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

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Background

European Green Deal

- Mobilising research and fostering innovation
- A zero pollution ambition for a toxic-free environment
- Preserving and restoring ecosystems and biodiversity
- From ‘Farm to Fork’: a fair, healthy and environmentally friendly food system
- Accelerating the shift to sustainable and smart mobility
- Building and renovating in an energy and resource efficient way
- Mobilising industry for a clean and circular economy
- Supplying clean, affordable and secure energy
- Increasing the EU’s Climate ambition for 2030 and 2050
- Transforming the EU’s economy for a sustainable future

The European Green Deal

Financing the transition

Leave no one behind (Just Transition)

The EU as a global leader

A European Climate Pact

Paris Agreement

(“well below 2°C”)

What does it mean?

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

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

Remark:
- conventional resources might be lower than depicted by Perez

### Key Rationale for Electrification: Efficiency

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<th>Transport</th>
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<td>Fossil-fuel condensing power station</td>
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<td>40 % efficiency</td>
<td>85 % efficiency</td>
<td>25 – 40 % efficiency*</td>
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<td><strong>Tomorrow</strong></td>
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<td><img src="image5" alt="Diagram" /></td>
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<td>Wind/solar energy</td>
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<td>100 % efficiency</td>
<td>340 % efficiency</td>
<td>80 % efficiency</td>
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*The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50%.*

**source:** Brown et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847
Nov 2016, COP-22, Marrakech: 48 countries (Climate Vulnerable Forum) decided for a 100% RE target

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

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

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

Companies with 100% RE targets, e.g.: Google, Microsoft, Coca-Cola, IKEA, Wärtsilä, Walmart, ...
Major Milestones on 100% RE Research

- Sørensen, 1975
- Sørensen, 1996
- Czisch, 2005
- Greenpeace, 2010
- LUT/EWG, 2019
- Lovins, 1976
- Lund, 2007
- Sterner, 2009
- Jacobson, 2011
- Bogdanov et al. 2019
100% RE Articles in recent Years

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


The 100% RE Opportunity
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Key Diagrams for massive PV induced Change

Key insights:
- massive continued cost decline for solar PV, wind, battery, electrolysers, CO₂ DAC
- massive pressure to eliminate all fossil fuels
- massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand

References:
- PV, battery: Vartiainen et al., Progress in PV
- Electrolyser: LUT model assumption, Nature
- CO₂ DAC: Fasihi et al., J of Cleaner Prod
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 et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, accepted.
Area demand:
- Wind: 4% max per region; 0.3% of land area used
- Solar PV rooftop is zero impact area; ground-mounted is 0.14% of total global land area

source: Breyer et al., 2018., PIP 26, 505-523; Bogdanov et al., 2019. Nature Comms, 10, 1077
Renewables for ALL energy demand (TPED)

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

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

Key insights:

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

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

source: EWG/LUT, 2019. Global Energy System based on 100% RE
Key insights:
- Jacobson et al. (2017) represents one of the very few peer-reviewed global 100% RE transition studies
- High energy efficiency gain due to thermal plant phase-out is highlighted
- The methodology is highly improvable, since only an annual match of supply and demand is done

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

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

source: Sgouridis et al., 2016. The sower’s way: quantifying the narrowing net-energy pathways to a global energy transition, Environmental Research Letters, 11, 094009
Pursiheimo et al., 2019 – 2010 - 2050

Key insights:

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

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

Key insights:

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

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

[Diagram showing Power to Hydrogen to X]

[Graph showing electricity generation and cumulative GHG emissions]

**Case: Sustainable Europe**

**Box 3: Power to Hydrogen to X**

- **Direct Use:** Hydrogen Gas, LNG, Methane
- **Liquefaction:** Methanol, Methanol Synthesis, Ammonia, Ammonia Synthesis
- **Fischer-Tropsch:** Diesel, Gasoline, Jet Fuel, Biomethane
- **Net-Zero:** Outside the scope of this study

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

[Link to report]
Key insights:

- **Week of least renewables supply (winter) and most renewables supply (spring) is visualised**
- **A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year:** Even in the dark winter days the region easily copes with energy demand
- **Key balancing components are electrolyzers (Power-to-fuels) which convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability**
- **Massive ramp rates in the energy system have to be managed, as well as forecasting errors require balancing**
- **Collaboration with SolarPower Europe.**

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe
Energy System Structure: Present (Europe)

**Figure 3.24 Energy Flows for the European Energy System in 2020**

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

Input:
- Solar PV: 174 TWh
- Wind: 582 TWh
- Hydro: 602 TWh
- Other RE: 1,772 TWh
- Coal (Electricity): 1,315 TWh
- Fossil coal: 4,722 TWh
- Fossil gas: 4,449 TWh
- Fossil oil: 6,916 TWh
- Environment heat: 84 TWh

Transformation:
- Nuclear: 1,025 TWh
- Gas (Electricity): 591 TWh
- Gas (Heat): 3,439 TWh
- Oil (Heat): 3.2 TWh
- Transport: 164 TWh
- Transport el: 170 TWh
- Other RE (Heat): 1,488 TWh

Output:
- Power: 3,876 TWh
- Direct use: 4,368 TWh
- Heat: 7,651 TWh
- Heat storage: 0 TWh
- Transport: 7,254 TWh

Source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe
**Energy System Structure: Future (Europe)**

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

**Input**
- Solar PV
- Wind
- Hydro
- Other RE
- Environment HP
- Uranium

**Transformation**
- RE electricity
- Electricity storage
- Heat storage
- Electrolysis

**Output**
- Power
- Heat
- Transport

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<td>Hydro: 716 TWh</td>
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<td>Nuclear: 237 TWh</td>
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<td>Other RE (Electricity): 279 TWh</td>
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| Other RE (Heat): 1,511 TWh | Heat storage: 754 TWh | |**Key insights:**
- 100% renewables will lead to strongly coupled energy system
- Most important energy carrier is electricity, while second most important is green hydrogen
- Fossil and nuclear fuels are not part of a sustainable and least cost energy system

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe
Overview on transport sector transition

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<td>4 %</td>
<td>0 %</td>
<td>2 %</td>
</tr>
<tr>
<td>US DoE EIA</td>
<td>98 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>

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

source: Khalili et al., 2019. Energies, 12, 3870
Regional and Global Super Grids

Key insights:

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

What say IEA and IAMs/IPCC on PV?

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

articles based on real PV cost
Heagel et al., 2019. Science 364(6443), 836-838
Vartiainen et al., 2020. PIP 28, 439-453
Breyer et al., 2018. PIP 26, 505-523
Breyer et al., 2017. PIP 25, 727-745
Summary

- Practically unlimited solar resource potential for energy supply
- Electrification of all energy sectors will boost PV demand, plus some wind
- 100% RE scenarios since 1975 and analytic global scenarios since 1996
- PV shares in global scenarios increases continuously: 70-80% may be the limit
- Key technologies: PV, wind energy, batteries, electrolysers and CO$_2$ DAC
- Green hydrogen enables solutions for hard-to-abate sectors
- Green hydrogen is the basis for direct hydrogen use, but also in particular for further synthesis to SNG, Fischer Tropsch fuels, ammonia and methanol
- Strong sector coupling is a major driver for a sustainable energy system
- The Solar Age is a key opportunity to fix multiple issues, first of all climate change
Thank you for your attention …  
… and to the team!

all publications at: [www.scopus.com/authid/detail.uri?authorId=39761029000](http://www.scopus.com/authid/detail.uri?authorId=39761029000)

new publications also announced via Twitter: [@ChristianOnRE](http://Twitter: [@ChristianOnRE)
Key questions

Conceptual difference between 100% RE power and 100% RE energy systems
- flexibility: power sector is most inflexible sector, while heat, transport and industry delivers flexibility
- key flexibilities: smart charging of BEV, heat pump + TES, electrolysers
- seasonal storage practically disappears and electrolysers can effectively balance the power system

Operability of a system with limited synchronous generators for high solar and wind shares
- batteries are key: synthetic inertia can perfectly balance the system
- electrolysers can effectively balance the power flows

Gap between the current speed of change and what needs to take to reach to 100% RE systems
- first: realistic scenarios are needed!! IAMs/IPCC fail, IEA fails, sorry, IRENA has also to improve
- second: clean up the grid, then electrify almost everything
- third: about 1 TWp/y PV (2030) and about 3 TWp/y PV (2040) for supplying a prosperous world
- fourth: be aware of that 2050 zero GHG emissions is 20 years (!) after the 1.5C budget is used

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

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

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

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

Key insights:

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

Solar Photovoltaics

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