100% renewable electricity for ambitious energy and industry transitions by mid-century

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Long-Term Energy Scenarios
Session 4: Role of 100% renewable electricity for the energy system transition in scenarios
Bonn, December 7-9, 2022
CO₂ Emissions: how it developed, where to go

Key insights:
- CO₂ emissions are dominated by fossil fuels
- Emissions are at historic record levels
- Emissions have to reach absolute zero
- Carbon budget for 1.5°C (67%) is to be used by 2030
- Faster transition and net negative CO₂ emissions are required
- Absolute zero CO₂ emissions around 2040 must be targeted

Key Drivers: Availability, Electrification, Cost

**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

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

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

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
Empiric trends:

Electricity supply dominated by PV and wind power

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

Fossil-nuclear generation will be increasingly irrelevant

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

Source: BloombergNEF

100% renewable electricity for ambitious transitions
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source: BNEF, Power Transition Trends 2022
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
On the History of 100% RE Systems Research


- 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”
- Stockholm Environment Institute & Greenpeace published the first report in 1993 for the target year 2100
- The first global analysis for a 100% RE system published in 1996 in a journal, by Sørensen
- 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

Key insights:
- Research field is growing at high dynamics
- Entirely renewable systems research now established
- Three leading teams: Lund et al. (Aalborg, DK), Breyer et al. (LUT, FI), Jacobson et al. (Stanford, US)
- International organisations are conservative in adoption of new insights, e.g. IPCC, IEA, World Bank, etc.

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

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## Leading Energy System Models used in the Field

<table>
<thead>
<tr>
<th>Model</th>
<th>citations</th>
<th>model used for 100% RE</th>
<th>interconnected</th>
<th>full hourly</th>
<th>multi-sector</th>
<th>detailed industry</th>
<th>relevant CDR</th>
<th>optimisation</th>
<th>simulation</th>
<th>transition</th>
<th>overnight</th>
<th>off-grid integration</th>
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- 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 CO₂ 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
LUT Energy System Transition Model

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, CO₂)

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

100% renewable electricity for ambitious transitions
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Europe: System Outlook – Energy Flows in 2020

Europe - 2020

- Solar PV fixed tilted: 62.4
- Solar PV (pansystems): 63.2
- Wind Onshore: 415.1
- Wind Offshore: 62.5
- Hydro Run: 306.1
- Hydro Dam: 218.7
- Geothermal: 25.4
- CSP: 0.4

- Uranium: 2204.9
- Environment HP: 49.7
- Solar thermal DH: 0.3
- Solar thermal IH: 6.8
- Biomass: 1820.9

Energy Flows in 2020

Source: Greens/EFA, Accelerating the European RE transition, Brussels, September, 2022
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 °C 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, September, 2022
**Power-to-X Economy as new characteristic Term**

- Zero CO₂ 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**


Diagram: Greens/EFA, 2022
Hourly Operation and Balancing

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\textsubscript{2}-to-Fuels) that convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability

Summer (May)

Winter (November)

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

Research on e-fuels demand in global studies

Table 1. Global 100% renewable energy system analyses. A threshold of minimum 95% renewables share in at least the electricity supply was considered for inclusion in the table. This criterion was applied to include the near-100% RE system analyses, but also to ensure appearance of fossil energy-free solution structures. Abbreviation: simulation (Sim), optimisation (Opt), power sector (P), all sectors (A), transition (T), overnight (O), e-hydrogen (e-H₂), e-methane (e-CH₄), power-to-liquids (PtL), CO₂ via electricity-based direct air capture (e-CO₂), total primary energy demand (TPED).

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Key insights:

- All following insights are for global energy system studies
- All energy system studies are limited
- Not a single energy system study exists with all five major e-fuels/chemicals
- Integrated Assessment Models for IPCC lack any insights beyond hydrogen
- Only two teams model e-liquids
- Only two teams model e-methane
- e-hydrogen is a standard feature
- Only one team uses e-CO₂
- Highest e-fuels demand around 30,000 TWh – but e-chemicals are missing
- Highest e-hydrogen demand around 40,000 TWh w/o chemicals
- Low results for e-fuels/chemicals due to outdated PV cost and high biofuel assumptions

source: Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, under review.
Global demand for e-fuels

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

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

source: Galimova et al., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability, under review
Africa: Electricity the Basis for all Energy

Highlights

- The generation mix across the scenarios is dominated by solar PV by 2050, representing 42 – 88% of the total electricity supply.

- In the BPS, the regional electricity supply mix is dominated by solar PV single-axis tracking in most of the regions due to excellent solar conditions and continuous cost reduction in PV technologies.

- Wind power and hydropower contribution remains important; however, these resources are not evenly distributed across the continent.

- Wind generation to be around 340 – 520 TWh in 2050, supplied mainly by countries around the Sahara Desert, Horn of Africa, and some parts of Southern Africa.

- In 2050, hydropower generation will be around 230 – 510 TWh, mainly supplied by countries in Central and East Africa.

Source: Oyewo et al. 2022. Contextualizing the scope, scale, and speed of energy pathways toward sustainable development in Africa. iScience, 25, 104965
India: Solar and Wind Deployment

Highlights

- Several states of India have passed 20% PV & wind shares in electricity generation
- Some states remain strong in hydropower, many keep wind power as a substantial source of power, and all benefit from high solar PV shares
- By 2040 the energy transition in electricity generation in India could be largely done

Not shown:

- solar PV share would be higher for all energy demand via Power-to-X applications and very good scalability
- Monsoon: strong grids, complementarity with wind and hydropower, and Power-to-X helps to manage the monsoon season

source: Gulagi et al., 2022, Nature Communications, 13, 5499
India: Capex, LCOE, CO₂, Storage, Grids

**Highlights**

- Most electricity is generated in states of demand, less than 25% of electricity demand needs to be stored, curtailment is low
- Substantial investments required: solar PV, wind power, batteries, grids
- Levelised cost of electricity (LCOE) can decline by 40%
- CO₂ emissions in power generation can be almost stopped by 2040

Source: Gulagi et al., 2022. Nature Communications, 13, 5499
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

source: VDMA, 2022. ITRPV
Haegel et al., 2019. Science
PV Projections of IEA and IRENA

Key insights:
- IEA massively underestimated PV in the past
- Not many signals for improvement, IEA & IRENA reach about 14 TW in 2050
- IEA WEO: 630 GW/a in 2030, then zero and negative market growth until 2050 …
- IRENA: 440 GW/a in 2030 to 2050 …
- Both, IEA WEO & IRENA seem to require more scientific support for techno-economic possible paths and business support what industry is delivering to markets; core deficit: lack of electrification in scenarios
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 transparency, thus could not be considered

Source: Aghahosseini et al., 2023, Applied Energy, 331, 120401
Do we have enough Raw Materials?

Key insights:

- This is ongoing research; almost no one linked materials demand to highly ambitious scenarios
- Solar PV
  - Silicon and glass should be fine, also aluminium if required
  - Silver will be not enough, but can be substituted by copper or aluminium
- Wind power
  - Cement, steel and copper should be fine
  - Neodymium and dysprosium for PMG limited, but not necessarily required
- Batteries
  - Cobalt-free Li-ion batteries may be soon the standard also in electric vehicles
  - Lithium is at the edge, even if reserves may be enough, then ramping extraction may be limited
  - Lithium from desalination brines and also oceans may be an ultimate solution
  - Batteries based on Mg, Al, Na, etc. may tackle the challenge
- Electrolysers
  - PEM is limited due to iridium need (15-50 GW/a)
  - AEL seems not to be limited
- CO₂ direct air capture
  - No limitation known so for

- more investigation required, but seems to be doable; AND, circular economy is a MUST

source: Breyer et al., 2022. IEEE Access 10, 78176-78218
Greim et al., 2020. Nature Communications, 11, 4570
Junne et al., 2020. Energy, 211, 118532
## Critiques and Responses on 100% RE Systems

<table>
<thead>
<tr>
<th>Critique</th>
<th>Response</th>
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</thead>
<tbody>
<tr>
<td>PV &amp; wind are no firm capacity for baseload</td>
<td>Hourly resolution is standard for real weather years, real demand profiles and detailed system representation</td>
</tr>
<tr>
<td>100% RE would be not affordable</td>
<td>100% RE systems for same or less costs than systems with substantial fossil CCS or nuclear shares</td>
</tr>
<tr>
<td>Transition would require fossil fuels for building renewable systems thus more CO(_2) emissions</td>
<td>Energy pay back time of PV around 1 year, wind &lt; 1 year and operation of 30 years; 100% RE system energy return on energy invested table between 10-15, while fossil EROI decline</td>
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<tr>
<td>Lack of materials for energy transition</td>
<td>Substantial materials supply ramping required, while the only really limiting material seems to be lithium, thus massive research for alternative chemistries required (e.g. Na, Al, Mg based batteries)</td>
</tr>
<tr>
<td>Degrowth and declining demand required</td>
<td>100% RE systems are scalable and support a prosperous economy, while circular economy is a must, powered by low-cost PV &amp; wind &amp; battery &amp; electrolysers &amp; DAC</td>
</tr>
</tbody>
</table>

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

- Energy transition reaching zero CO$_2$ emissions by mid-century is feasible
- Faster transition is required for true leaders, absolute zero by 2040 is possible
- Electrification is low-cost and highly efficient
- PV benefits most from comprehensive electrification (direct and indirect)
- **Power-to-X Economy** is THE characteristic structure of the arising energy system
- Common insights: 100% RE is doable, electrification is key, PtX for hard-to-abate
- Conflicts: role of PV vs wind, sustainability of bioenergy, hydrogen-to-X, CO$_2$-to-X
- Blind sports: Global South analyses, critical materials, true global-local view
- Learnings for policy makers: new investments matter, talk to progressive scientists
- Main constraint: clear legally binding targets and willingness to execute the paths
- Awareness required that international organisations (and consultants) lag behind
Thank you for your attention … … and to the team!

all publications at: www.scopus.com/authorid/detail.uri?authorId=39761029000
new publications also announced via Twitter: @ChristianOnRE
LUT model in Comparison

We have been ranked as one of the more advanced energy models among all available energy models, which is capable of handling long-term energy transitions with high time resolution, high geospatial spread and importantly built-in sector coupling.

Among models used for highly renewable energy systems we are in lead together with EnergyPLAN.

Leading Energy System Models ranked by number of published journal articles. Some selected key functionalities of the leading ESMs are displayed, as they are regarded to be key for further progress in the field of 100% RE system analyses. Selection criterion had been more than five articles detected for 100% RE system analyses. Citations comprise the Scopus recordings until early July 2021 for the total and the annual value for 2020.

*EnergyPLAN itself is not able for optimisation, however, the EPLAnOpt [45] derivative allows optimisation.*

The US is the country for which the most country studies have been performed (45 studies in total).

Europe leads with 181 studies in total: DK with 39 studies, DE with 35, all others below 15.

AU has been analysed with 30 studies.

Huge research gaps for sunbelt countries, in particular in Africa, South Asia and Southeast Asia.

Citations analysis of first author affiliation documents a high aggregation of 100% RE research in a few countries (DK, DE, US, FI), often also for countries without own 100% RE research, but with researchers from these countries.

source: Khalili and Breyer, 2022. IEEE Access, 10, 125792-125834
Scientific studies on PV demand

Key insights:
- Since 2018, almost all scientific 100% RE studies find round 40,000 TWh of PV in 2050 or higher (exception is Teske/DLR et al. who strongly bet on CSP which leads to higher cost)
- Two studies find around 100,000 TWh of PV in 2050 (Pursiheimo et al., Bogdanov/Breyer et al.)
- Related capacities are around 22-27 TW for 40 PWh and 49-63 TW for 100 PWh
- Energy-climate researchers started to notice PV with 58 PWh in 2050
- Contribution of wind power is declining since years, a consequence of low-cost PV/batteries/electrolysers

source: Breyer et al., 2022. IEEE Access 10, 78176-78218
e-fuels in 100% RE Systems Studies

- review basis: 550 articles on 100% RE system analyses (as for the bibliometric analysis)
- 45% of all 100% RE articles do NOT comprise e-fuels
- e-fuels/chemical beyond H₂/CH₄ are practically not used
- 1 single article covers the five main e-fuels/chemicals
- CO₂ source dominated by DAC, then bioenergy, no industry
- 48% of all CO₂-to-X articles from LUT
- gaps e-fuels: multiple gaps for all e-fuels/chemicals; huge gaps beyond H₂/CH₄
- gaps CO₂-to-X: models/modlers do not cover this; bio-CO₂ and industrial CCU lacking

Source: Galimova, Khalili, et al. 2022. Journal of Cleaner Production, 373, 133920
Finally, 80% of global CO₂ raw material demand needs to be covered by direct air capture (DAC), while the DAC demand in Europe is slightly lower at 76%

- Industrial phase-in of DAC is critical in 2020s, as point sources are available, while DAC requires a first market ramp-up for massive scaling in 2030s and 2040s
- DAC and carbon utilisation (DACCU) for e-fuels/chemicals is the first huge phase-in DAC deployment
- DAC of carbon and storage (DACCSS) is expected to be the second huge phase for DAC demand starting in 2040s (not included in diagrams)

Source: Galimova et al., 2022. Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals, Journal of Cleaner Production, 373, 133920
Lithium – a potentially limiting raw Material

Key insights:

- No consensus on the Lithium availability
- Matching various supply and demand scenarios almost always leads to supply shortage (total resource in 2060s/2070s, annual supply earlier)
- Circular economy is a must for Lithium
- Lithium based batteries can carry the energy transition far, but not fully
- Alternative battery concepts needed, such on Aluminium or Magnesium basis
- Extraction of Lithium from desalination brines may contribute in addition 15-50% of Lithium demand

Lundaev, Solomon, Caldera, Breyer, 2022. Minerals Engineering, 185, 107652