification).
- TPED is a weak indicator of energy development, since fossil-nuclear fuel is of low efficiency. Final energy demand as a proxy for energy services to be the key metric for development.

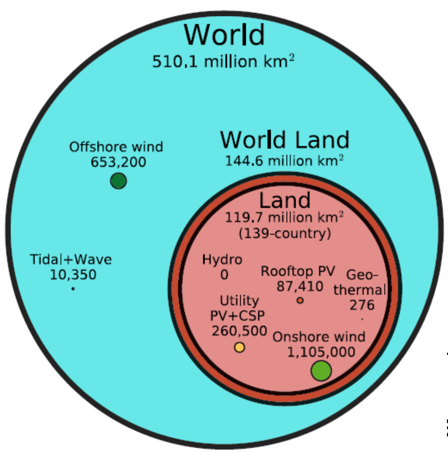
source: EWG/LUT, 2019. Global Energy System based on 100% RE

Jacobson et al., 2017 – 2015 - 2050



Projected Power Supply & Demand, 139 Countries
*ENERGY FOR ALL USES INCLUDING ELECTRICTY, HEATING, TRANSPORTATION, INDUSTRY





Key insights:

- Jacobson et al. (2017) represents one of the very few peer-reviewed global 100% RE transition studies
- high energy efficiency gain due to thermal plant phase-out is highlighted
- the methodology is highly improvable, since only an annual match of supply and demand is done

source: Jacobson et al., 2017. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World, Joule 1, 1–14

Sgouridis et al., 2016 – 2015 - 2100

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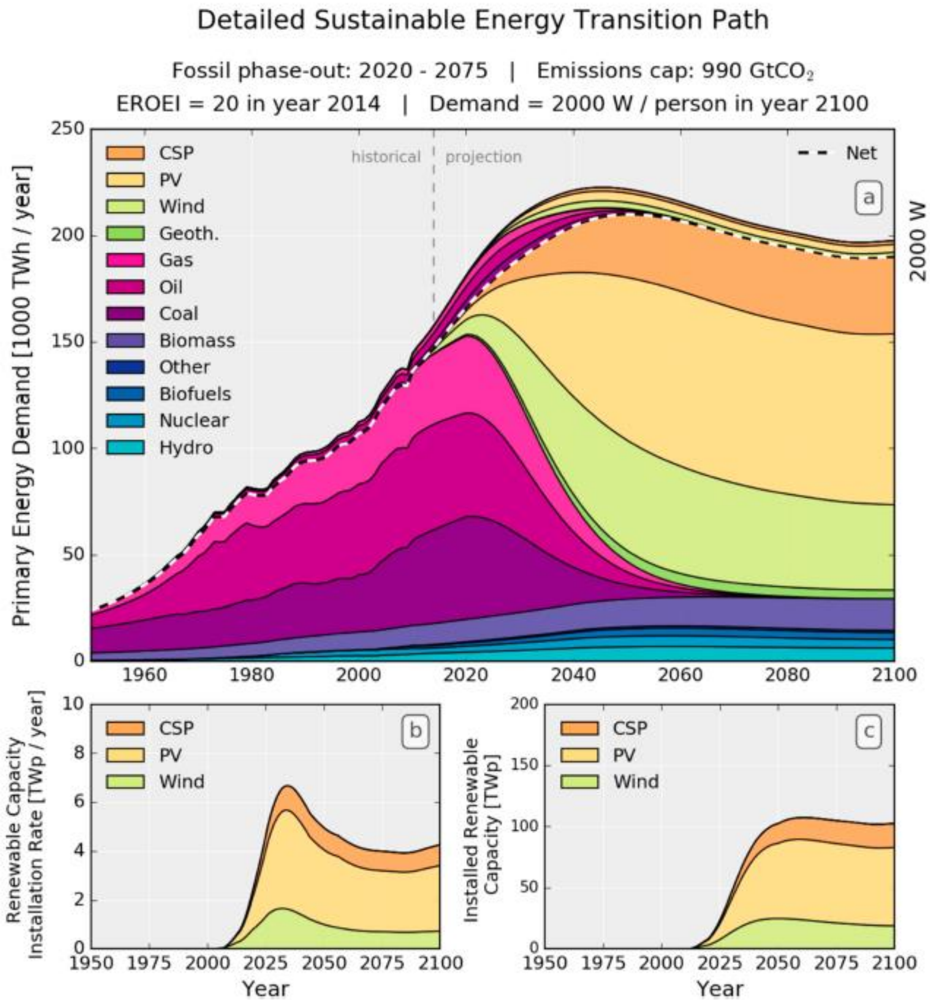
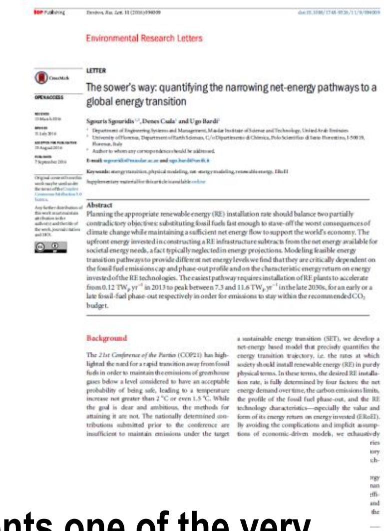


Figure 1. (a) SET-compliant primary energy supply evolution (in PWh) for providing 2000 W average net power per capita by 2100 to a population of 10.8 billion. Fossil fuel emissions comply with a 990 GtCO_2 cap peaking in 2020 and phased-out by 2075. The dashed line represents the net available energy while the values above it the energy investment in building and operating the energy system ('seed'). (b) RE portfolio installation rate profile (in $TW_p\,yr^{-1}$). (c) Installed RE capacity (in TW_p).


Environmental Research Letters
LETTER
The sower's way: quantifying the narrowing net-energy pathways to a global energy transition

Key insights:

- Sgouridis et al. (2016) represents one of the very few peer-reviewed global near 100% RE transition studies (more nuclear than today assumed)
- Unrealistic fast ramping of RE assumed
- Annual supply and demand is matched, hence no consideration of flexibility options
- Substantial CSP share rather unrealistic
- Shift-to-power megatrend is a scenario baseline
- Compatible to the Paris Agreement
- TPED decline in second half of 21st century is highly unrealistic
- Focus on net-energy pathways

source: Sgouridis et al., 2016. The sower's way: quantifying the narrowing net-energy pathways to a global energy transition, Environmental Research Letters, 11, 094009

Pursiheimo et al., 2019 – 2010 - 2050

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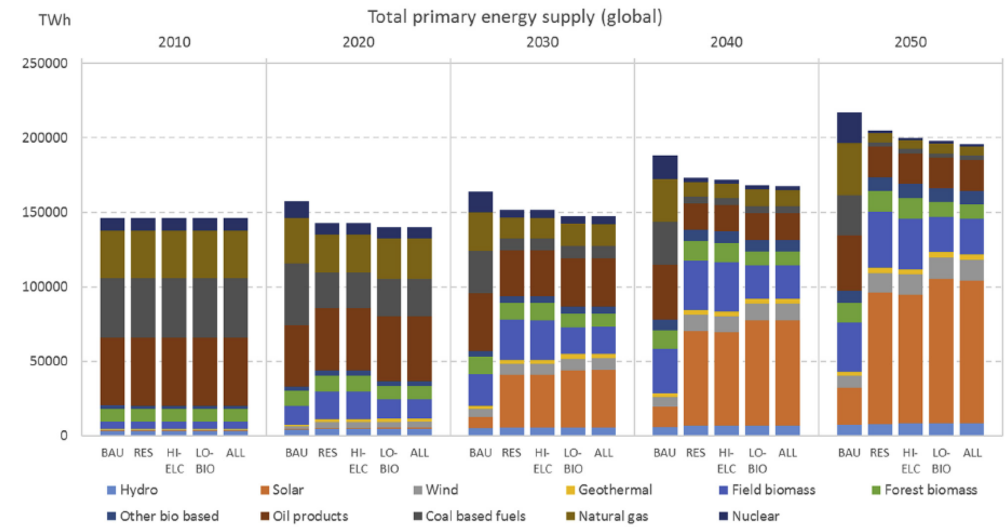
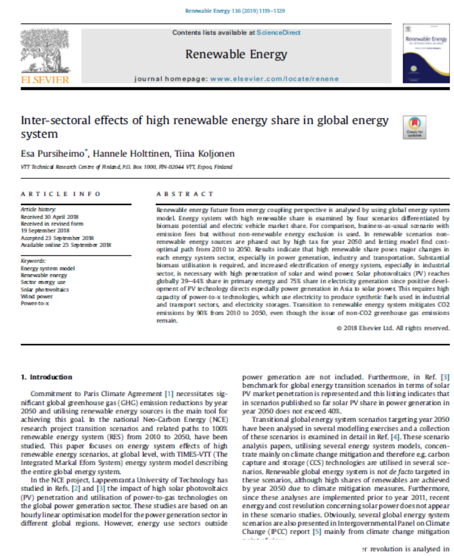
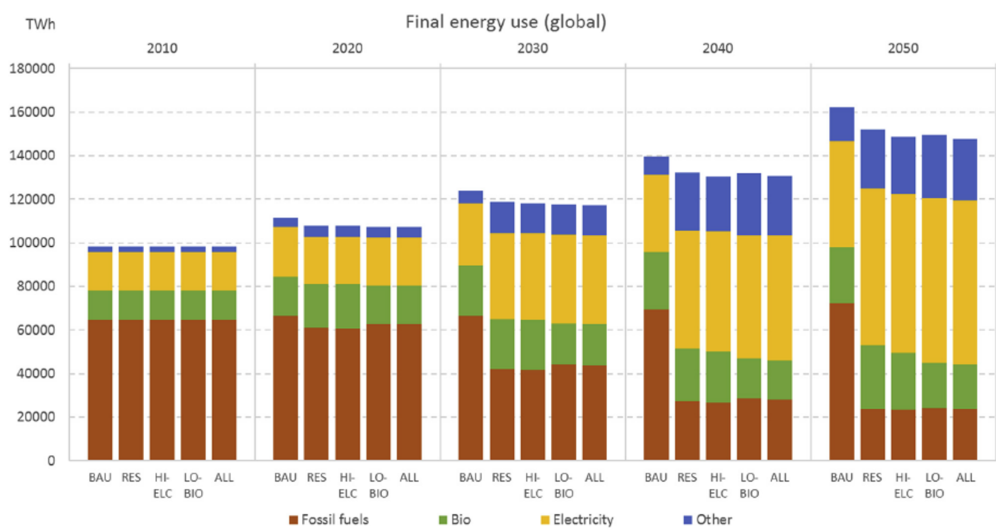




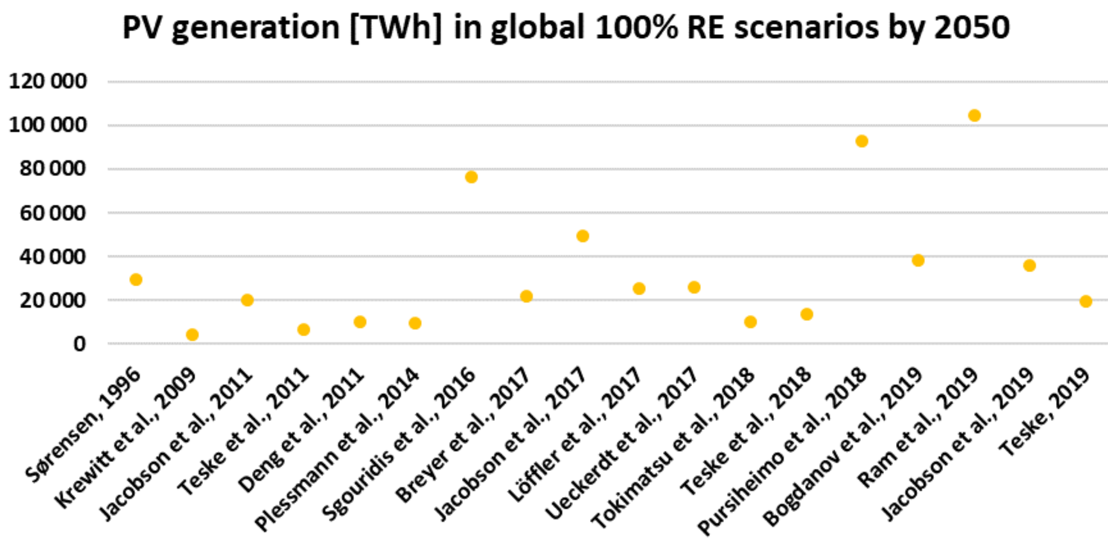


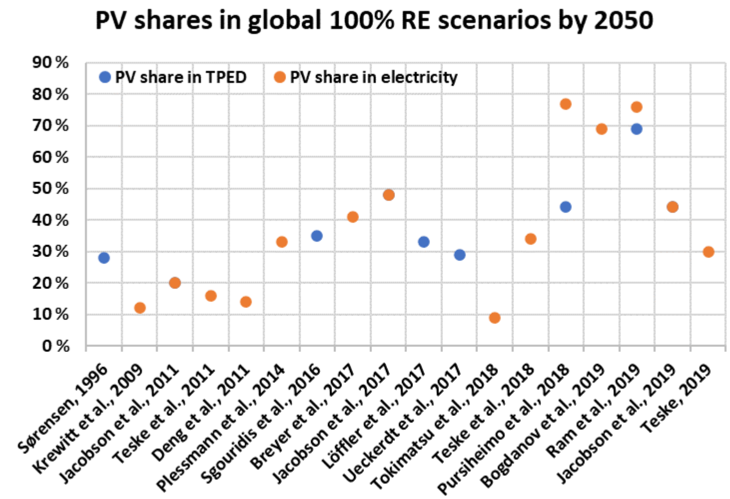
Key insights:

- Pursiheimo et al. (2019) represents the only global 100% RE transition studies carried out with TIMES
- solar PV is the dominating source of energy
- electricity is the dominating energy carrier
- more than 90,000 TWh solar PV in 2050
- 6.5 TW electricity storage
- 2 TW electrolyser capacity
- 2 TW Power-to-Gas capacity

source: Pursiheimo et al., 2019. Inter-sectoral effects of high renewable energy share in global energy system, Renewable Energy, 136, 1119-1129

Learnings for PV from Scenario Overview





Key insights:

- 20,000+ TWh (2050) is a standard finding, while beyond 50,000+ TWh requires optimisation, real PV cost, PtX
- simulation type scenarios often force CSP and lack cost considerations for CSP vs PV
- artificial area limitations can limit PV for higher shares
- unsustainable bioenergy use can reduce Power-to-X demand, also limiting PV
- outdated PV cost assumptions are a regular limit for higher PV shares
- Integrated Assessment Models from climate researchers use fully outdated PV cost assumptions, wrong PV grid integration cost and lack of modern Power-to-X understanding, leading to low PV shares
- full hourly modeling (dispatch, cost optimisation) on global level for all sectors still not yet standard

Power-to-X: the Core of Sector Coupling

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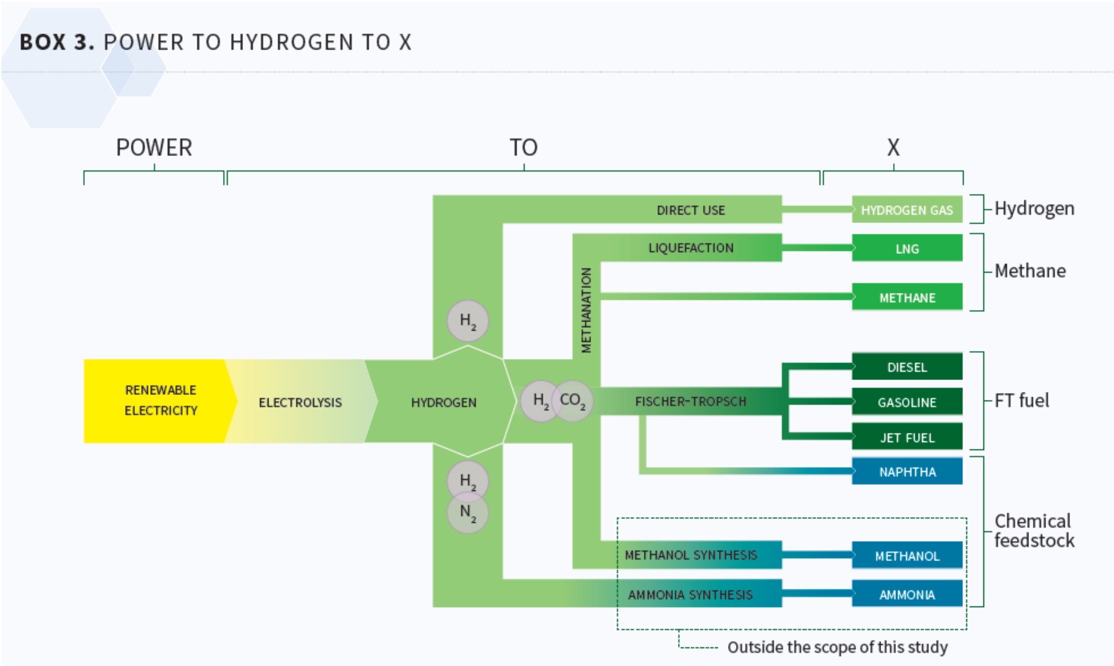
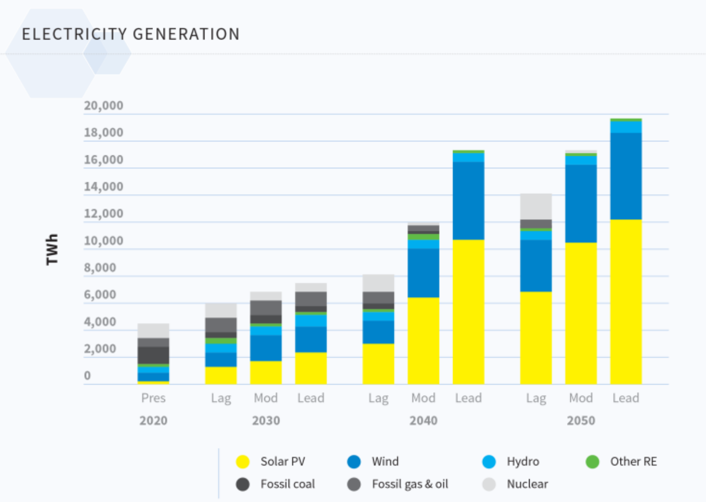
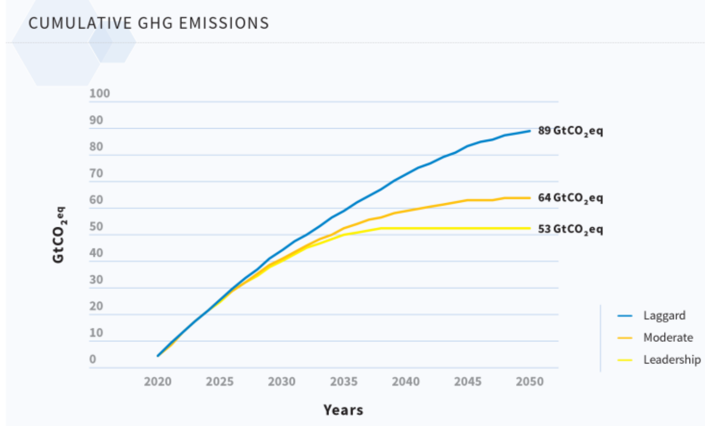


Case: Sustainable Europe

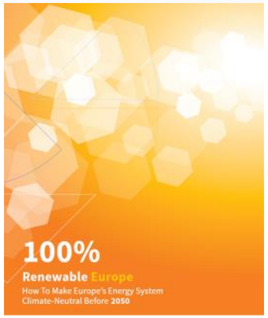




Source: SolarPower Europe.

Key insights:

- Power-to-X comprises: Mobility, Fuels, Chemicals, Heat, Steel, Desalinated Water
- Hydrogen is ONLY required, where direct electrification fails, e.g. chemicals, fuels for aviation/ marine
- Power-to-X is an essential core element for least cost zero GHG emissions and a booster for solar PV demand

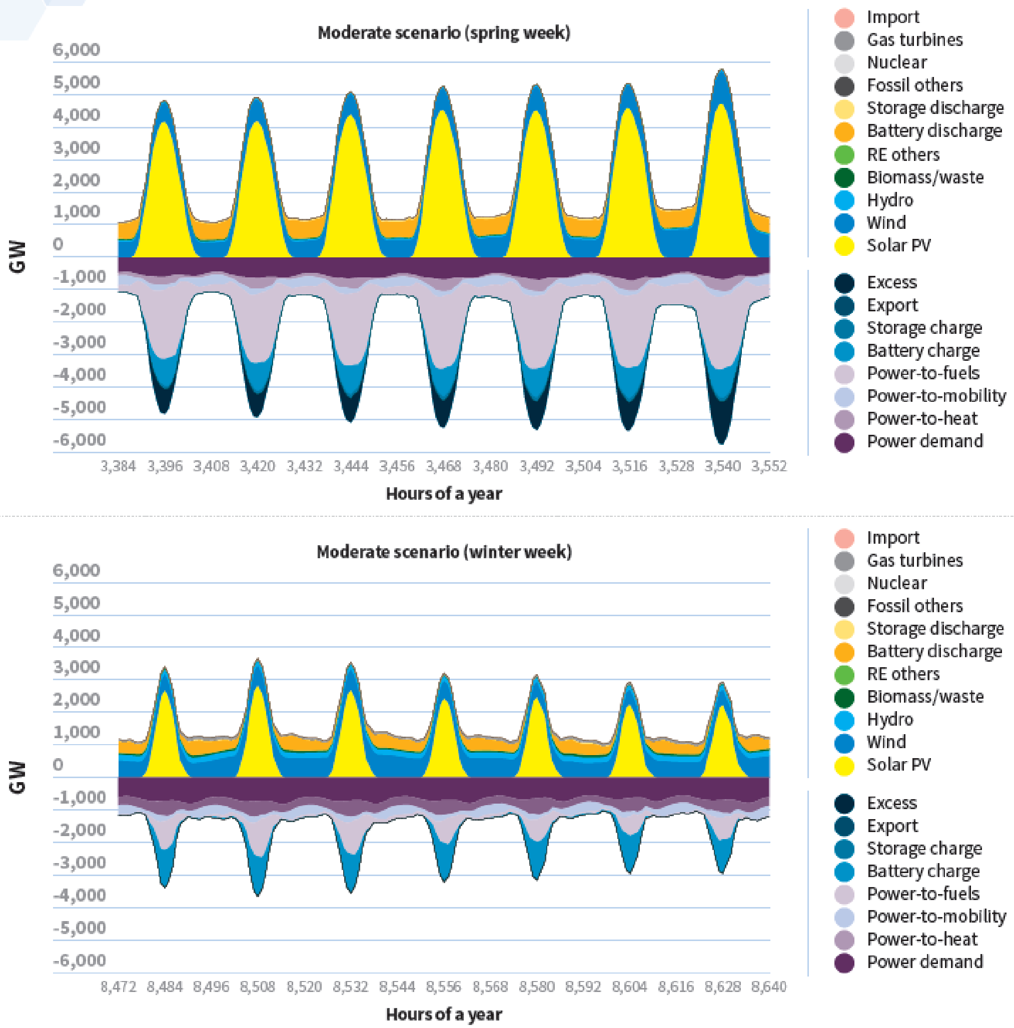


link to report

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

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.

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Energy System Structure: Present (Europe)

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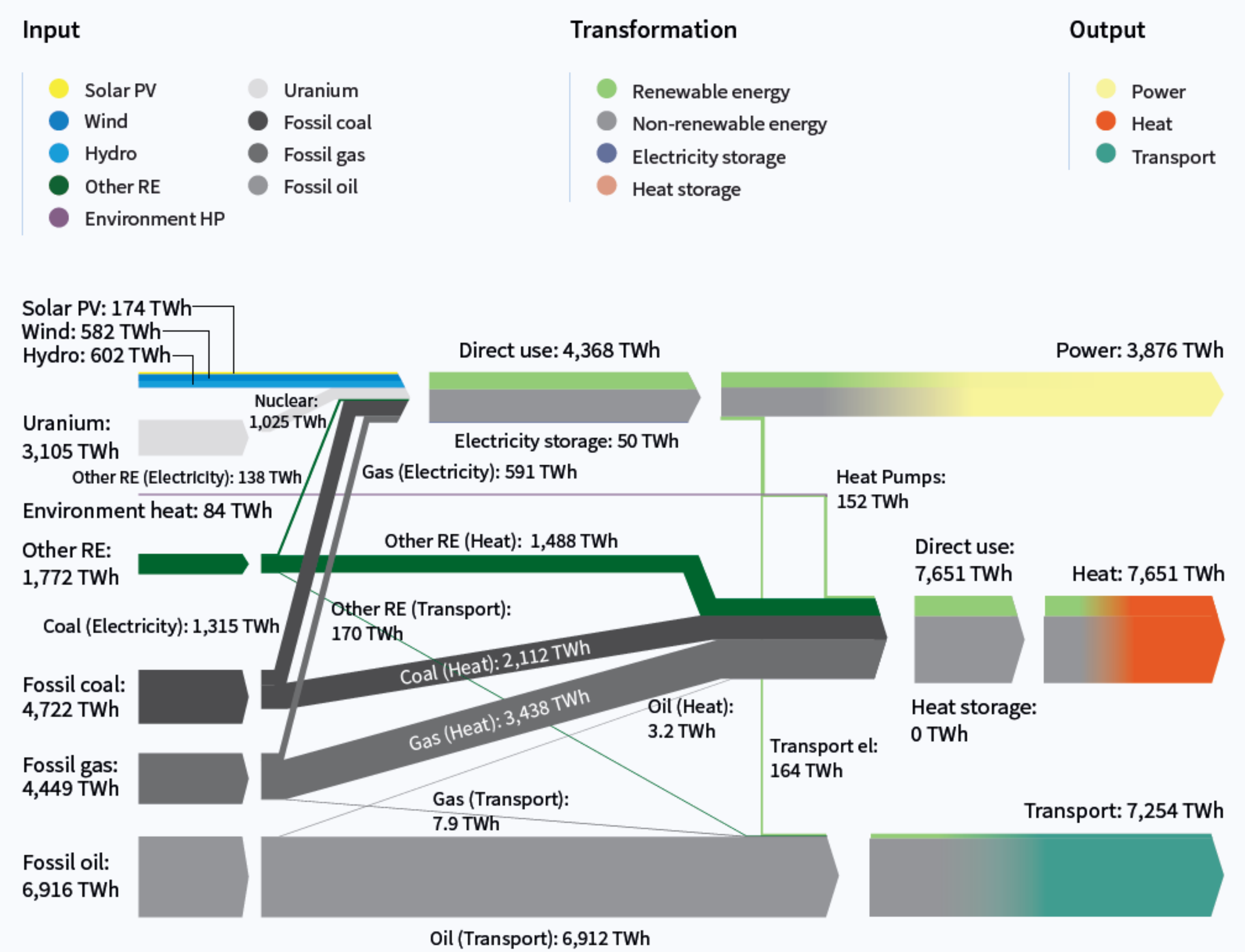
FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020



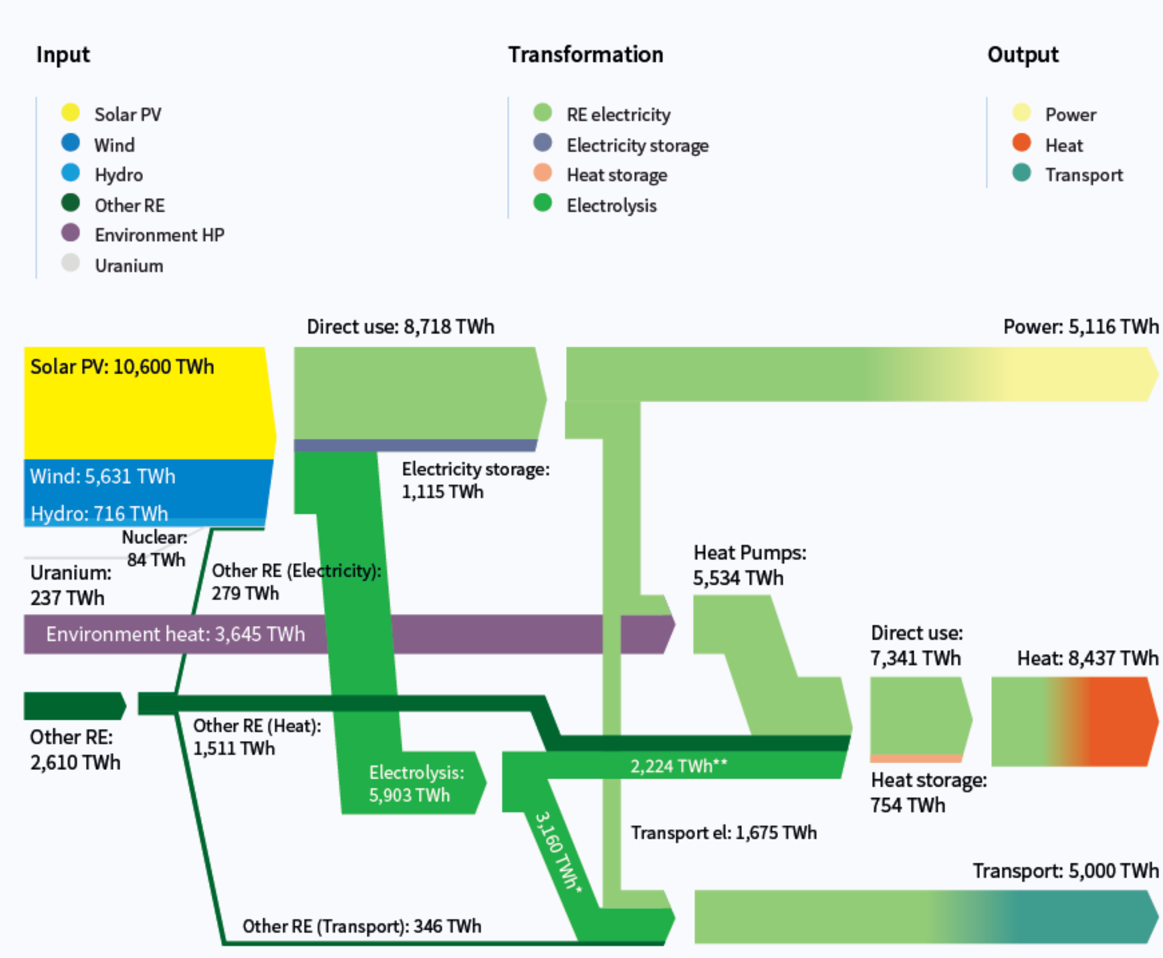
Key insights:

- Energy sectors (power, heat, transport) practically separated
- Dominating role of fossil fuels
- Transport sector has practically not yet started the transition

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Energy System Structure: Future (Europe)

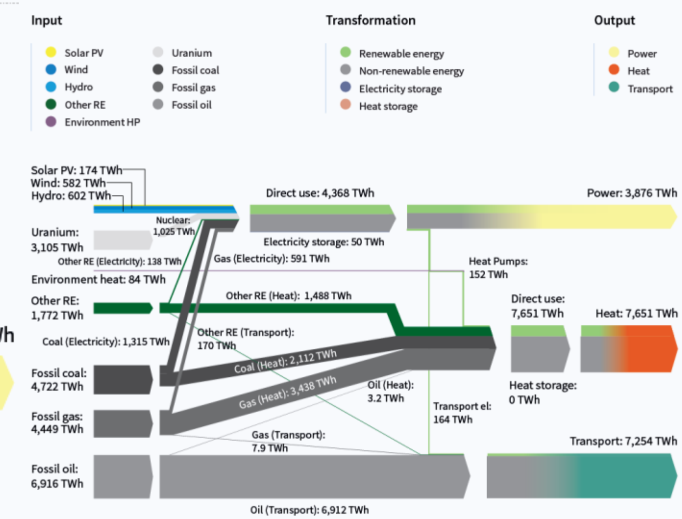
FIGURE 3.25 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN THE MODERATE SCENARIO IN 2050



*RE synthetic fuels for transport.

**RE synthetic fuels for heat, recovered heat.

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020



Key insights:

- 100% renewables will lead to strongly coupled energy system
- Most important energy carrier is electricity, while second most important is green hydrogen
- Fossil and nuclear fuels are not part of a sustainable and least cost energy system

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Overview on transport sector transition

											TFED share in 2050 *			
Source	Publication year	Unit	2015	2020	2025	2030	2035	2040	2045	2050	fossils	biofuels	synfuels	electricit
this study	2019	TWh/a	31613	34799	35848	35609	33761	32177	31758	32542	0 %	1 %	63 %	35 %
Greenpeace [E]R	2015	TWh/a	-	26129	25599	25070	-	21808	-	19159	29 %	14 %	20 %	38 %
Greenpeace [E]R adv.	2015	TWh/a	-	25850	24897	23207	-	18020	-	14836	0 %	14 %	35 %	51 %
Teske, 1.5 °C	2019	TWh/a	30752	-	29411	25606	-	19604	-	17001	0 %	16 %	36 %	48 %
Teske, 2 °C	2019	TWh/a	30752	-	26142	20371	-	15919	-	14279	0 %	25 %	29 %	46 %
Jacobson et al.	2018	TWh/a	-	-	-	-	-	-	-	13113	0 %	0 %	33 %	67 %
Löffler et al.	2017	TWh/a	31298	32434	28910	24069	20258	16706	13326	10414	0	15 %	44 %	41 %
Pursiheimo et al.	2019	TWh/a	-	-	-	-	-	-	-	23480	0 %	30 %	33 %	37 %
García-Olivares et al.	2018	TWh/a	-	-	-	-	-	-	-	28383	n/a	n/a	n/a	n/a
WWF / Deng et al.	2011	TWh/a	29102	29598	28714	25940	24420	19533	17998	17741	0 %	74 %	0 %	26 %
World Energy Council	2016	TWh/a	-	31842	-	35471	-	37018	-	37169	77 %	15 %	2 %	6 %
DNV GL	2018	TWh/a	29513	30555	31945	31388	30555	28472	25694	25000	42 %	16 %	2 %	40 %
IEA, WEO NPS	2018	TWh/a	31308	-	36564	38530	40088	42065	-	-	90 %	6 %	0 %	4 %
IEA, WEO SDS	2018	TWh/a	31308	-	34250	33668	-	30703	-	-	73 %	13 %	0 %	14 %
Luderer et al. B200	2018	TWh/a	-	-	-	-	-	-	-	31945	32 %	29 %	18 %	21 %
Luderer et al. B800	2018	TWh/a	-	-	-	-	-	-	-	36110	47 %	26 %	12 %	15 %
Shell, Sky	2018	TWh/a	30812	33019	34989	34611	36290	37686	38837	40630	67 %	13 %	2 %	18 %
BP Energy Outlook	2019	TWh/a	29656	32564	34890	36053	37216	37099	-	-	89 %	7 %	0 %	4 %
ExxonMobil	2017	TWh/a	32530	-	36633	-	-	40736	-	-	94 %	4 %	0 %	2 %
US DoE EIA	2017	TWh/a	32823	33703	35168	37806	40736	44400	-	-	98 %	0% **	0 %	2 %

source: Khalili et al., 2019. Energies, 12, 3870

- synthetic fuels is still very often only hydrogen
- LUT has the highest synthetic fuel share among all groups in the world
- no consolidated view on transport sector transition: range from US DoE (98% fossils) to 100% RE group
- different bets on biofuels, but many do not factor in sustainability limits
- IEA deserves massive pressure from civil society, but also IPCC for being laggard in progressive options
- Oil majors will go for bankruptcy, if they follow their own scenarios – for Shell might be hope

Regional and Global Super Grids

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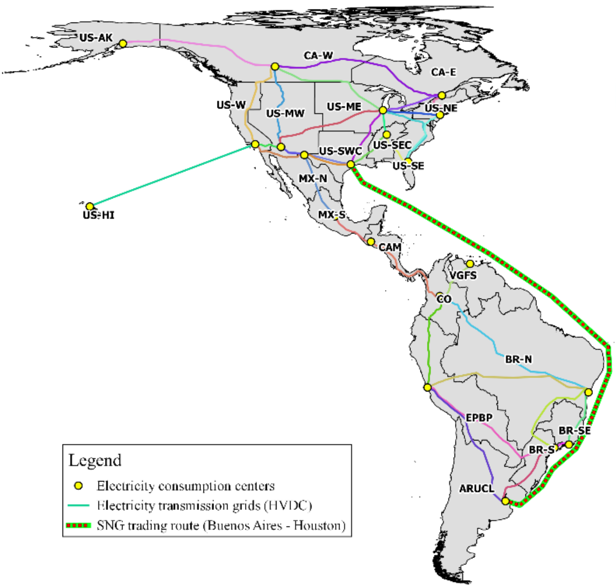
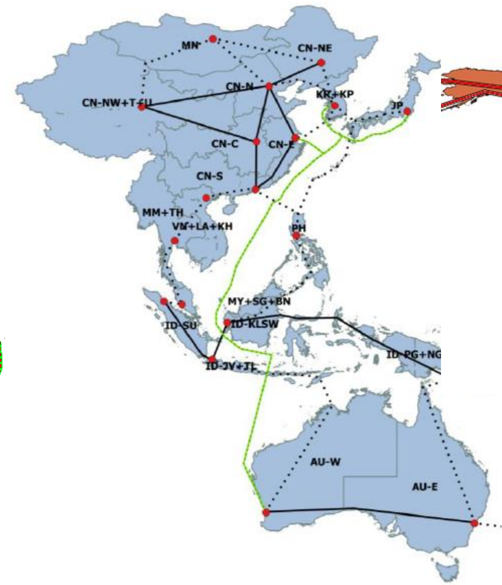
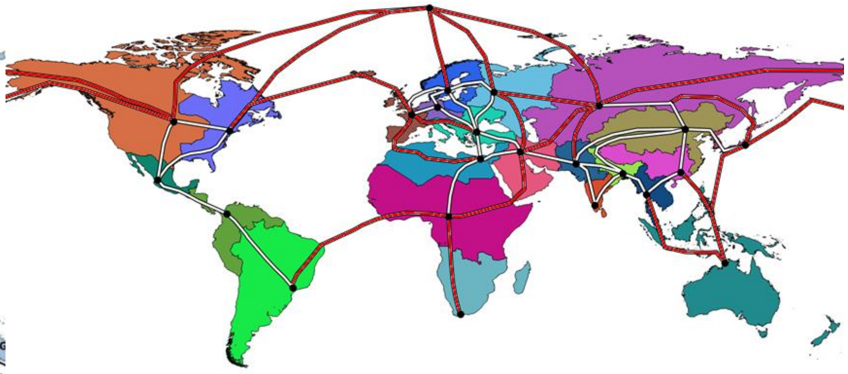
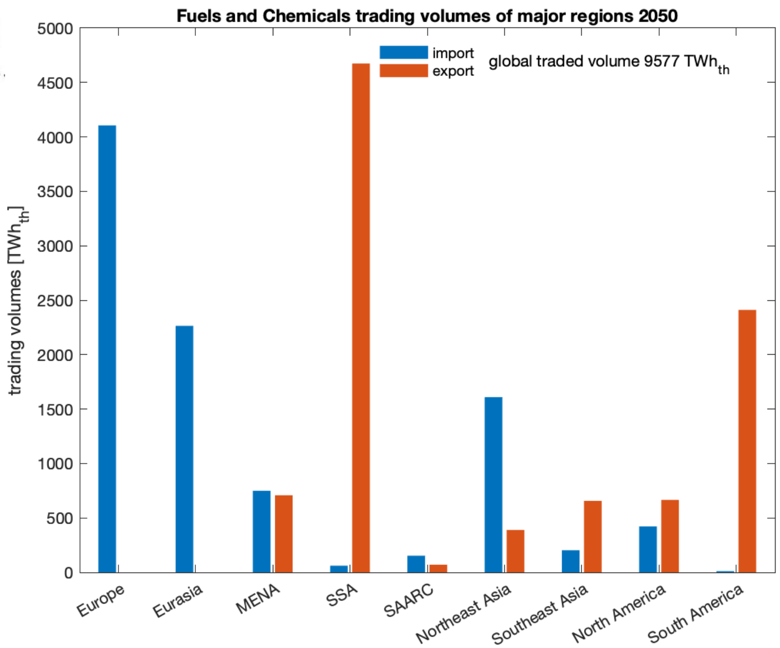








Key insights:

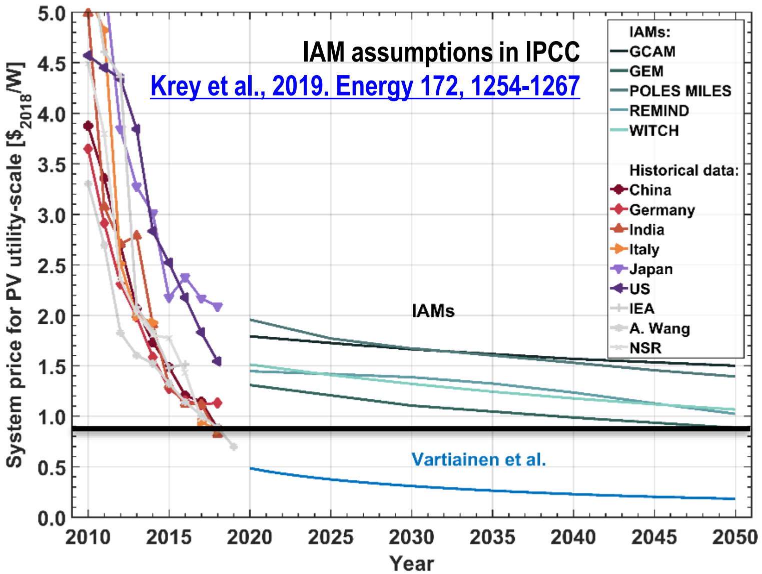
- What's the value add of very large Super Grids?
- Grids on a major region level (SAARC, Europe, etc.) reduce the system cost by about 10% by resource balancing, compared to state/ country level optimisation.
- The higher the solar PV share, the lower the balancing value.
- Integration beyond major region level, e.g. Americas North & South, Europe & Eurasia & MENA, Asia Northeast & Southeast, leads to negligible further cost reductions of about 1%.
- PtX powerfuels/ chemicals trade will generate substantial value.

source: Aghahosseini et al., 2019. Renew Sustain Energy Rev 105, 187-205; Gulagi et al., 2017. Energies 10, 583; Breyer et al., 2020. EEEP 9, 83-102

What say IEA and IAMs/IPCC on PV?

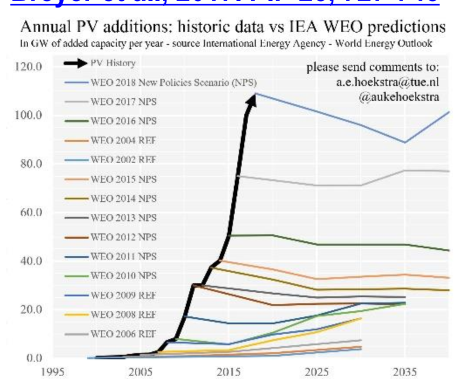
Key insights:

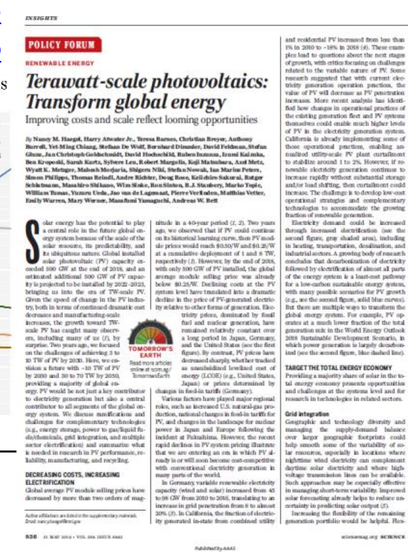
- **solar PV emerges as the major source of energy till 2050**
- practically ALL global scenarios dramatically fail in the right role of solar PV
- **steep cost decline of the last 10 years is ignored by IEA, IPCC (based on IAMs), and others**
- climate change mitigation could be enhanced, if major institutions would perform better
- massive and fundamental re-thinking on solar PV, plus supporting batteries, is needed
- historic failure of major international institutions on our energy future must end, asap
- **IEA** started with its latest WEO a renewal with the new Net Zero Emission 2050 (NZE2050) scenario, but it is only shown until 2030, full disclosure is required to avoid further stranded fossil assets



articles based on real PV cost

[Heagel et al., 2019. Science 364(6443), 836-838]
[Vartiainen et al., 2020. PIP 28, 439-453]
[Breyer et al., 2018. PIP 26, 505-523]
[Breyer et al., 2017. PIP 25, 727-745]

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RENEWABLE ENERGY

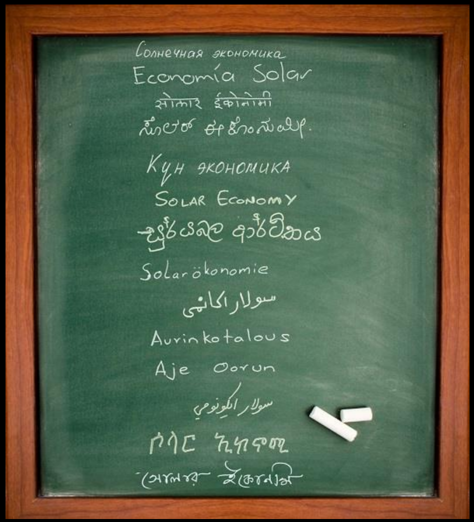
Terawatt-scale photovoltaics: Transform global energy

Improving costs and scale reflect looming opportunities

Summary

- Practically unlimited solar resource potential for energy supply
- Electrification of all energy sectors will boost PV demand, plus some wind
- 100% RE scenarios since 1975 and analytic global scenarios since 1996
- PV shares in global scenarios increases continuously: 70-80% may be the limit
- Key technologies: PV, wind energy, batteries, electrolysers and CO_2 DAC
- Green hydrogen enables solutions for hard-to-abate sectors
- Green hydrogen is the basis for direct hydrogen use, but also in particular for further synthesis to SNG, Fischer Tropsch fuels, ammonia and methanol
- Strong sector coupling is a major driver for a sustainable energy system
- The Solar Age is a key opportunity to fix multiple issues, first of all climate change

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



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

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Key questions

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Conceptual difference between 100% RE power and 100% RE energy systems

- flexibility: power sector is most inflexible sector, while heat, transport and industry delivers flexibility
- key flexibilities: smart charging of BEV, heat pump + TES, electrolysers
- seasonal storage practically disappears and electrolysers can effectively balance the power system

Operability of a system with limited synchronous generators for high solar and wind shares

- batteries are key: synthetic inertia can perfectly balance the system
- electrolysers can effectively balance the power flows

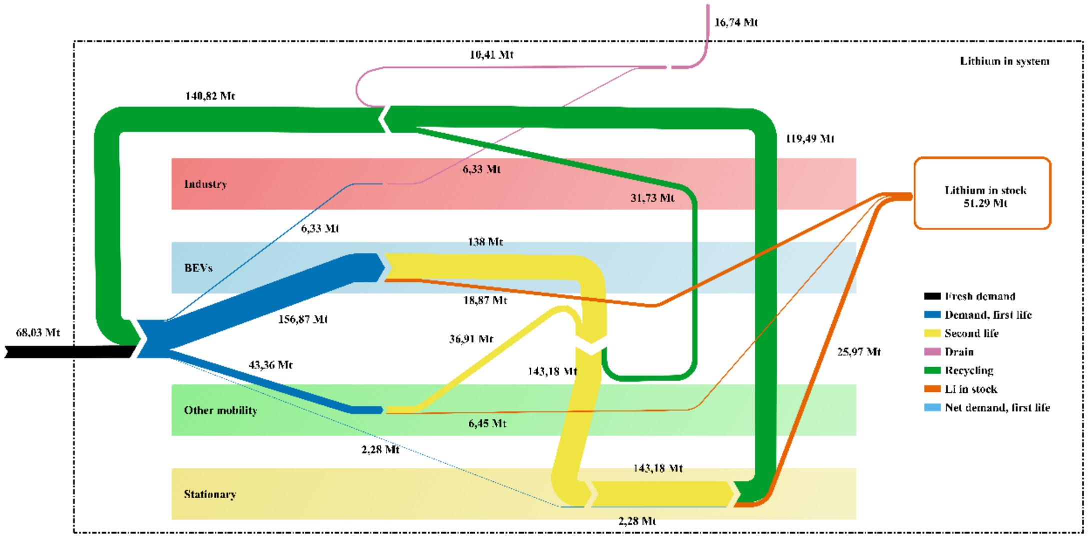
Gap between the current speed of change and what needs to take to reach to 100% RE systems

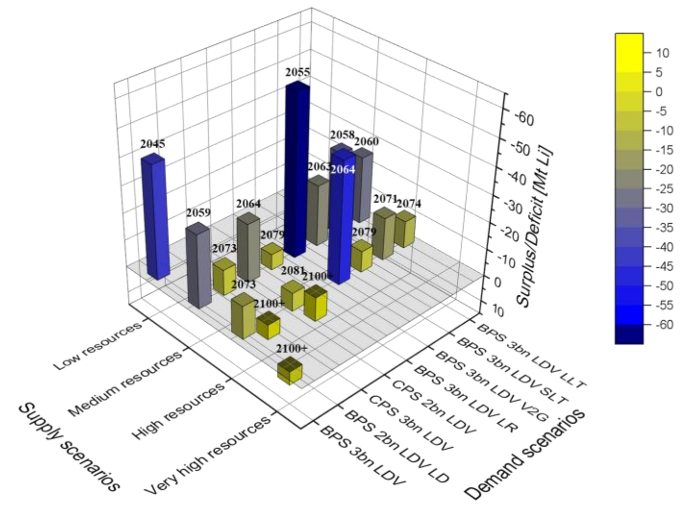
- first: realistic scenarios are needed!! IAMs/IPCC fail, IEA fails, sorry, IRENA has also to improve
- second: clean up the grid, then electrify almost everything
- third: about 1 TWp/y PV (2030) and about 3 TWp/y PV (2040) for supplying a prosperous world
- fourth: be aware of that 2050 zero GHG emissions is 20 years (!) after the 1.5C budget is used

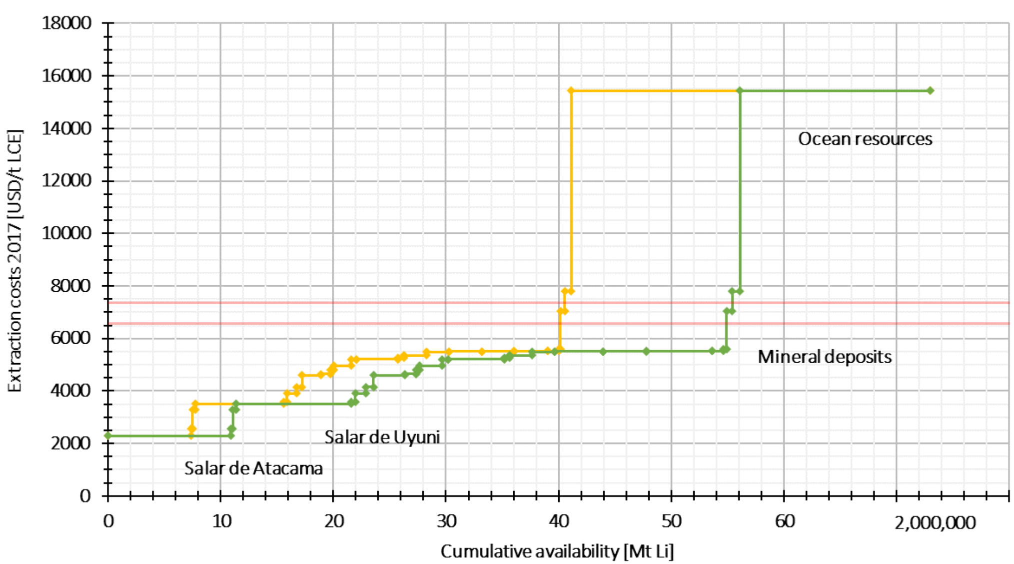
Supply chain and land footprint

- supply chain: more realistic scenarios, then industry can anticipate and adapt; Lithium alternative
- land footprint: biofuels ban to be considered, wind in forests, PV efficiency and yield policy
- PV: 75 TWp in 2050, thereof 65 GW on ground leads to 0.35% of global land mass, w/o offshore PV

Lithium – a potentially limiting raw material





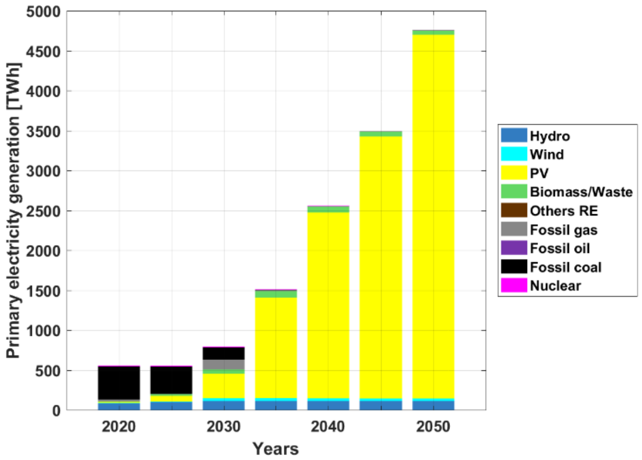


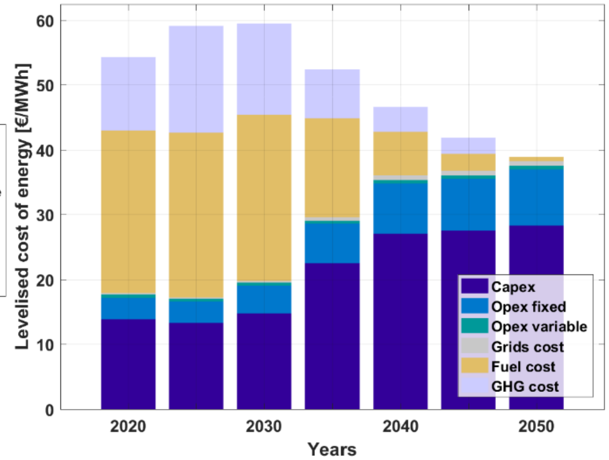
Key insights:

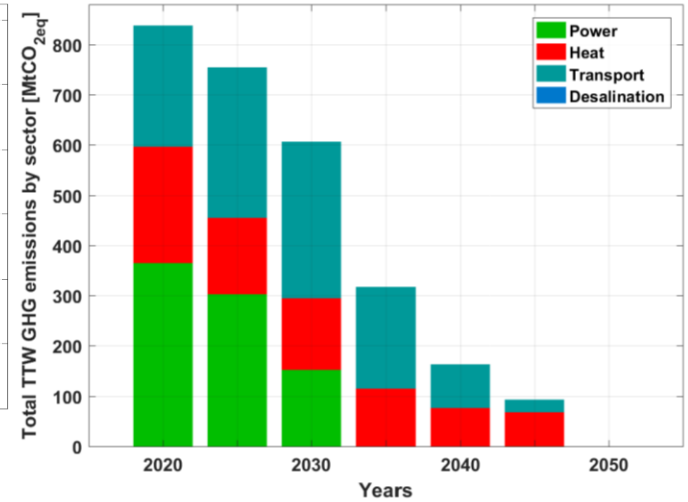
- No consensus on the Lithium availability
- Matching various supply and demand scenarios almost always leads to supply shortage (total resource in 2060s/2070s, annual supply much earlier)
- Circular economy is a must for Lithium
- Lithium based batteries can carry the energy transition far, but not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

source: Greim et al., 2020. Nature Communications, 11, 4570

India North and Delhi (power, heat, transport)



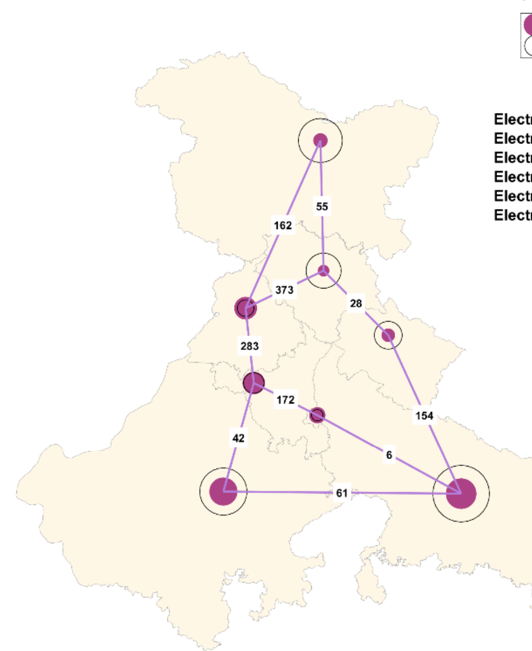




Key insights:

- How to get the largest metropolitan area on Earth by mid-century energetically sustainable?
- Very strong role of solar PV for entire energy supply via direct and indirect electrification.
- System costs (excluding GHG emission cost) remain stable until 2040, then decline.
- GHG emissions, and energy-related air pollution, can be reduced to zero, while jobs increase, in particular for PV and battery.
- Delhi can utilise building-based PV, and imports from neighbouring states.
- Collaboration with Climate Trends for this research.

Annual imported and exported electricity (TWh)



link to summary

India in state resolution (power sector)

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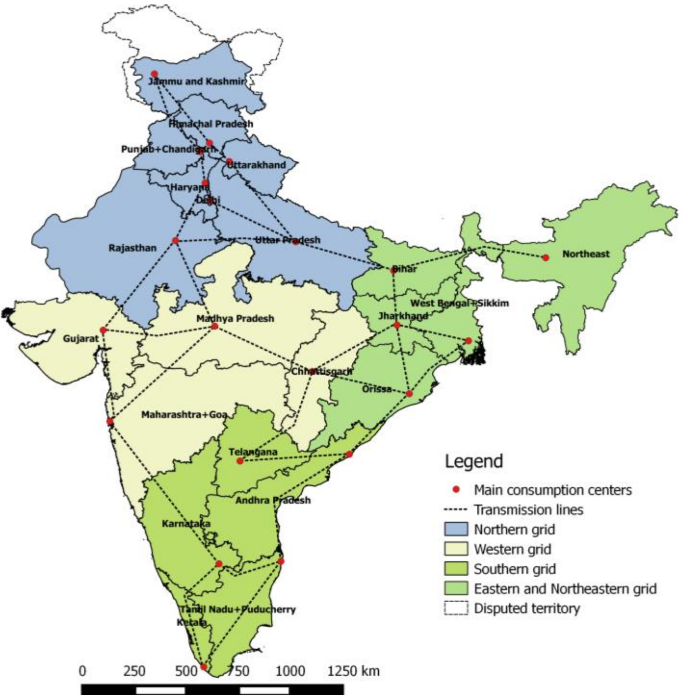
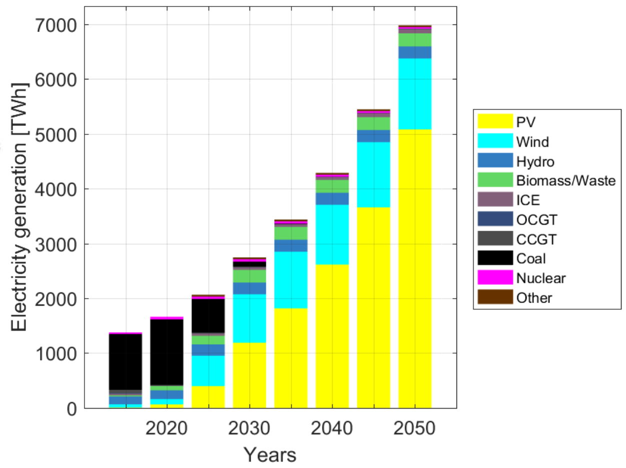
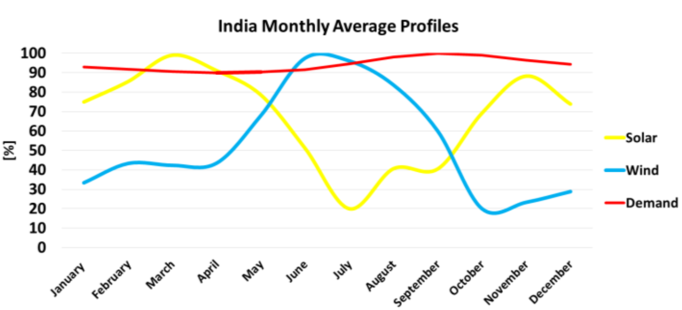
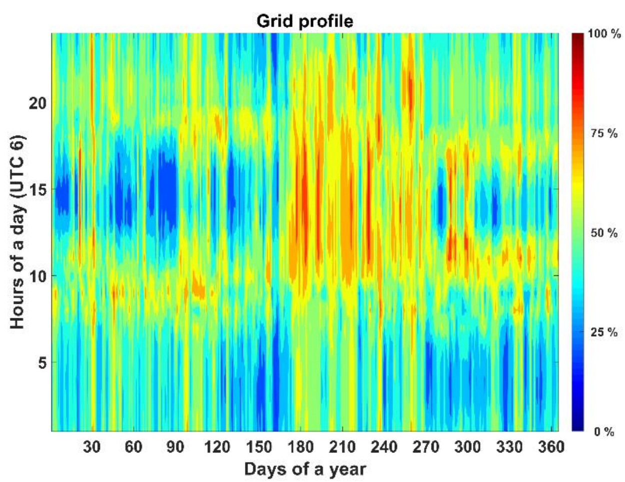






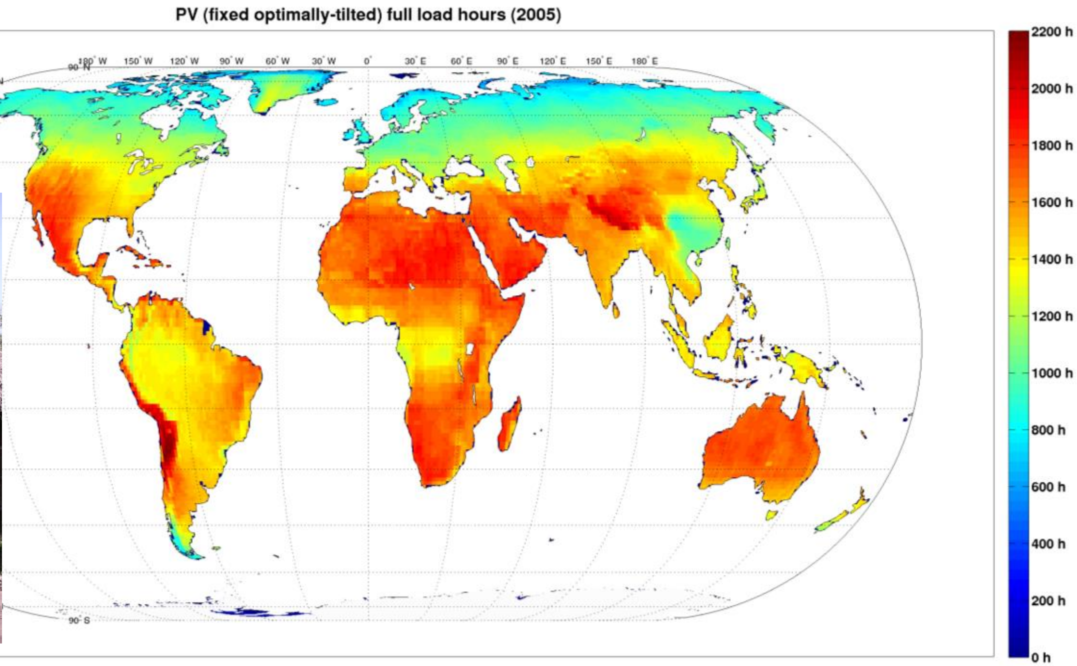


Key insights:

- How to transition the most populated country in the 21st century to sustainable energy?
- Indian state level modeling for a fully integrated power system.
- Monsoon is a stark stress test for a solar PV based system.
- Two fundamental solutions: complementarity of PV and wind, and intrastate transmission of PV electricity negates the monsoon impact
- About 12% of total electricity is traded between states, similar to other large integrated regions.
- Collaboration with Wärtsilä.

source: 22-states resolution not yet published. 10-regions interconnected results for India: Gulagi et al., 2020. IET Renew Energy Gen 14, 254-262; Gulagi et al., 2018. J of Energy Storage 17, 525-539

Solar Photovoltaics



Key insights:

- accessible everywhere – no resource conflicts
- highly modular technology – off-grid, distributed roofs, large-scale
- high learning rate due to 'simple' technology
- efficiency limit 86%, best lab efficiency 46%, best in markets 20%+
- high growth rate - >40% last 20 years – fast cost decline
- least cost electricity source in a fast growing number of regions
- key enabling technology for survival of civilization