




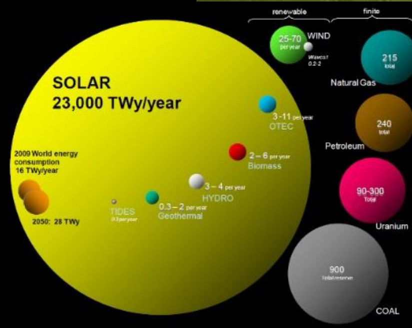

Die Rolle der Solarenergie in der Energiewende

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Christian Breyer
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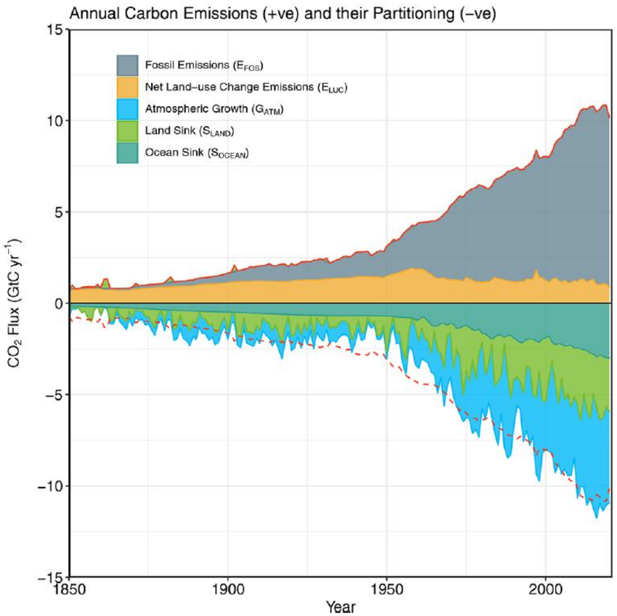
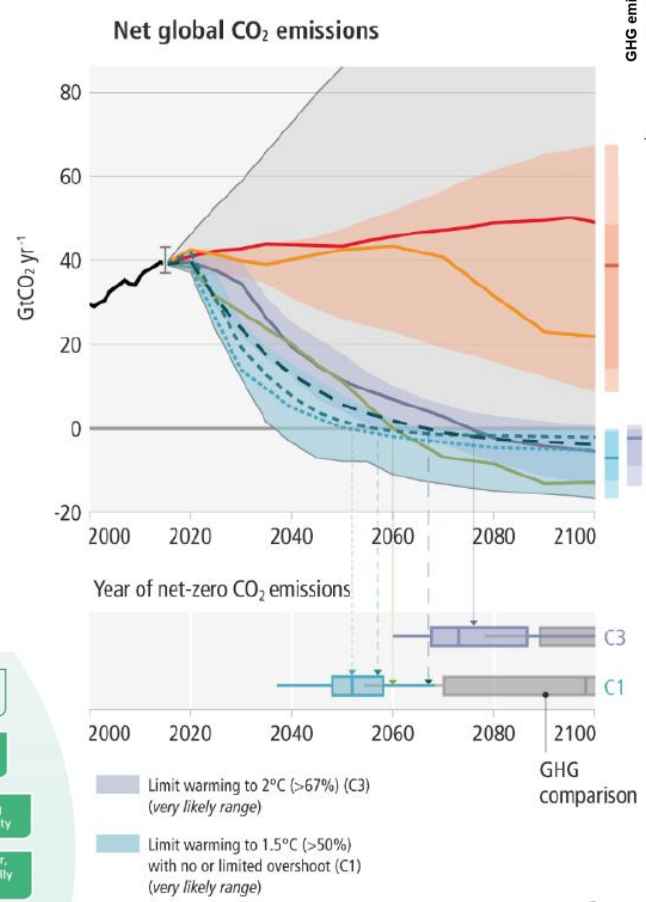
DAAD-Alumni-Verein Ringvorlesung ”Energie der Zukunft”
online, April 10, 2024

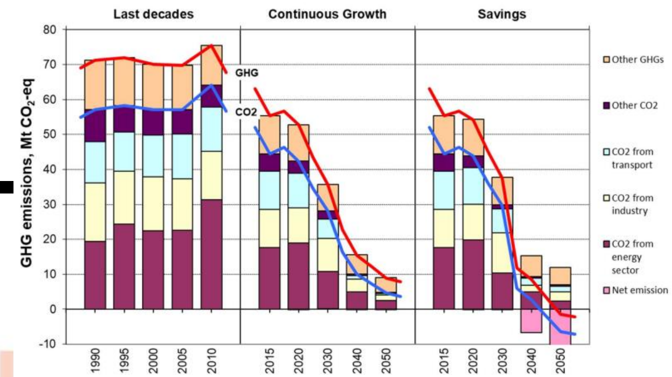
Agenda

- Background
- 100% Renewable Energy Research
- Global: 100% Renewables
- Europe: 100% Renewables
- Finland: Highly Renewables
- Summary

CO_2 Emissions development





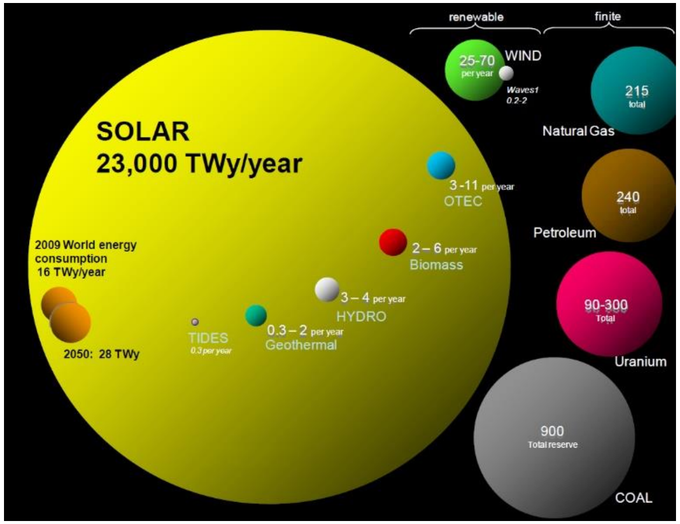


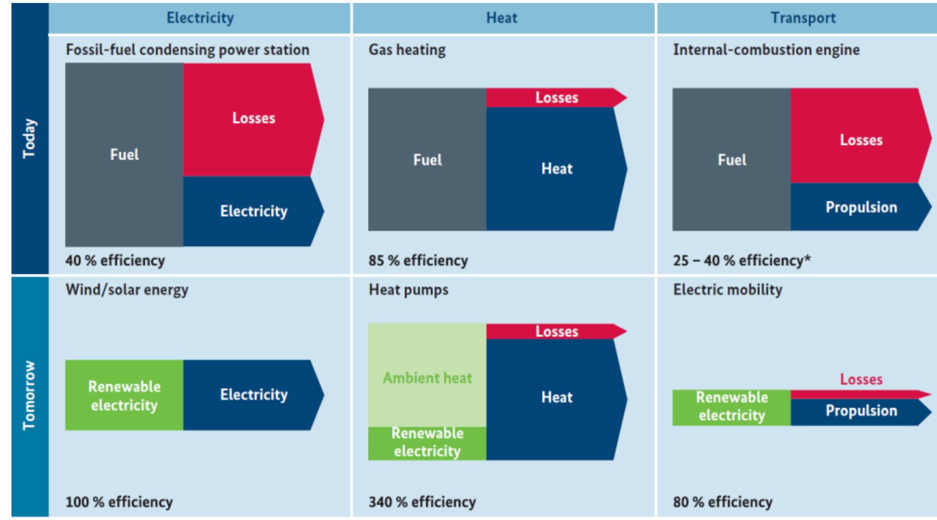
Key insights:

- 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 is consumed in 2023
- Faster transition and net negative CO_2 emissions are required
- Absolute zero CO_2 emissions around 2040 must be targeted

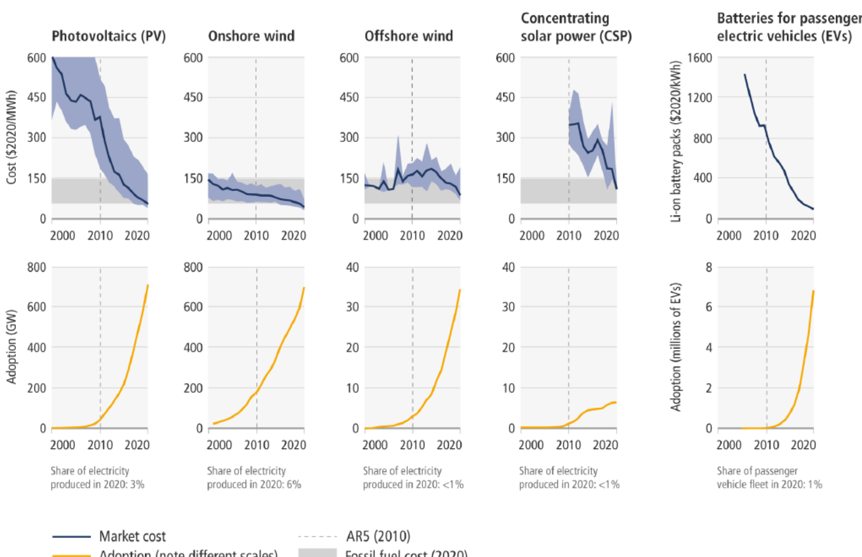
source: IPCC, 2020. 6th Assessment Report WG III

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 %.

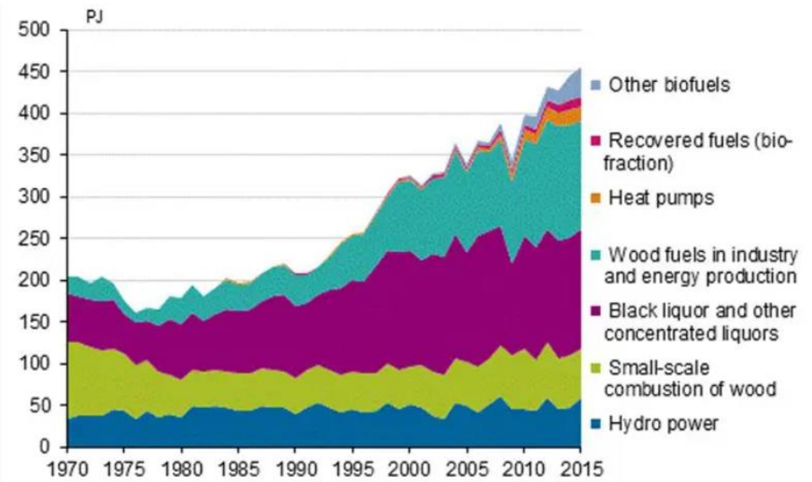


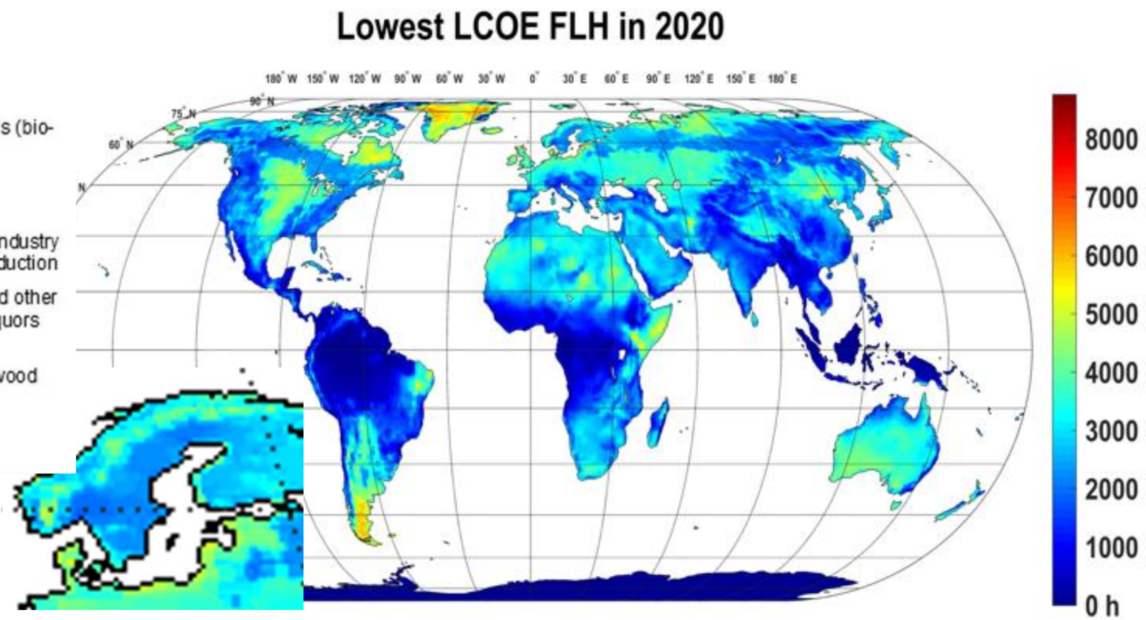
Key insights:

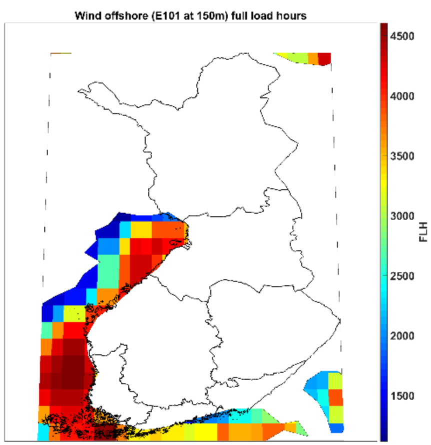
- Solar energy **resource availability** is 1000x larger than the global demand
- **Direct electricity** use is highly efficient
- Renewables **costs have declined** steeply and continued: solar PV, wind power, batteries, electrolyser, and others
- Combination of these three major drivers leads to massive uptake of solar PV

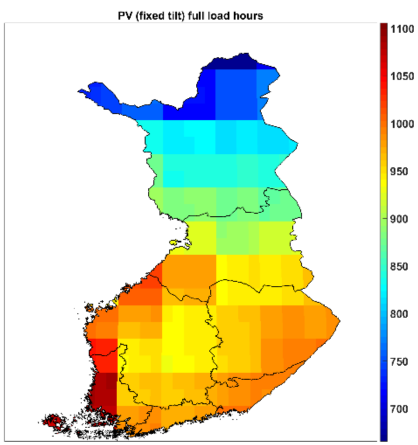
source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50
Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847
IPCC, 2020. 6th Assessment Report WG III

Resources in Finland





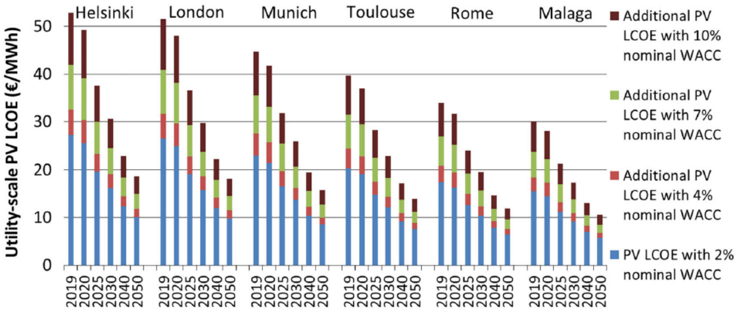


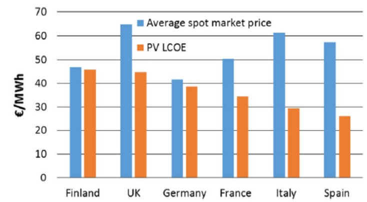


Key insights:

- bioenergy is very important for Finland, however, will be limited, maybe even shrinking
- Wind energy is excellent in northern hemisphere, also in Finland, onshore and offshore
- Solar energy is good in Finland maybe the least cost energy source in Finland in future

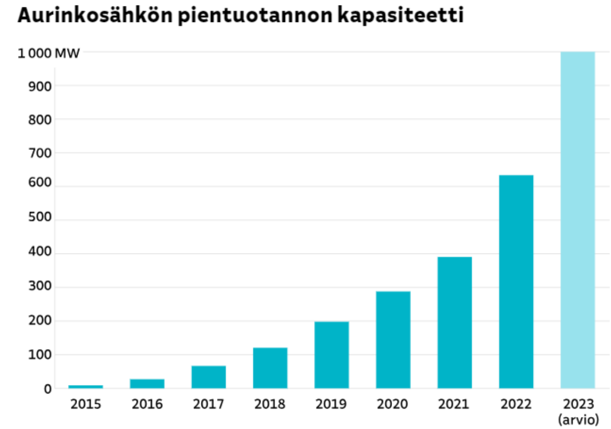
Cost development of PV in Finland

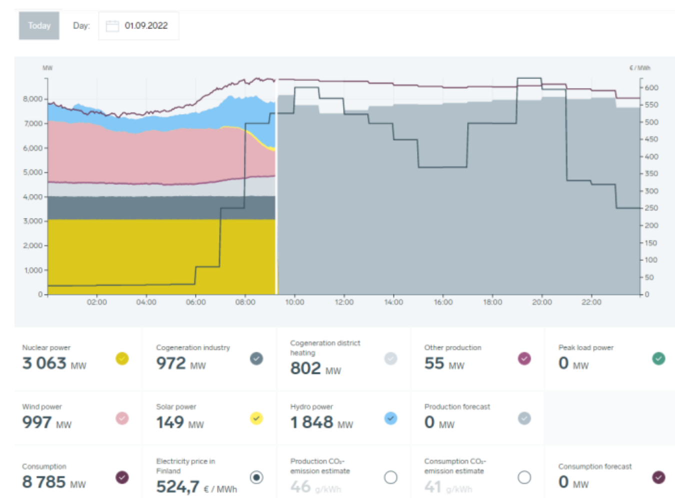


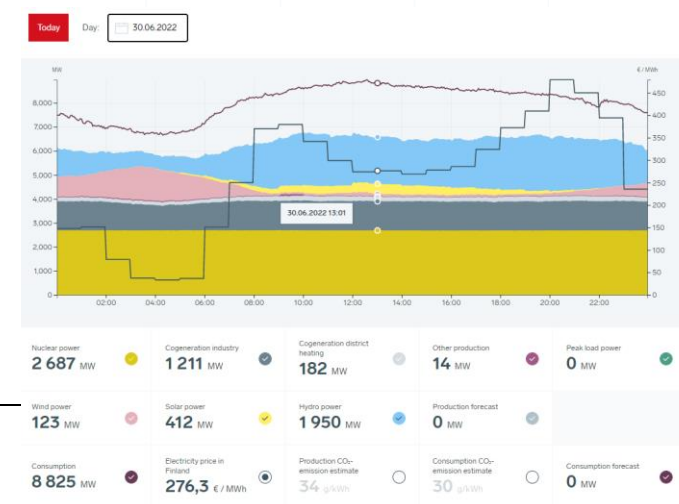


source: [Vartiainen et al., 2020. Progress in PV, 28, 439-453]()

FIGURE 10 Comparison of photovoltaics (PV) levelised cost of electricity (LCOE) and average day-ahead spot market prices 2018 in six European locations. 2018 capital expenditure (CAPEX) assumption 0.50 €/Wp and operational expenditure (OPEX) 10 €/kWp/a, nominal weighted average cost of capital 7%, annual inflation 2%



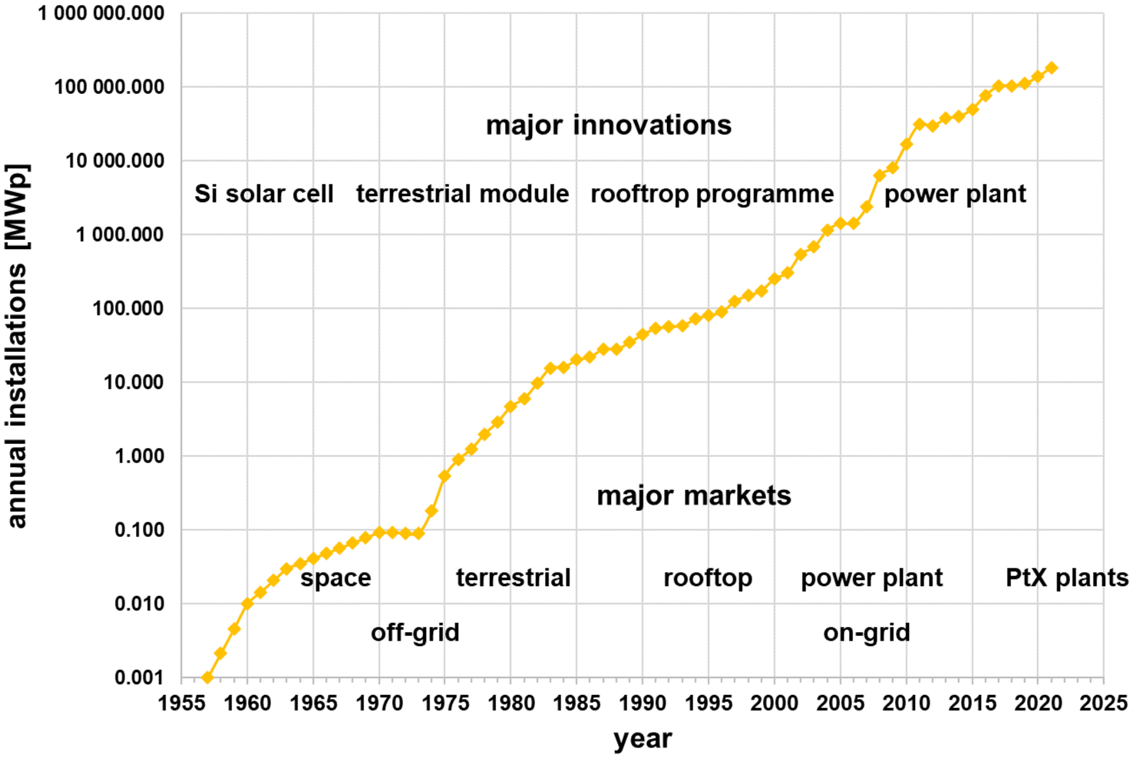


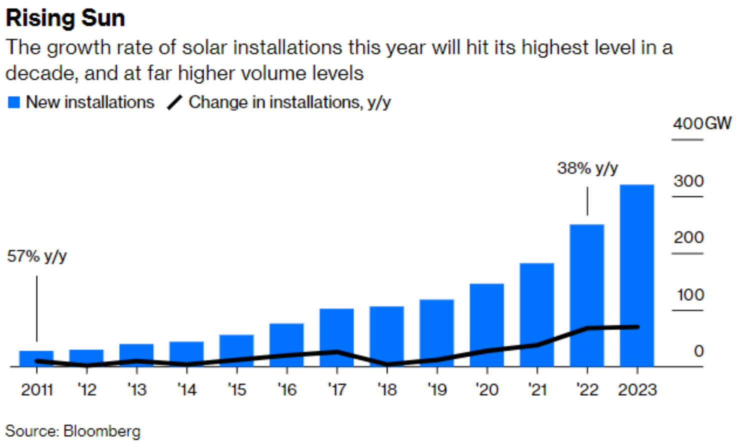


Key insights:

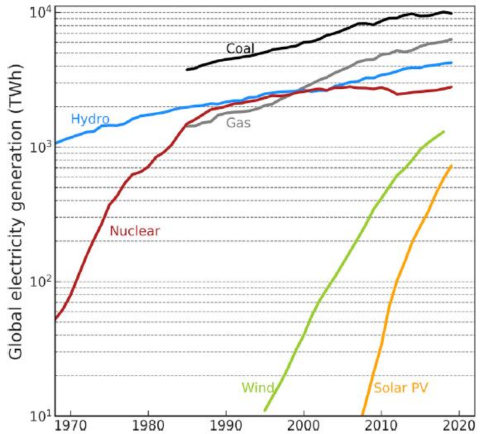
- Solar PV is most likely the by far most underestimated source of domestic energy
- It is low-cost, already today, with about 40-50 €/MWh
- Rooftop PV costs about 1100 €/kWp installed (early 2024).
- The 2022 wholesale electricity prices have been typically 200-600 €/MWh
- Best day of the year 2022 was 412 MW of PV according to Fingrid; in early February 2024 already 200 MW.
- Solar and wind energy are complementary (see 30.6. daytime and 1.9. as of now
- Massive ramping of solar PV (and wind power) would create an enormous benefit for Finland

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 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:

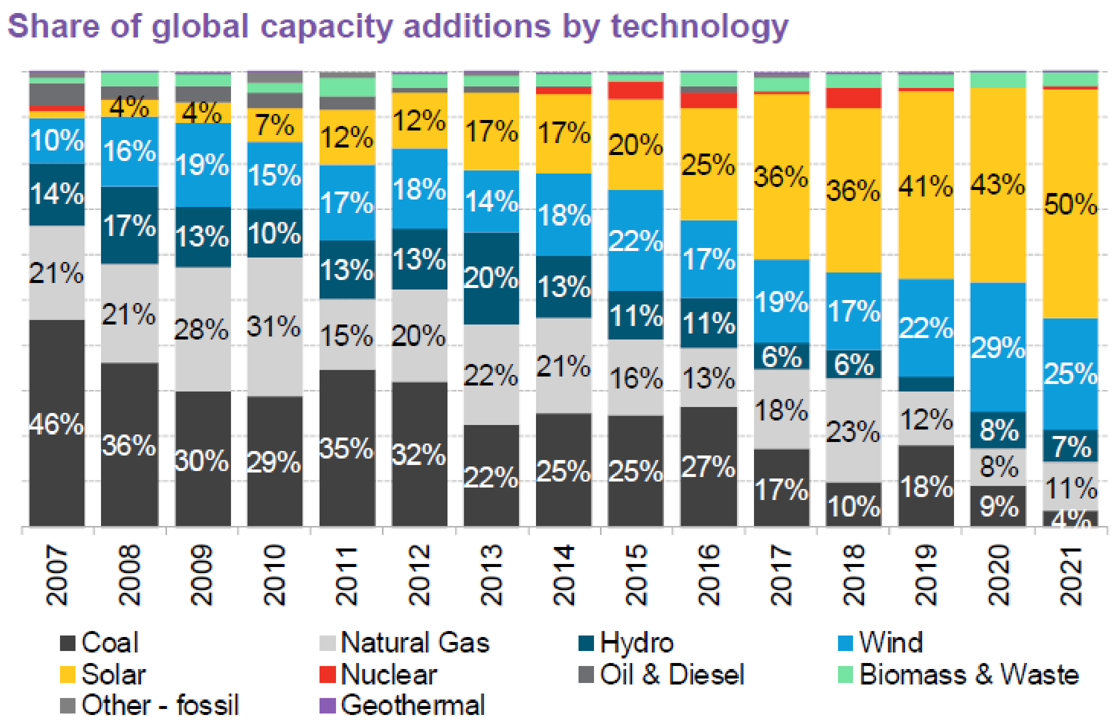
Electricity supply dominated by PV and wind power

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

PV is outside any historic experience



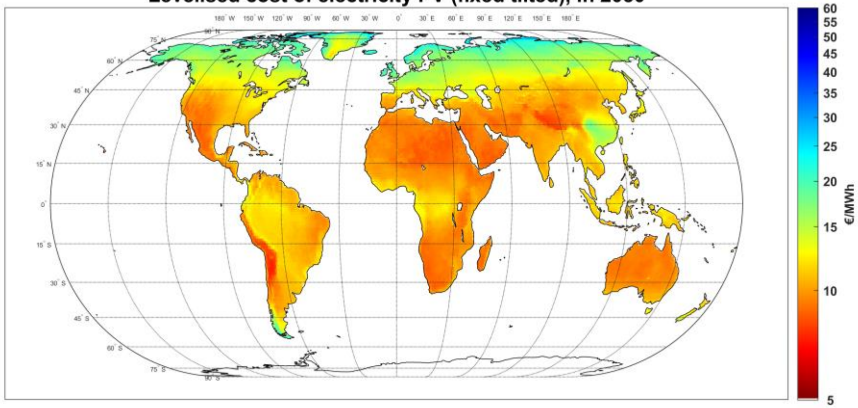
Source: BloombergNEF

Key insights:

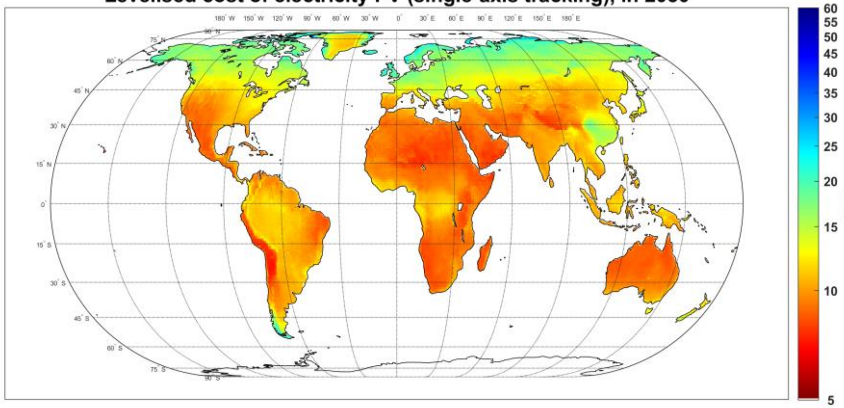
- **Solar PV and wind power dominate new installations, with clear growth trends for PV**
- **Hydropower share declines, a consequence of overall capacity rise, and sustainability limits**
- **Bioenergy (incl. waste) remain on a constant low share**
- **New coal plants are close to fade out**
- **New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

Levelised Cost of Electricity for PV and Wind

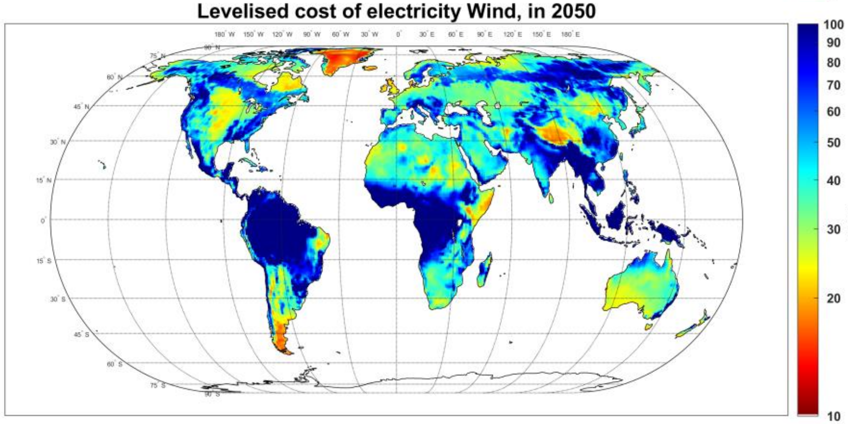
Levelised cost of electricity PV (fixed tilted), in 2050



Levelised cost of electricity PV (single-axis tracking), in 2050



Levelised cost of electricity Wind, in 2050



- **Low-cost electricity is a pillar of e-fuels**
- **Single-axis tracking PV provides lower LCOE at 20-30% higher FLh, compared to fixed tilted PV**
- **The least PV LCOE (in Atacama Desert) declines from about 12 to 7 €/MWh in 2030 to 2050, respectively.**
- **More than 10 real projects already announced for LCOE below 20 €/MWh.**
- **Low-cost PV would be accessible worldwide by 2030 and beyond.**
- **The least wind LCOE (in Patagonia) declines from about 18 to 15 €/MWh in 2030 to 2050, respectively**

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On the History of 100% RE Systems Research

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

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

2005 – first 100% RE article of Lund (2004) who is the architect of EnergyPLAN and formed the research team with the most citations in the history of 100% RE research

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

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

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

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

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

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

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

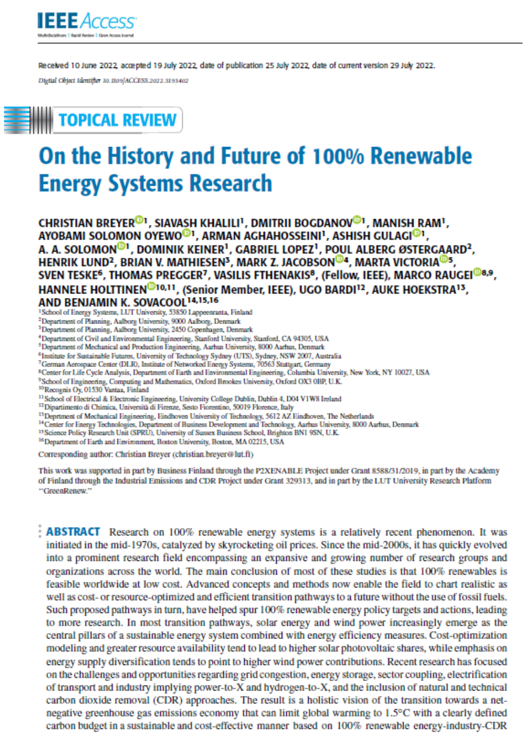
first global transition study showing a cost-neutral transition study for the entire energy system in hourly resolution using the LUT-ESTM by Bogdanov and Breyer et al. (2021)

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

- The first 100% RE system analysis was published in 1975 by Sørensen, on Denmark
- Lovins published in 1976 the second article on 100% RE, on the United States: "the soft energy path"
- The first global analysis for a 100% RE system published in 1996 in a journal, by Sørensen
- The first multi-node, hourly and large region 100% RE analysis in 2005 by Czisch
- Power-to-X concept for fuels, chemicals & sector coupling on energy systems emerged in 2009 by Sterner
- LUT established a state-of-the-art for 100% RE systems in 145 regions for the world in hourly resolution and cost optimisation as energy transition pathway
- 1000+ articles have been published in which 100% RE system analysis have been taken into consideration

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

100% Renewables Energy Systems Research



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TOPICAL REVIEW

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

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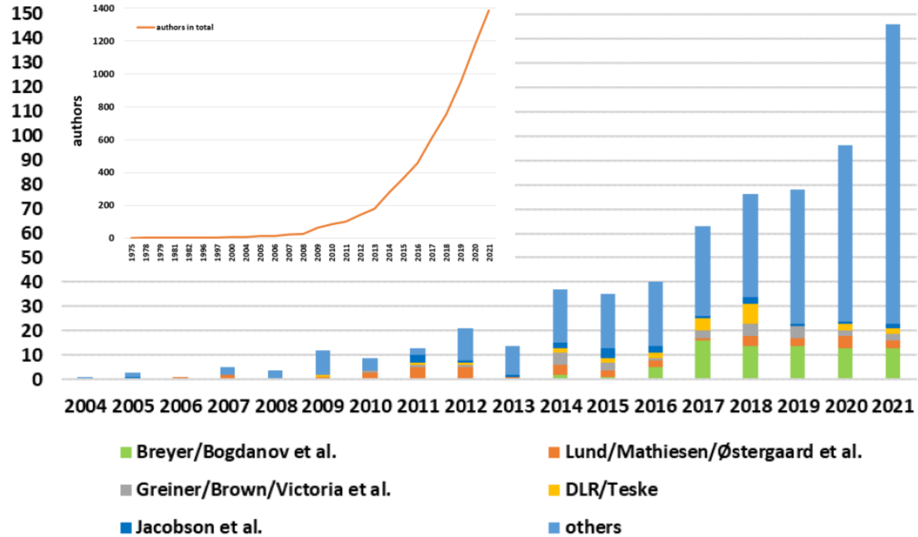
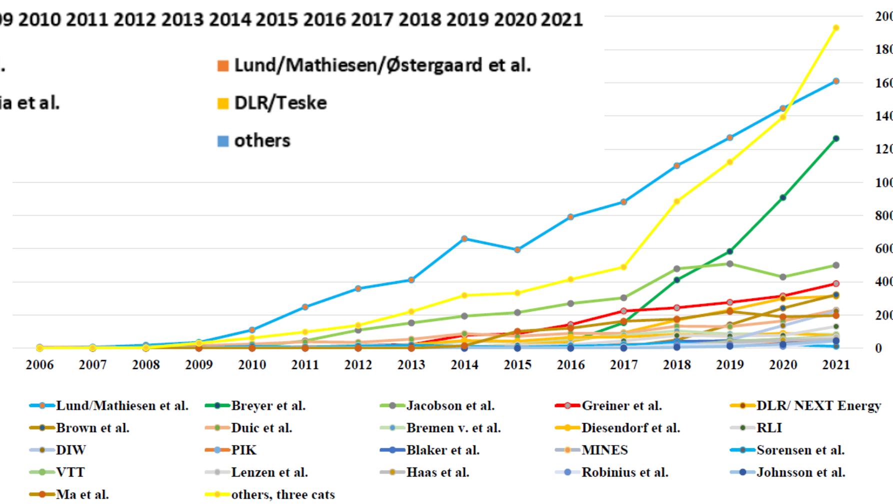
ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and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

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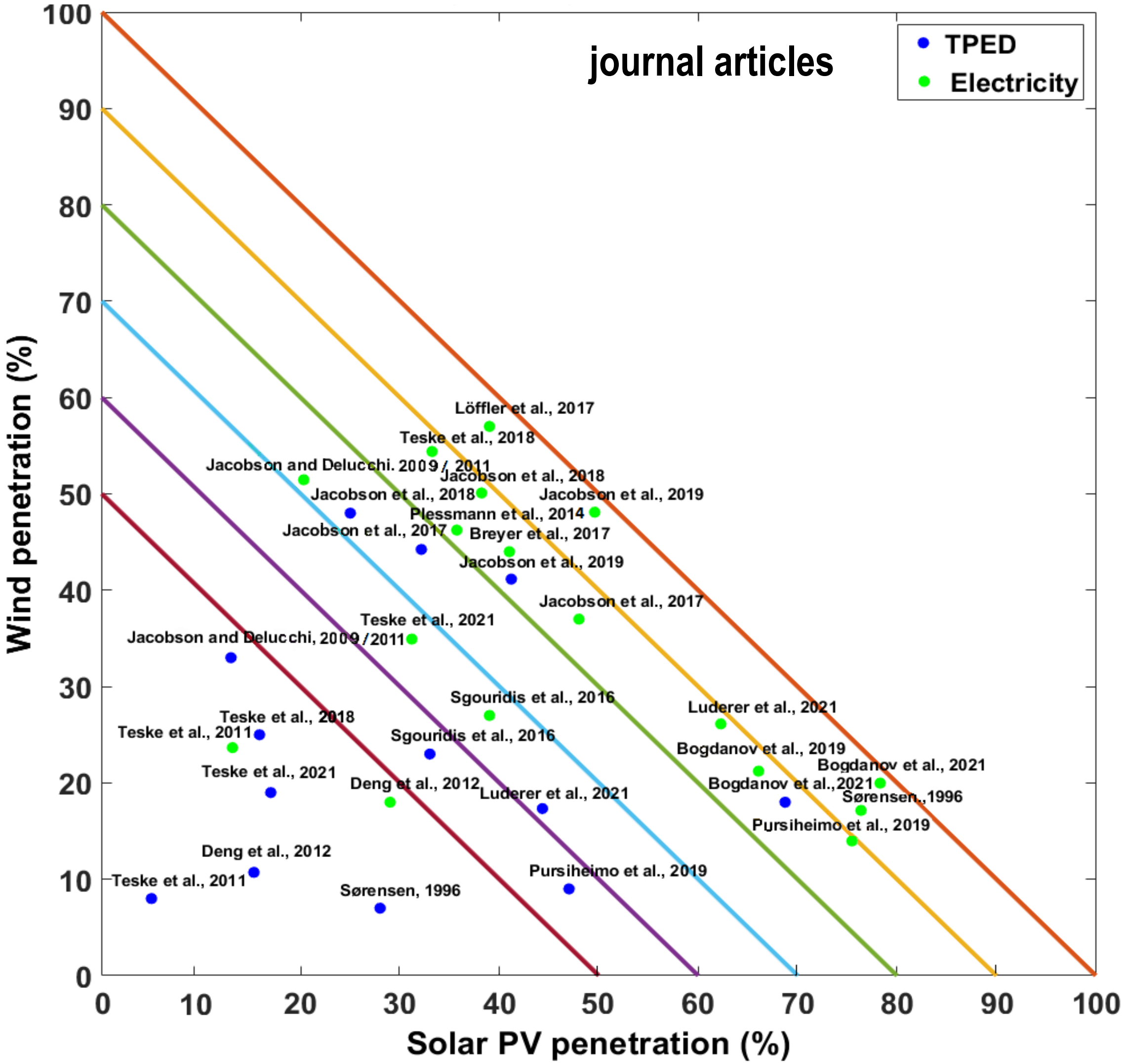
Global: PV and Wind Share in 100% RE Studies

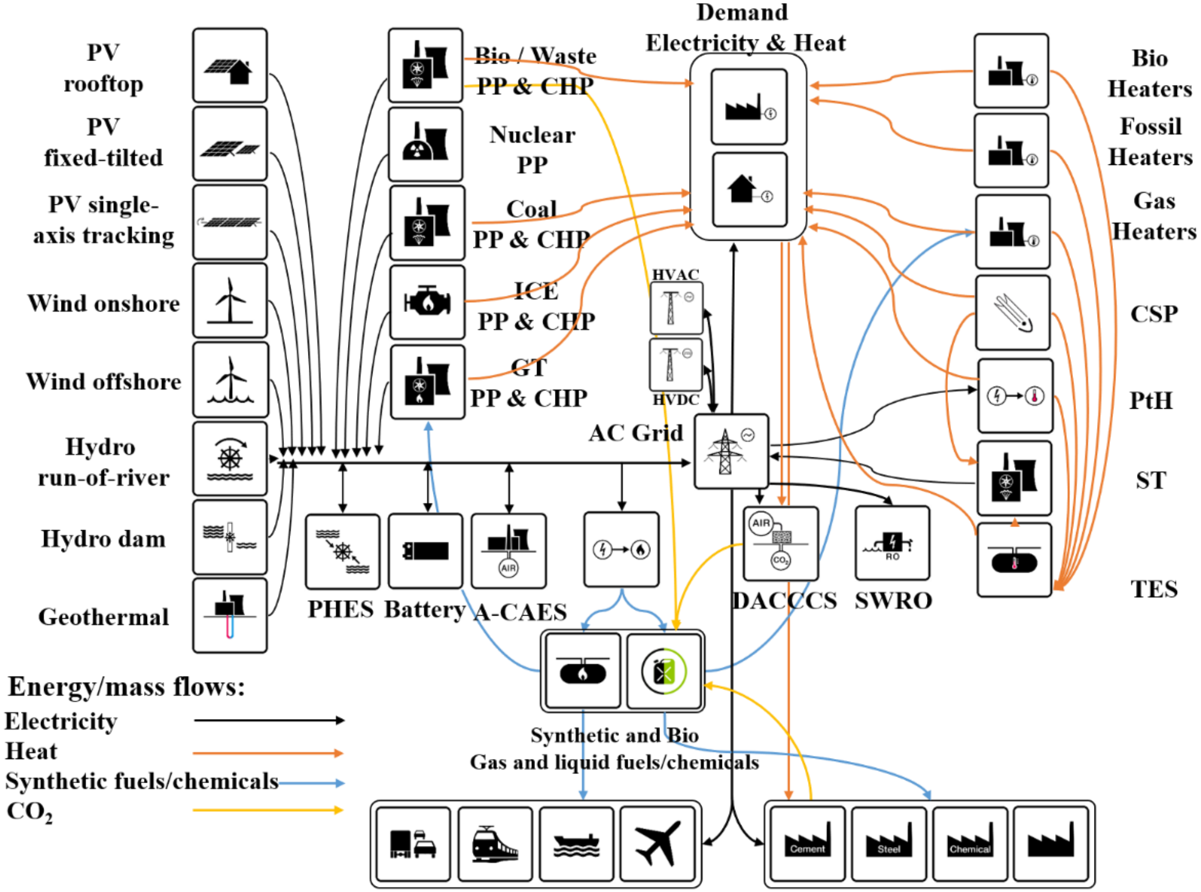


Key insights:

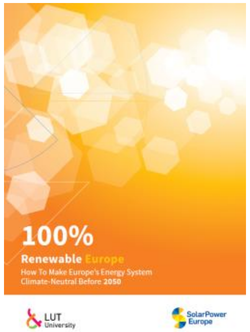
- 3 main groups:
  - High PV & wind: more PV
  - High PV & wind: more wind
  - Lower PV & wind
- PV share of around 50% by 2050 is standard
- Group of studies with high PV shares (70-80%) have all in common that they anticipate continued PV cost decline
- PV strongly benefits from electrification, low-cost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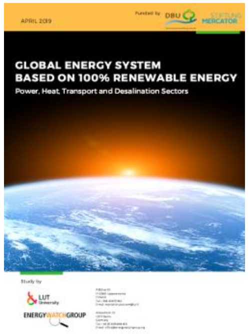

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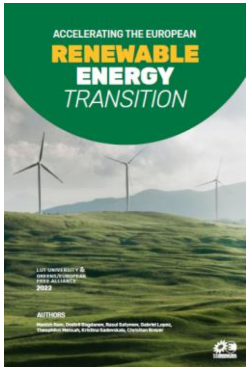

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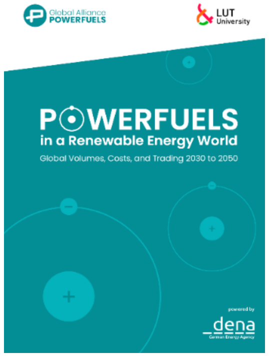

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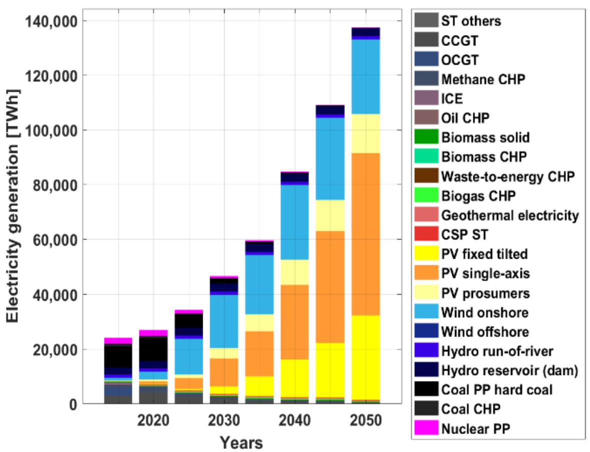
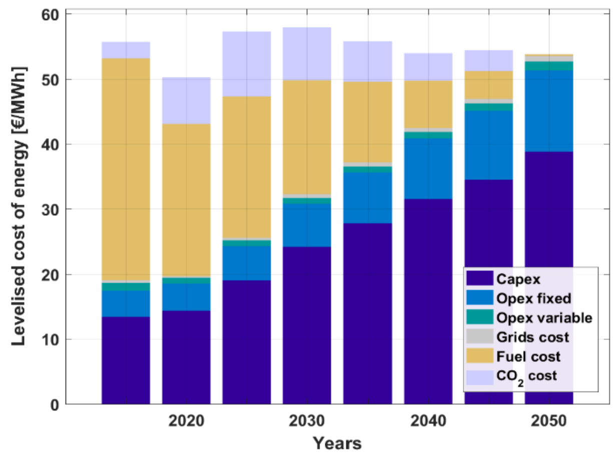
Key features:

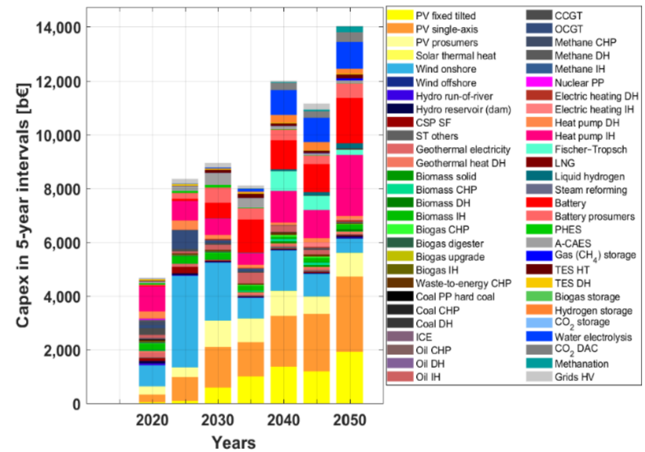
- full hourly resolution, applied in global-local studies, comprising about 150 technologies
- used for several major reports, in about 75 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (heat, fuels, chemicals, materials, freshwater, CO_2,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

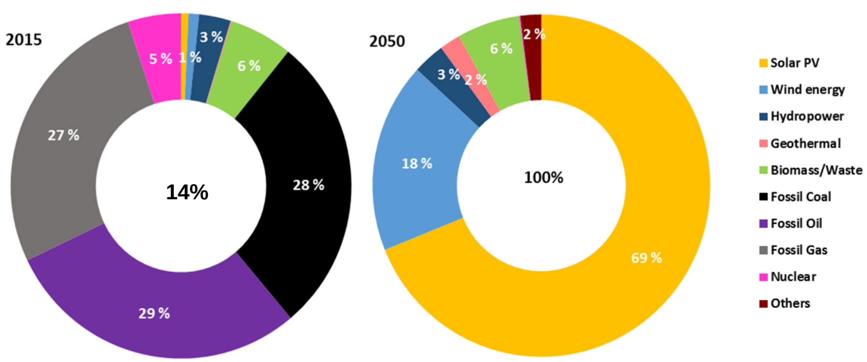
source: Bogdanov, Breyer et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, 283, 116273

Global: 100% Renewable Energy System by 2050







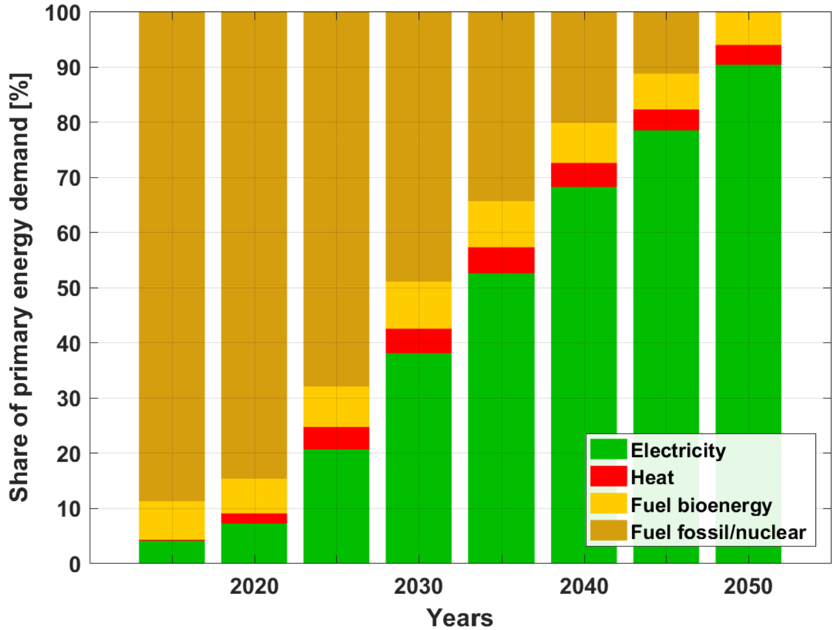


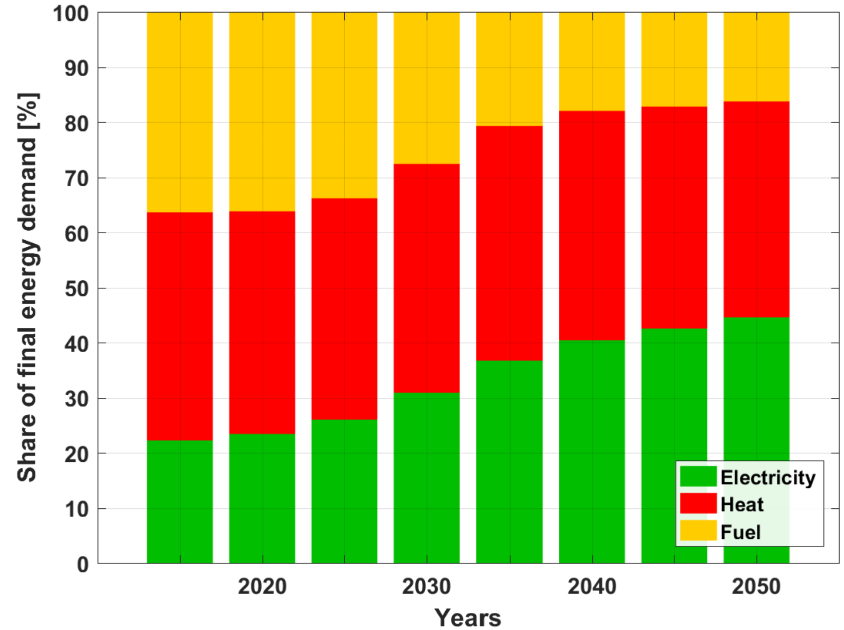
Key insights:

- 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



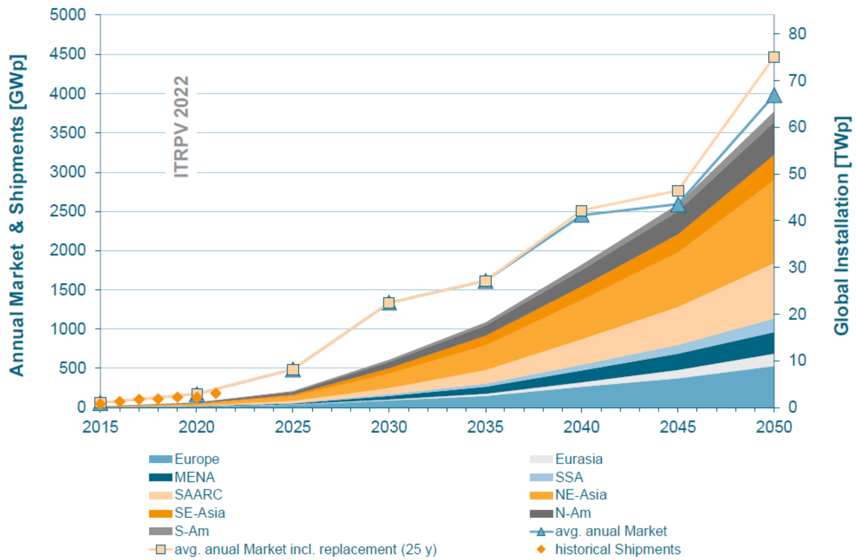


Key insights:

- 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

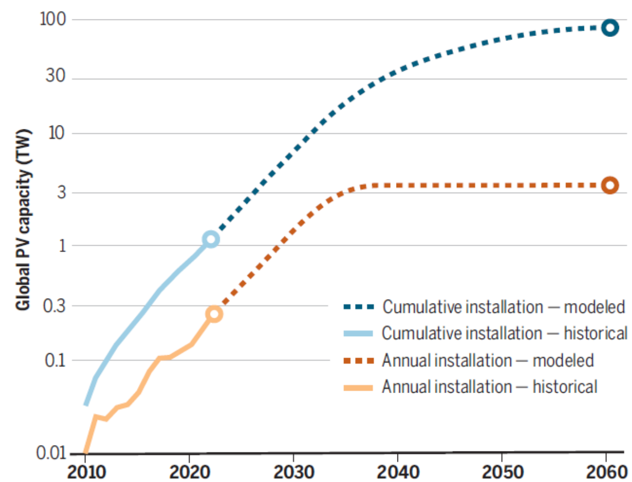
source: [Bogdanov et al., 2021. Energy, 227, 120467](#)
[EWG/LUT, 2019. Global Energy System based on 100% RE](#)

100% Renewable Energy System by 2050



PV installations and growth toward 75 TW by 2050

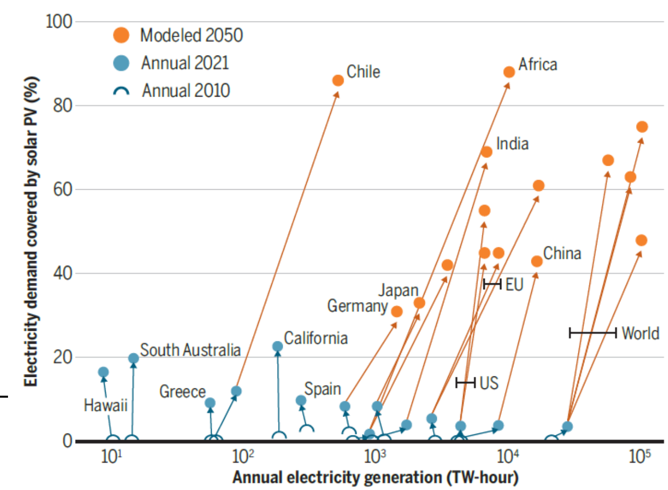
Modeled cumulative capacity going forward is based on sustaining 25% production rate growth over the next 7 years and then reducing slowly to steady state. Replacement needs are included by simple subtraction of installations 25 years before the modeled date.



source: [VDMA, 2022. ITRPV](#)
[Haegel et al., 2023. Science](#)

Regional electricity demand supplied by solar PV

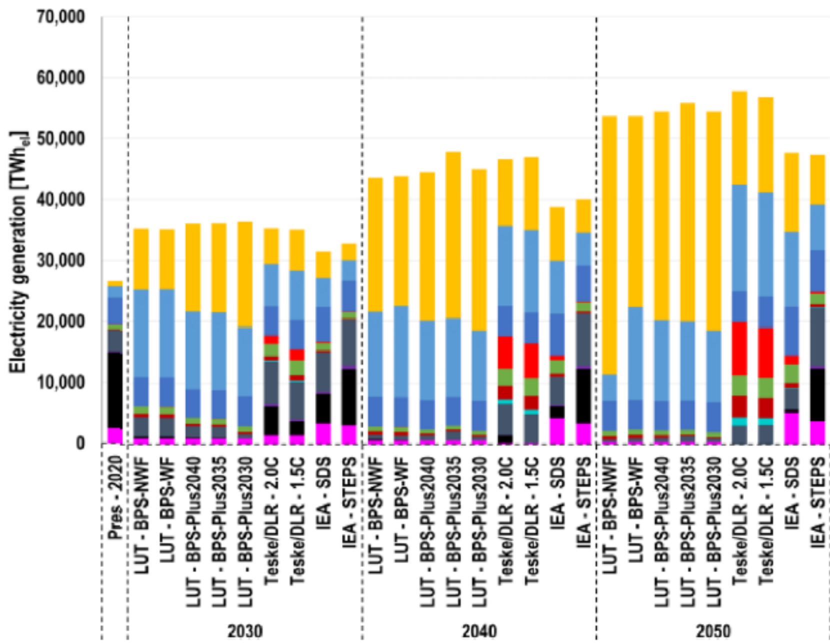
The data reflect annual percentages of historical regional demand (2010 and 2021) and modeled demand projections (2050). See supplementary materials for details.



Key insights:

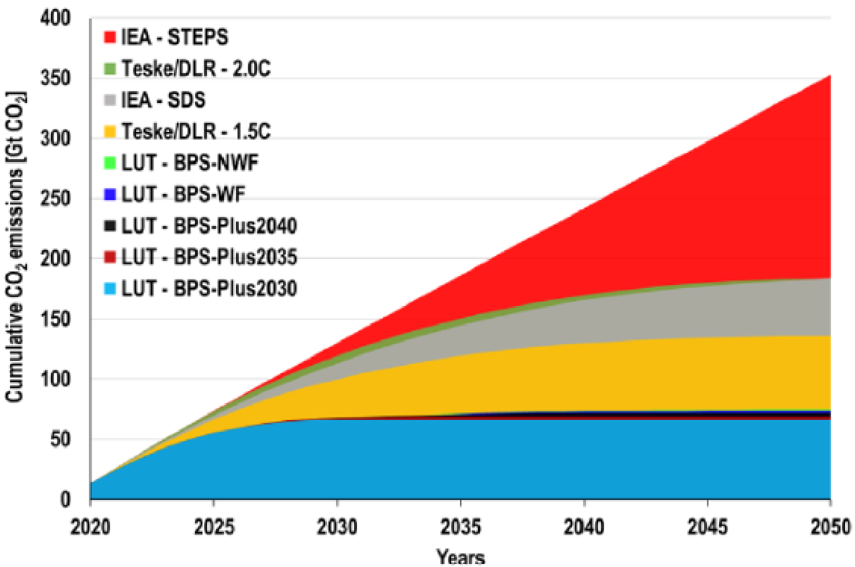
- Low-cost PV leads to a cost-neutral energy transition towards 2050
- This implies about 63 TW of PV by 2050 for the energy system & about 75 TW of PV for the energy-industry system (chemicals, etc.)
- This leads to about 3 TW/a of PV installations in 2040s
- This view is now common sense among PV experts
  - 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

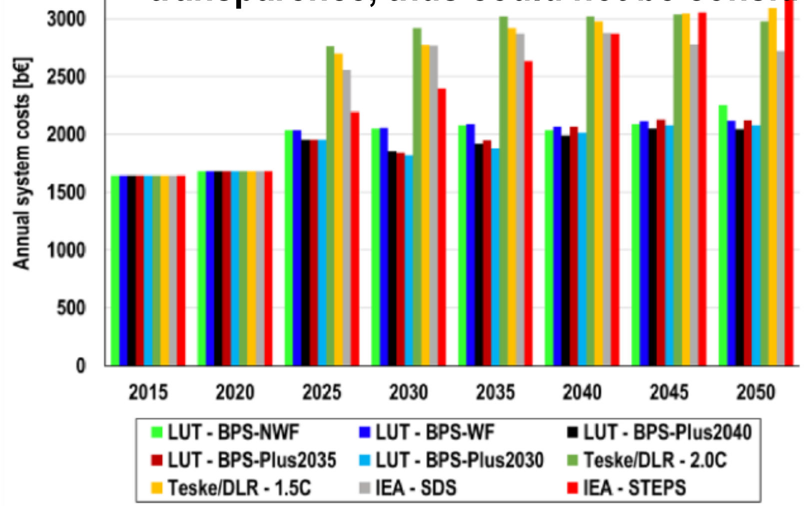
Comparing Scenarios of varying Ambitions



Background and insights:

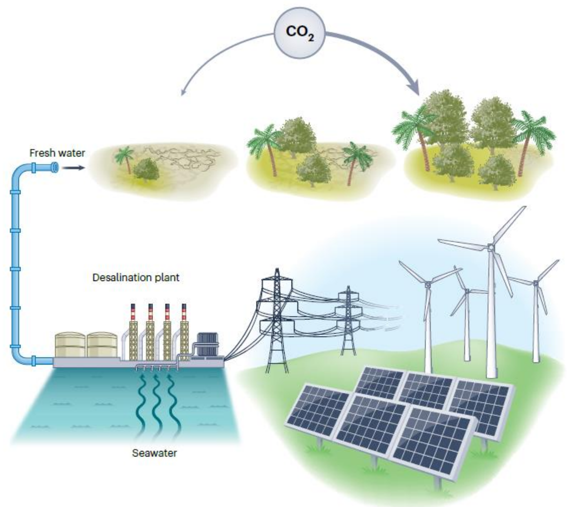
- Power sector analysed
- World in 9 regions studied
- Hourly resolution used
- Transition till 2050 compared
- IEA WEO, Teske/DLR, LUT scenarios considered
- IEA WEO scenarios represent worst case: high cost and lowest CO_2 reduction performance, also due to higher cost of fossil CCS and nuclear
- 100%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

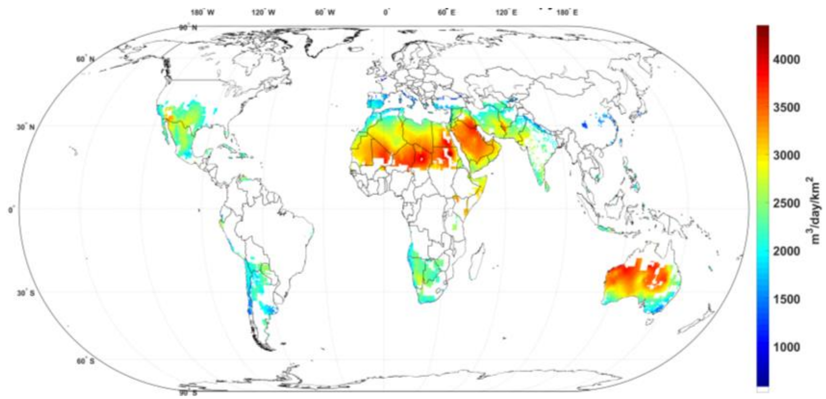




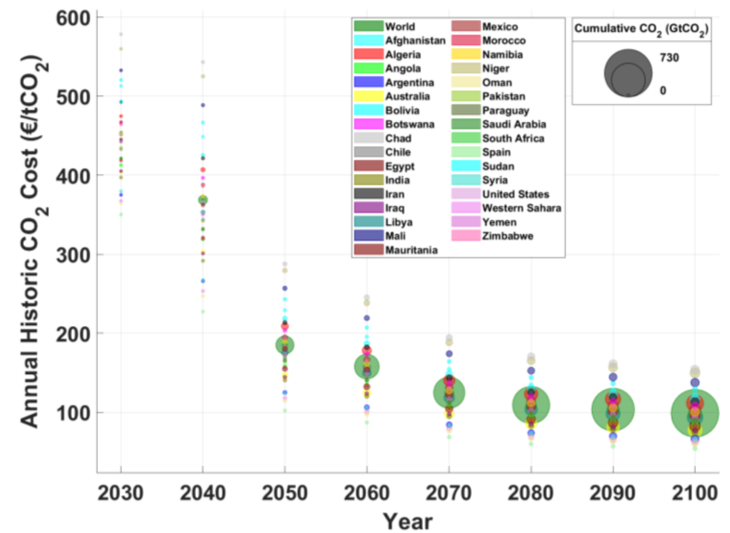
Source: [Aghahosseini et al., 2023. Applied Energy, 331, 120401]

Desalination-based Afforestation





- Why not greening the deserts? With substantial CDR potential, enormous co-benefits and little land-use issues
- Precondition: extremely low electricity cost and seawater reverse osmosis desalination
- This is a conceptionally new CDR option
- CDR potential in this century about 700 $GtCO_2$
- Cost potential below 200 €/tCO_2 with below 100 €/tCO_2 in best regions
- Co-benefits with regional cooling may be very attractive
- Time lag of about 20 years between investment and substantial CO_2 sequestration is a challenge



source: Caldera U, Breyer C., 2023. Afforesting arid land with renewable electricity and desalination to mitigate climate change, Nature Sustainability, online

Global: 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.

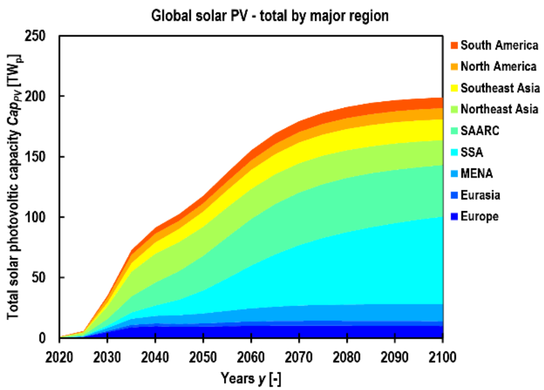
		2030	2040	2050	ref
Electricity demand for electrolysis					
Energy system	TWh_{el}	548	17,069	48,908	[49]
Steelmaking	TWh_{el}	2,718	5,621	6,284	[58]
Chemical feedstocks	TWh_{el}	2,808	17,319	33,031	[59]
Total	$\mathbf{TWh_{el}}$	**6,074**	**40,009**	**88,223**	
Hydrogen demand					
Energy system	$TWh_{H2,LHV}$	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	$\mathbf{TWh_{H2,LHV}}$	**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	$\mathbf{GW_{H2,LHV}}$	**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	$\mathbf{MtCO_2}$	**594**	**4,057**	**9,125**	

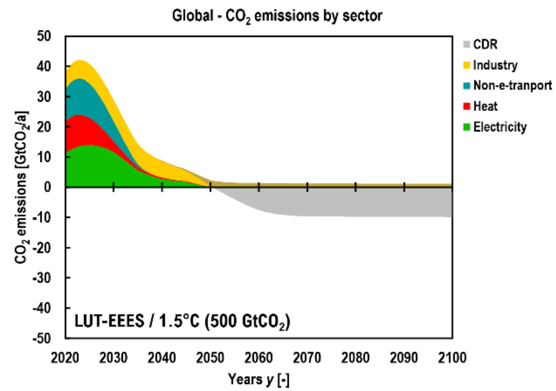
- Hydrogen is a subset of the PtX Economy
- Main demand: e-fuels (marine, aviation), e-chemicals, e-steel – ammonia, methanol kerosene jet fuel
- Primary energy supply from renewable electricity: mainly PV plus wind power
- Direct electrification wherever possible: electric vehicles, heat pumps, desalination, 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, Lopez, et al., 2023. The role of electricity-based hydrogen in the emerging Power-to-X Economy, International J of Hydrogen Energy
Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, RSER

Solar PV in the 21st century





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Energy demand estimation using a pre-processing macro-economic modelling tool for 21st century transition analyses

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Demand
Transition
Modelling
Macro-economic scenarios

ABSTRACT

Energy systems research requires a variety of demand scenarios for possible futures. Comprehensive energy demand modelling is often made with a simplified approach or based on assumptions scattered among various sources, if it is published at all. There is no detailed discussion of the impact of various macro-economic scenarios on different levels of energy demand available. This study uses LUT-DEMAND, a novel modelling tool for energy demand, to create comprehensive demand input data in high spatial resolution globally and high temporal resolution until 2100. A multi-step approach is applied to estimate the energy demand. A variety of economic and demographic scenarios are explored, including the shared socio-economic pathways. The total primary energy demand is estimated for possible limitations caused by the overall energy demand and chosen technologies. The results for this century's energy supply for ambitious transition targets are presented, and they show a significant impact of macro-economic assumptions on scale and trajectory on all levels of energy demand. Among the explored scenarios, the total primary energy demand may rise to 399 PWh (1435 EJ) by 2100, with a maximum estimated solar photovoltaic capacity demand of about 200 TW$_p$. LUT-DEMAND and its documentation are available in an open-access online repository.

1. Introduction

Climate change caused by emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) into the atmosphere forces humankind to act in order to mitigate its repercussions. One major step was made in the year 2015, when the Paris Agreement was signed [1]. In this agreement, almost 200 countries agreed to limit global warming far below 2.0 °C and to make efforts to limit global warming to 1.5 °C compared to pre-industrial levels. Such goals require solutions. Since consensus on the fact that global warming is caused by humans in not in question anymore [2,3], the warming effect of CO_2 on the atmosphere has been principally known since 1856 [4], and the vast majority of global CO_2 emissions can be linked to the burning of fossil fuels and industrial activities [5], the development of pathways for the defossilisation of the energy industry is one of the most important solutions. Analyses on such pathways require studies on a global level but also in a higher spatial resolution.

In recent years, energy system transition research has seen steep diversification. According to a review done by Hansen et al. [6], the research field on highly renewable energy system analyses mostly covered the power sector in the past, while the other energy sectors heat, transport, industry, desalination, and carbon dioxide removal (CDR) were of less interest in the field of energy system modelling. Less than 20% of the investigated studies until 2018 included all relevant energy sectors. Essentially, most studies investigate a time horizon till 2050. However, with increasing diversification and sector coupling, comprehensive input data are required. Up to now, comprehensive scenarios for energy system transition modelling input are defined only for known integrated assessment models (IAMs), agencies, or private entities dealing with energy system modelling, such as the shared socio-economic pathways (SSP) [7] used for the reports of the Intergovernmental Panel on Climate Change (IPCC) [5], the International Energy Agency (IEA) and scenarios used in their annual World Energy Outlook (WEO) [8–10], or Shell's energy transformation scenarios [11]. However, open-source input data and a fully transparent methodology for the calculation of energy demand are not fully available.

The two most prominent institutions with a major impact on ongoing discussions about mitigation options for climate change are the IPCC,

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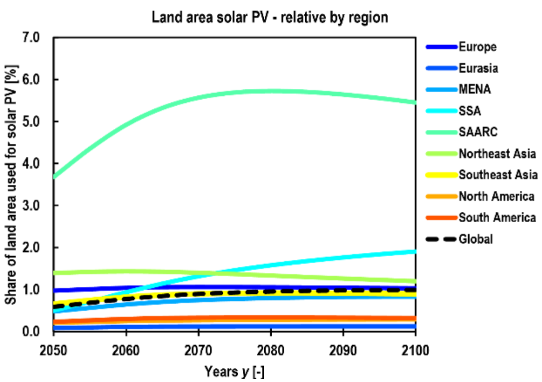

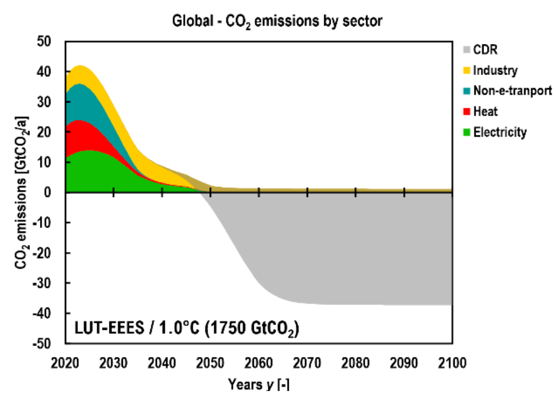

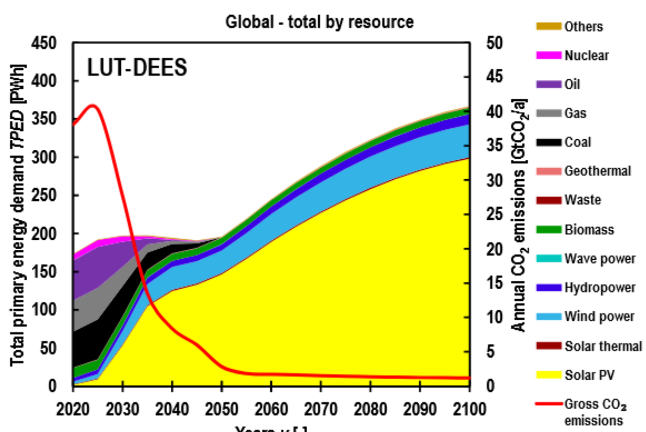

Key insights:

- PV demand by 2100 up to 200 TW (highest number so far)
- Climate safety with revised 1.0ºC climate target enabled by PV-based DACCS
- Area limitation, in particular in South Asia with 5-6% land demand
- Power-to-X Economy may evolve to a Solar-to-X Economy

source: Keiner et al., 2023. Energy demand estimation using a pre-processing, macro-economic modelling tool for 21st century transition analyses, Energy, 272, 127199

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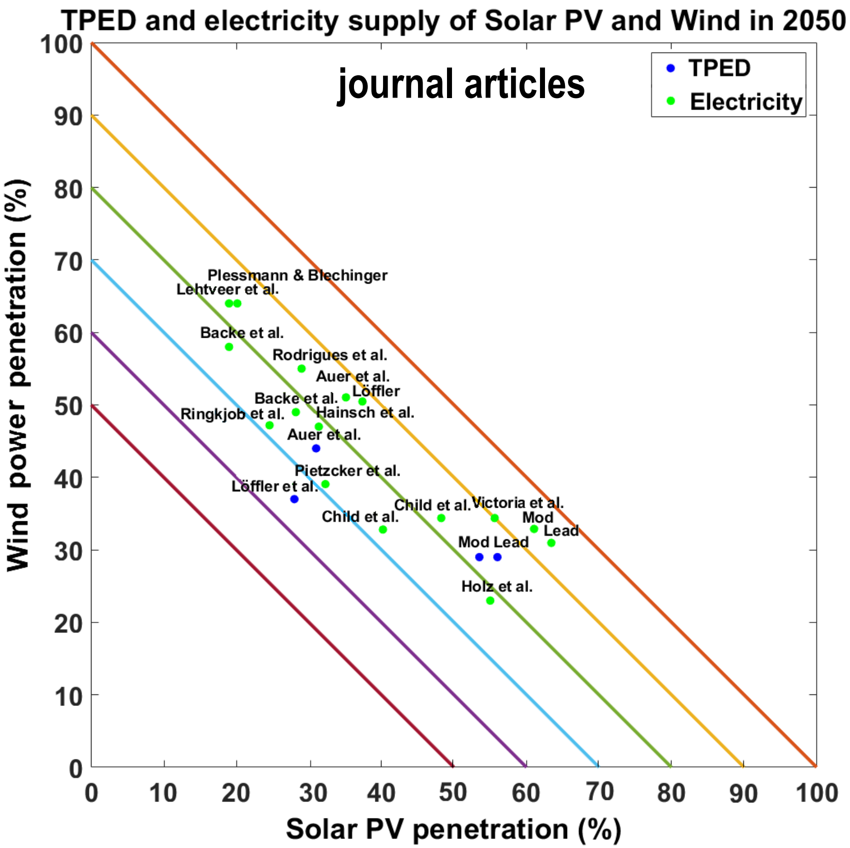
Agenda

- Background
- 100% Renewable Energy Research
- Global: 100% Renewables
- Europe: 100% Renewables
- Finland: Highly Renewables
- Summary

Solar PV Share in 100% RE Studies for Europe



Key insights:

- 2 main groups:
  - high PV & wind: more PV
  - high PV & wind: more wind
- PV & wind electricity share >80% standard
- PV & wind TPED share in 65-85% range
- PV shares around 30-40% by 2050 standard for Europe
- Victoria et al. is very close with 56% PV share
- This research (link below) finds 61-63% PV share while a most recent one finds 54% PV share
- Reasons for PV shares >50%
  - low-cost of PV & batteries & electrolysers
  - high levels of electrification
  - high levels of PtX: PV benefits strongly from H_2 buffering
- Difference between 50% and 60% PV share
  - PV differentiation: PV prosumers (R/C/I), fixed and 1-axis
  - independent optimisation of PV options
  - forcing of supply, e.g. wind offshore, also wave, etc.

- Major reports for public discourse document lack of up-to-date knowledge of consultants
  - McKinsey (20% PV share in 2050), DNV (15%), Navigant (14%); IEA WEO SDS (13%) NZE without regional data
  - lack of ambition: no 100% RE scenario known, much fossil CCS and nuclear, low levels of electrification
  - oversimplified models: low temporal and spatial resolution, no cost optimisation, low levels of PtX and sector coupling
  - cost assumptions used often violate market trends (too high renewables cost, too low CCS & nuclear costs)

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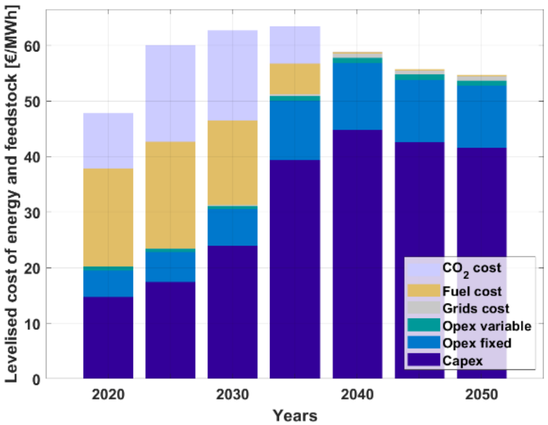
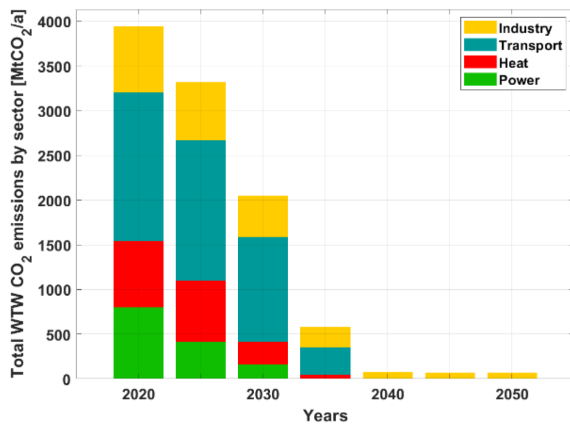
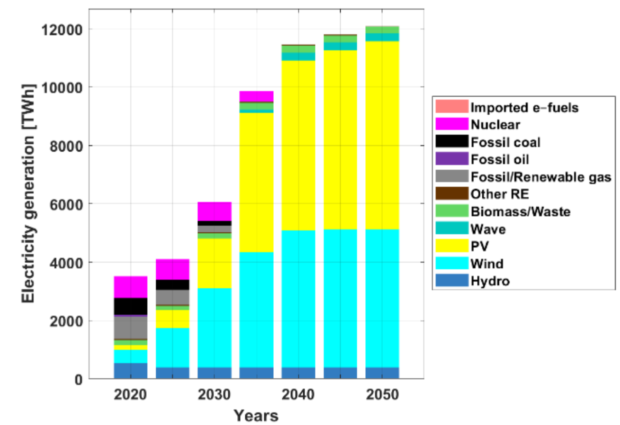
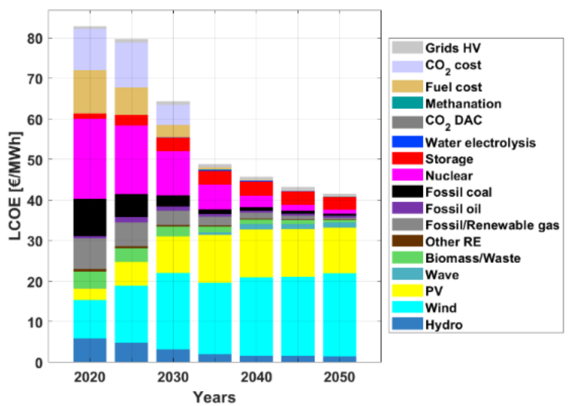
source: Breyer, Bogdanov, Ram, et al., 2023. Energy transition from a European perspective. Progress in Photovoltaics

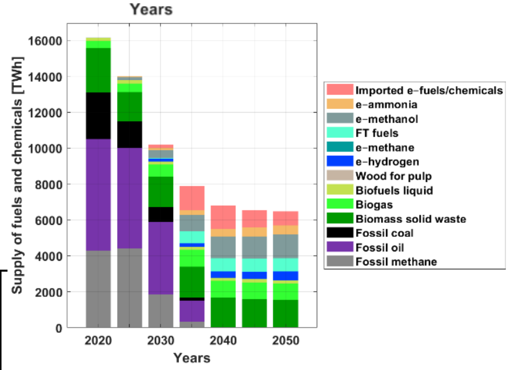
Europe: Highly Ambitious Energy-Industry Transition





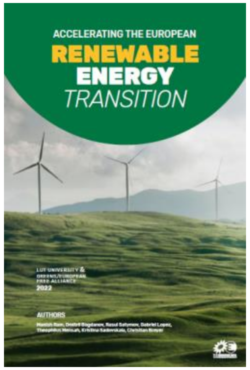






- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: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

Overview
Europe – 20 Regions (inclusive of EU-27)

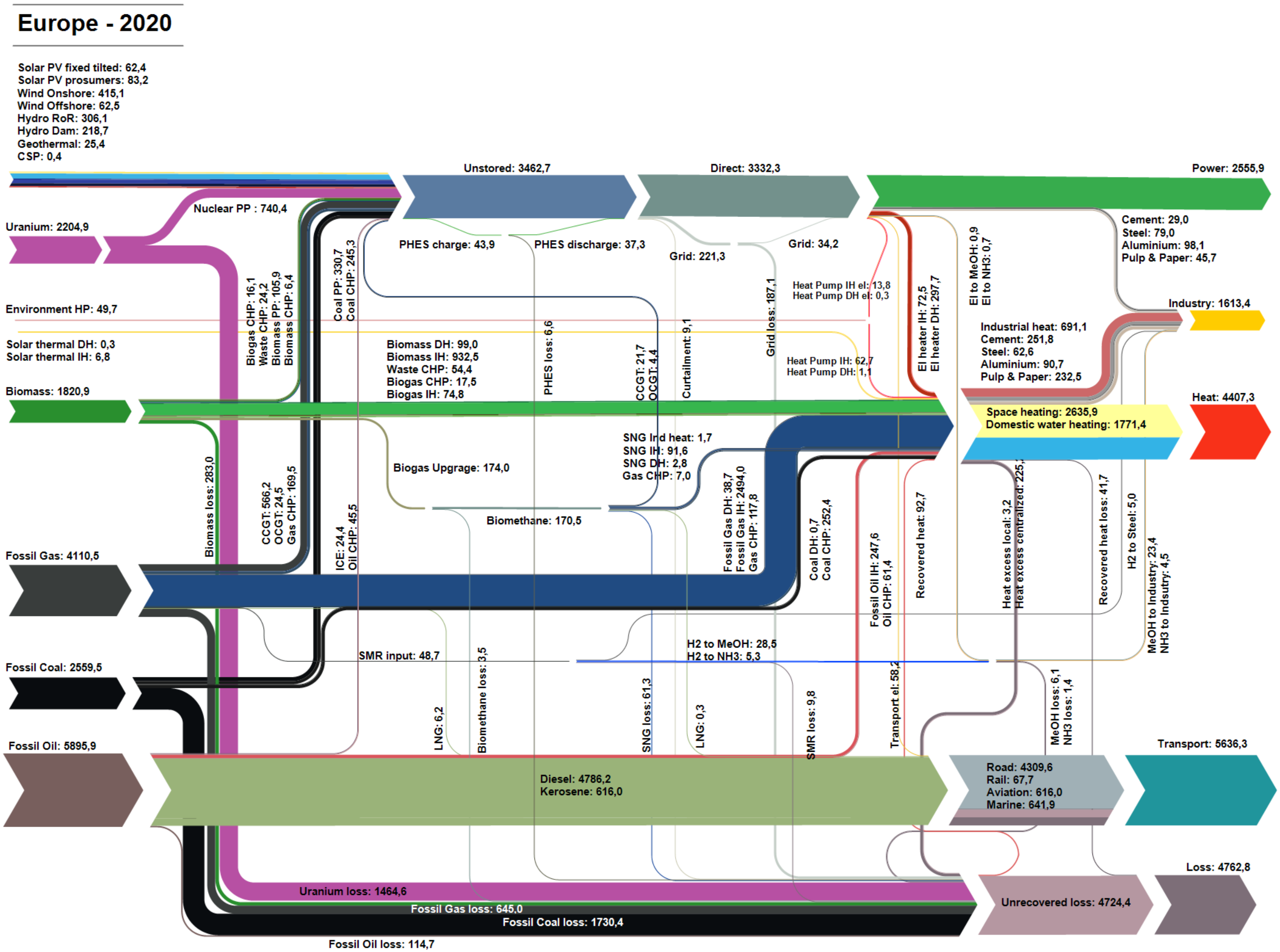


[link to report]

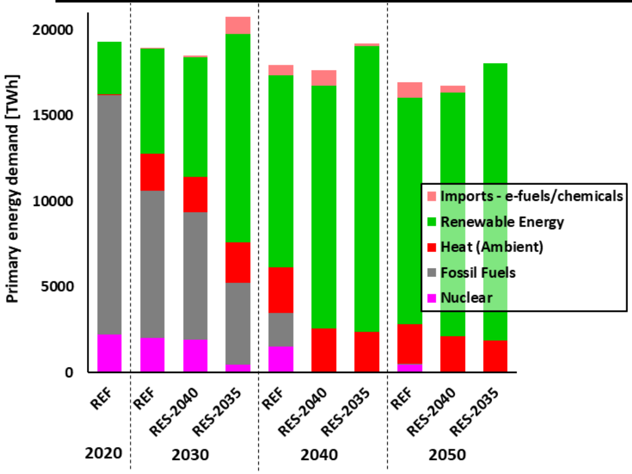
Important information:
- report is for EU-27
- investigation was done for entire Europe (grid integration, overall European perspective)
- results shown in the following are for entire Europe
- there are no structural differences

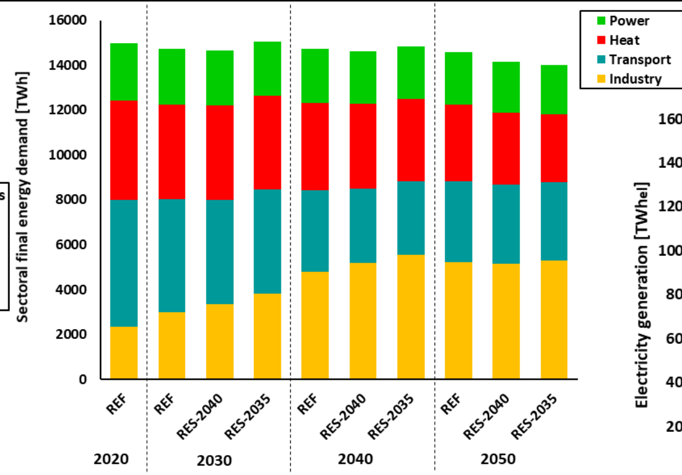
Europe is structured into 20 Regions that includes all 27 EU member states:
- Iceland, Norway, Denmark, Sweden, Finland, BALTIC (Estonia+Latvia+Lithuania),
- Germany, Poland, CRS (Czech Republic+Slovakia), AUH (Austria+Hungary), CH (Switzerland+Liechtenstein)
- IBERIA (Portugal+Spain+Gibraltar), France (France+Monaco+Andorra), Italy (Italy+San Marino+Vatican+Malta)
- BRI (Ireland+United Kingdom), BNL (Belgium+Netherlands+Luxembourg)
- BKN-W (Slovenia+Croatia+Bosnia and Hertzegovina+Kosovo+Serbia+Montenegro+Macedonia+Albania), BKN-E (Romania+Bulgaria+Greece), UA (Ukraine+Moldova), TR (Turkey+Cyprus)

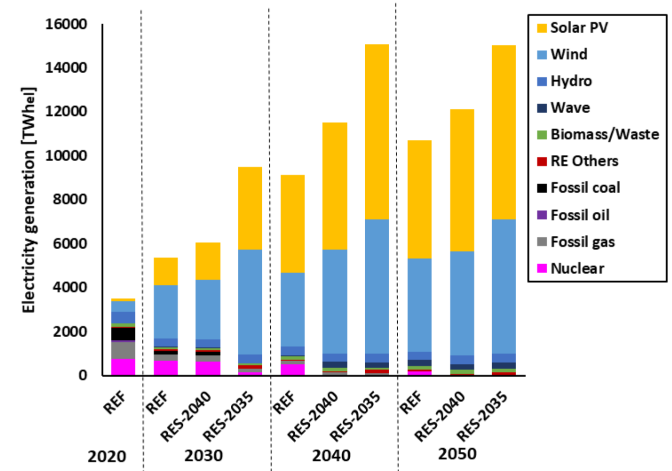
System Outlook – Energy Flows in 2020

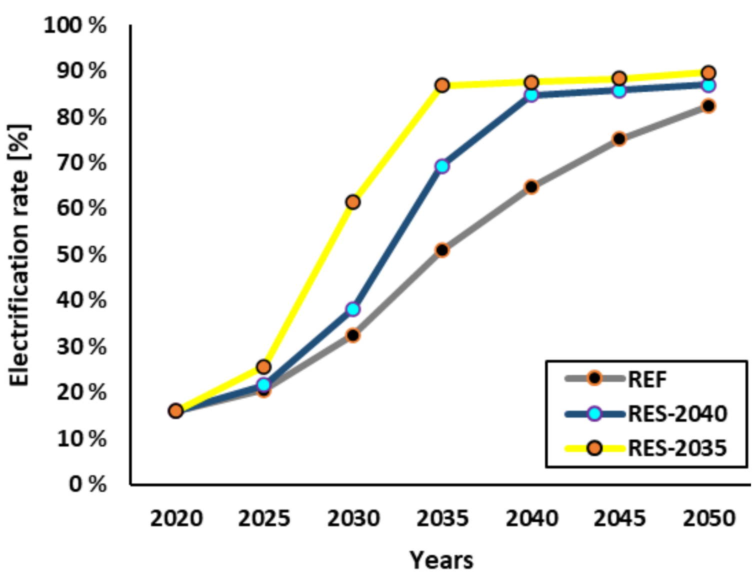


Long-term Demand: Primary, Final, Electricity
Scenario Comparison









Key insights:

- Energy demand growth in the power, heat, transport and industry sectors is aggregated and linked to powertrain transformation and diffusion of conversion technologies.
- Comprehensive electrification is the underlying theme, which massively increases overall energy efficiency to an even higher growth rate in provided energy services.
- Massive increase in electricity generation required, scaled by PV & wind
- Efficiency gains vary across the scenarios, with all the 3 scenarios gaining around 34-42% in comparison to a low electrification demand with an assumed business-as-usual growth with current levels.
- Increased electrification combined with high shares of renewables is far more efficient than the current fossil fuels dominated energy system.

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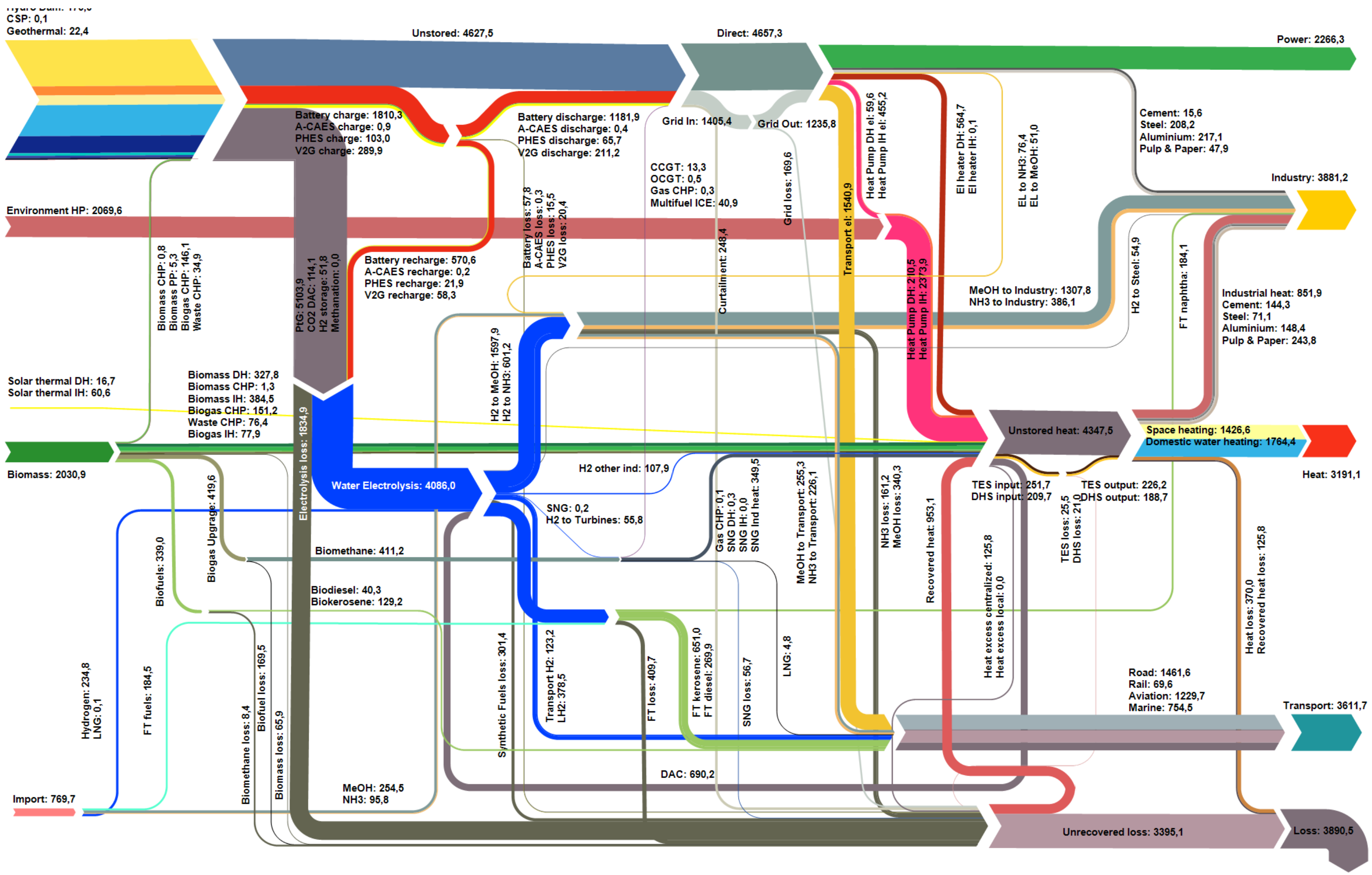
source: Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022

Power-to-X Economy as new characteristic Term

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

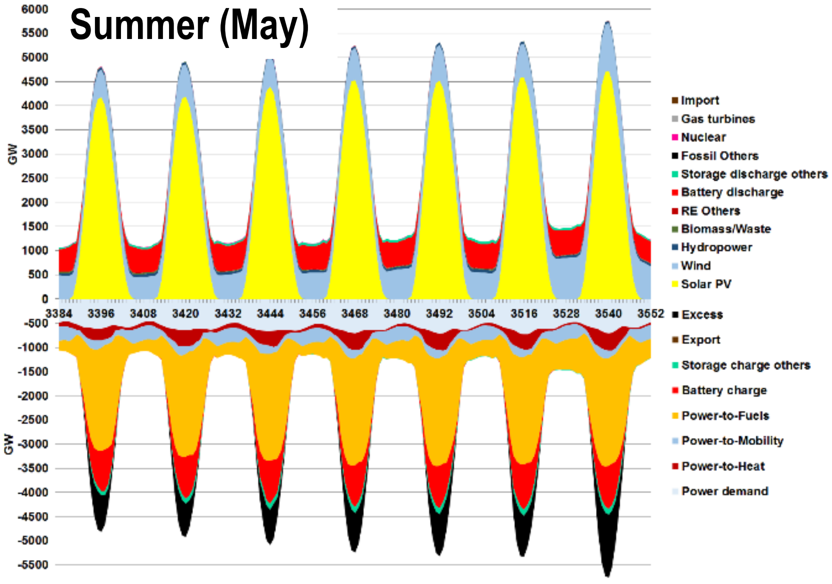


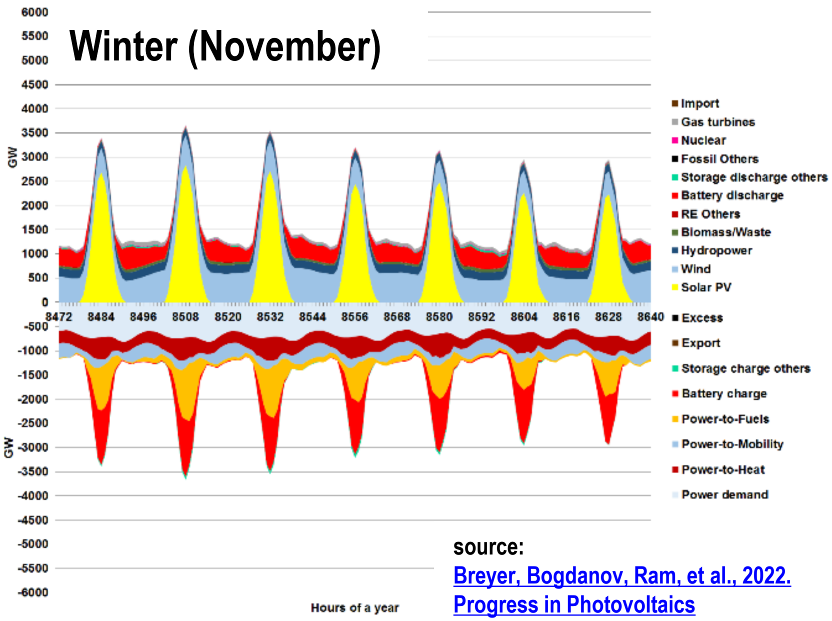
Source:
Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2023. Progress in Photovoltaics

Breyer et al., 2024. International Journal of Hydrogen Energy

Diagram: Greens/EFA, 2022
scenario: RES-2040 for 2050

Hourly Operation and Balancing

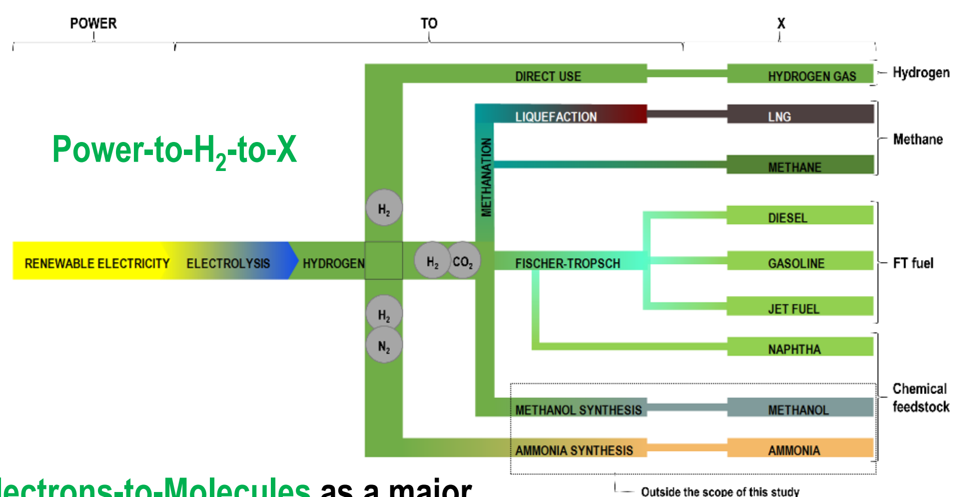




source:
[Breyer, Bogdanov, Ram, et al., 2022. Progress in Photovoltaics]

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

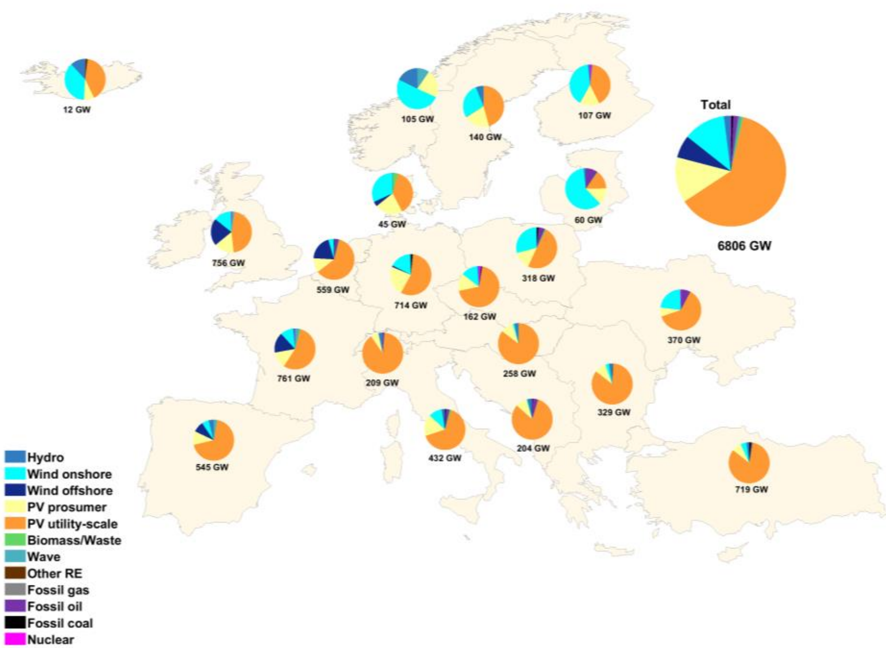


Electrons-to-Molecules as a major piece of **Power-to-X Economy**

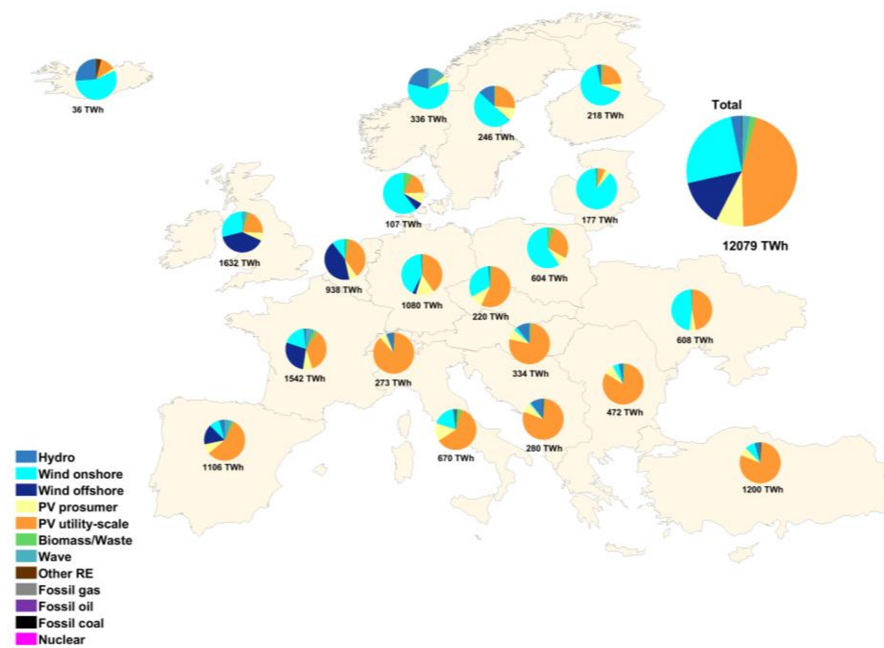
Regional Outlook – Electricity capacities and generation in 2050

RES-2040 Scenario

Regional electricity capacities



Regional electricity generation

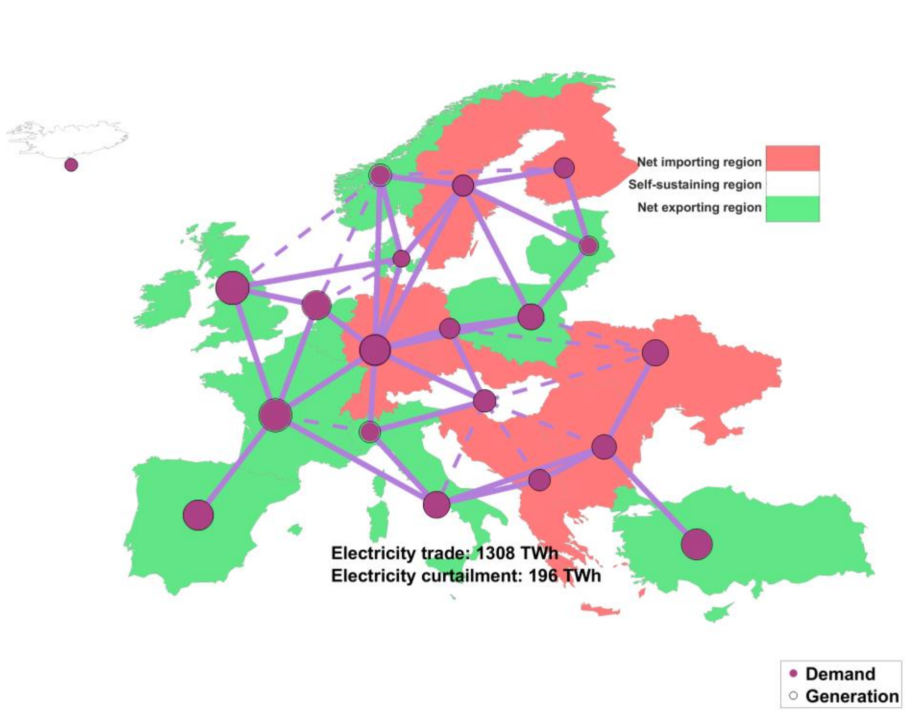


Key insights:

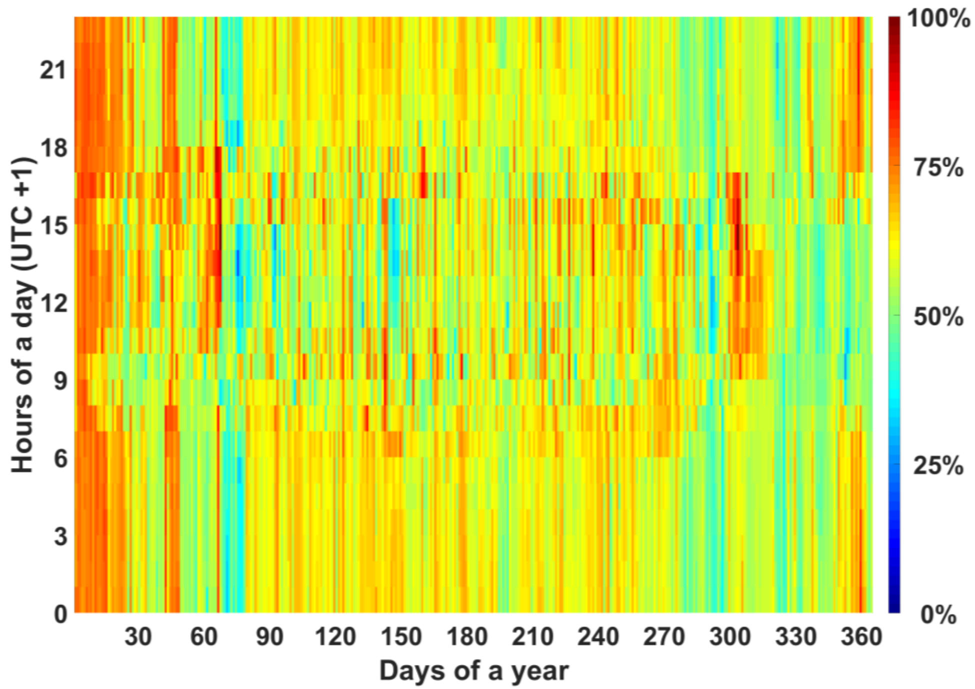
- Electricity generation is comprised of demand for the sectors power, heat, transport and industry
- Solar PV capacities are predominantly in the southern regions of Europe, while wind power capacities are mainly in the northern regions of Europe with total electricity generation of 12,079 TWh in 2050
- Solar PV generation is higher in the southern region, while wind power generation is higher in the northern regions with better wind conditions throughout the year complementing different regions
- Overall, solar PV (54%) and wind (39%) generate most of the electricity needed across Europe by 2050

Regional Outlook – Electricity grids and utilisation in 2050
RES-2040 Scenario

Annual imported and exported electricity



Grid profile (2050)



Key insights:

- Transmission grids play a vital role in enabling a highly electrified and integrated energy system across Europe in 2050 with 1308 TWh of electricity traded across the different regions
- Northern, Central and Eastern regions emerge as net importers, while the Southern and Western regions are net exporters in 2050 for the RES-2040 scenario
- Grid utilisation remains high with a range of 50-95% throughout the year and higher utilisation in the winter months across Europe in 2050

Agenda

- Background
- 100% Renewable Energy Research
- Global: 100% Renewables
- Europe: 100% Renewables
- Finland: Highly Renewables
- Summary

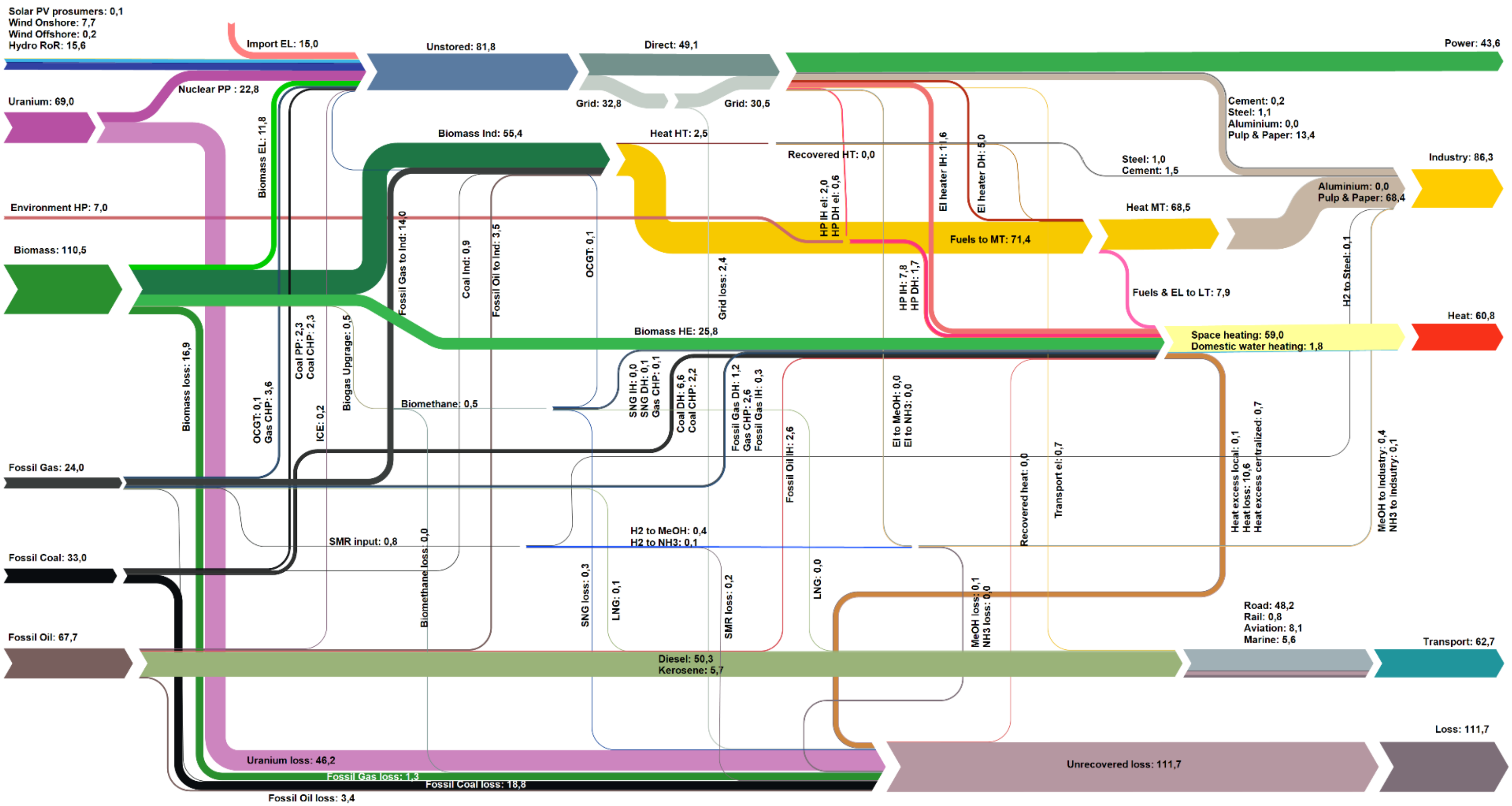
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Energy flow Finland today

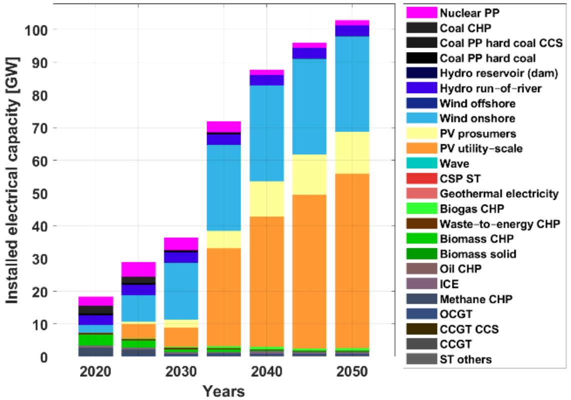
- Energy supply based on bioenergy, oil, uranium, coal, gas, hydropower, wind power
- High losses due to thermal processes
- High demand by industry, transport, heat
- Huge imports: oil, uranium, coal, gas

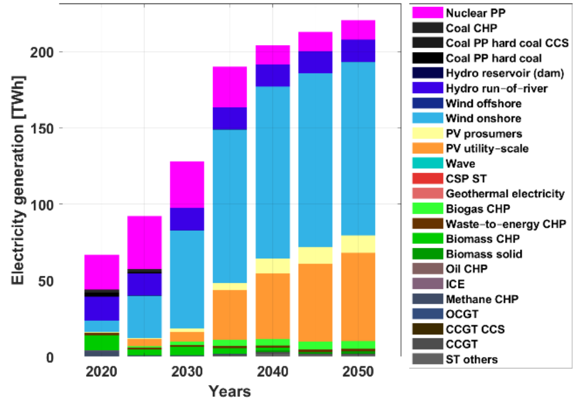
Finland - BPS

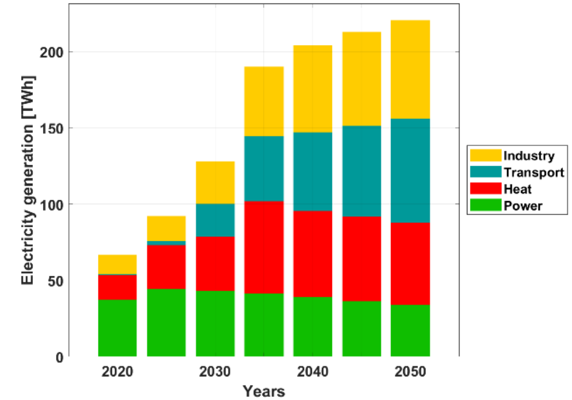
2020



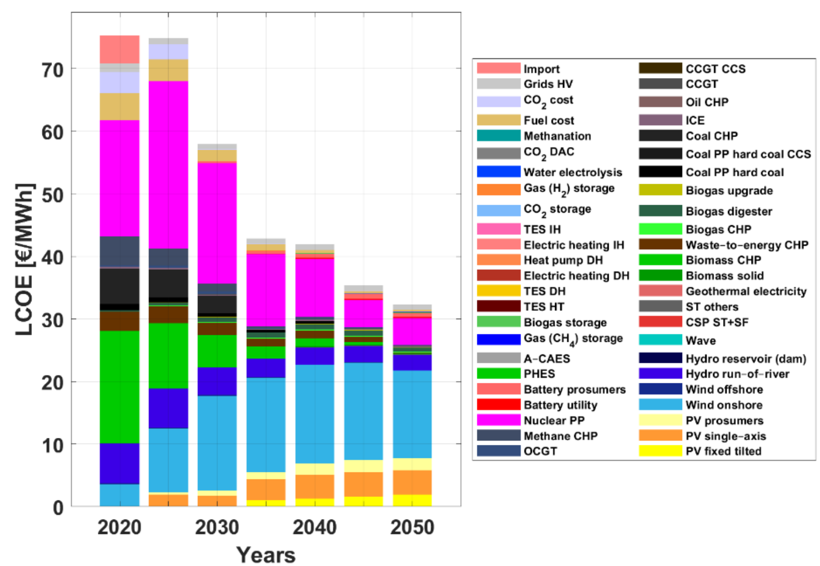
Electricity the basis for a sustainable energy system





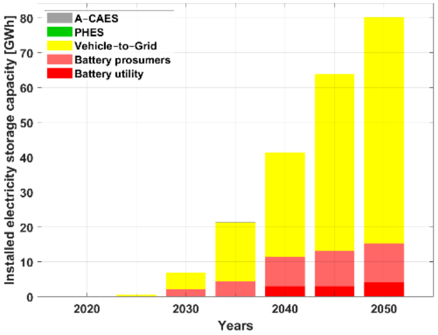


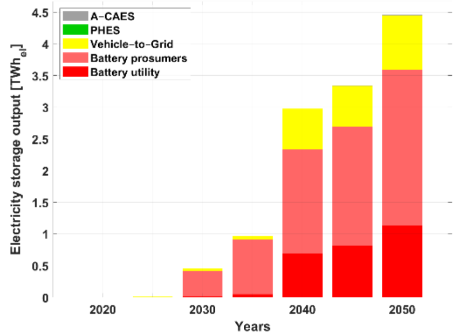
- Massive ramping of wind power, then solar PV, bioenergy largely for heat supply, existing nuclear used
- Seasonal match of wind and solar power with bioenergy seasonal balancing – massive PV capacities
- Additional demand from heat, transport and industry; direct and indirect electricity applications
- Low-cost wind and solar and phasing out of higher cost fossil/nuclear leads to cost reduction

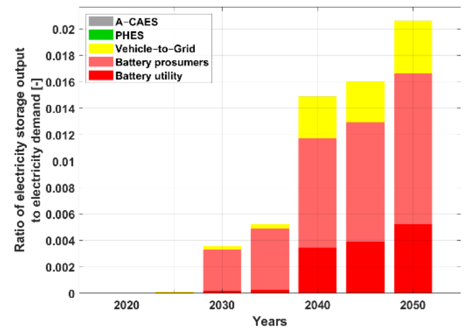


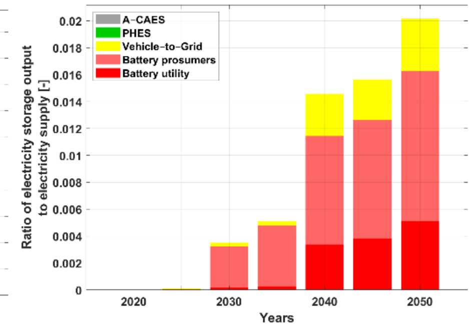
scenario: BPS_v9 optimisation

Electricity storage is surprisingly low

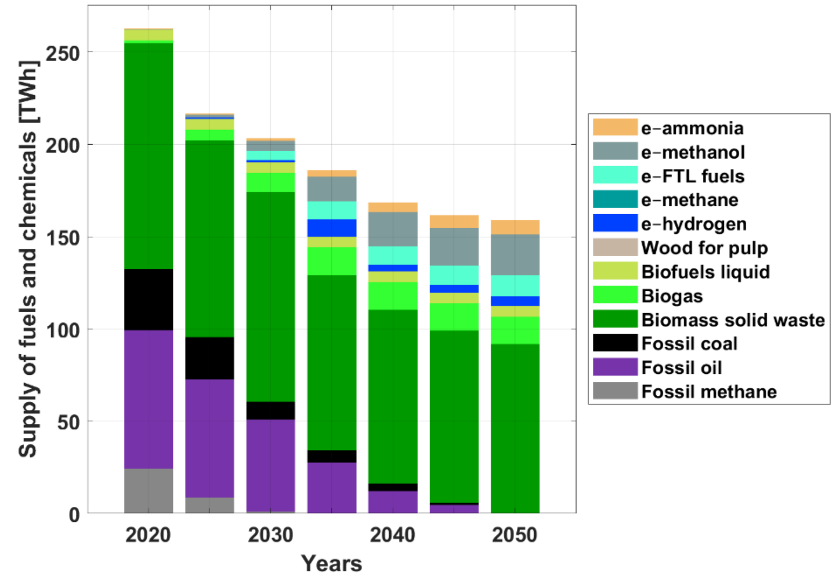




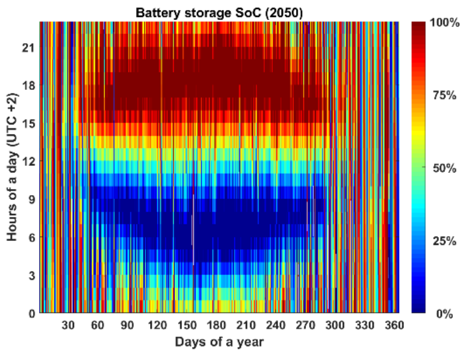


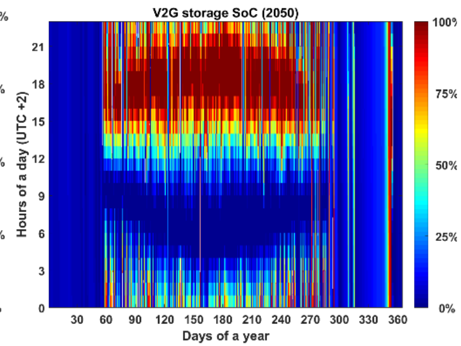


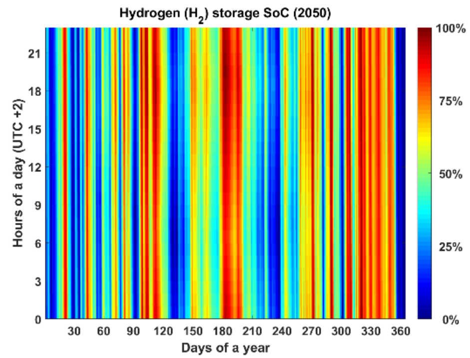
- Electricity storage grows substantially, based on batteries (stationary, vehicles), but also gas (H_2)
- Storage potential in vehicles is very high, but usage is assumed to support stationary batteries
- Overall electricity storage supply is low: 3% in total supply, thereof almost all by batteries
- Hydrogen as final energy carrier is almost negligible

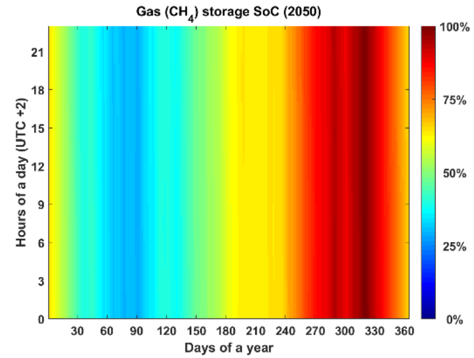


System Dynamics: Storage, Heat, Grid

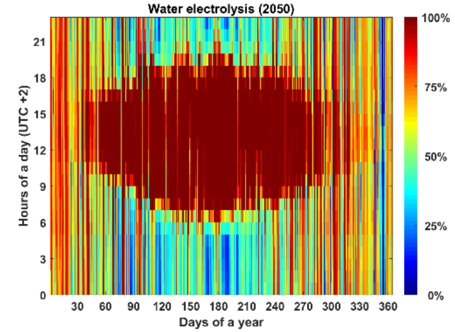


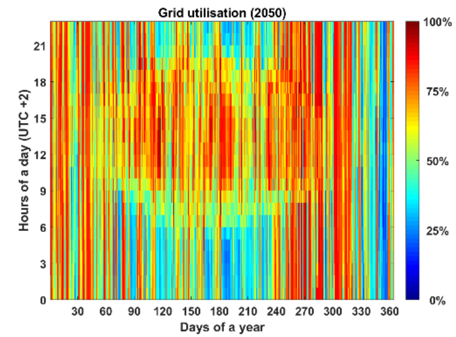


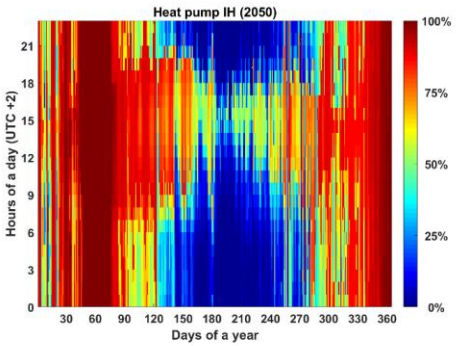


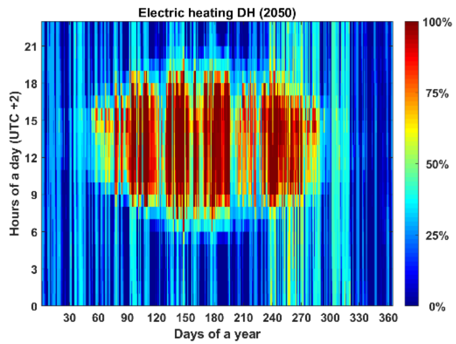


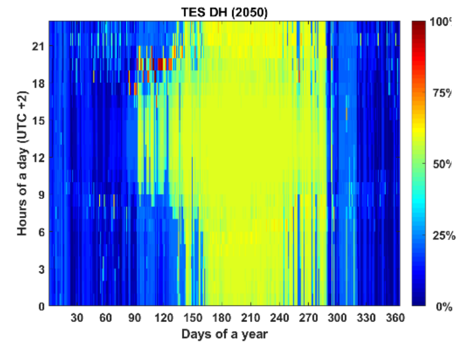
- Operation in hourly resolution shows day-night battery dispatch & wind support
- Hydrogen storage as classical buffer storage for H_2-to-X, mainly for synthesis
- Methane storage is used as seasonal storage
- Electrolysers use wind and PV electricity, and much of the latter
- Grid utilisation reflects wind and solar supply, high use in winter, PtX in summer (more details on a following slide)
- Heat pumps in full operation in the winter, supported by direct electric heating, while direct operation seems favourable with TES rather in the summer





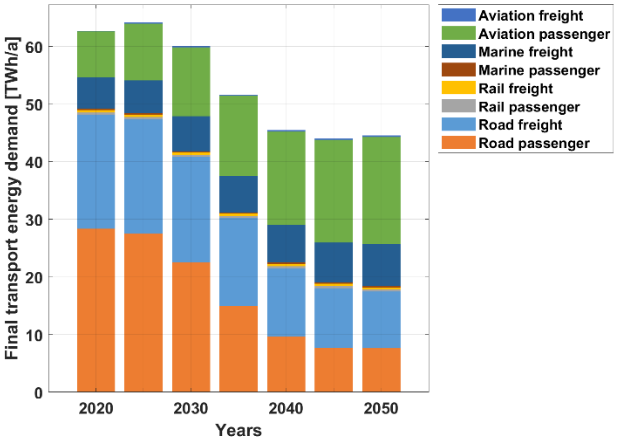


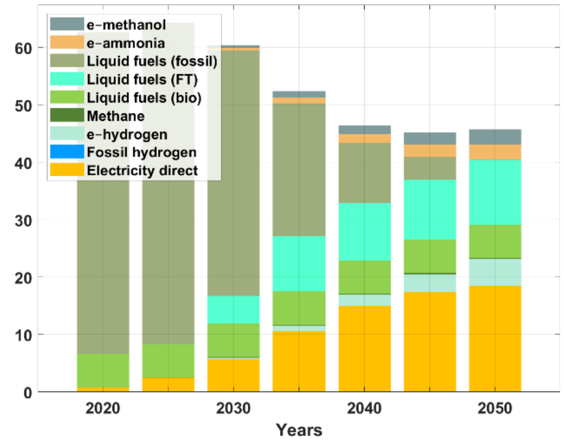


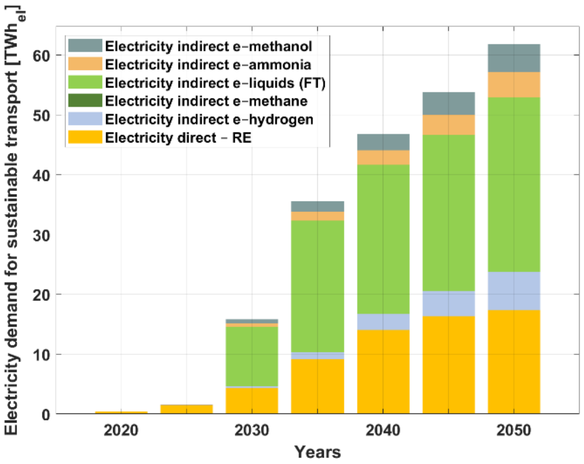


source:
Satymov et al., 2023. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, submitted

Transport sector in energy transition

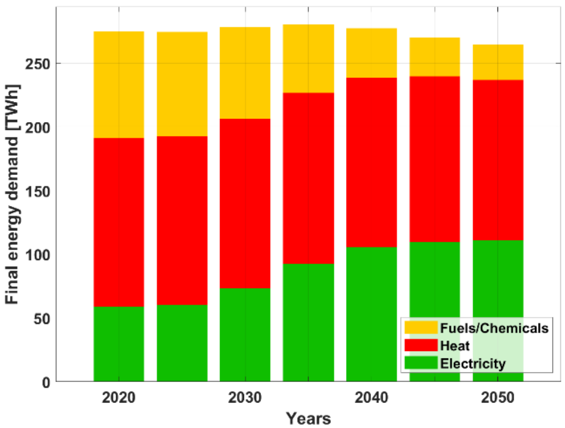


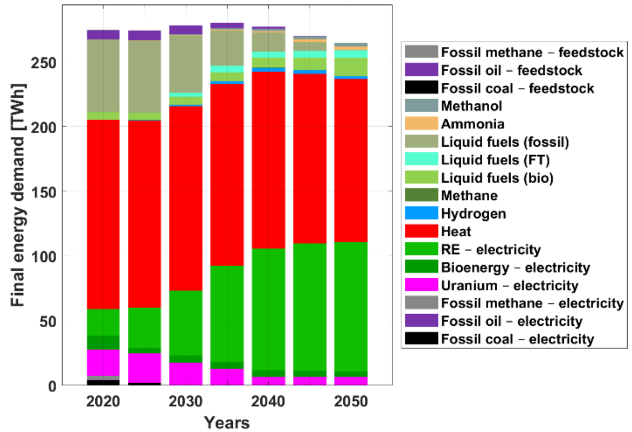


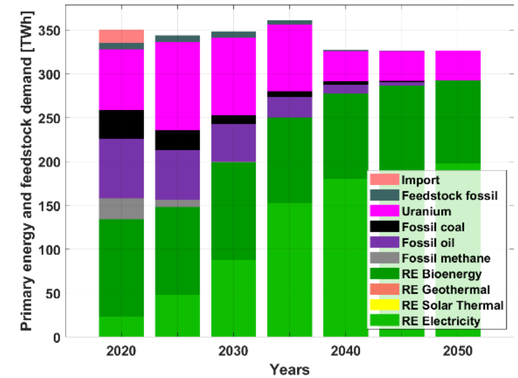


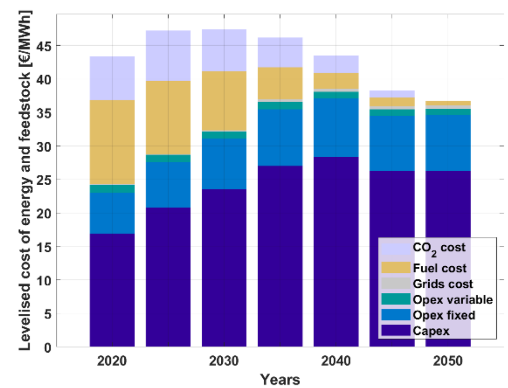
- Final transport energy demand decreases from 64 TWh to 46 TWh due to efficiency gains from electrification
- The long-haul aviation and marine transportation switch to electricity-based fuels such as e-kerosene, e-diesel, e-methanol and e-ammonia driving up the demand for electricity in the transport sector from less than 1 TWh to over 60 TWh
- Biofuels continue playing an important role as its absolute value stays constant but relative share increases
- e-Hydrogen is used in road and aviation transportation, e.g., in fuel cell EVs, while the later has a higher risk of substitution by battery EVs; might be adjusted to zero FCEV given latest trends

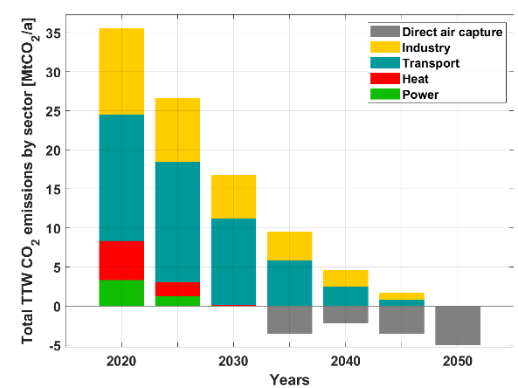
Overall trends in energy system





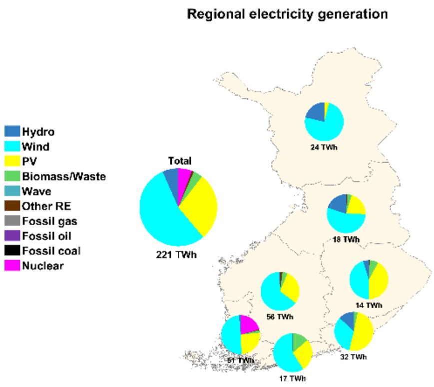


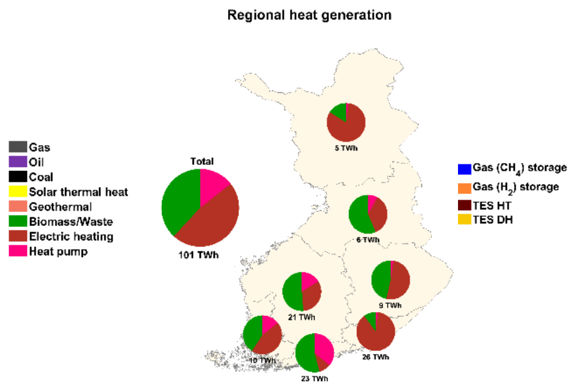


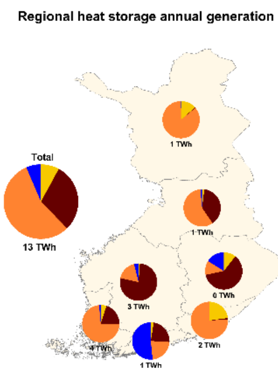


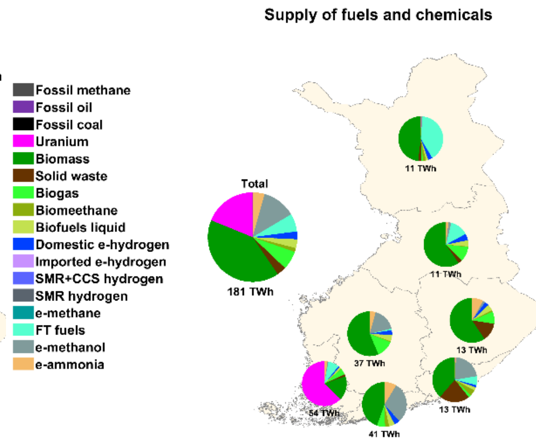
- Final energy demand roughly stable, shift towards electricity, fuels decline, heat stable
- Primary energy supply is roughly stable, fossil fuels phase out, bioenergy stable, renewable electricity dominates
- Energy system cost is roughly stable with a tendency to decline in 2040s
- Net emissions in 2035 are below 6.5 $MtCO_2$, meeting the target of the Finnish government, transport sector has to deliver

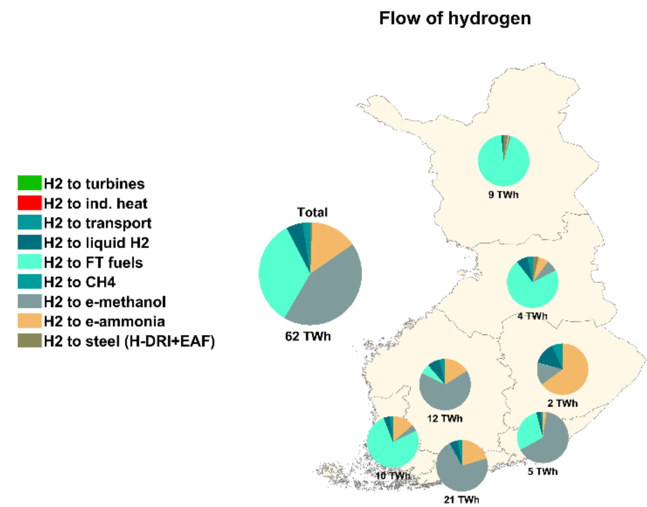
Regional energy system trends by 2050







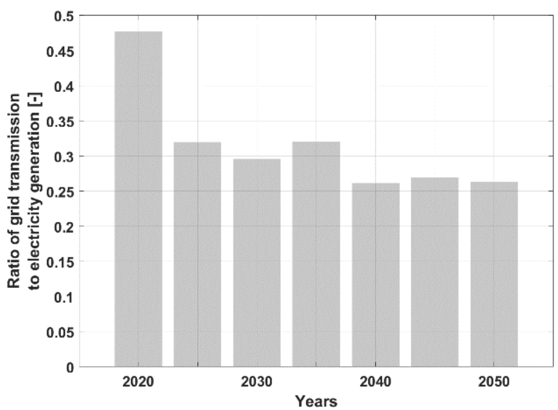


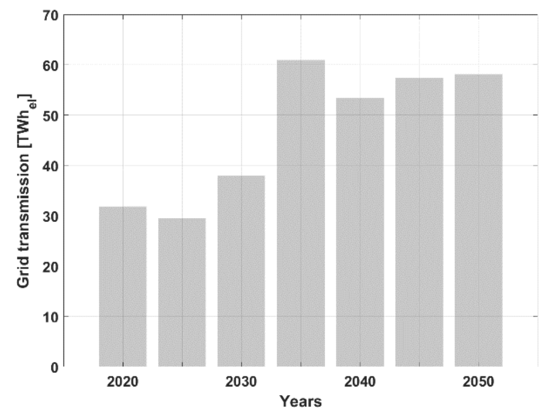


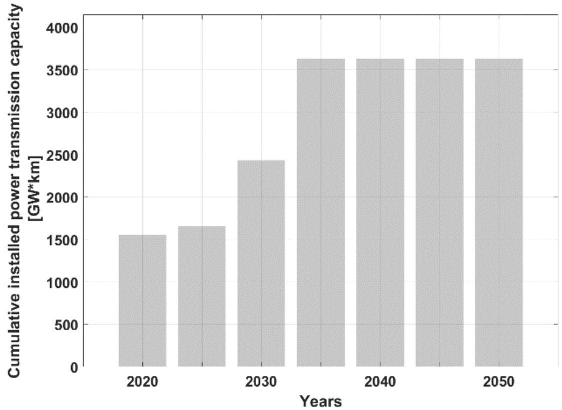
- Maximum wind power is allowed in FI-SE and FI-CE according to the 4% of area rule, thereof almost all potential is used in this wind forcing scenario. Wind power is only forced in FI-SE and FI-CE.
- More wind power in FI-SE and FI-CE due to wind forcing, but solar PV still dominates
- Relative shares of wind and solar PV electricity generation remain almost same in the country

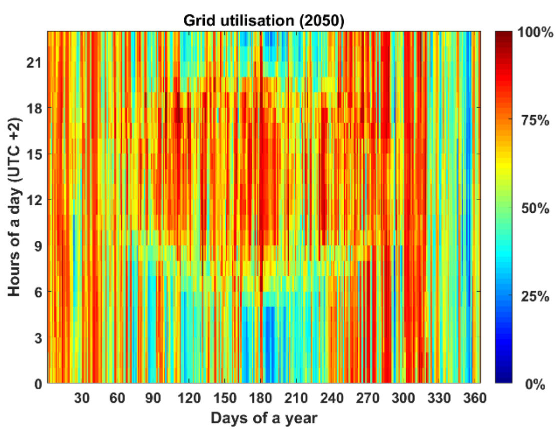
scenario: BPS_v9 wind forcing
(radar issues overcome)

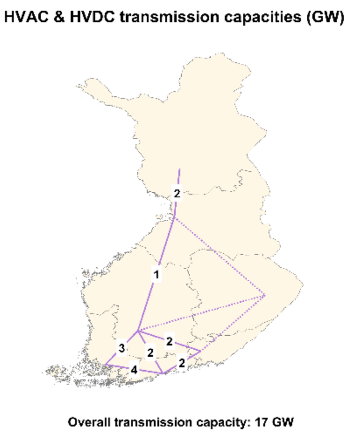
Role of Grids

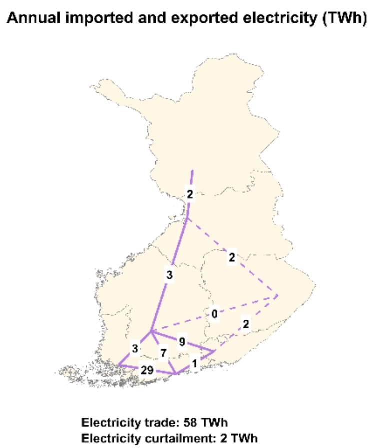


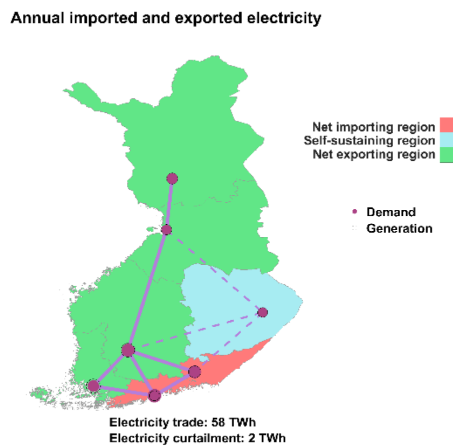












- Even more is generated in regions of demand; FI-CE turned to a self-sustaining region
- Lower overall transmission capacity: 17 GW vs 19 GW; less grid capacity is required in 2035 and onwards
- Lower electricity trade between the regions: 58 TWh vs 64 TWh (-9.4%)

scenario: BPS_v9 wind forcing (radar issues overcome)

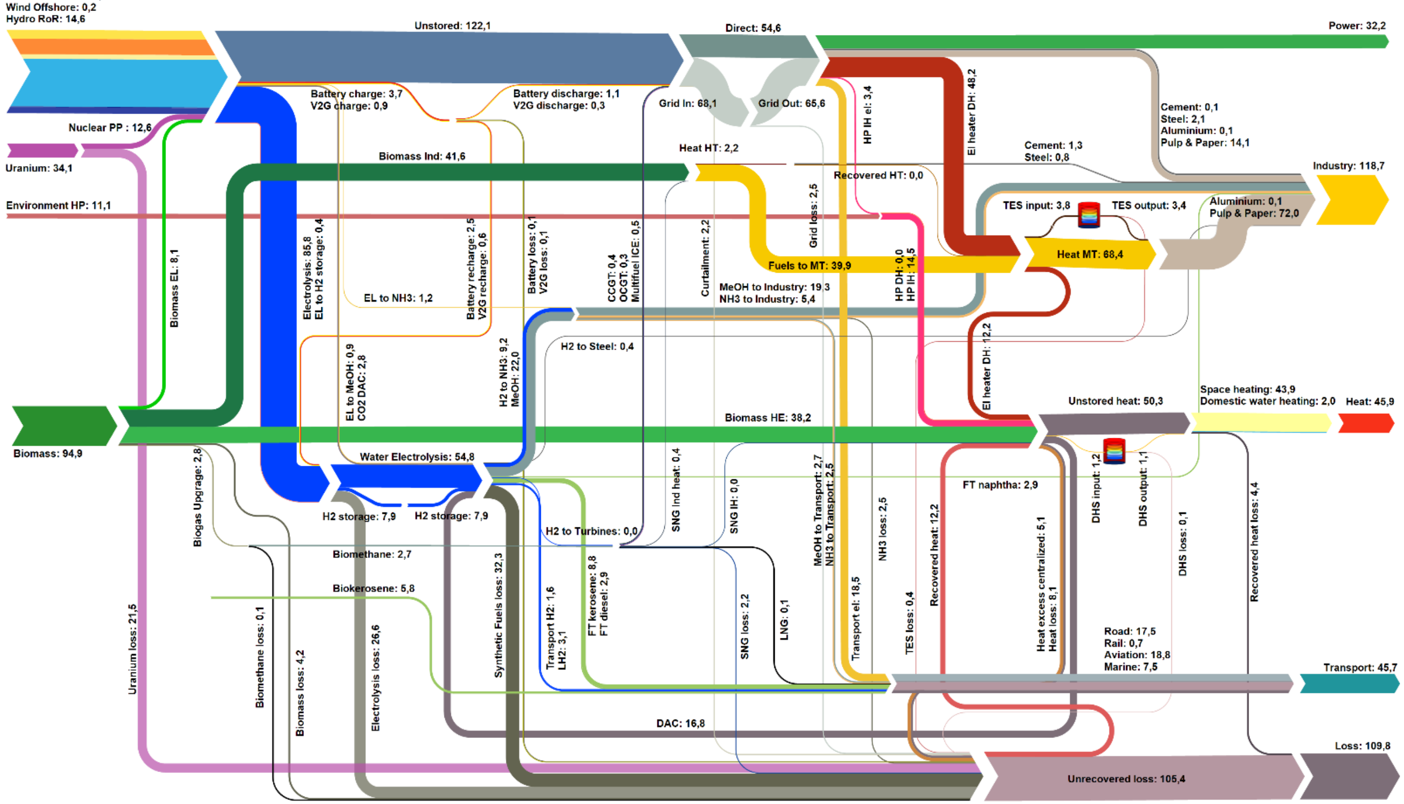
Energy flow Finland in future: PtX Economy

- 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

Finland - BPS

2050

Solar PV fixed tilted: 21,1
Solar PV single-axis: 36,9
Solar PV prosumers: 11,3
Wind Onshore: 113,6
Wind Offshore: 0,2
Hydro RoR: 14,6



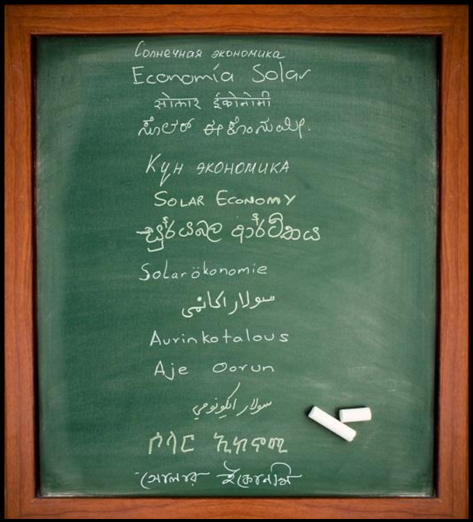
Agenda

- Background
- 100% Renewable Energy Research
- Global: 100% Renewables
- Europe: 100% Renewables
- Finland: Highly Renewables
- Summary

Summary

- Electrification is low-cost and highly efficient
- Solar PV develops beyond any historic experience of energy technologies
- Solar and wind power are central for comprehensive electrification (direct, indirect)
  - Global: Solar PV may reach about 70% of primary energy supply
  - Europe: Solar PV (about 54% of supply) and wind power (about 40%)
  - Finland: Solar PV may contribute about 20-25% of primary energy supply
- Flexibility is key for a low-cost energy system: supply complementarity, grids, demand response, curtailment, and storage
- Hydrogen hype blocks the view on the real solutions
  - direct electrification
  - H_2-to-X for e-fuels and e-chemicals: e-ammonia, e-methanol, e-kerosene jet fuel
- Power-to-X Economy is THE core characteristic of the energy system

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



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

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Lappeenranta University of Technology

Leading Energy System Models used in the Field

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

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

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

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