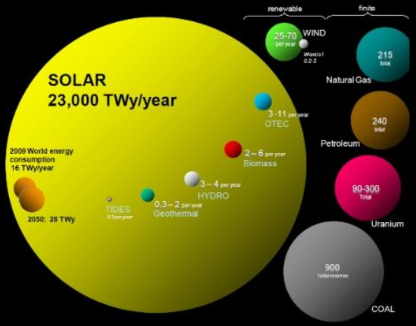
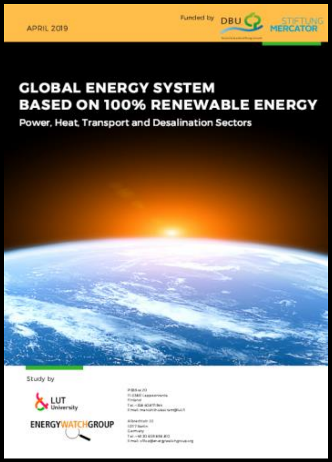


Why and how 100% Renewables



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Lappeenranta University of Technology

Christian Breyer
Professor for Solar Economy

10th Dii Desert Energy Leadership Summit
Energy Transition: Towards 100% Emission Free Energy System
Berlin, November 26, 2019

Key diagrams why there will be massive change

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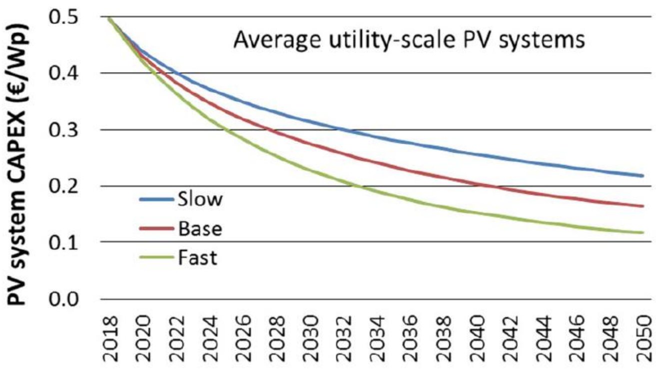
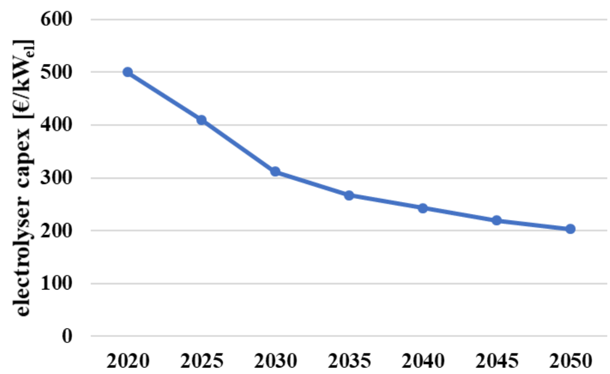
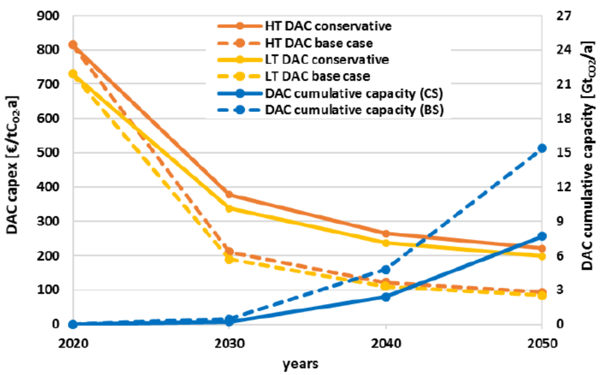
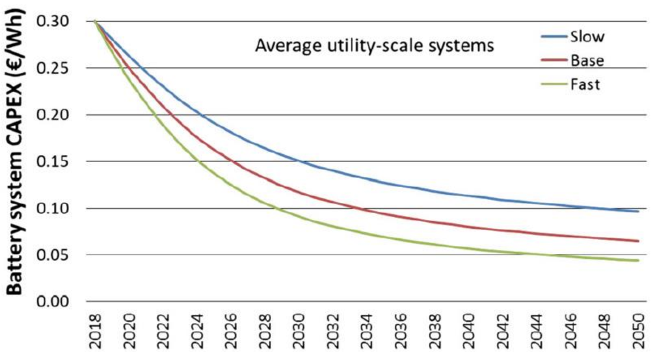
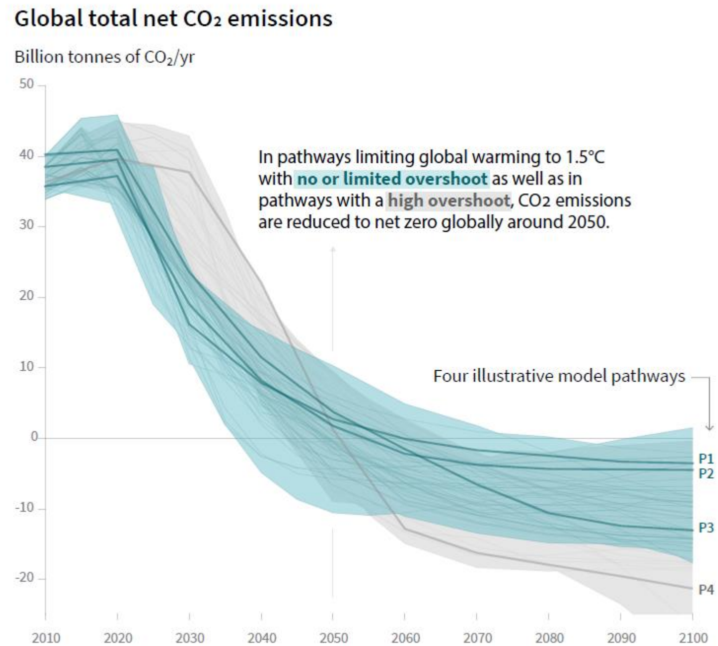








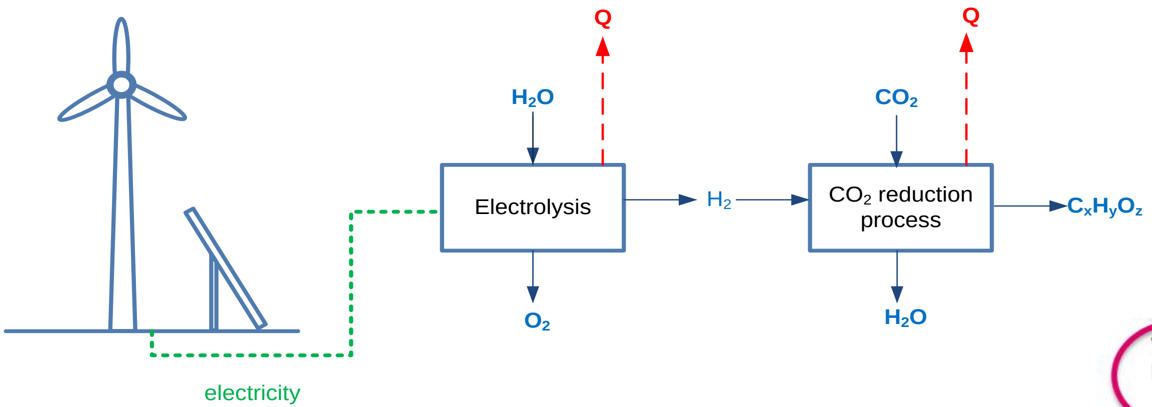
References:
PV, battery: Vartiainen et al., Progress in PV
Electrolyser: LUT model assumptio, Nature
CO_2 DAC: Fasihi et al., J of Cleaner Prod
CO_{2eq} decline: IPCC SR1.5

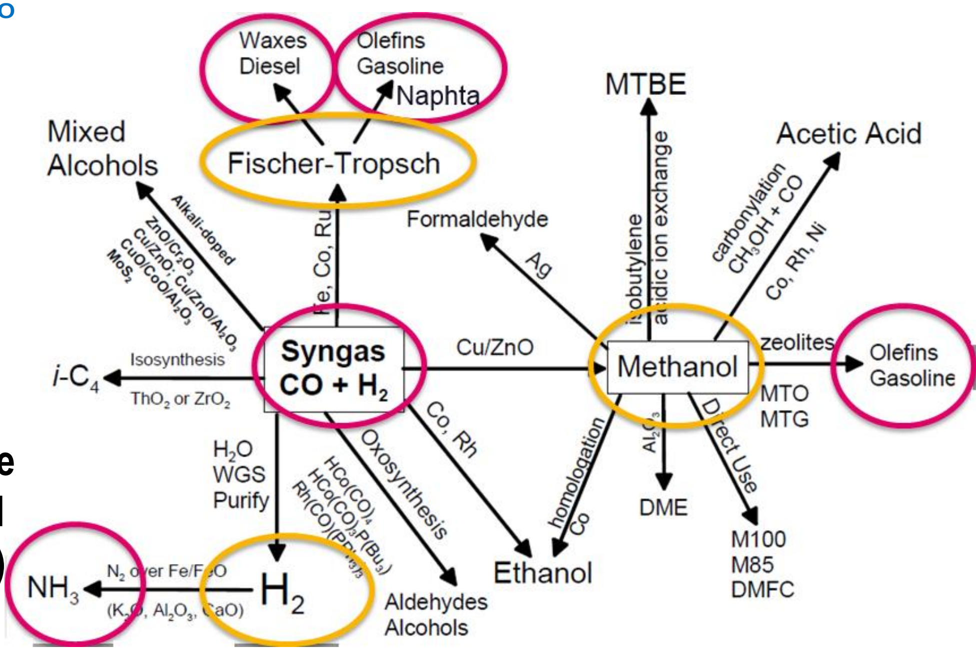


Key insights:

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

Power-to-X – covering hydrocarbon demand



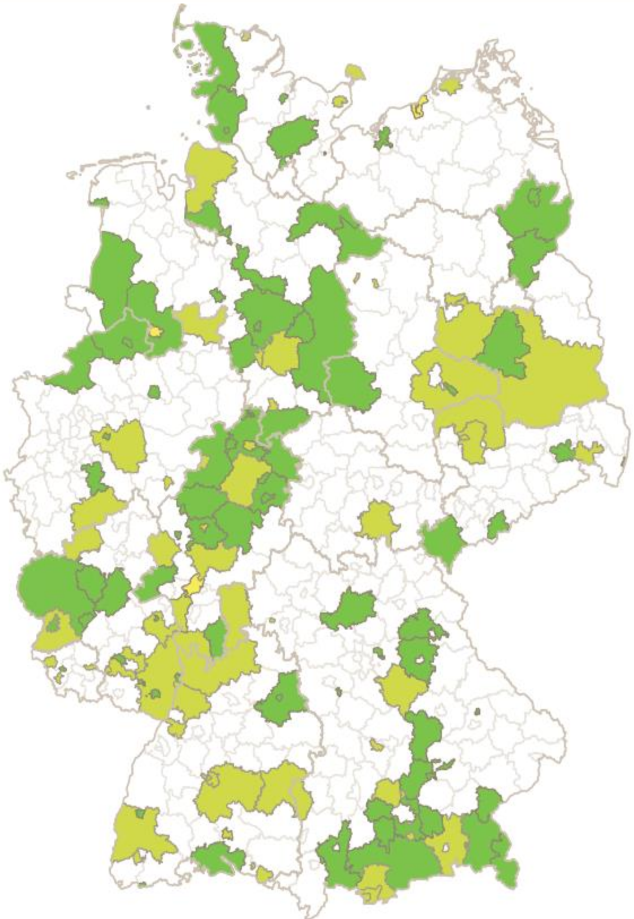


Key insights:

- PtX enables sustainable production of hydrocarbons
- Inredients: electricity, water, air
- w/o PtX Paris Agreement would be wishful thinking
- Profitability from 2030 onwards
- Flexible seasonal storage option
- Global hydrocarbon downstream infrastructure usable
- Most difficult sectors to decarbonise can be managed with PtX (aviation, chemistry, agriculture, metals, etc.)
- CO_2 direct air capture is part of PtX

100% RENEWABLES

www.go100re.net



www.100-ee.de/

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

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

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

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

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25 July 1975, Volume 189, Number 4199
SCIENCE

Energy and Resources

A plan is outlined according to which solar and wind energy would supply Denmark's needs by the year 2050.

Bent Sørensen

SCENARIOS FOR GREENHOUSE WARMING MITIGATION

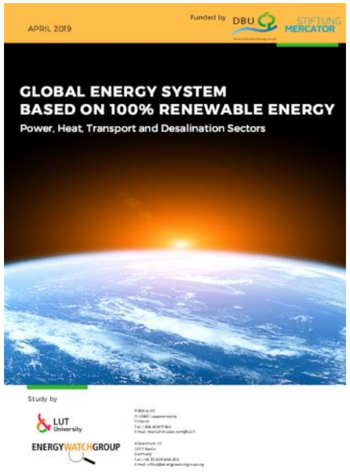
BENT SØRENSEN

Szenarien zur zukünftigen Stromversorgung

Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien

vorgelegt von: Dipl.-Phys. Gregor Czisch

1. Gutachter: Univ.-Prof. Dr.-Ing. Jürgen Schmid
2. Gutachter: Univ.-Prof. Dr.-Ing. Dietmar Hein



Sorensen, 1975 | **Sorensen, 1996** | **Czisch, 2005** | **Greenpeace, 2010** | **LUT/EWG, 2019**

Lovins, 1976 | **Lund, 2007** | **Sterner, 2009** | **Jacobson, 2011** | **Bogdanov et al. 2019**

Energy Strategy:
The Road Not Taken?
By Amory B. Lovins

ScienceDirect
ENERGY

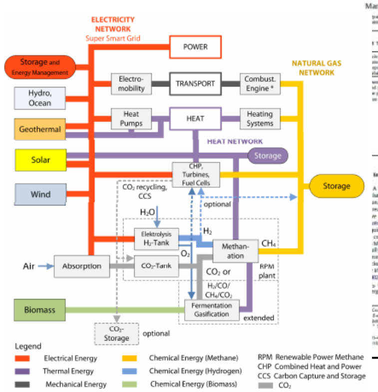
Renewable energy strategies for sustainable development

Henrik Lund

Michael Sterner

Bioenergy and renewable power methane in integrated 100% renewable energy systems

Limiting global warming by transforming energy systems



Energy Policy

Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials

Mark Z. Jacobson, Mark A. Delucchi

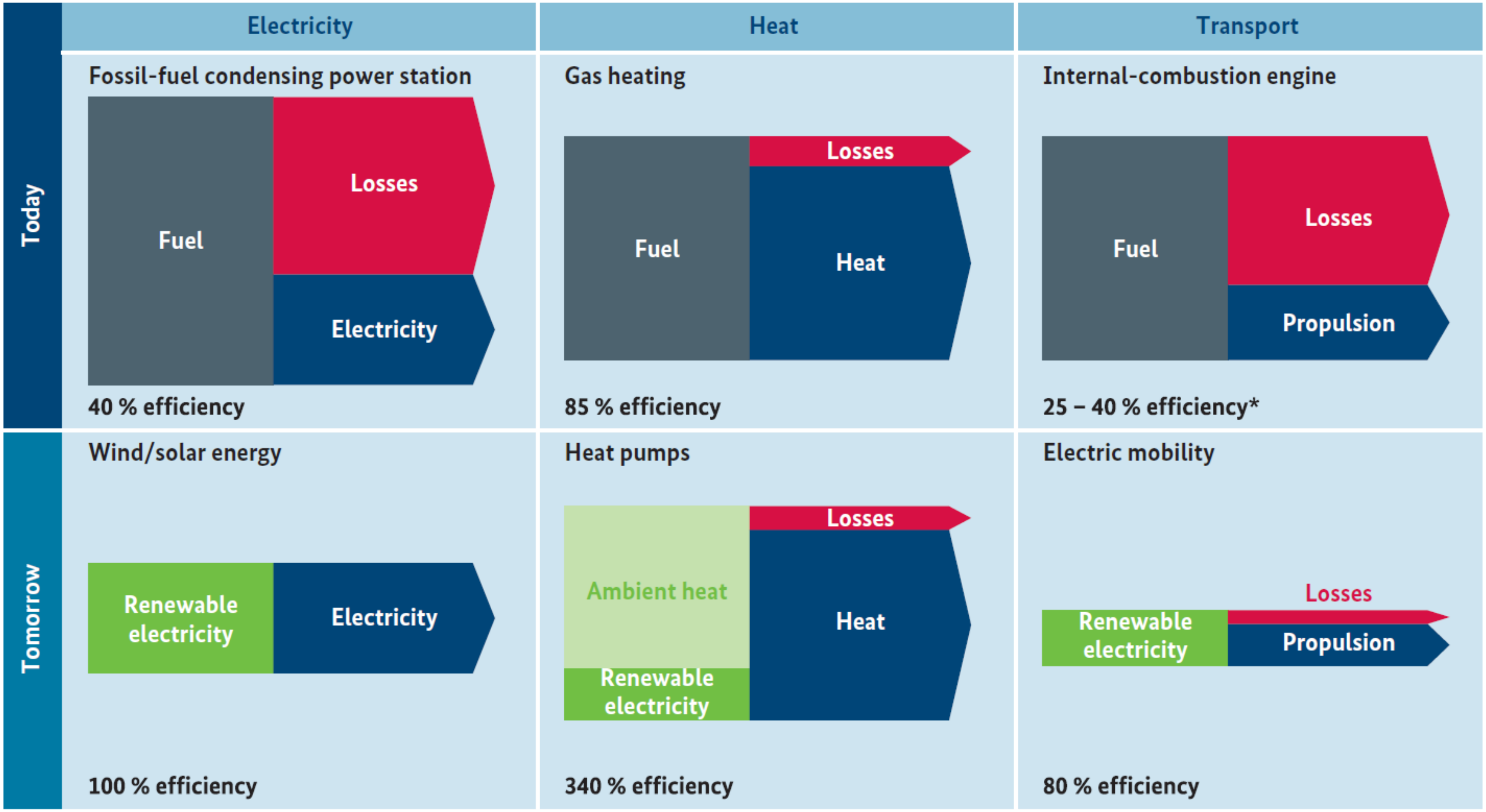
nature COMMUNICATIONS

ARTICLE

Radical transformation pathway towards sustainable electricity via evolutionary steps

100% Renewable Energy
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Key rationale for electrification: Efficiency



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

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

100% RE for Power Sector

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nature COMMUNICATIONS

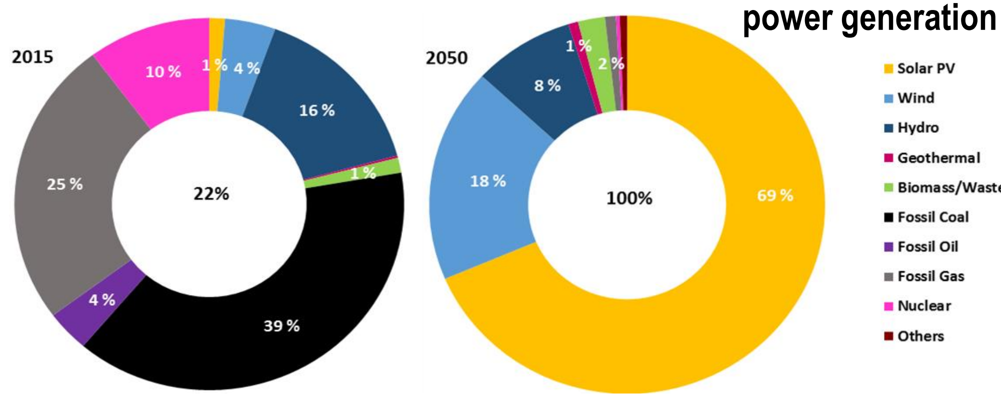
ARTICLE

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

Radical transformation pathway towards sustainable electricity via evolutionary steps

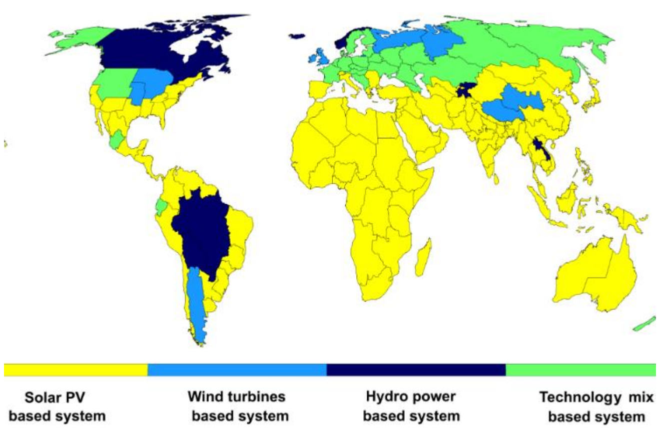
Dmitrii Bogdanov[1], Javier Farfan[1], Kristina Sadovskaia[1], Arman Aghahosseini[1], Michael Child[1], Ashish Gulagi[1], Ayobami Solomon Oyewo[1], Larissa de Souza Noel Simas Barbosa[2] & Christian Breyer[1]

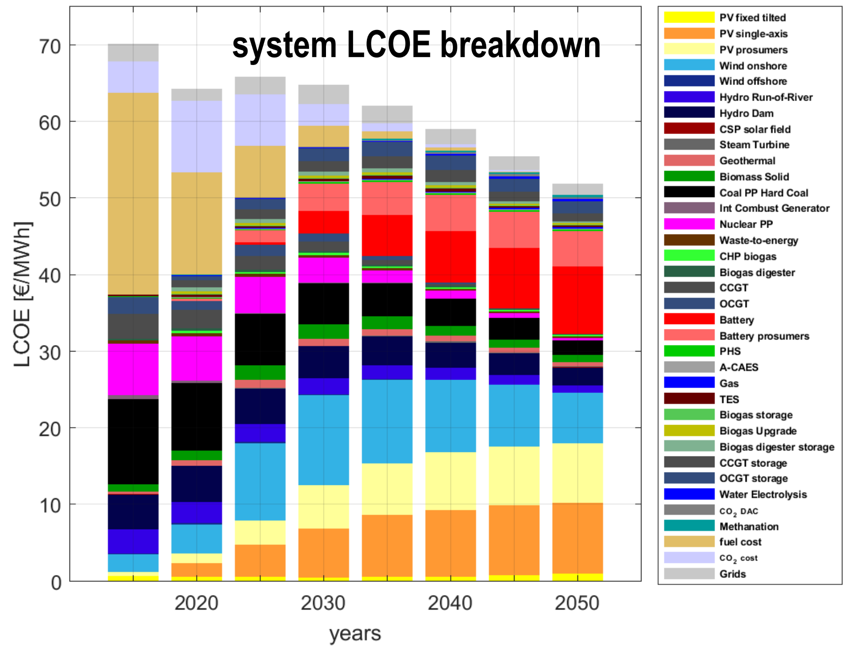
A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: greenhouse gas emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the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



Area demand:

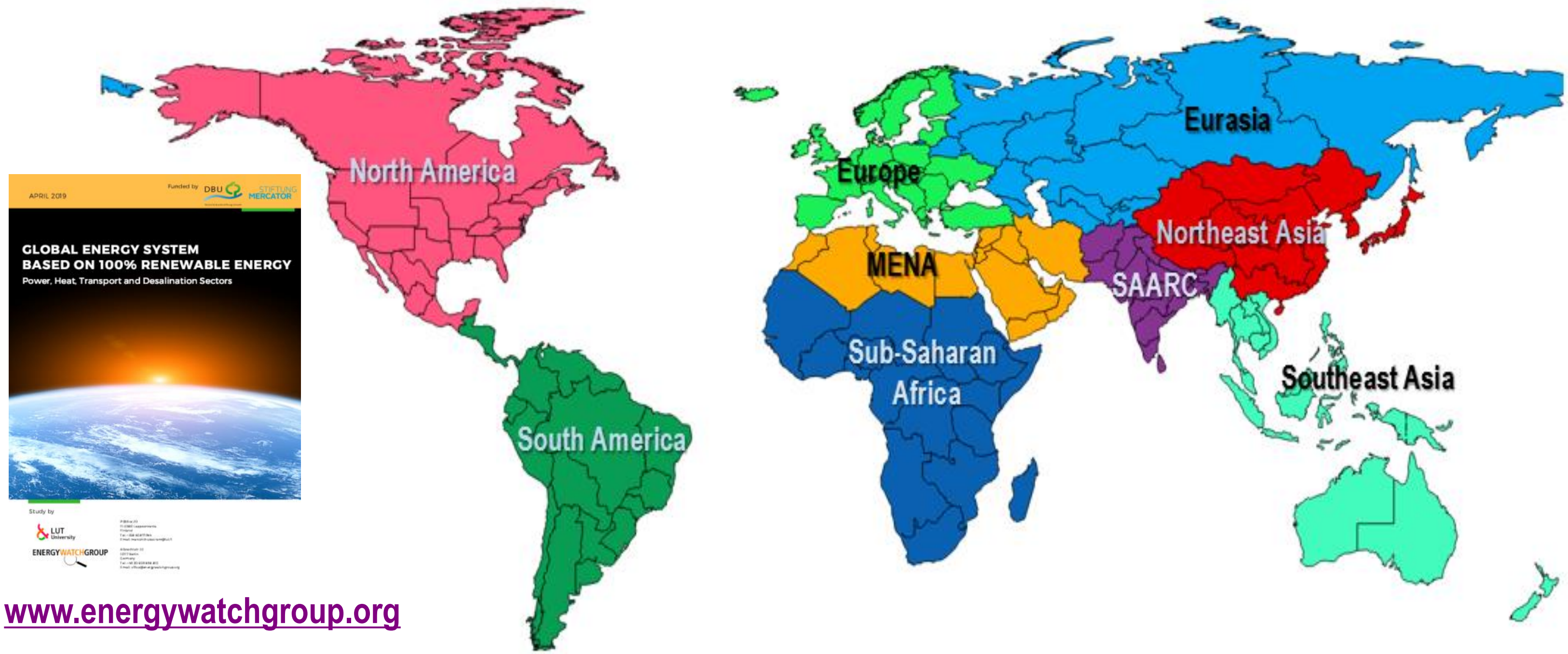
- Wind: 4% max per region; 0.3% of land area used
- Solar PV rooftop is zero impact area; ground-mounted is 0.14% of total global land area





source: Breyer et al., 2018., Progress in Photovoltaics, 26, 505-523; Bogdanov et al., 2019. Nature Communications, 10, 1077

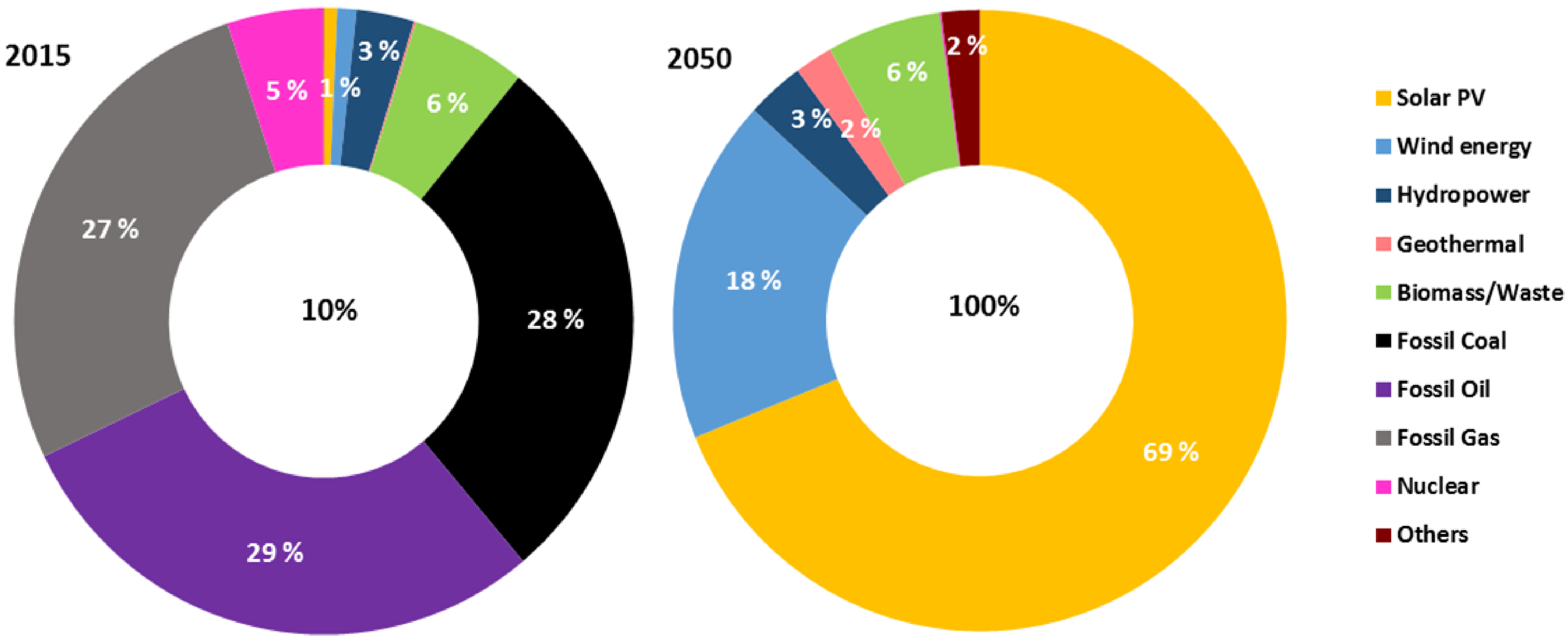
Global Overview



www.energywatchgroup.org

- The world is structured into 9 major regions, which are further divided to 145 sub-regions
- Some sub-regions represent more than one country, others parts of a larger country
- The sub-regions are interconnected by power lines within the same country
- The results shown are for the Power, Heat, Transport, Desalination sectors
- The energy transition scenario is carried out in full hourly resolution for all energy sectors
- In total 106 different technologies are applied

Total Primary Energy Demand Shares



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 just 22% 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

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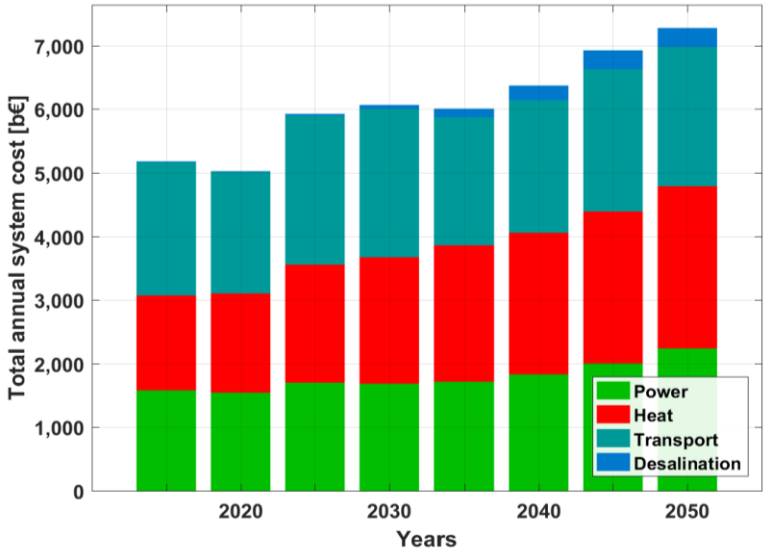
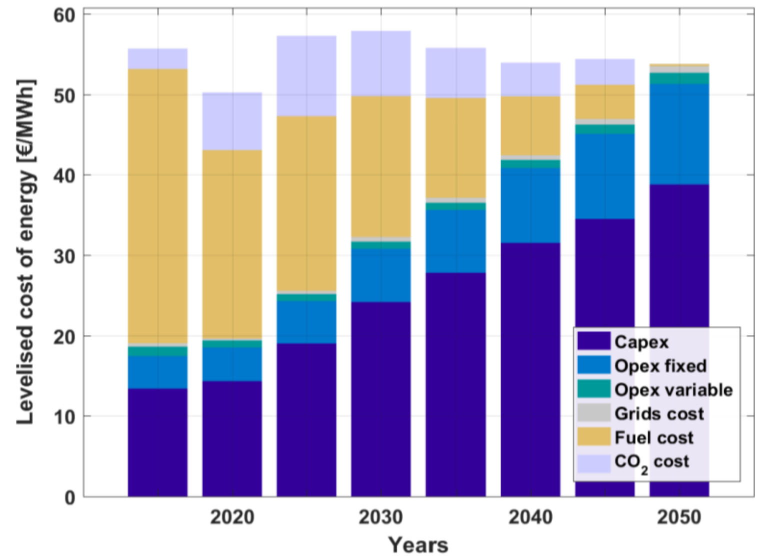
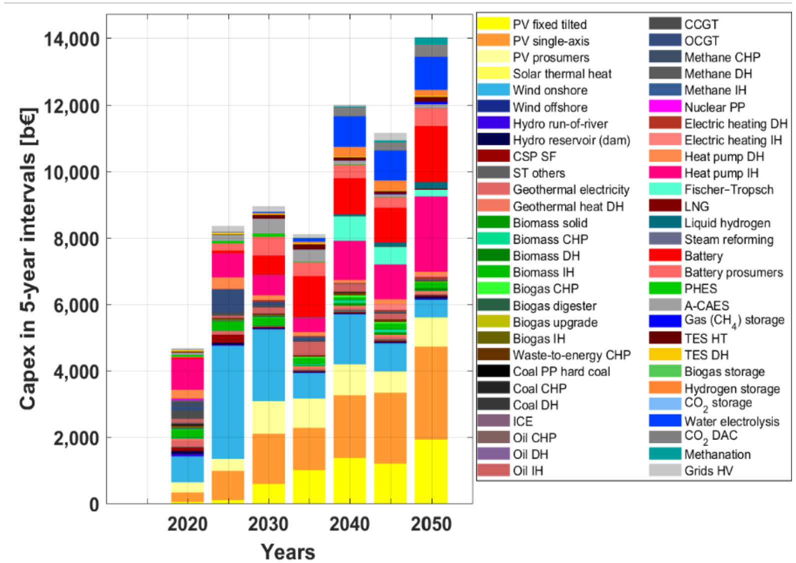
Energy System Cost







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
- LCOE 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€

Regional Variation in 2050

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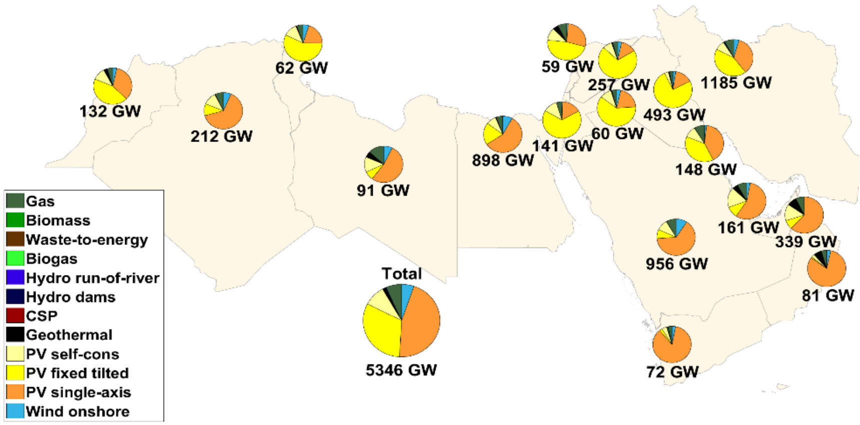
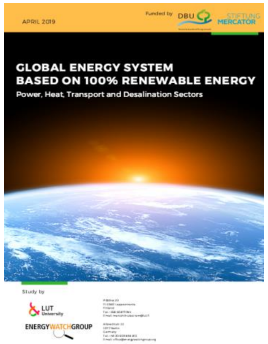
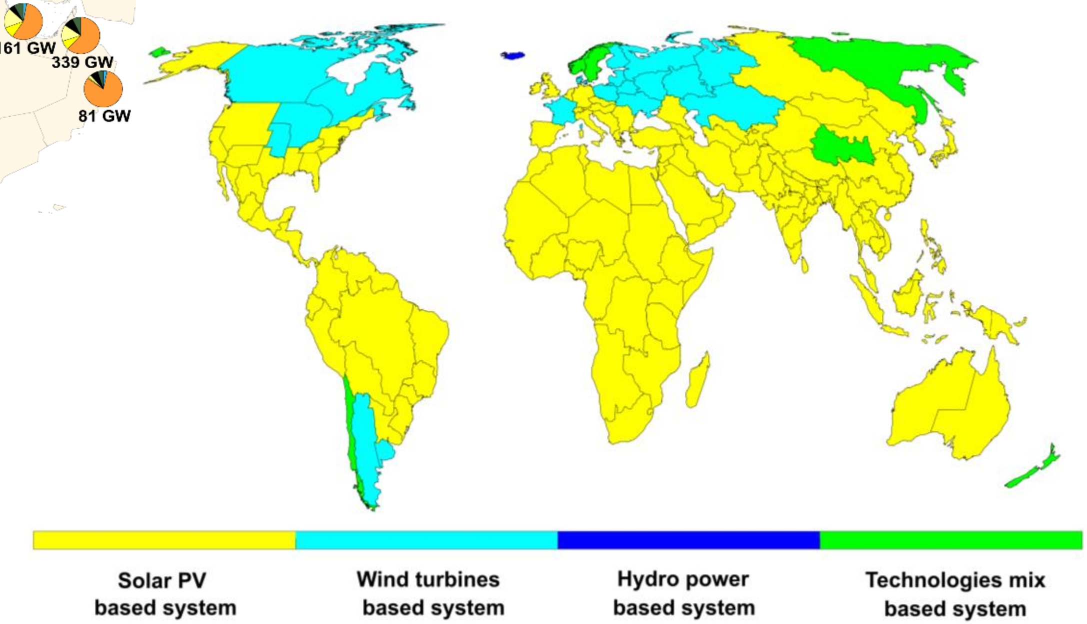
Regional electricity capacities





www.energywatchgroup.org



Key insights:

- Solar PV dominates most of regions around the world and particularly in the Sun Belt
- Wind energy drives systems in the Northern and Southern hemispheres with excellent wind conditions and lacking seasonal solar energy
- Some regions are further complemented with hydropower to form a mixed system

Why we do not yet hear more about 100% RE?

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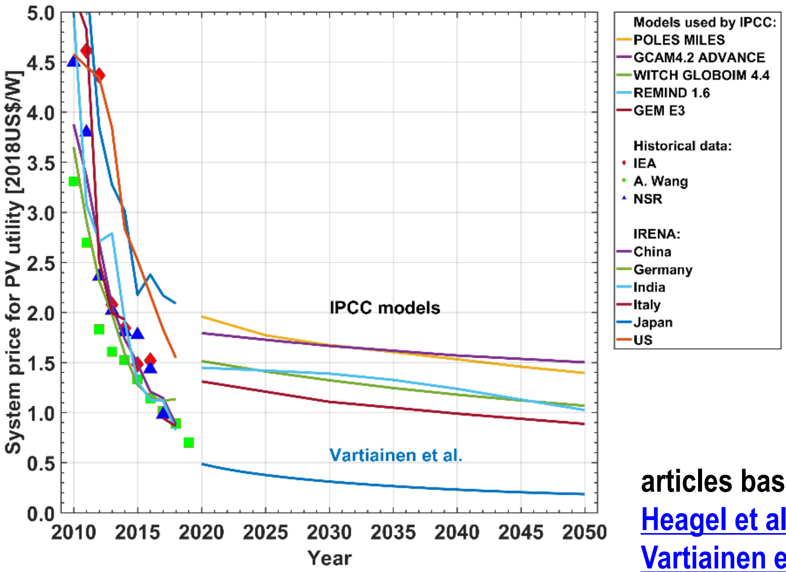
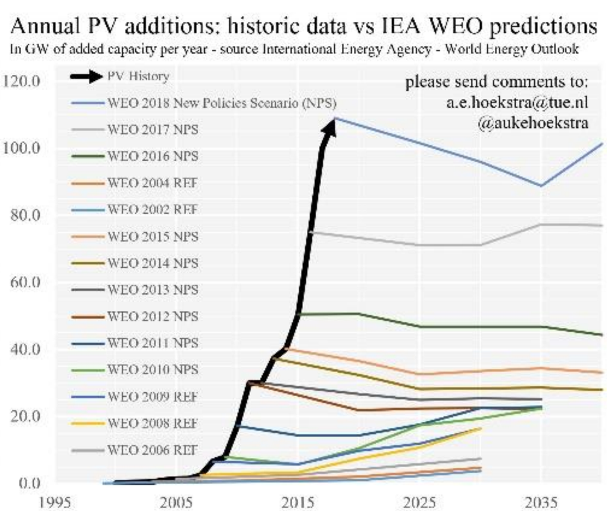
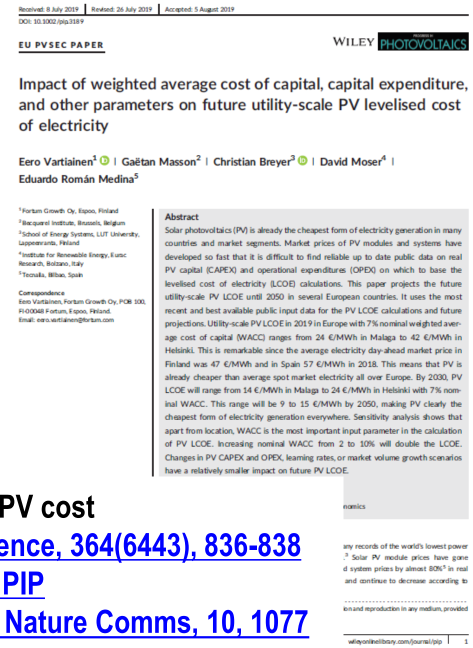





Received: 8 July 2019 | Revised: 26 July 2019 | Accepted: 5 August 2019

DOI: 10.1002/pip.3189

EU PVSEC PAPER

WILEY PHOTOVOLTAICS

Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity

Eero Vartiainen[1] | Gaëtan Masson[2] | Christian Breyer[3] | David Moser[4] | Eduardo Román Medina[5]

[1] Fortum Growth Oy, Espoo, Finland
[2] Becquerel Institute, Brussels, Belgium
[3] School of Energy Systems, LUT University, Lappeenranta, Finland
[4] Institute for Renewable Energy, Eurac Research, Bolzano, Italy
[5] Tecnalia, Bilbao, Spain

Correspondence
Eero Vartiainen, Fortum Growth Oy, POB 100, FI-00048 Fortum, Espoo, Finland.
Email: eero.vartiainen@fortum.com

Abstract

Solar photovoltaics (PV) is already the cheapest form of electricity generation in many countries and market segments. Market prices of PV modules and systems have developed so fast that it is difficult to find reliable up to date public data on real PV capital (CAPEX) and operational expenditures (OPEX) on which to base the levelised cost of electricity (LCOE) calculations. This paper projects the future utility-scale PV LCOE until 2050 in several European countries. It uses the most recent and best available public input data for the PV LCOE calculations and future projections. Utility-scale PV LCOE in 2019 in Europe with 7% nominal weighted average cost of capital (WACC) ranges from 24 €/MWh in Malaga to 42 €/MWh in Helsinki. This is remarkable since the average electricity day-ahead market price in Finland was 47 €/MWh and in Spain 57 €/MWh in 2018. This means that PV is already cheaper than average spot market electricity all over Europe. By 2030, PV LCOE will range from 14 €/MWh in Malaga to 24 €/MWh in Helsinki with 7% nominal WACC. This range will be 9 to 15 €/MWh by 2050, making PV clearly the cheapest form of electricity generation everywhere. Sensitivity analysis shows that apart from location, WACC is the most important input parameter in the calculation of PV LCOE. Increasing nominal WACC from 2 to 10% will double the LCOE. Changes in PV CAPEX and OPEX, learning rates, or market volume growth scenarios have a relatively smaller impact on future PV LCOE.


INSIGHTS

POLICY FORUM

RENEWABLE ENERGY

Terawatt-scale photovoltaics: Transform global energy

Improving costs and scale reflect looming opportunities

By Nancy M. Haegel, Harry Atwater Jr., Teresa Barnes, Christian Breyer, Anthony Burrell, Yet-Ming Chiang, Stefaan De Wolf, Bernhard Dimmler, David Feldman, Stefan Glunz, Jan Christoph Goldschmidt, David Hochschild, Ruben Inzunza, Izumi Kaizuka, Ben Kroposki, Sarah Kurtz, Sylvere Leu, Robert Margolis, Koji Matsubara, Axel Metz, Wyatt K. Metzger, Mahesh Morjaria, Shigeru Niki, Stefan Nowak, Ian Marius Peters, Simon Philipps, Thomas Reindl, Andre Richter, Doug Rose, Keiichiro Sakurai, Rutger Schlatmann, Masahiro Shikano, Wim Sinke, Ron Sinton, B.J. Stanbery, Marko Topic, William Tumas, Yuzuru Ueda, Jao van de Lagemaat, Pierre Verlinden, Matthias Vetter, Emily Warren, Mary Werner, Masafumi Yamaguchi, Andreas W. Bett

Solar energy has the potential to play a central role in the future global energy system because of the scale of the solar resource, its predictability, and its ubiquitous nature. Global installed solar photovoltaic (PV) capacity exceeded 500 GW at the end of 2018, and an estimated additional 500 GW of PV capac- … nitude in a 40-year period (1, 2). Two years ago, we observed that if PV could continue on its historical learning curve, then PV module prices would reach $0.50/W and $0.25/W at a cumulative deployment of 1 and 8 TW, respectively (1). However, by the end of 2018, with only 500 GW of PV installed, the global average module selling price was already …

articles based on real PV cost

Heagel et al. 2019. Science, 364(6443), 836-838

Vartiainen et al., 2019. PIP

Bogdanov et al., 2019. Nature Comms, 10, 1077

IPCC cost for PV

Krey et al., 2019. Energy, 172, 1254-1267

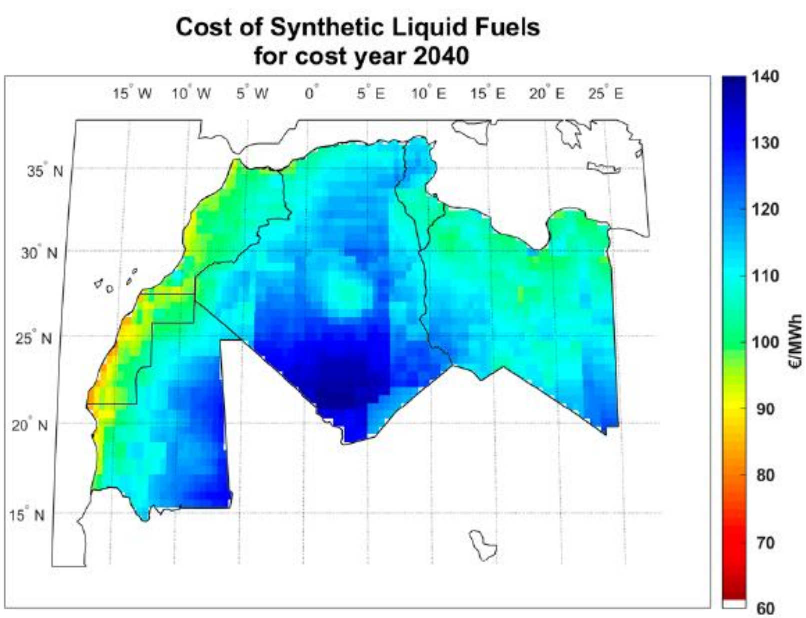
Key insights:

- practically ALL global scenarios dramatically fail in the right role of solar PV
- **fast cost decline of the last 10 years is ignored by IEA, IPCC (based on IAMs), and others**
- climate change mitigation could be more powerful, if major institutions would perform better
- massive and fundamental re-thinking on solar PV plus batteries is needed

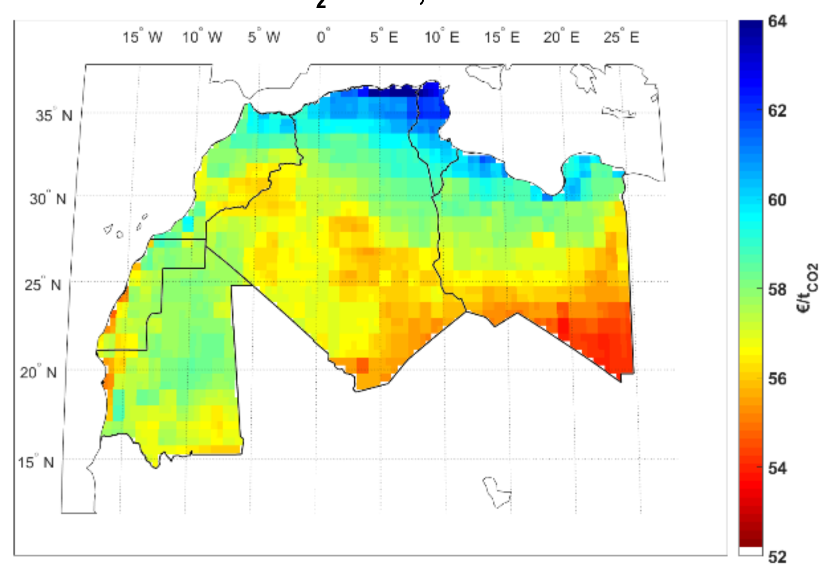
Desertec Reloaded

Key insights:

- power line based Desertec is most likely limited due to lack of relative cost benefits
- excellent solar and very good wind resources enable new opportunities in entire MENA
- Power-to-X for fuels, chemicals, material refining and NETs opens a new door
- **sustainable fuels (Fischer-Tropsch) and chemicals (Methanol, Ammonia) are key**
- negative CO_2 emissions (DACCS) may be a new business opportunity on the horizon



Levelised cost of CO_2 Direct Air Capture (LCOD)
for $PtCO_2$ onsite, in 2050

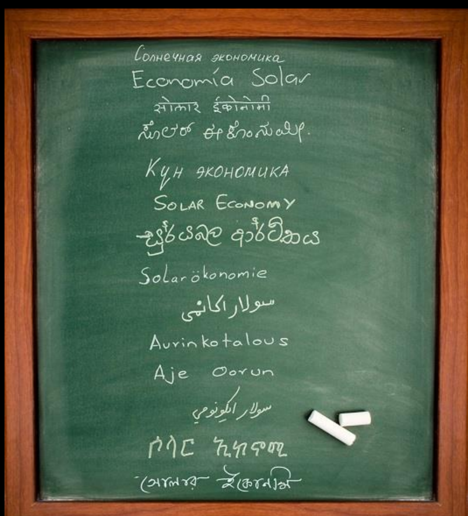


Role of Sector Coupling

Key insights:

- **Power-to-X is the central element of a future energy system, since electricity is the universal platform**
- Electricity-based hydrogen emerges to the 2^{nd} relevant energy carrier (for fuels, chemicals)
- Flexibility in the energy system is key:
  - Supply response (hydro reservoirs, bioenergy) for indirect balancing of solar and wind
  - Grid interconnections, in particular for balancing wind energy
  - Smart demand response: BEV (smart charging, V2G), heat pumps, electrolysers
  - Storage (hours, days, weeks, seasons; electricity, heat, fuels)
- **Cross-border integration may be less important than cross-sectoral cost reduction**
- **Efficient sector coupling substantially reduces curtailment**
- Low-capex batteries and low-capex electrolysers are key for the energy transition
- No flexibility from CO_2 direct air capture units, H_2-to-X synthesis and desalination

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



SCIENTISTS FOR FUTURE

NEO CARBON ENERGY
TRUST IN RENEWABLE.

all publications at: www.researchgate.net/profile/Christian_Breyer
new publications also announced via Twitter: @ChristianOnRE

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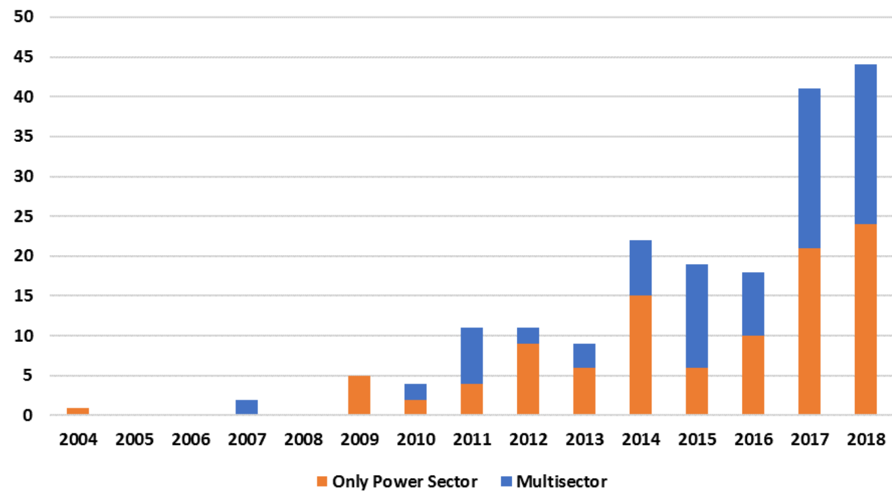
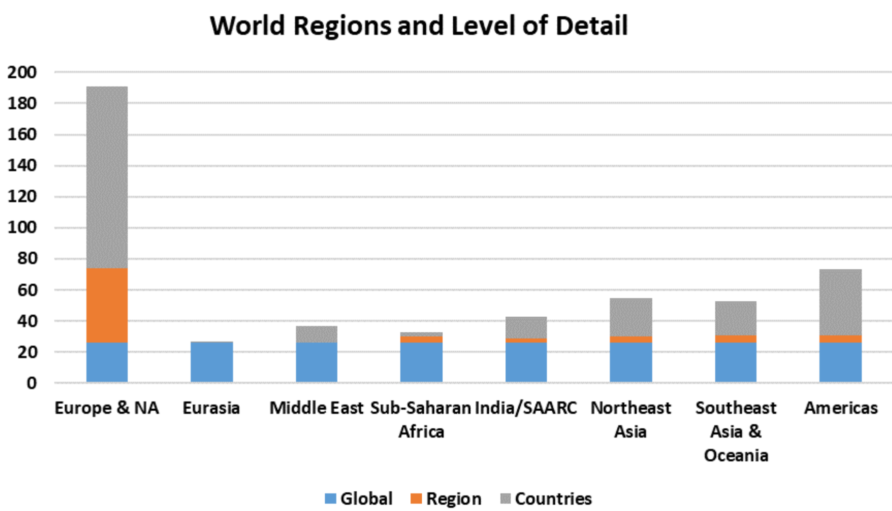
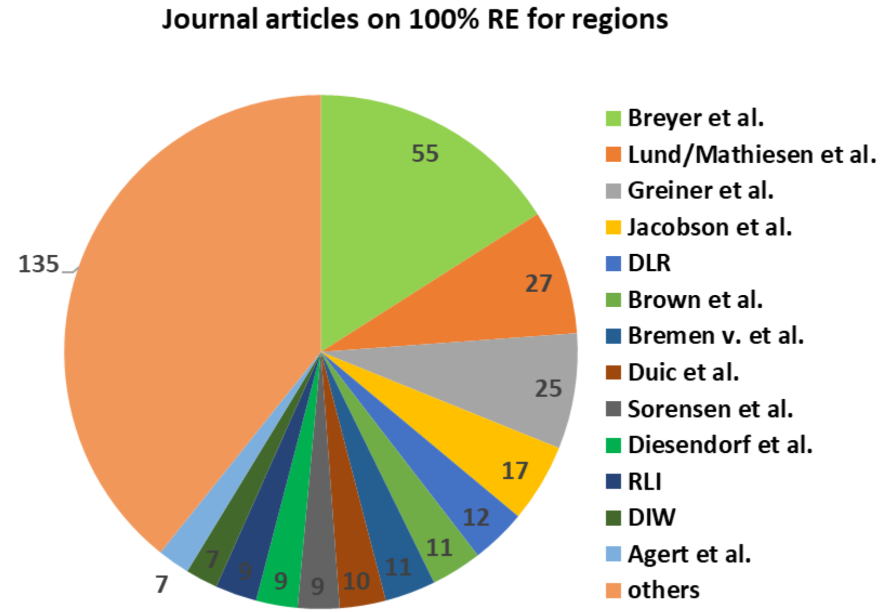
100% RE articles in recent years







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

Key insights:

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