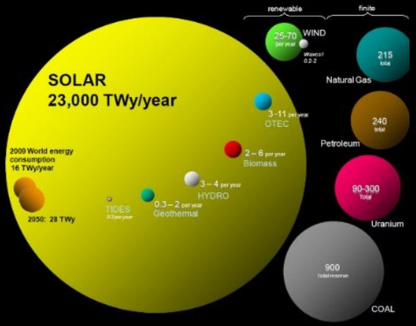
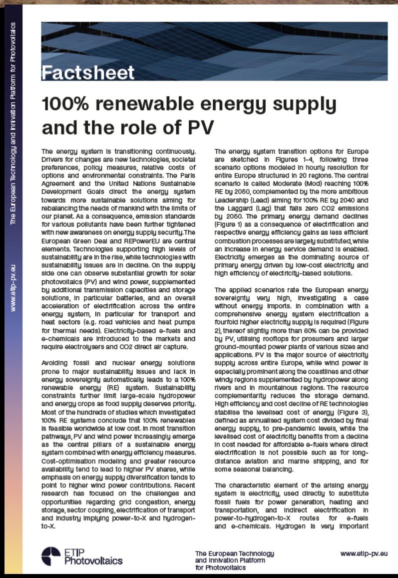


The role of PV in a 100% renewable energy system - Highlighting Europe


Factsheet

100% renewable energy supply and the role of PV

The energy system is transitioning continuously. Drivers for changes are new technologies, societal preferences, policy measures, relative costs of options and environmental constraints. The Paris Agreement and the United Nations Sustainable Development Goals direct the energy system towards more sustainable solutions aiming for rebalancing the needs of mankind with the limits of our planet. As a consequence, emission standards for various pollutants have been further tightened with new awareness on energy supply security.The European Green Deal and REPowerEU are central elements. Technologies supporting high levels of sustainability are in the rise, while technologies with sustainability issues are in decline. On the supply side one can observe substantial growth for solar photovoltaics (PV) and wind power, supplemented by additional transmission capacities and storage solutions, in particular batteries, and an overall acceleration of electrification across the entire energy system, in particular for transport and heat sectors (e.g. road vehicles and heat pumps for thermal needs). Electricity-based e-fuels and e-chemicals are introduced to the markets and require electrolysers and CO2 direct air capture.

Avoiding fossil and nuclear energy solutions prone to major sustainability issues and lack in energy sovereignty automatically leads to a 100% renewable energy (RE) system. Sustainability constraints further limit large-scale hydropower and energy crops as food supply deserves priority. Most of the hundreds of studies which investigated 100% RE systems conclude that 100% renewables is feasible worldwide at low cost. In most transition pathways, PV and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimisation modeling and greater resource availability tend to lead to higher PV 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.

The energy system transition options for Europe are sketched in Figures 1-4, following three scenario options modeled in hourly resolution for entire Europe structured in 20 regions. The central scenario is called Moderate (Mod) reaching 100% RE by 2050, complemented by the more ambitious Leadership (Lead) aiming for 100% RE by 2040 and the Laggard (Lag) that falls zero CO2 emissions by 2050. The primary energy demand declines (Figure 1) as a consequence of electrification and respective energy efficiency gains as less efficient combustion processes are largely substituted, while an increase in energy service demand is enabled. Electricity emerges as the dominating source of primary energy driven by low-cost electricity and high efficiency of electricity-based solutions.

The applied scenarios rate the European energy sovereignty very high, investigating a case without energy imports. In combination with a comprehensive energy system electrification a fourfold higher electricity supply is required (Figure 2), thereof slightly more than 60% can be provided by PV, utilising rooftops for prosumers and larger ground-mounted power plants of various sizes and applications. PV is the major source of electricity supply across entire Europe, while wind power is especially prominent along the coastlines and other windy regions supplemented by hydropower along rivers and in mountainous regions. The resource complementarity reduces the storage demand. High efficiency and cost decline of RE technologies stabilise the levelised cost of energy (Figure 3), defined as annualised system cost divided by final energy supply, to pre-pandemic levels, while the levelised cost of electricity benefits from a decline in cost needed for affordable e-fuels where direct electrification is not possible such as for long-distance aviation and marine shipping, and for some seasonal balancing.

The characteristic element of the arising energy system is electricity, used directly to substitute fossil fuels for power generation, heating and transportation, and indirect electrification in power-to-hydrogen-to-X routes for e-fuels and e-chemicals. Hydrogen is very important

The European Technology and Innivation Platform for Photovoltaics

ETIP Photovoltaics — The European Technology and Innivation Platform for Photovoltaics — www.etip-pv.eu

Christian Breyer
Professor for Solar Economy
Cooperation of SERENDI-PV, ETIP-PV, TRUST-PV
webinar, February 8, 2023

ETIP Photovoltaics

SERENDI PV

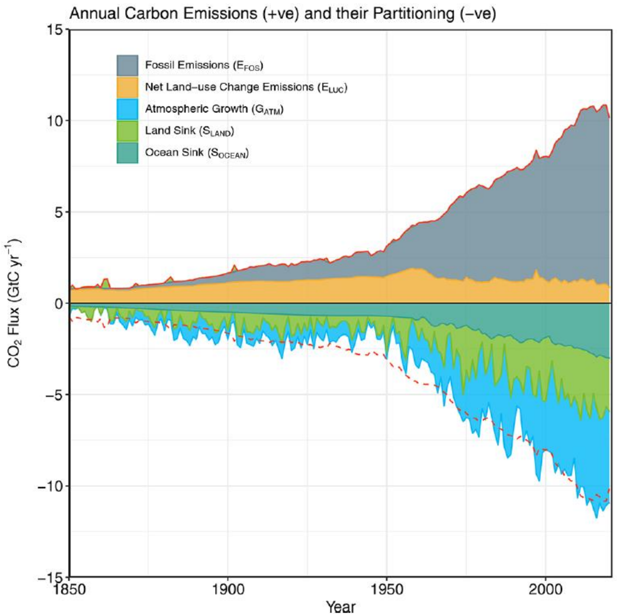
TRUSTPV
SOLAR PV, PERFORMANCE & RELIABILITY

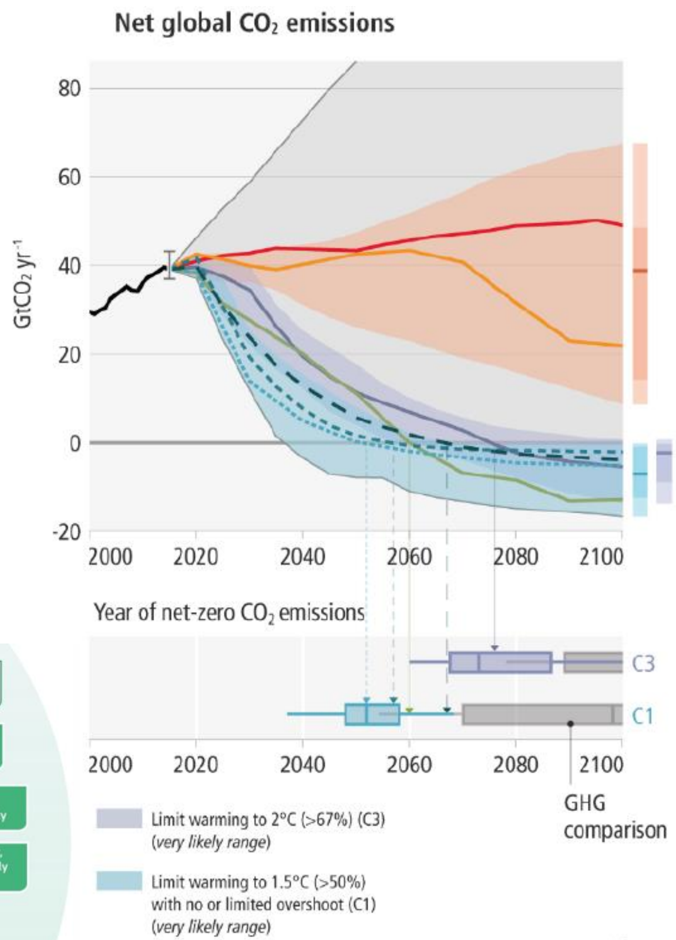
LUT University

Agenda

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

CO_2 Emissions: how it developed, where to go



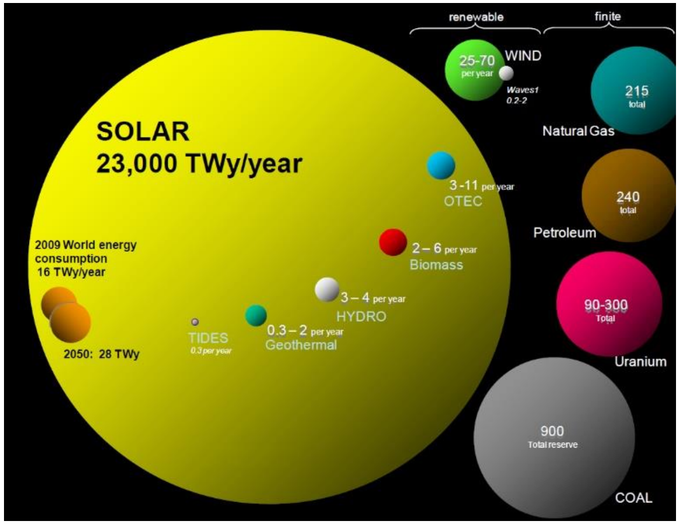


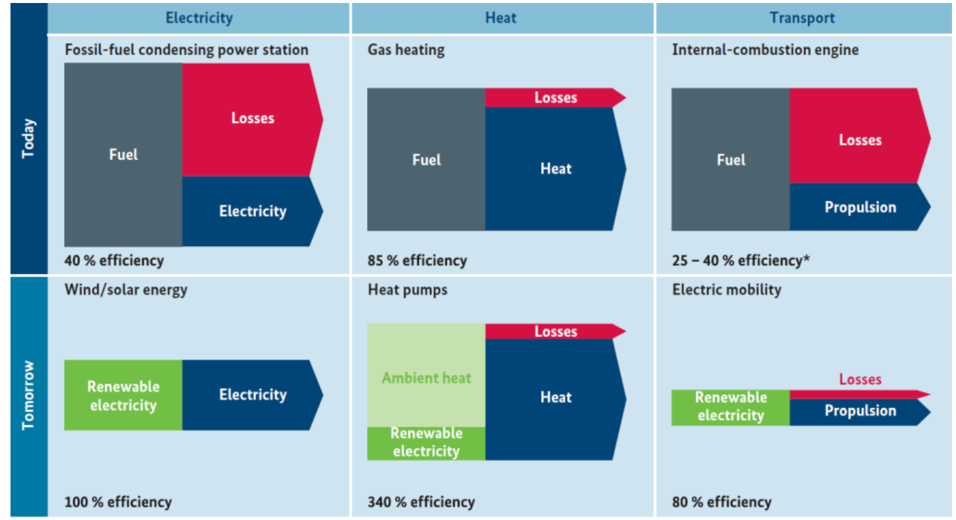
Key insights:

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

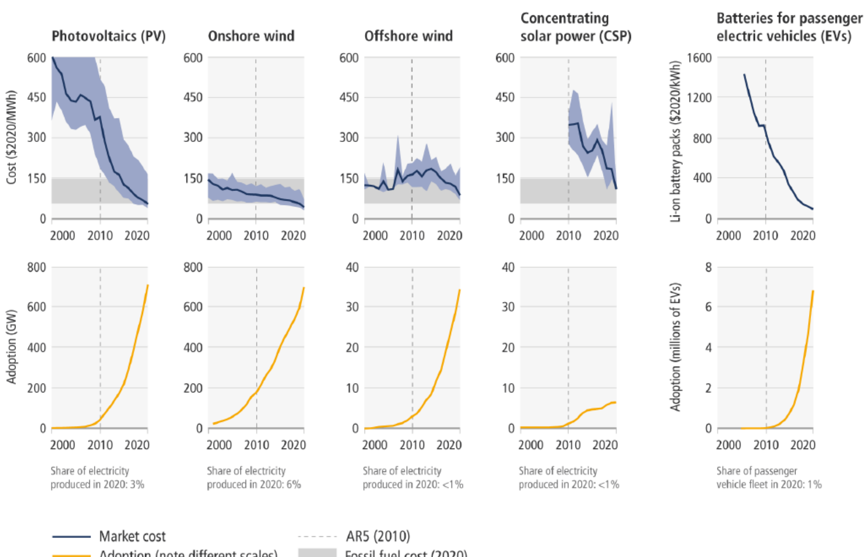
source: IPCC, 2020. 6th Assessment Report WG III

Key Drivers: Availability, Electrification, Cost





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

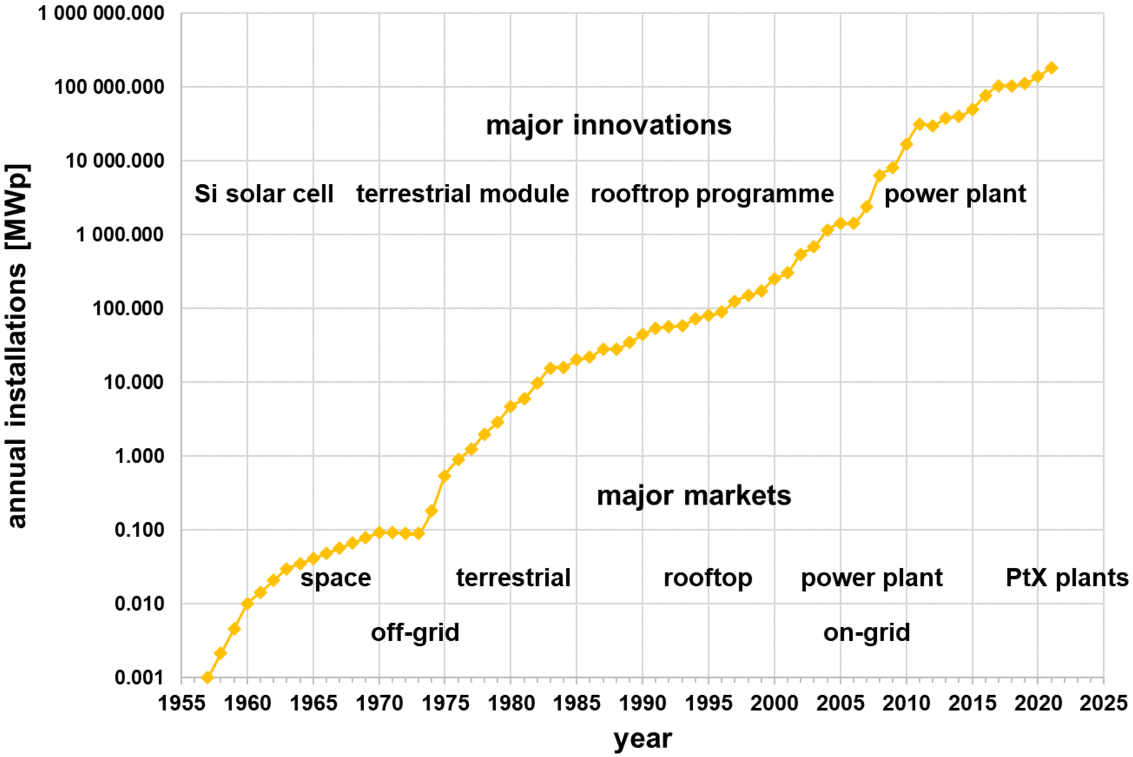


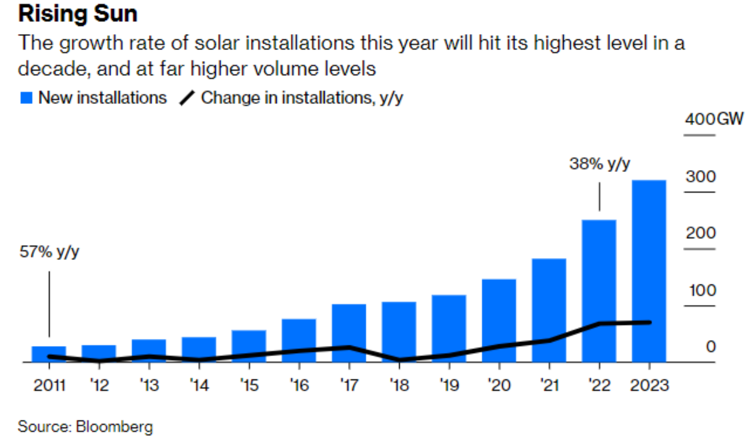
Key insights:

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

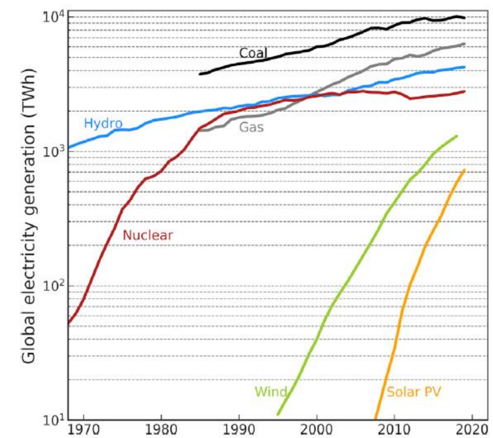
source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50
Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847
IPCC, 2020. 6th Assessment Report WG III

Solar PV Installations: past and near Future





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 (+53% 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

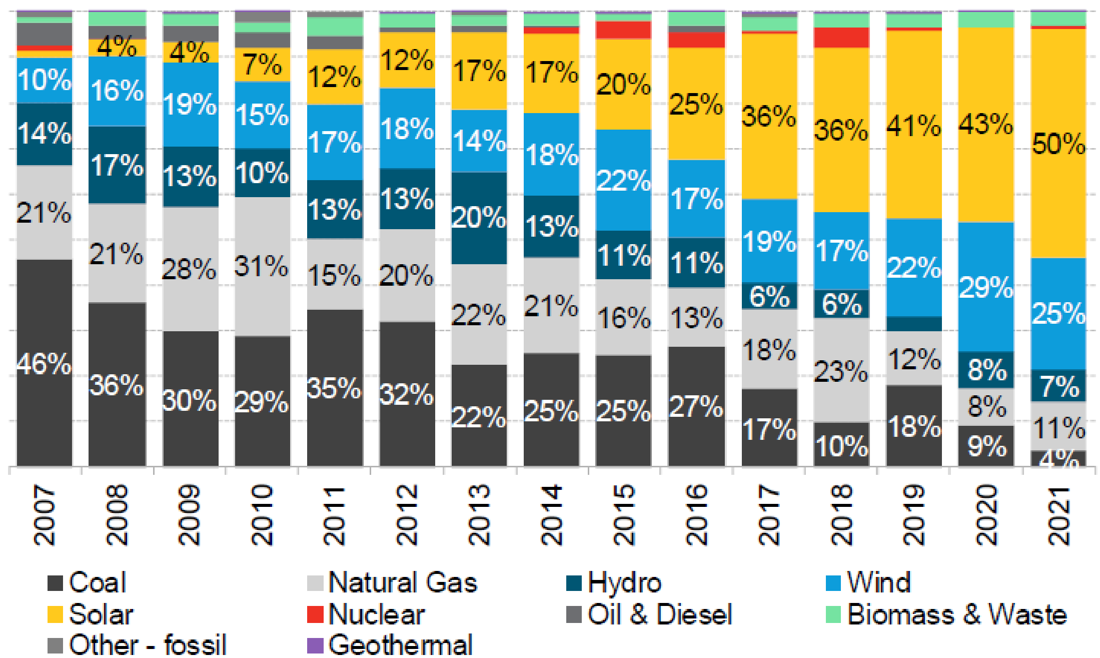
Generation mix will adapt to the mix of new installations, year by year

Fossil-nuclear generation will be increasingly irrelevant

Solar PV grew by +53% YoY in 2022 (note: newly PV electricity > wind)

PV is outside any historic experience

Share of global capacity additions by technology



Source: BloombergNEF

Key insights:

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

source: BNEF, Power Transition Trends 2022

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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)

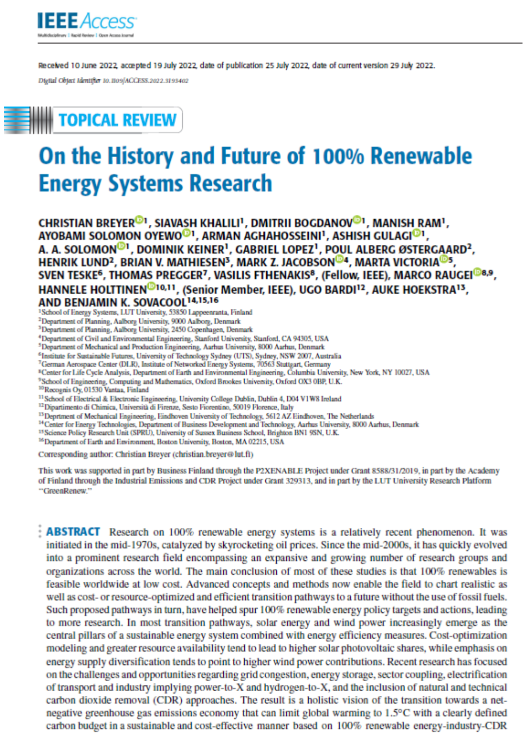
first global transition study showing a cost-neutral transition study for the entire energy system in hourly resolution using the LUT-ESTM by Bogdanov and Breyer et al. (2021)

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
- 950+ articles have been published in which 100% RE system analysis have been taken into consideration

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

100% Renewables Energy Systems Research



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TOPICAL REVIEW

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

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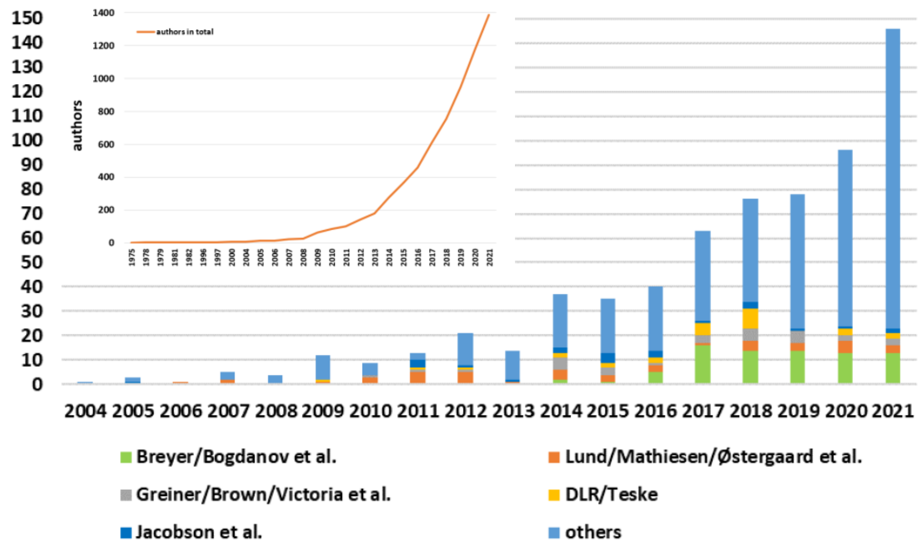
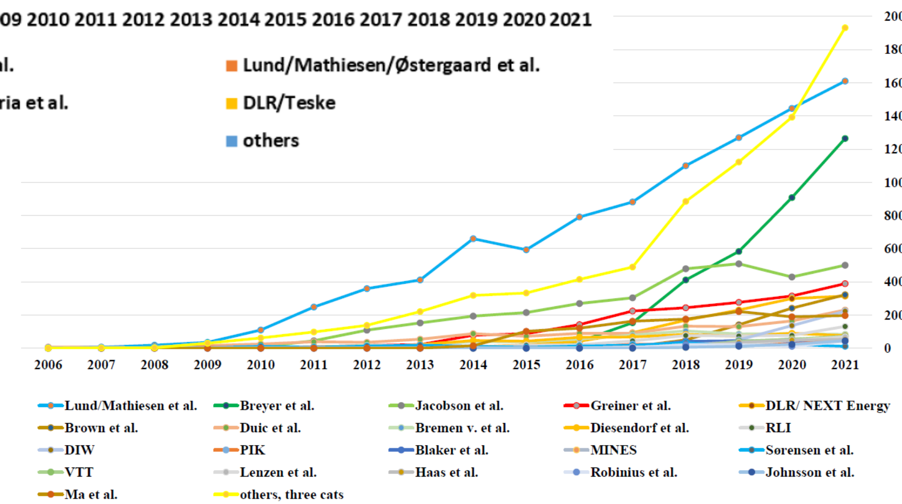
ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and 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, UK), Breyer et al. (LUT, FI), Jacobson et al. (Stanford, US)
- International organisations are conservative in adoption of new insights, e.g. IPCC, IEA, World Bank, etc.

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

Leading Energy System Models used in the Field

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

		citations		model used for 100% RE		inter-connected									
Model	articles	total	2021	earliest	latest	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

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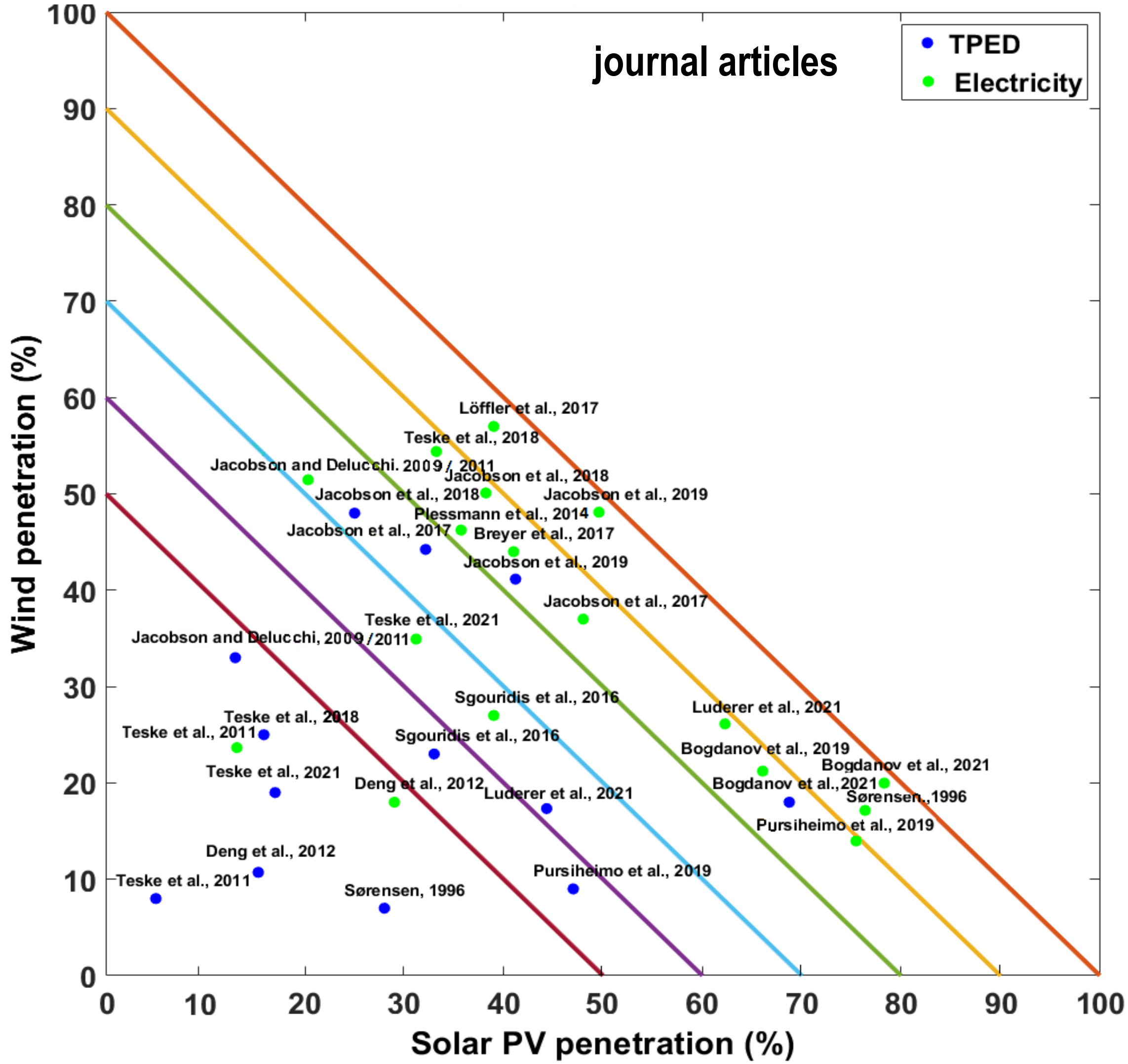
Global: PV and Wind Share in 100% RE Studies

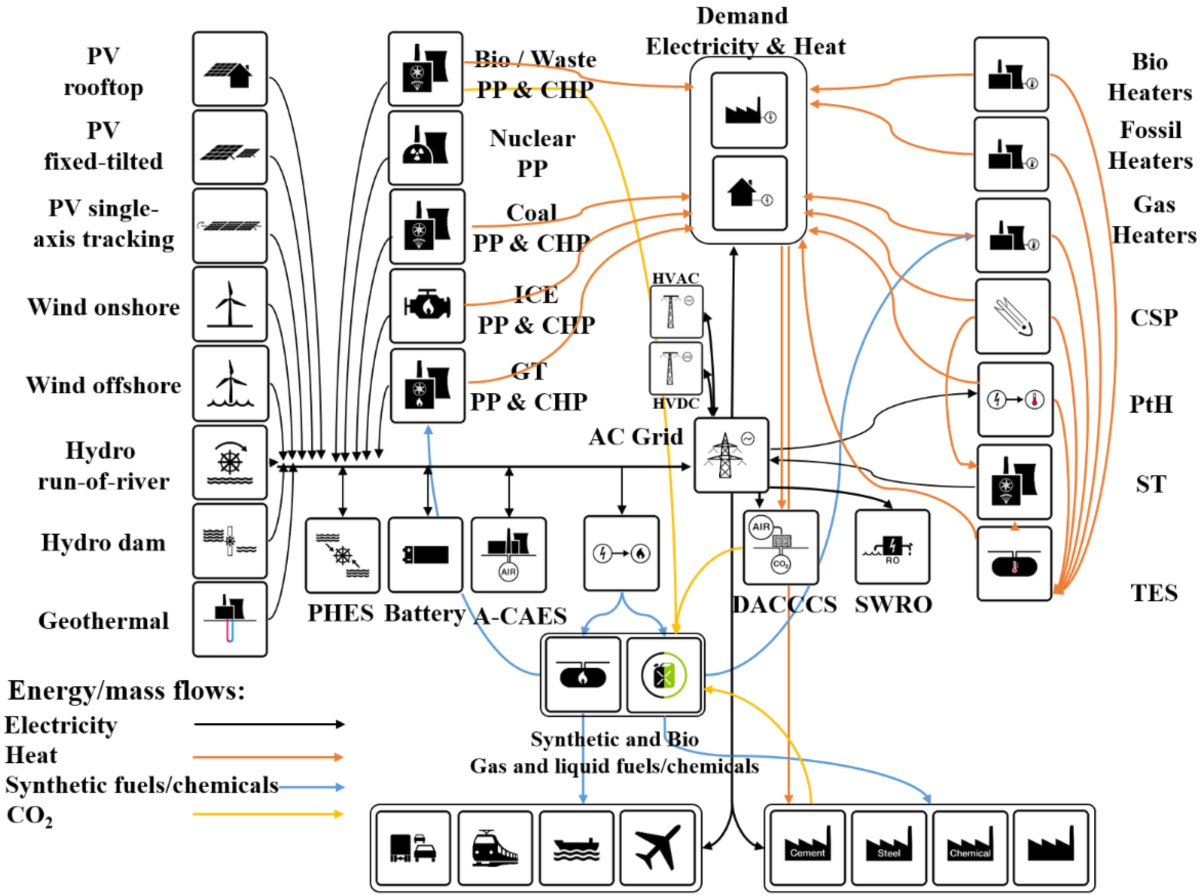


Key insights:

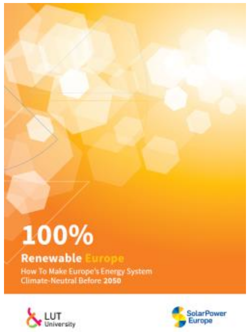
- 3 main groups:
  - High PV & wind: more PV
  - High PV & wind: more wind
  - Lower PV & wind
- PV share of around 50% by 2050 is standard
- Group of studies with high PV shares (70-80%) have all in common that they anticipate continued PV cost decline
- PV strongly benefits from electrification, low-cost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

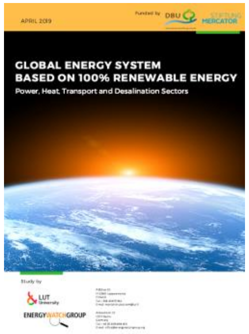
LUT Energy System Transition Model (LUT-ESTM)



recent reports



[link to report]



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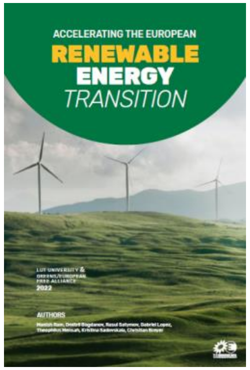

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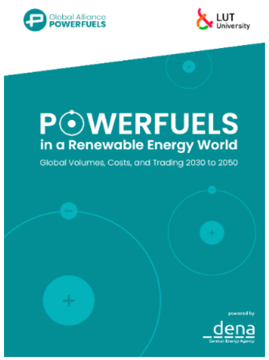


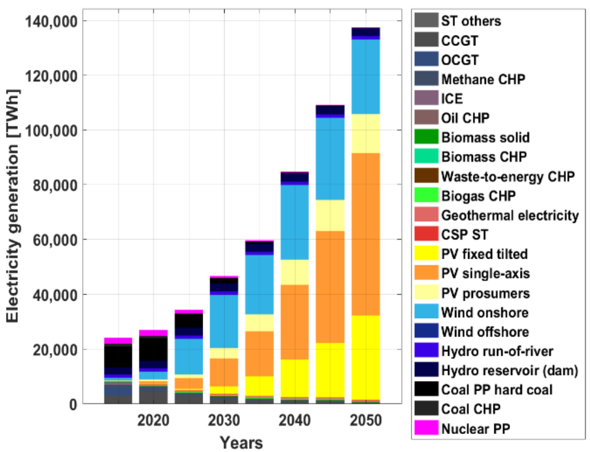
[link to report]

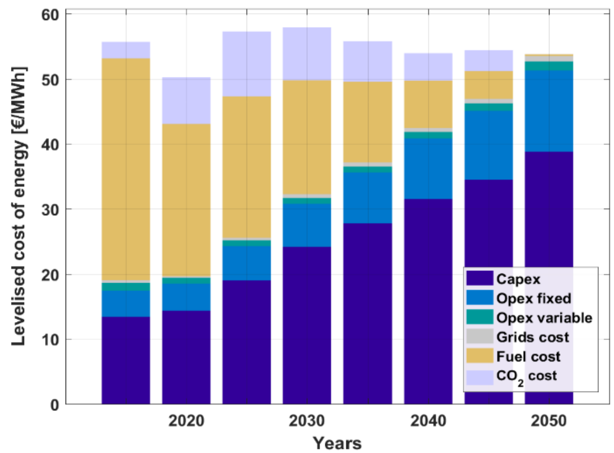
Key features:

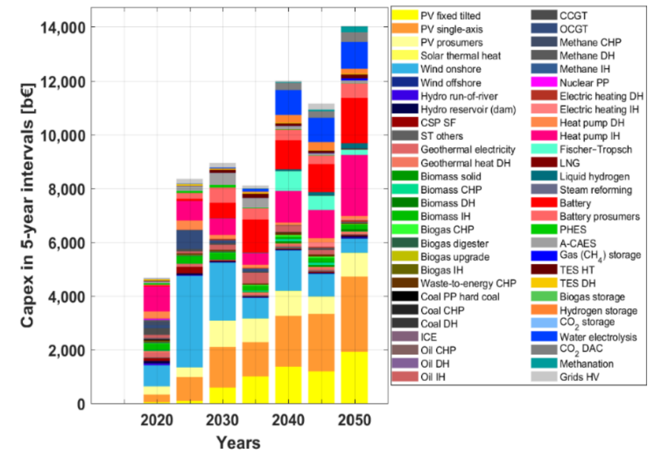
- full hourly resolution, applied in global-local studies, comprising about 120 technologies
- used for several major reports, in about 50 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (mobility, heat, fuels, chemicals, desalinated water, CO_2)

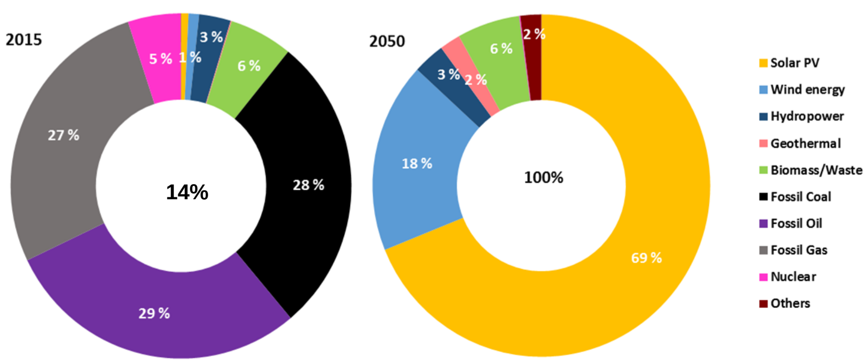
source: Bogdanov, Breyer et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, 283, 116273

Global: 100% Renewable Energy System by 2050







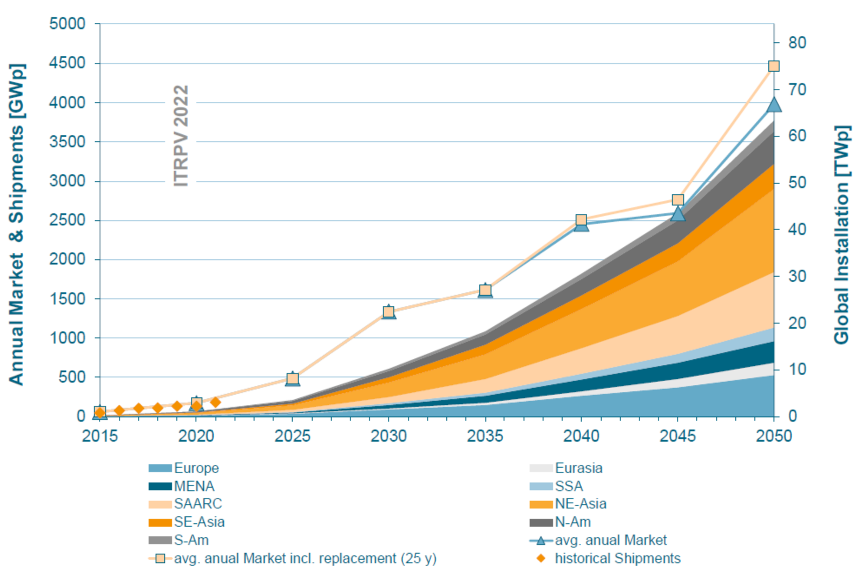


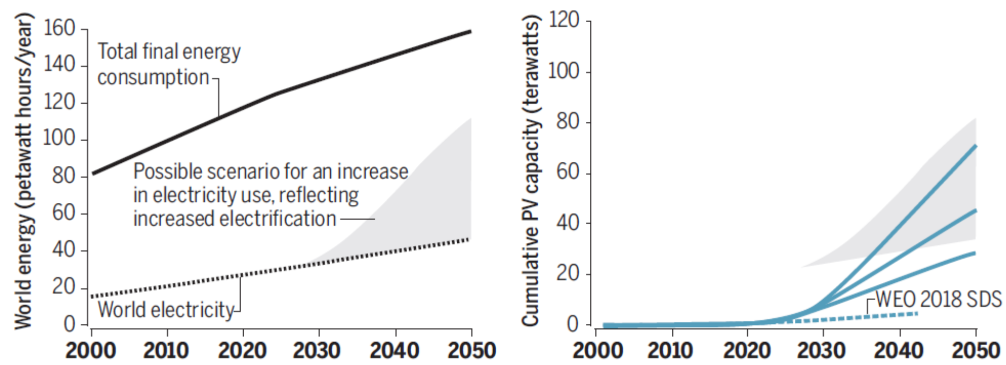
Key insights:

- Low-cost PV-wind-battery-electrolyser-DAC leads to a cost-neutral energy transition towards 2050
- This implies about 63 TW of PV, 74 TWh_{cap} of battery, 13 TW_{el} of electrolysers by 2050 for the energy system
- This leads to about 3 TW/a of PV, 850 GW_{el} of electrolyser installations in 2040s
- PV contributes 69% of all primary energy
- Massive investments are required, mainly for PV, battery, heat pumps, wind power, electrolysers, PtX

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

100% Renewable Energy System by 2050





Key insights:

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

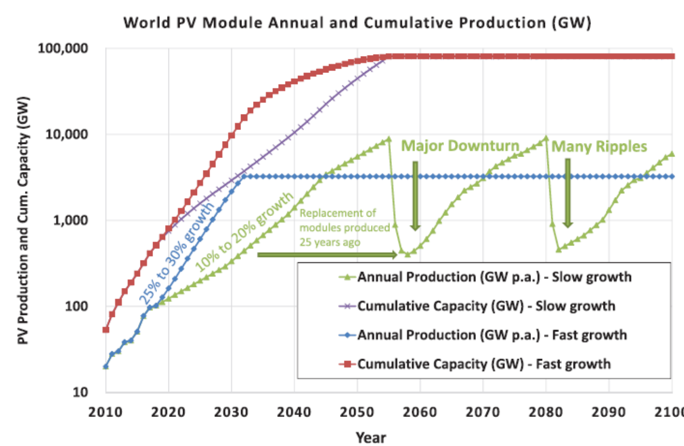
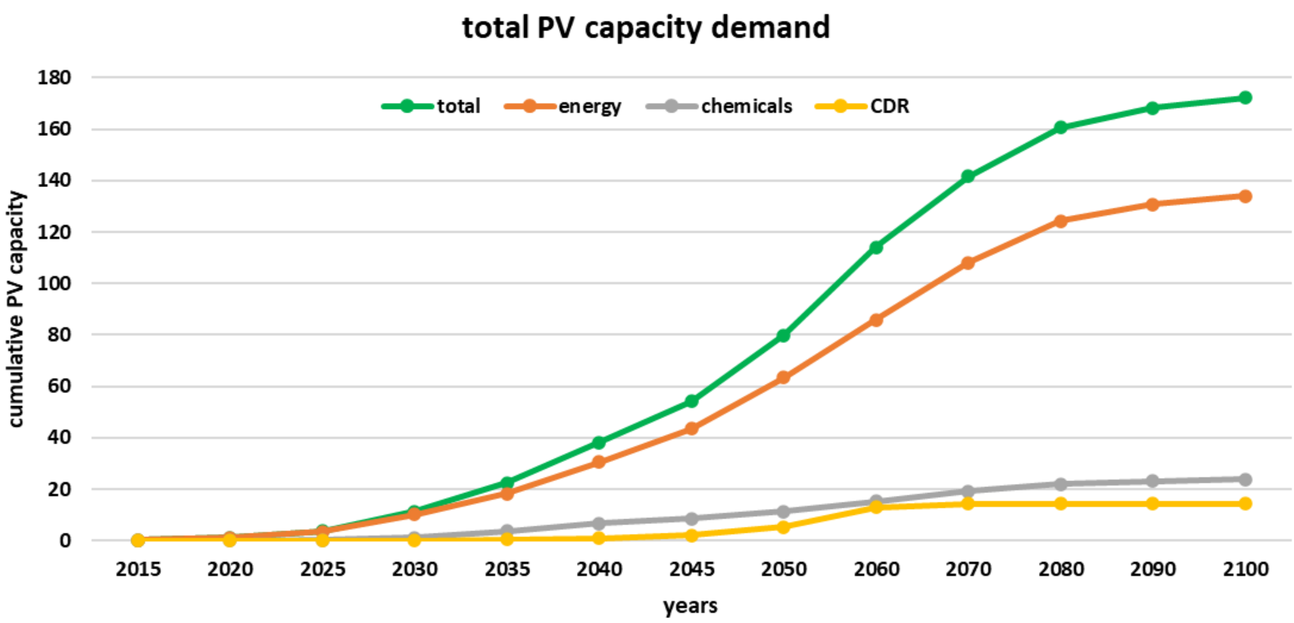


FIG. 4. Slow growth scenario of the PV industry would require increasing the annual production volume to almost 10 GW p.a. with a risk of a major downturn in 2055 and several ripples every 25 years, compared to a fast growth scenario of 25% p.a. minimum, bringing the annual production to a stabilized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

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

Is 3 TW/a sufficient?



Assumptions:

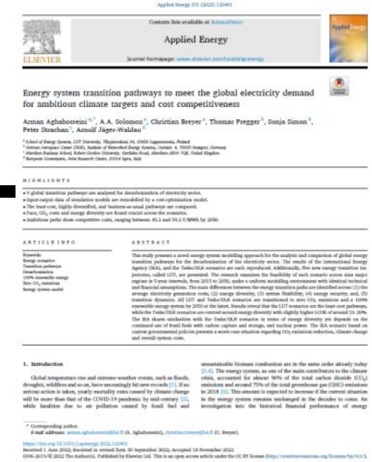
- energy-industry-CDR focus
- no one left behind by 2100
- 350 ppm/ 1.0ºC climate target
- based on Bogdanov et al. (2021), Ram et al./ dena (2020), Breyer et al. (2020)

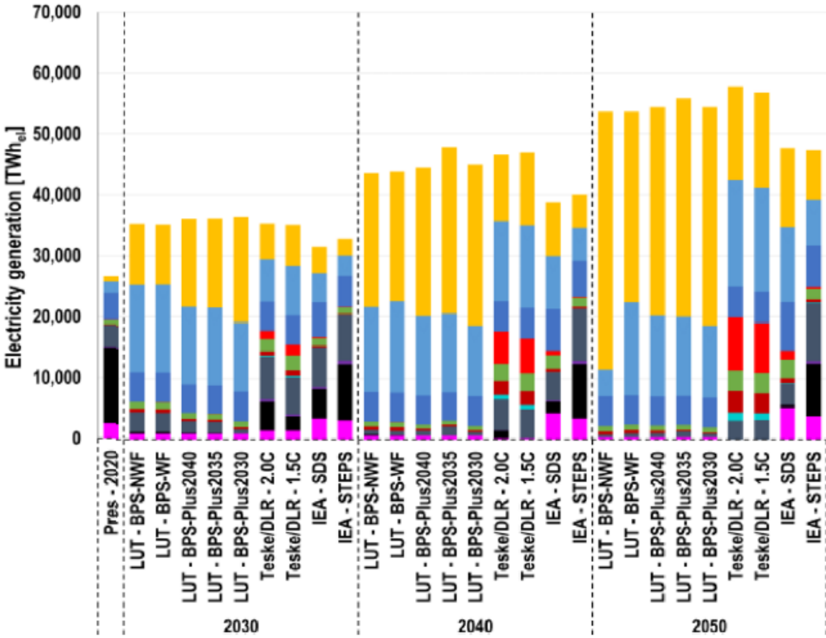
Key insights:

- The 63 TW in 2050 scenario neglects: chemical industry, CO_2 removal and global equity by 2100
- Updated PV target 170 TW by 2100 with an increase to about 80 TW by 2050
  - Energy system: 63 TW, chemicals: 14 TW, CO_2 removal (DACCS): 3 TW
  - 2030s: about 3 TW/a installations required to reach from about 10 TW to about 40 TW
  - 2040s: about 4 TW/a installations required to reach from about 40 TW to about 80 TW
- Installation need (simple calculation): 170 TW and 40 years lifetime means about 4 TW/a
- The 170 TW target was independently suggested by ISE and PIK researchers

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

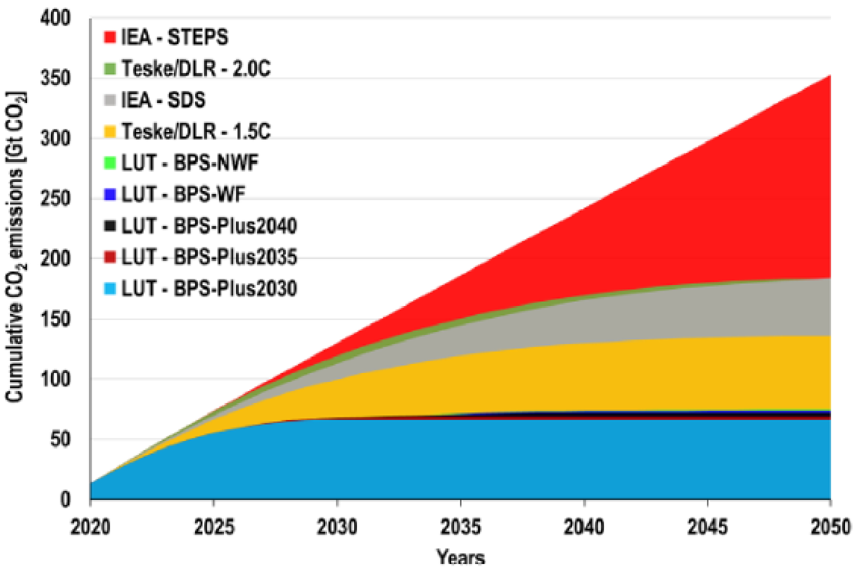
Comparing Scenarios of varying Ambitions

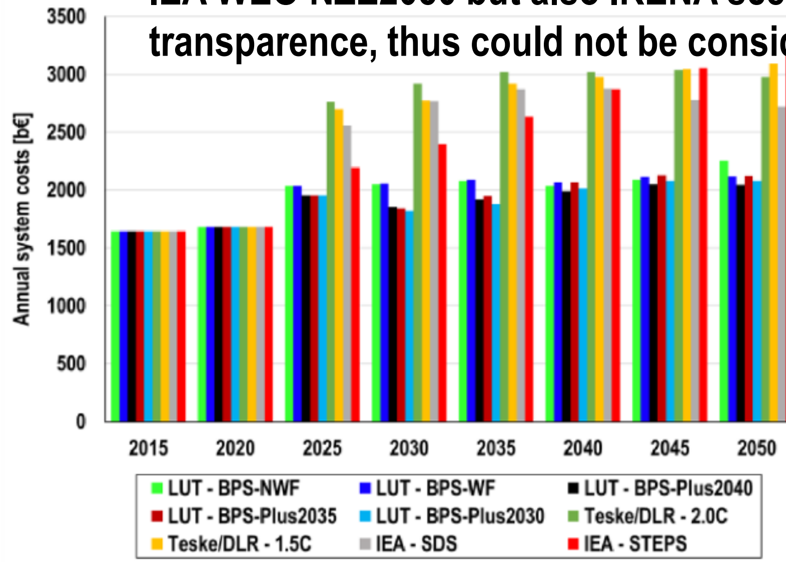




Background and insights:

- 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



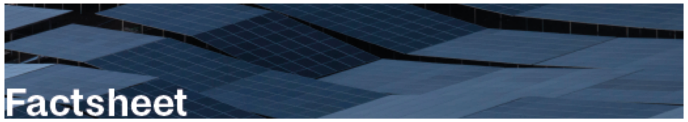


Source: Aghahosseini et al., 2023. Applied Energy, 331, 120401

Agenda

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

Factsheet: 100% RE supply and the role of PV



100% renewable energy supply and the role of PV

The energy system is transitioning continuously. Drivers for changes are new technologies, societal preferences, policy measures, relative costs of options and environmental constraints. The Paris Agreement and the United Nations Sustainable Development Goals direct the energy system towards more sustainable solutions aiming for rebalancing the needs of mankind with the limits of our planet. As a consequence, emission standards for various pollutants have been further tightened with new awareness on energy supply security. The European Green Deal and REPowerEU are central elements. Technologies supporting high levels of sustainability are in the rise, while technologies with sustainability issues are in decline. On the supply side one can observe substantial growth for solar photovoltaics (PV) and wind power, supplemented by additional transmission capacities and storage solutions, in particular batteries, and an overall acceleration of electrification across the entire energy system, in particular for transport and heat sectors (e.g. road vehicles and heat pumps for thermal needs). Electricity-based e-fuels and e-chemicals are introduced to the markets and require electrolysers and CO2 direct air capture.

Avoiding fossil and nuclear energy solutions prone to major sustainability issues and lack in energy sovereignty automatically leads to a 100% renewable energy (RE) system. Sustainability constraints further limit large-scale hydropower and energy crops as food supply deserves priority. Most of the hundreds of studies which investigated 100% RE systems conclude that 100% renewables is feasible worldwide at low cost. In most transition pathways, PV and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimisation modeling and greater resource availability tend to lead to higher PV 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.

The energy system transition options for Europe are sketched in Figures 1-4, following three scenario options modeled in hourly resolution for entire Europe structured in 20 regions. The central scenario is called Moderate (Mod) reaching 100% RE by 2050, complemented by the more ambitious Leadership (Lead) aiming for 100% RE by 2040 and the Laggard (Lag) that fails zero CO2 emissions by 2050. The primary energy demand declines (Figure 1) as a consequence of electrification and respective energy efficiency gains as less efficient combustion processes are largely substituted, while an increase in energy service demand is enabled. Electricity emerges as the dominating source of primary energy driven by low-cost electricity and high efficiency of electricity-based solutions.

The applied scenarios rate the European energy sovereignty very high, investigating a case without energy imports. In combination with a comprehensive energy system electrification a fourfold higher electricity supply is required (Figure 2), thereof slightly more than 60% can be provided by PV, utilising rooftops for prosumers and larger ground-mounted power plants of various sizes and applications. PV is the major source of electricity supply across entire Europe, while wind power is especially prominent along the coastlines and other windy regions supplemented by hydropower along rivers and in mountainous regions. The resource complementarity reduces the storage demand. High efficiency and cost decline of RE technologies stabilise the levelised cost of energy (Figure 3), defined as annualised system cost divided by final energy supply, to pre-pandemic levels, while the levelised cost of electricity benefits from a decline in cost needed for affordable e-fuels where direct electrification is not possible such as for long-distance aviation and marine shipping, and for some seasonal balancing.

The characteristic element of the arising energy system is electricity, used directly to substitute fossil fuels for power generation, heating and transportation, and indirect electrification in power-to-hydrogen-to-X routes for e-fuels and e-chemicals. Hydrogen is very important

ETIP Photovoltaics

The European Technology and Innovation Platform for Photovoltaics

www.etip-pv.eu

get the Factsheet
link

closely linked to this research
link

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RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Reflecting the energy transition from a European perspective and in the global context—Relevance of solar photovoltaics benchmarking two ambitious scenarios

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LUT University Research Platform 'GreenRenew'

Abstract
Multiple energy-related crises require a fast transition towards a sustainable energy system. The European Green Deal aims for zero CO_2 emission by 2050, while accelerating climate change impacts obligate a faster phase-out of fossil fuels. Energy transition studies for Europe at and near 100% renewable energy are used as a benchmark for two newly introduced scenarios for Europe reaching zero CO_2 emissions by 2050 and 2040. A technology-rich energy system model was applied in hourly resolution for Europe in 20 interconnected regions and in full sector coupling covering all energy demands. The results reveal a cost-neutral energy transition towards 2050 based on declining levelised cost of electricity and a pathway with 9% higher energy costs leading to 17% lower total CO_2 emissions with an accelerated energy transition by 2040. The two scenarios find shares of solar photovoltaic (PV) in total generation of 61%–63% by 2050, the highest ever estimated for Europe, still below the highest global average shares ranging between 75% and 77% form three independent studies. The central energy system components are solar PV, wind power, batteries, electrolysers and CO_2 direct air capture for carbon capture and utilisation. The core characteristic of the European energy future may be best described by a power-to-X economy, which may evolve on the global scale to a solar-to-X economy.

KEYWORDS
100% renewable energy, energy transition, Europe, power-to-X economy, solar PV, wind power, zero CO_2 emissions

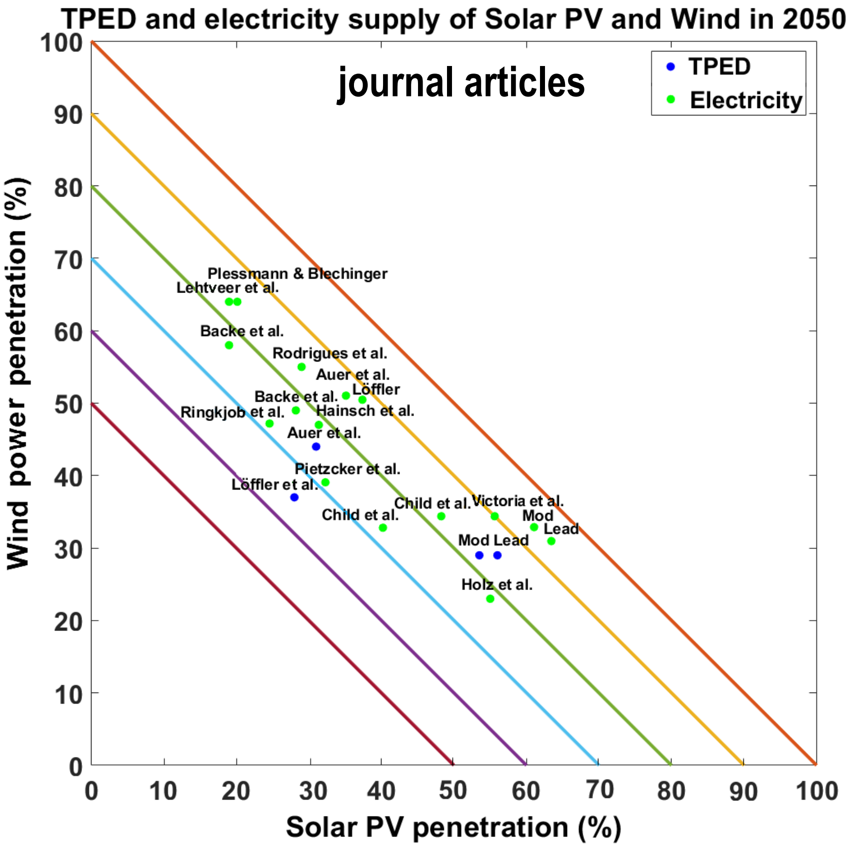
Disclaimer: The views expressed are based on the current information available to the author and may not in any circumstances be regarded as stating an official or policy position of the European Commission.

Prog Photovolt Res Appl. 2022;1–27. wileyonlinelibrary.com/journal/pip | 1

Background and insights:

- Global & EU policies & scaling of RE technologies are the basis
- Power-to-X Economy: direct and indirect electrification
- Core technologies: PV, wind, batteries, electrolysers, CO_2 DAC
- PV can reach up to 60% of energy supply
- PV prosumers are the basis plus utility-scale PV

Solar PV Share in 100% RE Studies for Europe



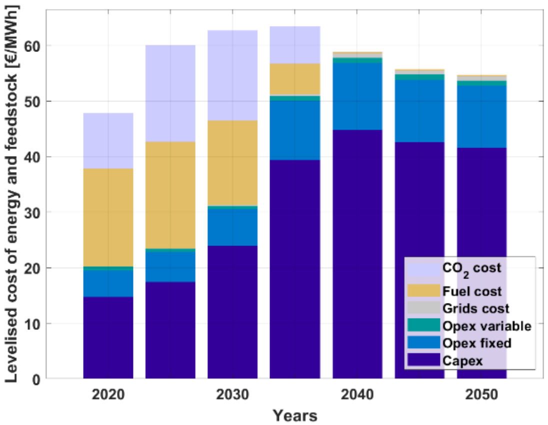
Key insights:

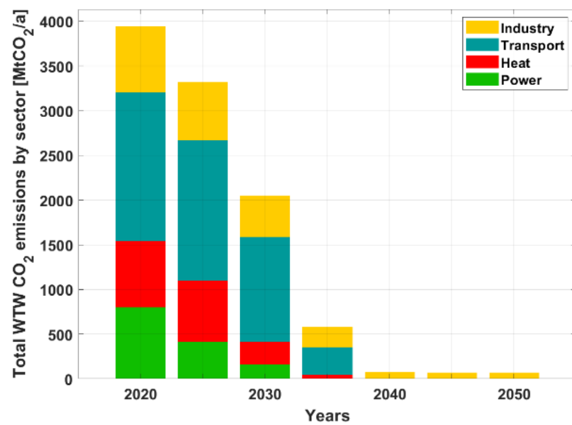
- 2 main groups:
  - high PV & wind: more PV
  - high PV & wind: more wind
- PV & wind electricity share >80% standard
- PV & wind TPED share in 65-85% range
- PV shares around 30-40% by 2050 standard for Europe
- Victoria et al. is very close with 56% PV share
- This research (link below) finds 61-63% 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.

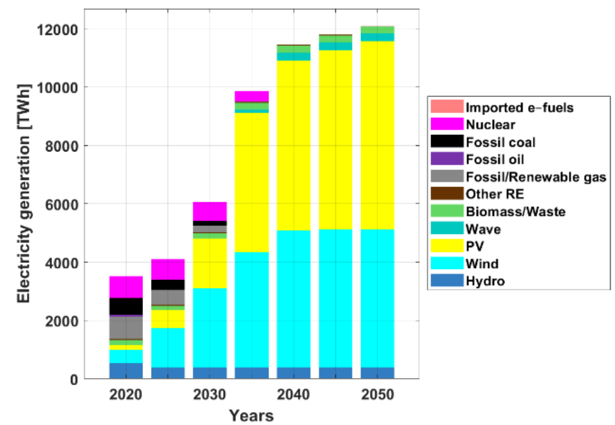
- Major reports for public discourse document lack of up-to-date knowledge of consultants
  - McKinsey (20% PV share in 2050), DNV (15%), Navigant (14%); IEA WEO SDS (13%) NZE without regional data
  - lack of ambition: no 100% RE scenario known, much fossil CCS and nuclear, low levels of electrification
  - 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)

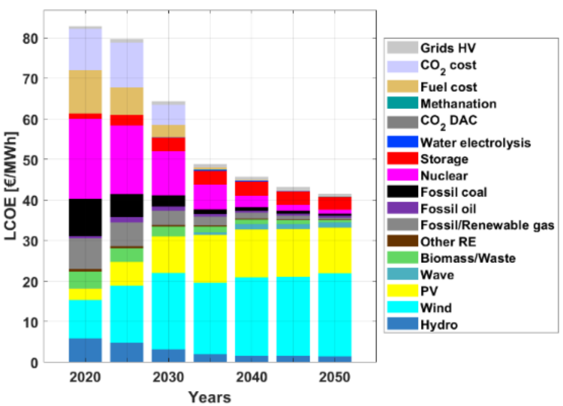
Source: Breyer, Bogdanov, Ram, et al., 2022. Energy transition from a European perspective. Progress in Photovoltaics

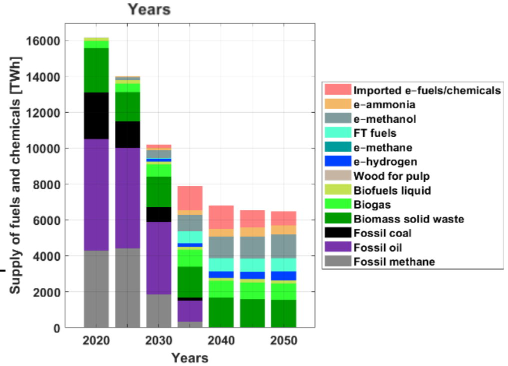
Europe: Highly Ambitious Energy-Industry Transition









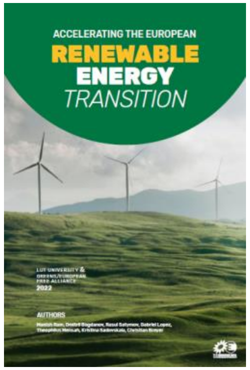


- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: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

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

Overview

Europe – 20 Regions (inclusive of EU-27)



[link to report]

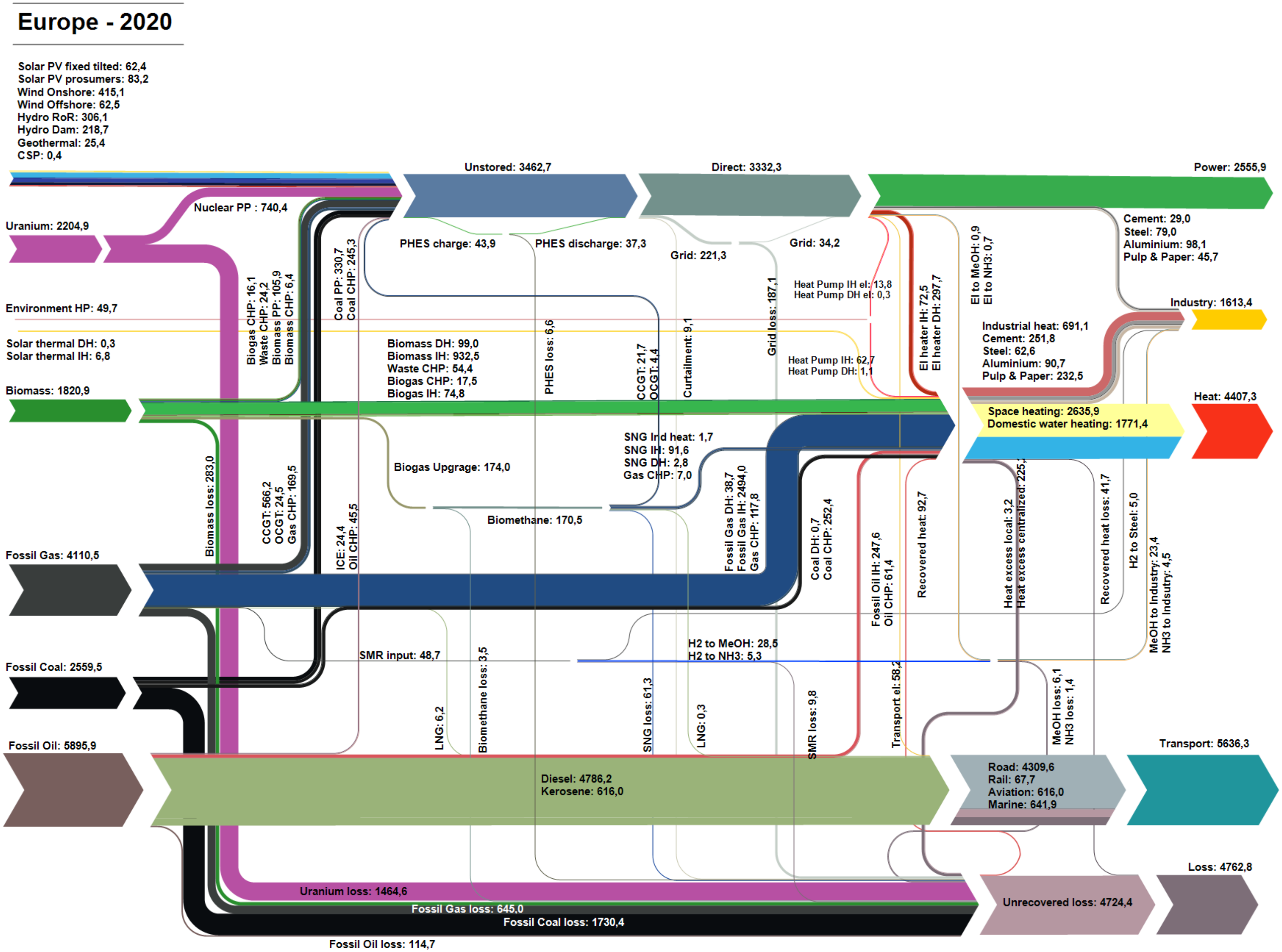
Important information:

- 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



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

European Energy Transition Scenarios

REF, RES-2040 and RES-2035

The European energy system is modelled for 3 distinctive scenarios

- Reference scenario (REF): the energy system across the EU continues with current market trends up to 2030 with renewable energy contributing 40% of the final energy demand across the EU, ramping up efficiency in buildings by doubling current rates and 100% RE by 2050, enabling GHG emissions reduction of 55-65% by 2030, not compatible with the ambitious climate target of limiting temperature rise to below 1.5° C.

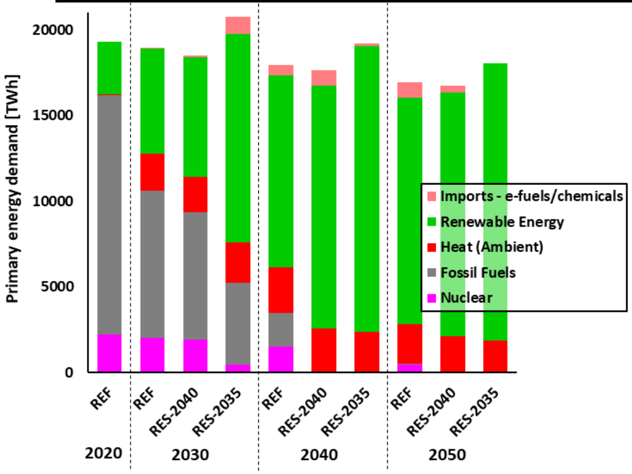
- Renewable Energy System – 2040 scenario (RES-2040): increased efforts are envisioned by all member states to drive the renewable energy share in final energy demand across the EU to 100% by 2040, ramping up efficiency in buildings by tripling current rates and enabling GHG emissions reduction of around 65% by 2030, which is compatible with the ambitious climate target of limiting temperature rise to below 1.5° C with zero emissions in 2040.

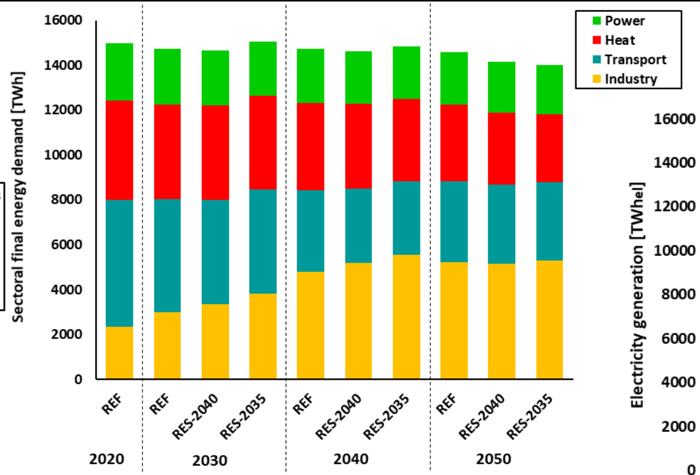
- Renewable Energy System – 2035 scenario (RES-2035): with increased impetus the EU takes a global leadership role in mitigating climate change and drives renewable energy share in final energy demand across the EU to around 60% in 2030 and 100% by 2035, ramping up efficiency in buildings by four times the current rates and enabling GHG emissions reduction of around 65% by 2030 and zero emissions by 2035, which is compatible with the ambitious climate target of limiting temperature rise to well below 1.5° C. 100% renewable energy across the power sector in all EU countries in 2030 and towards 100% renewables by 2035.

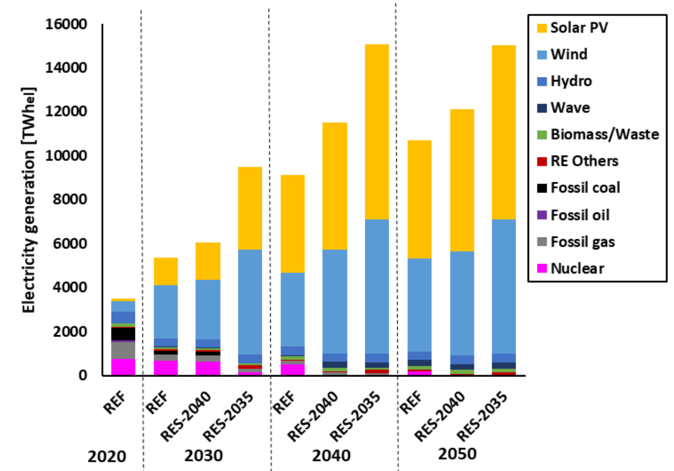
source: Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022

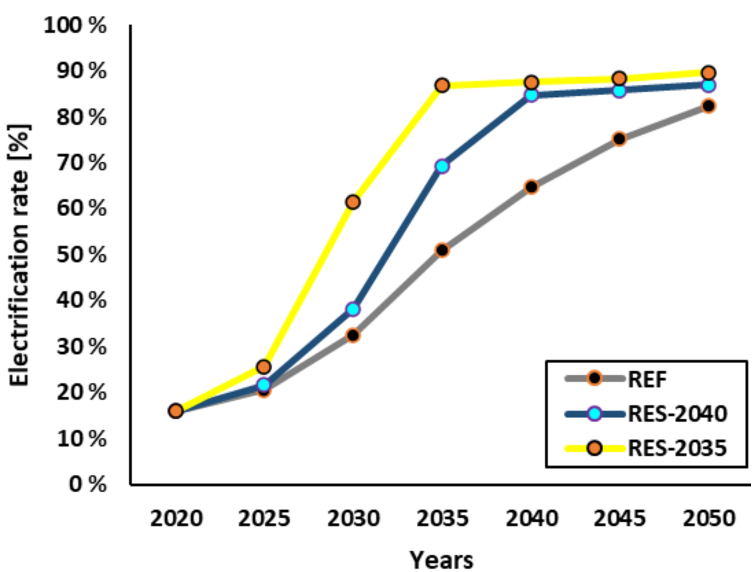
Long-term Demand: Primary, Final, Electricity

Scenario Comparison









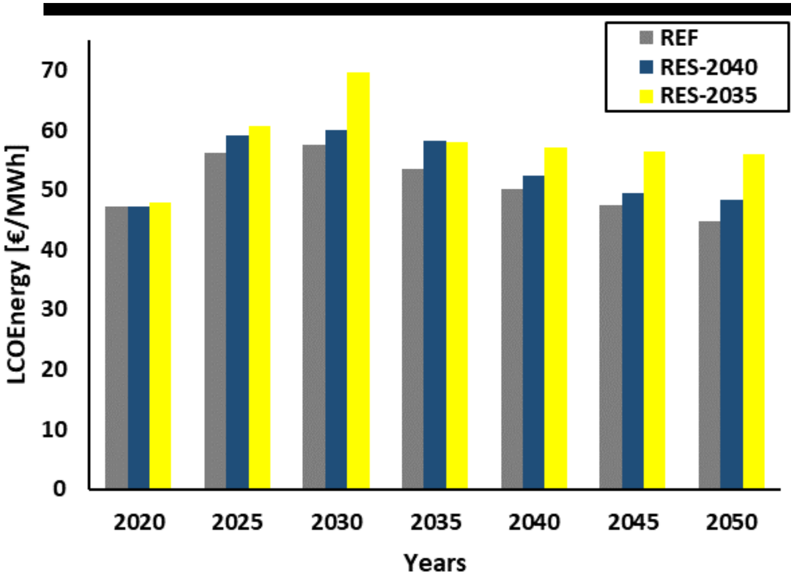
Key insights:

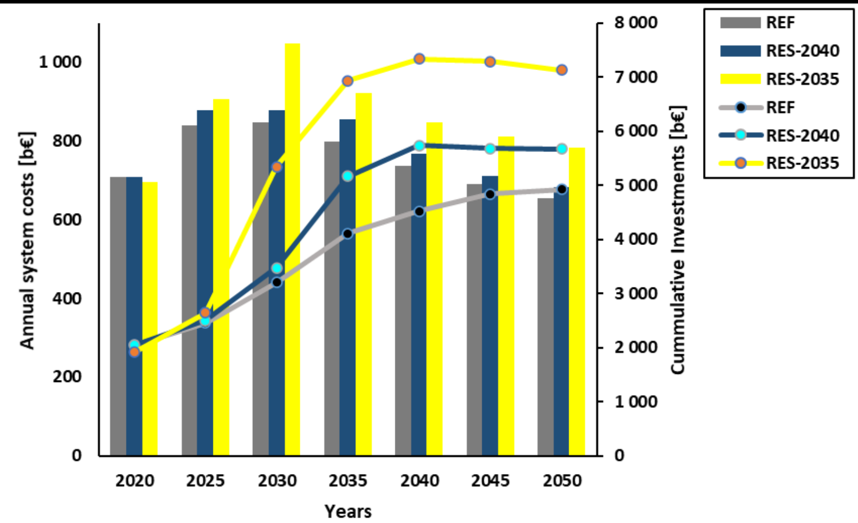
- Energy demand growth in the power, heat, transport and industry sectors is aggregated and linked to powertrain transformation and diffusion of conversion technologies.
- Comprehensive electrification is the underlying theme, which massively increases overall energy efficiency to an even higher growth 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.

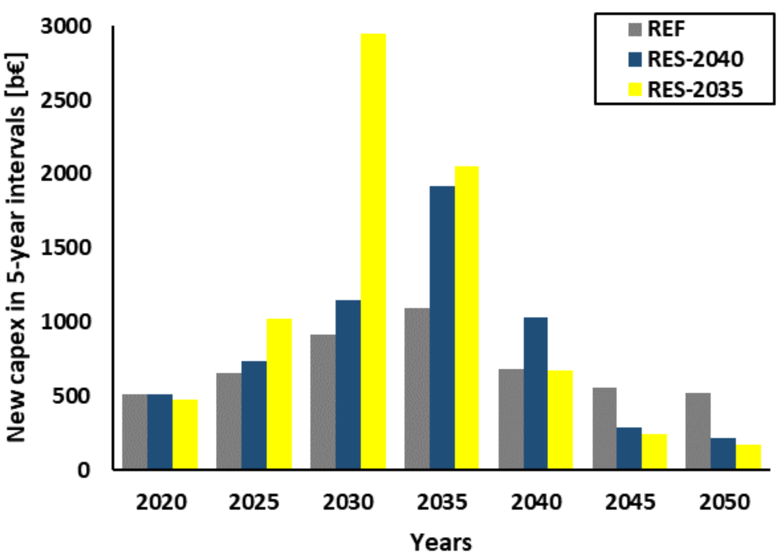
SERENDIPV

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

Costs and Investments
Scenario Comparison





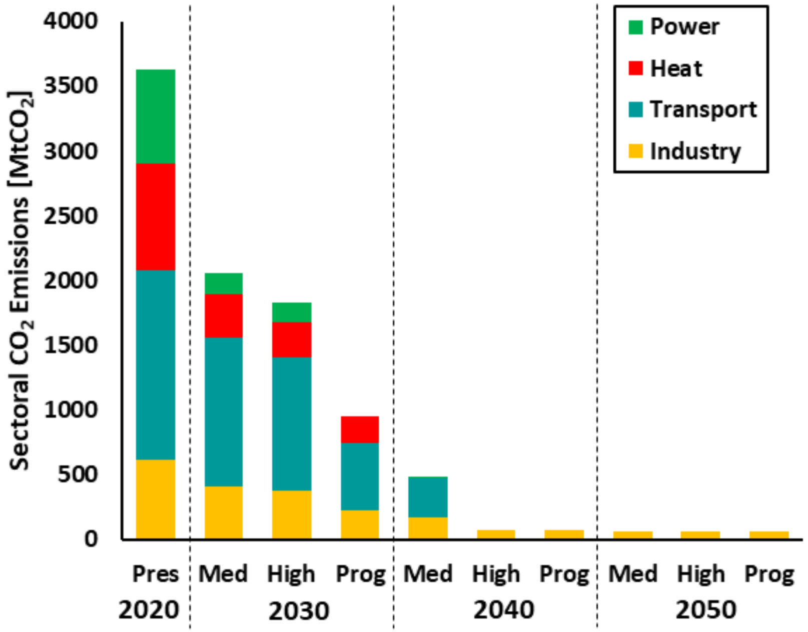


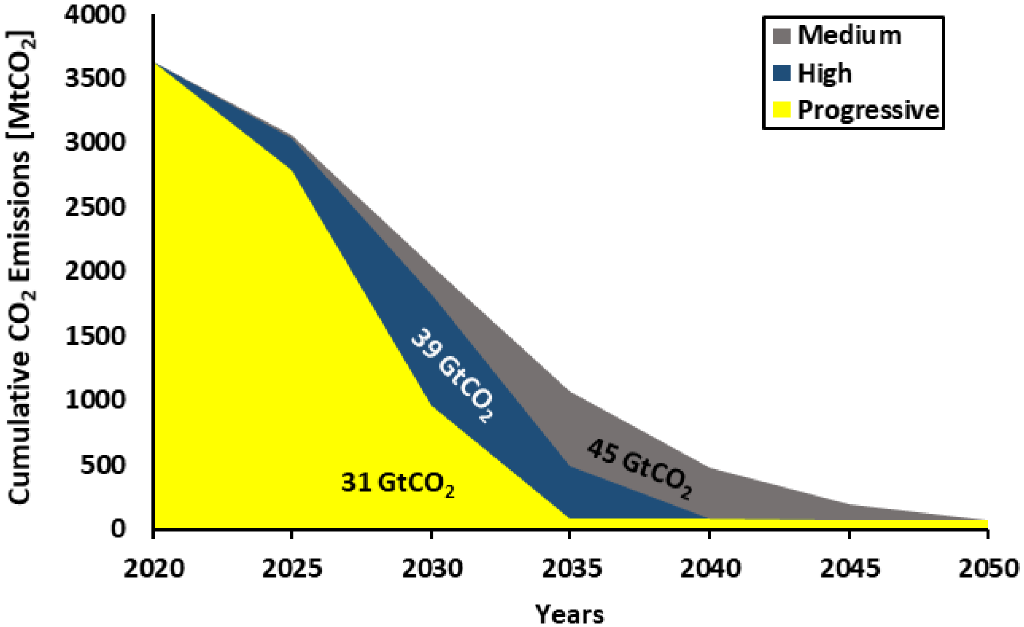
Key insights:

- The total annual system costs are in the range of 600-1000 b€ through the transition period across the 3 scenarios, with the RES-2040 scenario having the least annual system costs in 2050, while the RES-2035 and REF scenarios have higher annual system costs in 2050
- The RES-2035 scenario has a marginally higher LCOEnergy through the transition compared to the RES-2040 and REF scenarios having lower LCOEnergy through the transition, with 15% lower LCOEnergy in 2050
- Annual system costs indicate that pathways towards 100% renewables will not require significant energy system costs, while LCOEnergy remains close to current levels in 2050, expect in RES-2035 scenario with some increase
- Capital expenditures vary drastically across the 3 scenarios, rapid scaling of investments (about 3000 b€) until 2030 in the RES-2035 scenario, while reaching 2000 b€ and 1200 b€ up to 2035 in the RES-2040 and REF scenarios
- Rate of capital diffusion into renewable energy and sustainable technologies will decide the pace of the energy transition across Europe

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

CO_2 Emissions
Scenario Comparison





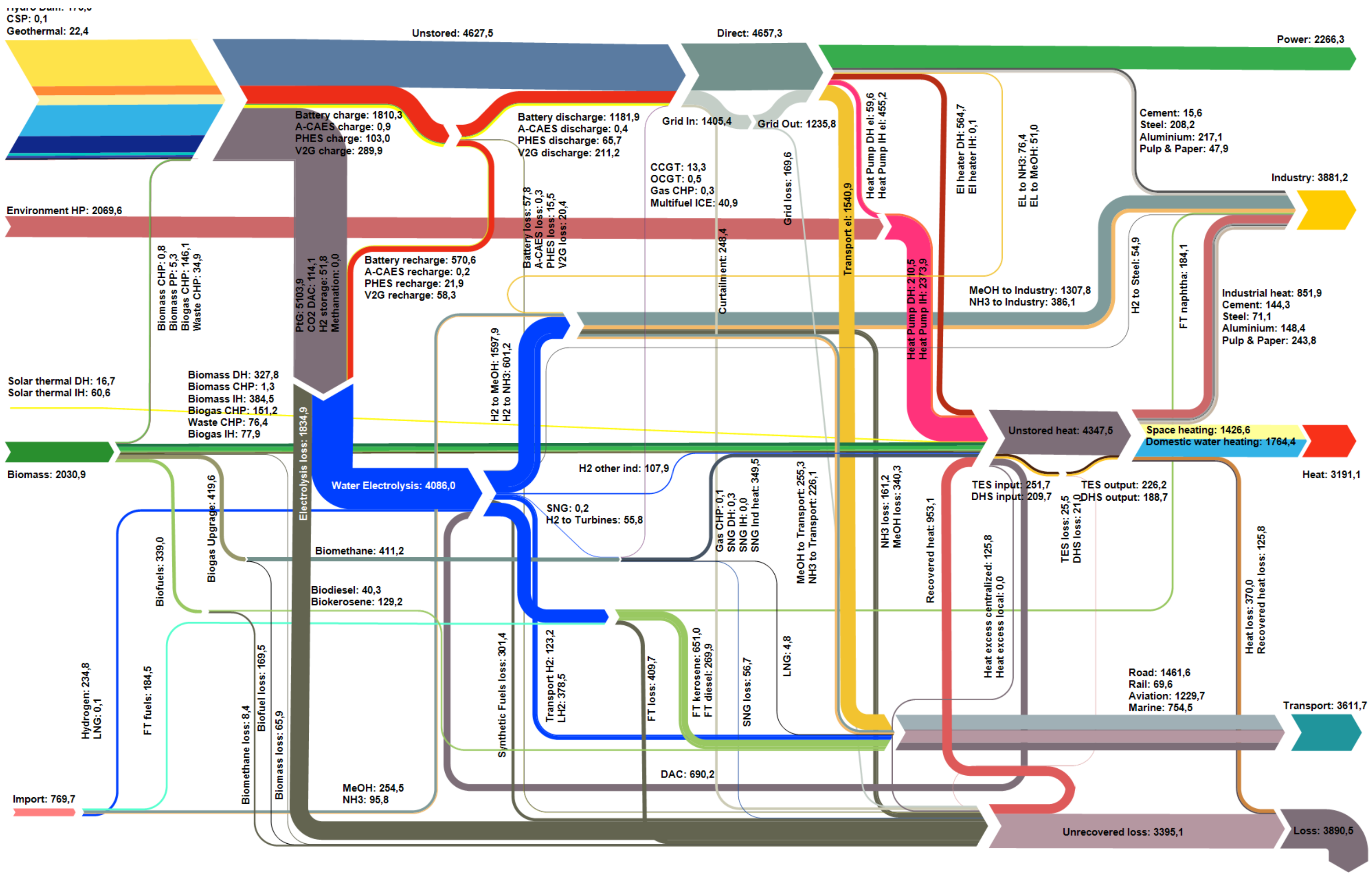
Key insights:

- CO_2 emissions decline in all the 3 scenarios, from over 3500 $MtCO_2$ in 2020 to nearly zero by 2035 in the RES-2035 scenario, nearly zero by 2040 in the RES-2040 scenario and nearly zero by 2050 in the REF scenario (emissions from cement industry persist, can be mitigated with CCS/NCS solutions)
- The remaining cumulative CO_2 emissions comprise around 31 $GtCO_2$ from 2020 to 2035 in the RES-2035 scenario, around 39 $GtCO_2$ from 2020 to 2040 in the RES-2040 scenario and 45 $GtCO_2$ from 2020 to 2050 in the REF scenario
- The presented 100% RE scenarios for the European energy system are compatible with the Paris Agreement, with the RES-2035 scenario highlighting an accelerated pathway for achieving the ambitious target of limiting temperature rise to about 1.5°C, while the RES-2040 scenario shows a less ambitious pathway of achieving 1.5°C - 2°C target and the REF scenario is at the less ambitious end of the Paris Agreement with over 45 $GtCO_2$ of CO_2 emissions until 2050
- A deep defossilisation of the power, heat, transport and industry sectors across Europe is possible by 2035

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

Power-to-X Economy as new characteristic Term

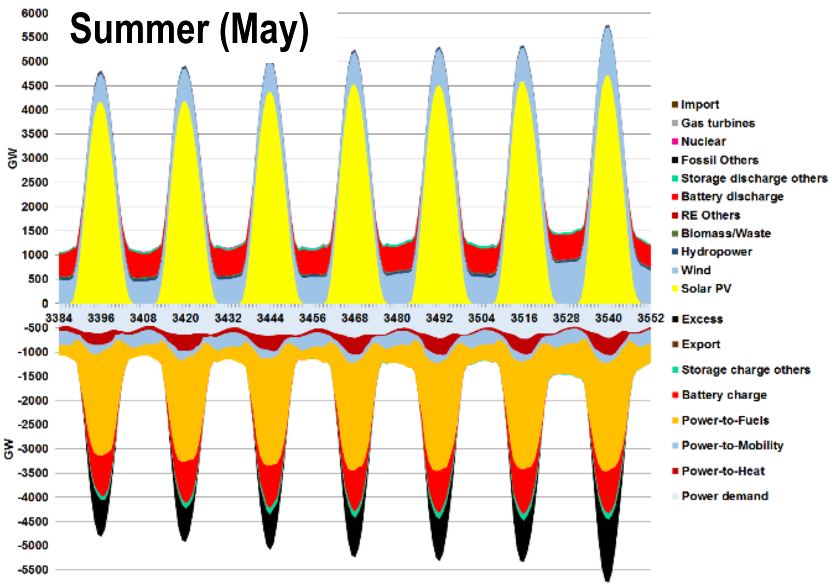
- Zero CO_2 emission low-cost energy system is based on electricity
- Core characteristic of energy in future: Power-to-X Economy
  - Primary energy supply from renewable electricity: mainly PV plus wind power
  - Direct electrification wherever possible: electric vehicles, heat pumps, desalination,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

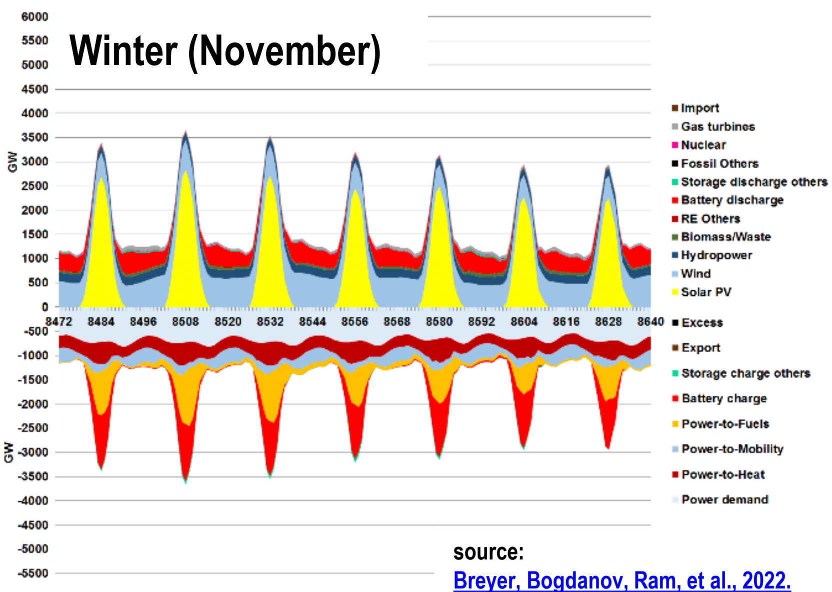


Source:
Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2022. Progress in Photovoltaics

Diagram: Greens/EFA, 2022

Hourly Operation and Balancing



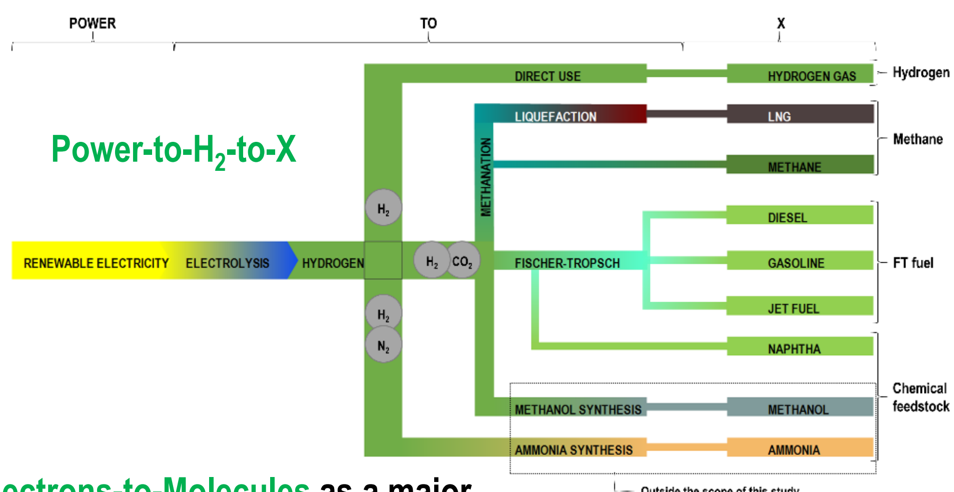


Hours of a year

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

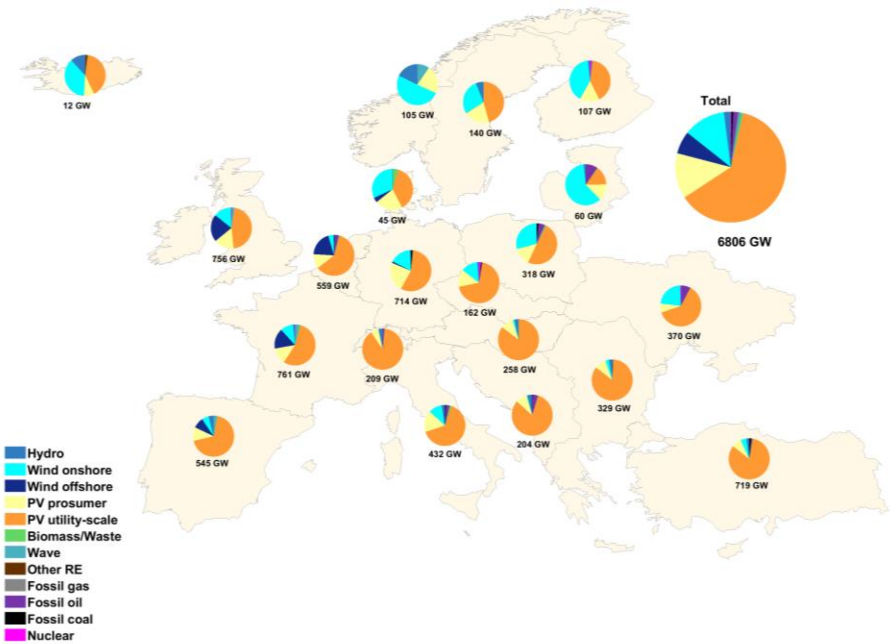


Electrons-to-Molecules as a major piece of Power-to-X Economy

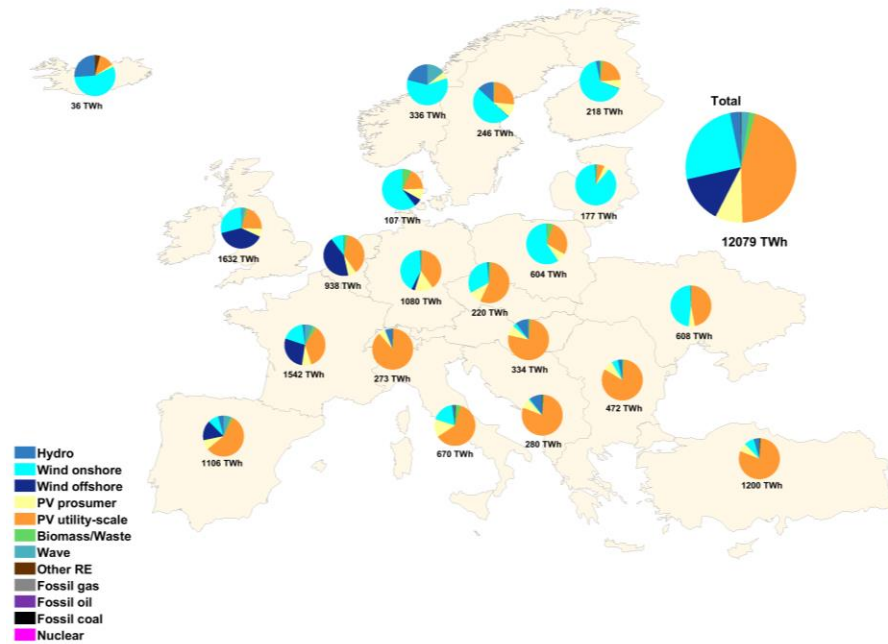
Regional Outlook – Electricity capacities and generation in 2050

RES-2040 Scenario

Regional electricity capacities



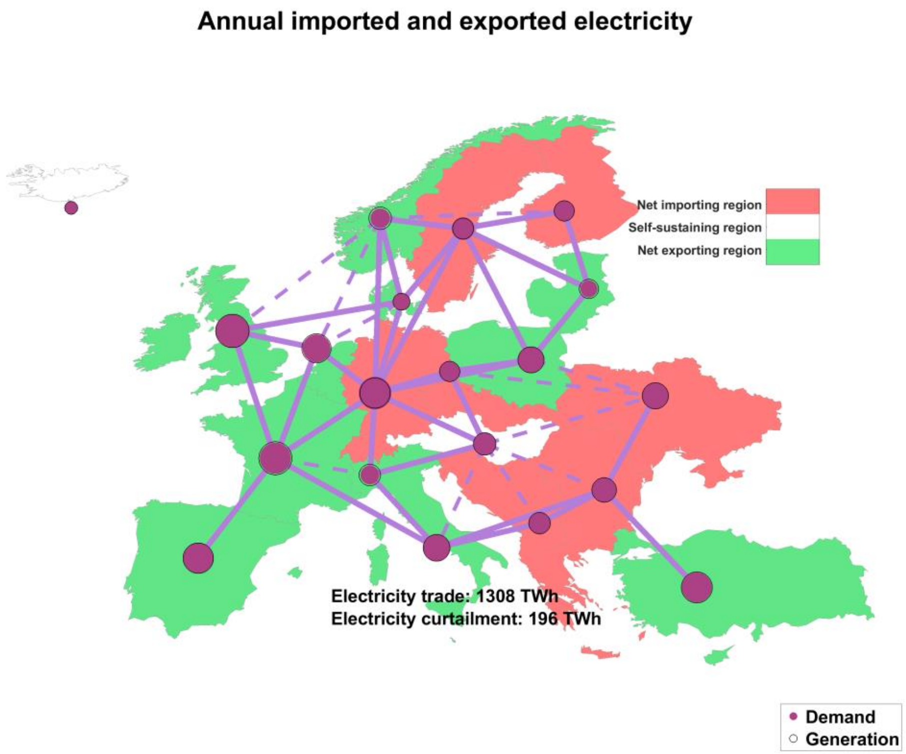
Regional electricity generation

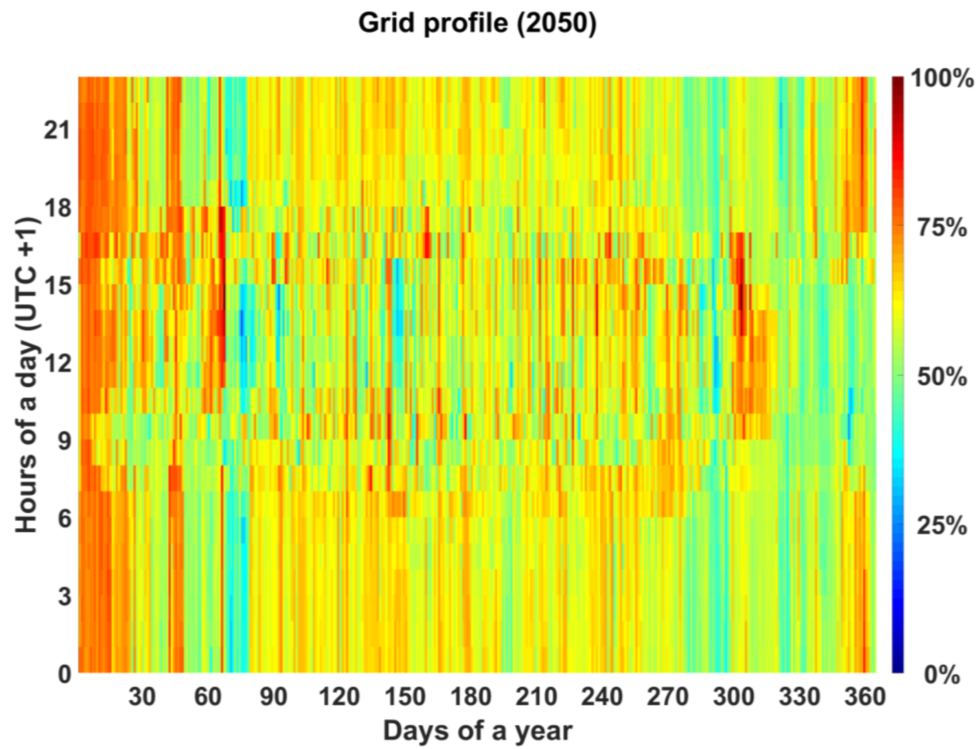


Key insights:

- 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





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

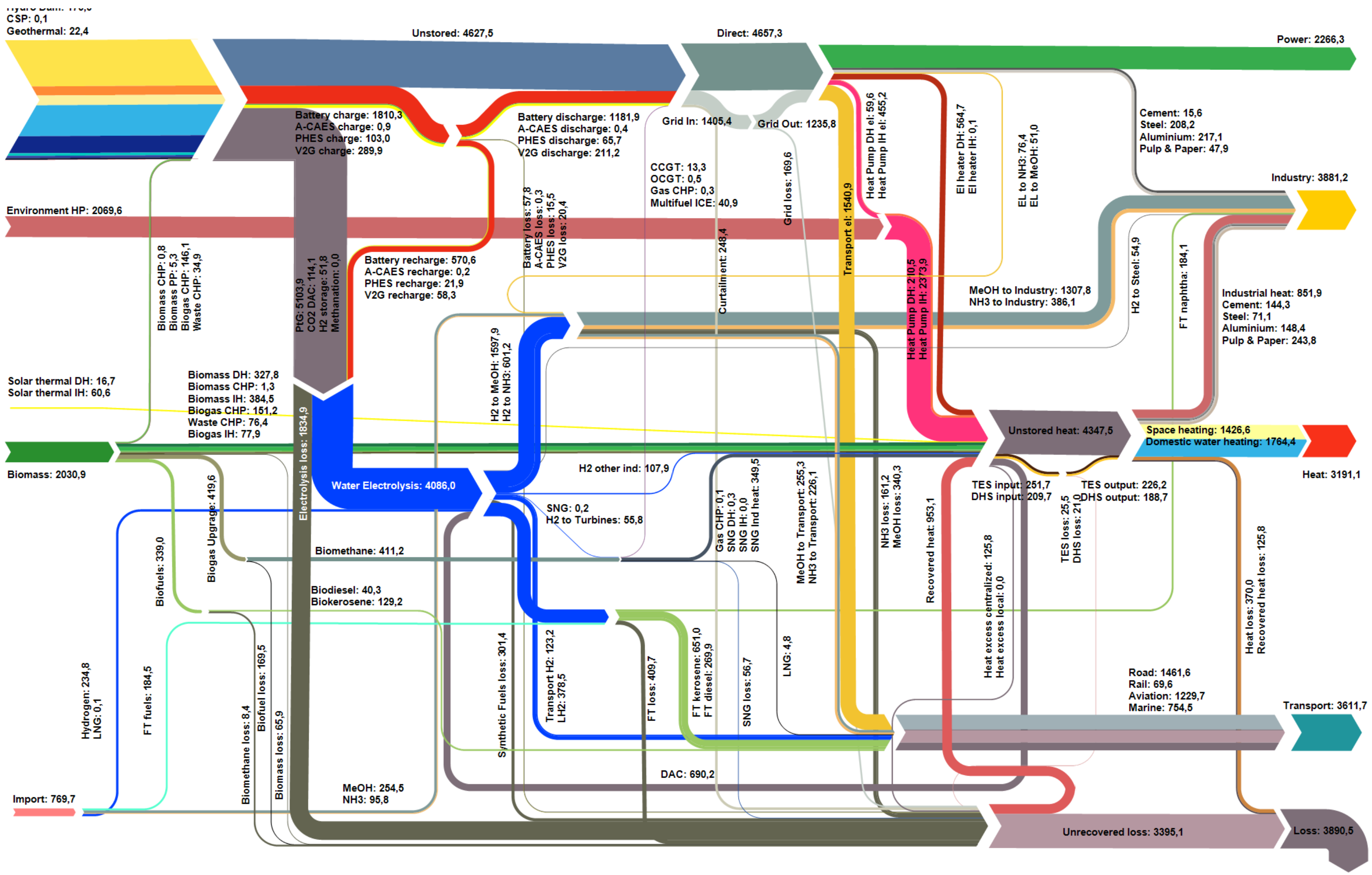
Concrete numbers for achieving the set target

Exemplarily figures for EU-27 for the RES-2040 scenario:

- **solar PV**: annual installation 3x
- **wind onshore**: annual installations 3x
- **wind offshore**: annual installations 15x
- **per year**: 1.3 million **residential roofs** (1% of stock)
- **per year**: 104k **commercial and industrial** systems
- **per year**: 1000 standard 50 MW **PV plants**
- **per year** 5000-6000 **onshore turbines**
- **per year** about 1000 **offshore turbines**
- **in 2040**: **0.4-0.5%** of EU area covered with PV
- **in 2040**: **1.5%** of EU area **gross** covered with wind (**net 0.015%**)

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., 2022. Progress in Photovoltaics

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

Agenda

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

System Outlook – Energy Flows in 2050

RES-2040 Scenario – Power-to-X Economy

Discussion on PtX Economy:
[Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., 2022. Progress in Photovoltaics]

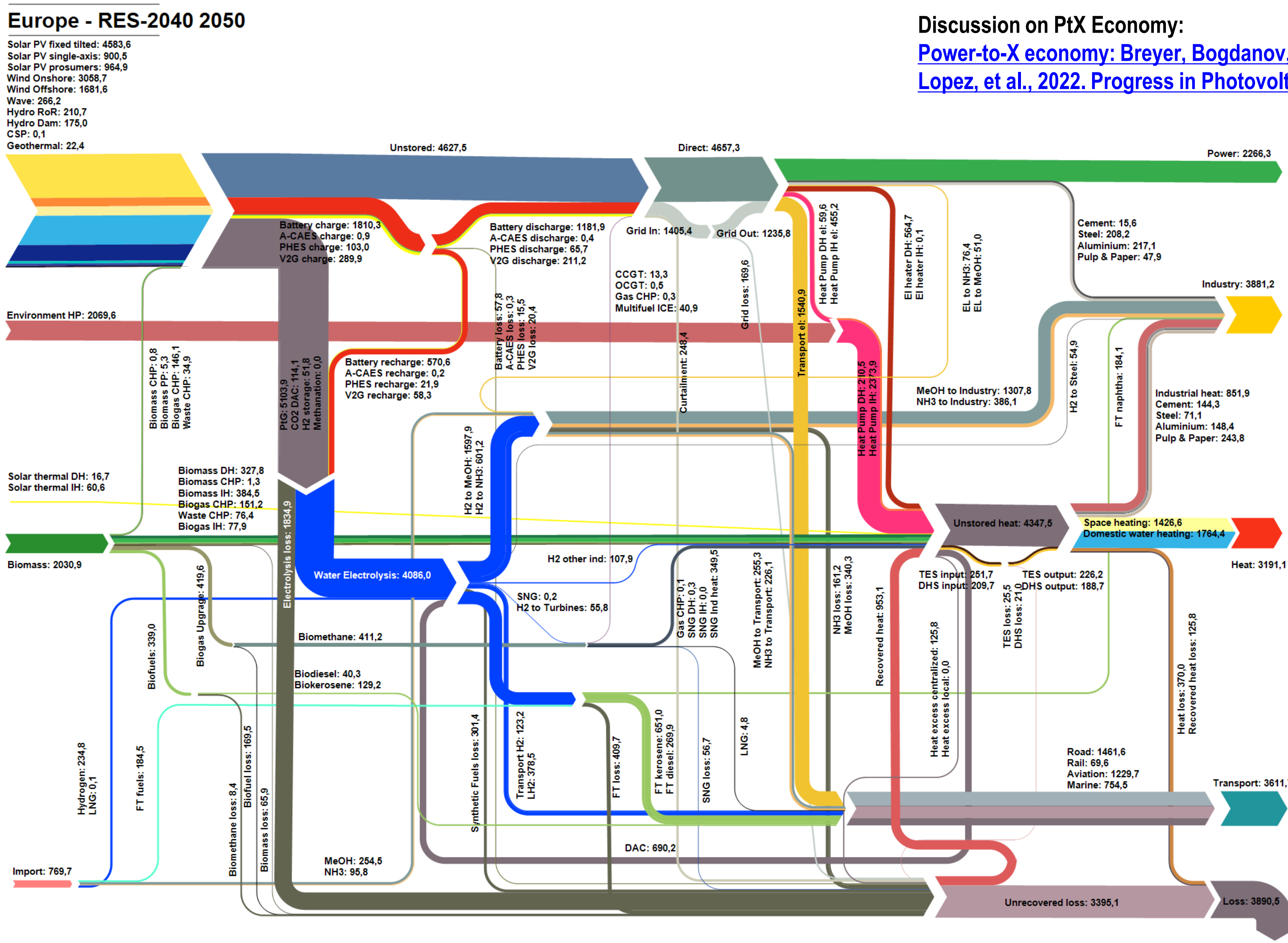


diagram: [Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022]

Summary

- European energy transition needs to be accelerated by at least 10 years
  - absolute zero CO_2 emissions by 2035 would be required
  - efforts to achieve zero by 2035 may be beyond the European capabilities
- Electrification is low-cost and highly efficient
- Solar and wind power are central for comprehensive electrification (direct, indirect)
  - Solar PV (about 54% of supply) and wind power (about 40%)
- 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!

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