

# Why and how 100% Renewables

APRIL 2019 Funded by DBU STEFANO MERCATO

**GLOBAL ENERGY SYSTEM  
BASED ON 100% RENEWABLE ENERGY**  
Power, Heat, Transport and Desalination Sectors



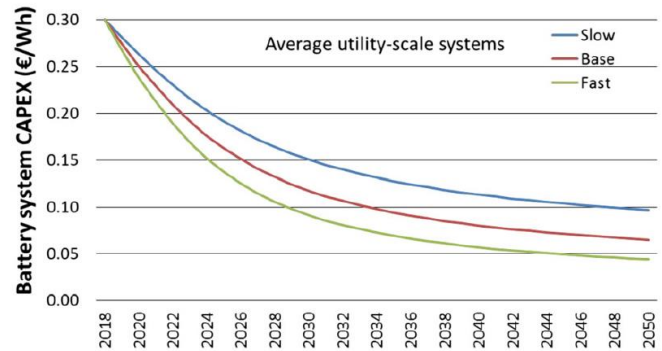
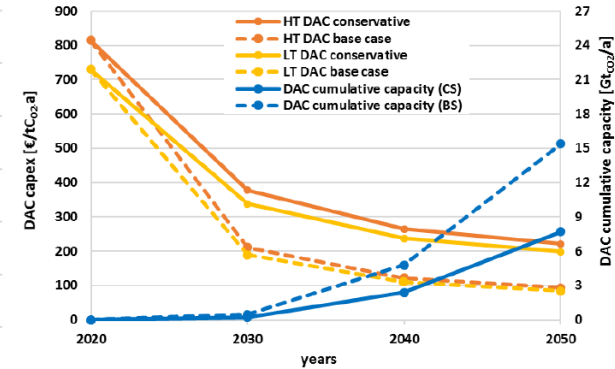
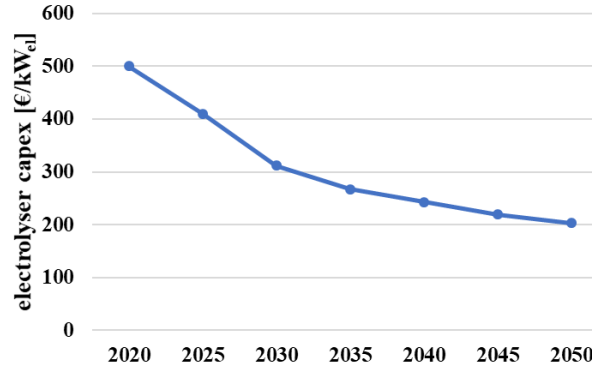
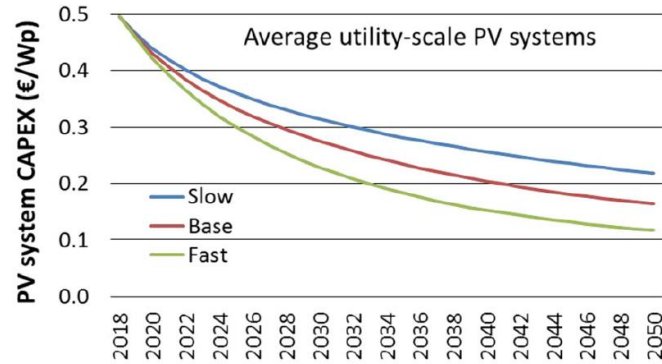
Study by  
LUT University  
ENERGYWATCHGROUP



Open your mind. LUT.  
Lappeenranta University of Technology

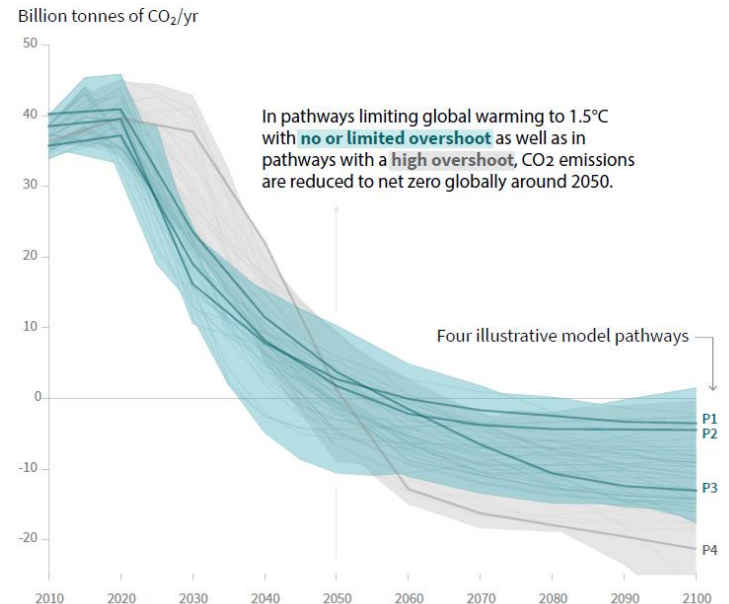
**Christian Breyer**  
**Professor for Solar Economy**  
**10<sup>th</sup> Dii Desert Energy Leadership Summit**  
**Energy Transition: Towards 100% Emission Free Energy System**  
**Berlin, November 26, 2019**

# Key diagrams why there will be massive change



References:  
 PV, battery: [Vartiainen et al., Progress in PV](#)  
 Electrolyser: [LUT model assumptio, Nature](#)  
 CO<sub>2</sub> DAC: [Fasihi et al., J of Cleaner Prod](#)  
 CO<sub>2eq</sub> decline: IPCC SR1.5

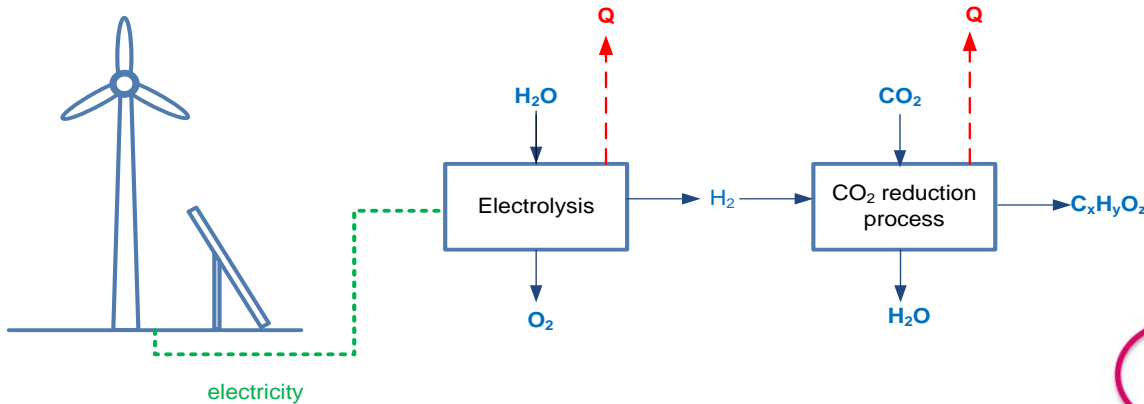
## Global total net CO<sub>2</sub> emissions



## Key insights:

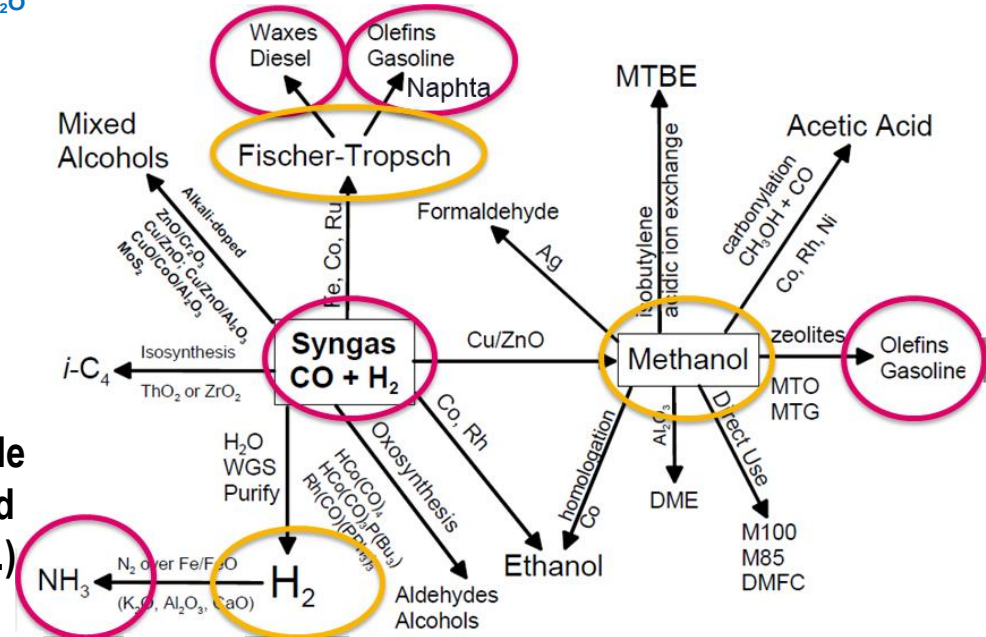
- massive continued cost decline for solar PV, wind, battery, electrolysers, CO<sub>2</sub> DAC
- massive pressure to eliminate all fossil fuels
- massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand

# Power-to-X – covering hydrocarbon demand



## Key insights:

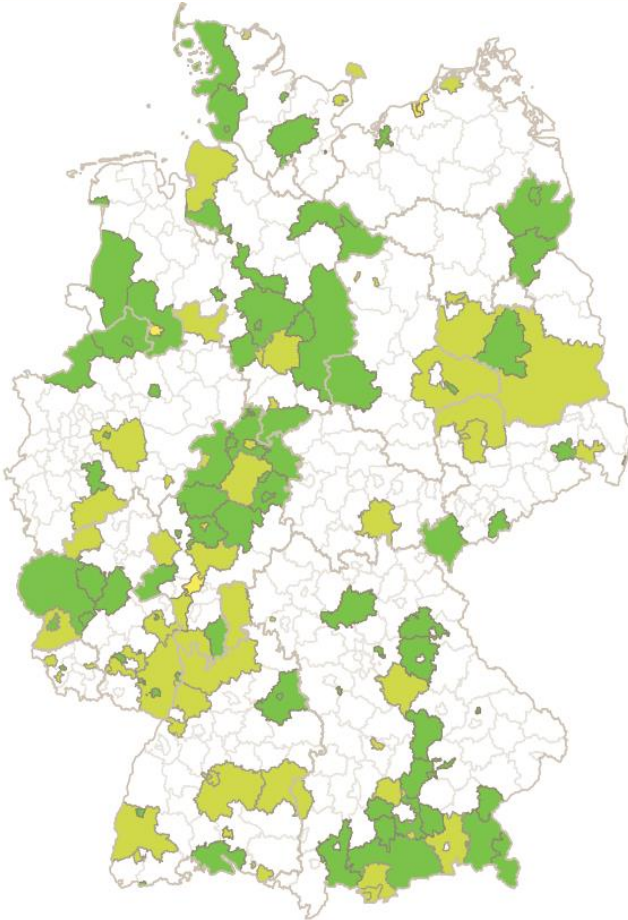
- PtX enables sustainable production of hydrocarbons
- Ingredients: electricity, water, air
- w/o PtX Paris Agreement would be wishful thinking
- Profitability from 2030 onwards
- Flexible seasonal storage option
- Global hydrocarbon downstream infrastructure usable
- Most difficult sectors to decarbonise can be managed with PtX (aviation, chemistry, agriculture, metals, etc.)
- CO<sub>2</sub> direct air capture is part of PtX





# 100% RENEWABLES

[www.go100re.net](http://www.go100re.net)



**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](http://www.wartsila.com), Walmart, ...

[www.100-ee.de/](http://www.100-ee.de/)

# Major milestones on 100% RE research

23 July 2015, Volume 193, Number 6199

SCIENCE

Progress  
Energy Conversion, August 2015, pp. 401-408, doi:10.1016/j.pecs.2015.07.001  
RESEARCH ARTICLE  
SCENARIOS FOR GREENHOUSE WARMING MITIGATION  
NENT SIMONSEN  
Roskilde University, Denmark  
P.O. Box 260, DK-4000 Roskilde, Denmark

## 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



APRIL 2019

Global Energy System  
BASED ON 100% RENEWABLE ENERGY

Power, Heat, Transport and Desalination Systems

Study by  
LUT  
ENERGYWATCHGROUP

## Energy and Resources

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

## Best Practices

By choosing resources according to their properties, for example, in construction, for example, in construction, and materials, one can obtain more energy-efficient buildings. This is the main message of a new report from the Danish Energy Research Centre, which outlines the best practices for energy-efficient buildings. The report is based on a survey of 100 energy-efficient buildings in Denmark. The report shows that the use of renewable energy sources is the most important factor for energy efficiency. Other factors include the use of passive solar energy, energy-efficient windows, and energy-efficient lighting.

## Energy Policy in Industrialized Countries

Associated with the effects of industrial countries is a strong dependence on imported energy. This is a major challenge for industrialized countries. The report discusses the energy policies of industrialized countries and compares them with the energy policies of developing countries. The report shows that industrialized countries have a higher energy consumption per capita than developing countries. This is due to the higher energy efficiency of industrialized countries. The report also discusses the role of energy in the economy and the environment.

## Energy Conversion

The IPCC Working Group II has broadly identified options for mitigation of the greenhouse warming associated with extrapolating the current energy supply structure (1), but it also identifies the absence of full-length-and-lead scenarios that address the technical options for a credible picture of the overall future energy supply. The present contribution is a preliminary attempt at such a picture, based on the assumption that the energy supply structure will be determined by the market, and that the energy supply structure will be determined by the market. The report shows that the energy supply structure will be determined by the market. The report also discusses the role of energy in the economy and the environment.

## 2. BASIC ASSUMPTIONS AND DEMAND MODEL

The scenario year 2050 is used to allow for a complete replacement of all equipment (except some buildings) with the best technology available. This implies a further assumption of high conversion efficiency, called the 'best' technology available (BTA). For all scenarios, the energy supply structure is assumed to be determined by the market. The report shows that the energy supply structure will be determined by the market. The report also discusses the role of energy in the economy and the environment.

## THE CLEAR FOSSIL CO2 SCENARIO

The clear fossil fuel scenario assumes that by 2050, fossil energy will be used without emission of carbon dioxide. This is the clear fossil fuel scenario. The report shows that the energy supply structure will be determined by the market. The report also discusses the role of energy in the economy and the environment.

## Sorensen, 1975

## Sorensen, 1996

## Czisch, 2005

## Greenpeace, 2010

## LUT/EWG, 2019

## Lovins, 1976

## Lund, 2007

## Sternier, 2009

## Jacobson, 2011

## Bogdanov et al. 2019



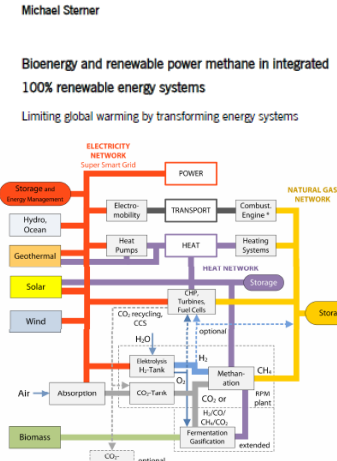
## Energy Strategy: The Road Not Taken?

By Amory B. Lovins

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)  
ScienceDirect  
Energy 120 (2016) 111–114  
ENERGY  
Renewable energy strategies for sustainable development  
Henrik Lund  
Department of Development and Planning, Aalborg University, Høegh-Holten 8, 9220 Aalborg, Denmark

**Abstract**  
This paper discusses the perspective of renewable energy (wind, wave and biomass) in the making of strategies for a sustainable development. Such strategies typically involve three major technological domains: energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy. Conventions, largely renewable energy technologies, have been used to describe the energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy. Conventions, largely renewable energy technologies, have been used to describe the energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy. Conventions, largely renewable energy technologies, have been used to describe the energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy.

**1. Introduction**  
Sustainable energy development strategies typically involve three major technological domains: energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy. Conventions, largely renewable energy technologies, have been used to describe the energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy. Conventions, largely renewable energy technologies, have been used to describe the energy storage, the demand side, efficiency improvements in the energy production, and extraction of fossil fuels by various sources of renewable energy.



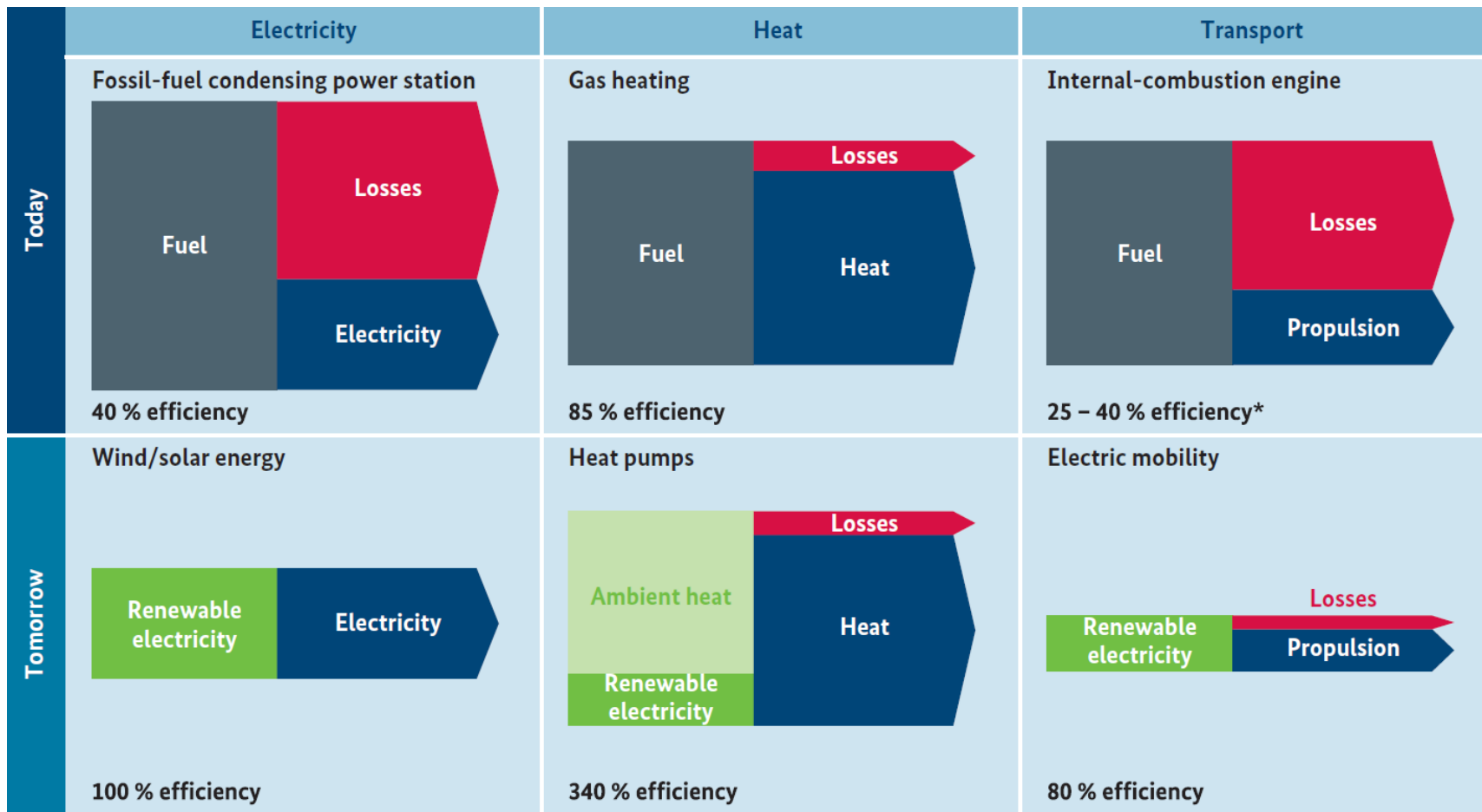
Energy Policy 120 (2016) 111–114  
Contents lists available at ScienceDirect  
Energy Policy  
Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials  
Mark Z. Jacobson<sup>a</sup>, Mark A. Delucchi<sup>b</sup>  
a) Professor of Industrial Engineering, Stanford University, Stanford, CA 94305-5080, USA  
b) Director, Institute for Energy Efficient Buildings and Indoor Climate, ETH Zurich, CH-8092 Zurich, Switzerland

**Introduction**  
This paper addresses the problem of providing all global energy with wind, water, and solar power. The paper discusses the energy resources, quantities, and areas of infrastructure, and materials. The paper shows that it is possible to provide all global energy with wind, water, and solar power. The paper also discusses the role of energy in the economy and the environment.

nature COMMUNICATIONS  
ARTICLE  
Radical transformation pathway towards sustainable electricity via evolutionary steps  
Dimitri Bogdanov<sup>a</sup>, Arnan Tarfaei<sup>a</sup>, Kirilina Sedsova<sup>a</sup>, Aman Agrawal<sup>a</sup>, Michael Orlitzky<sup>a</sup>, Armin Ghalghal<sup>a</sup>, Aydin Sarmadpour<sup>a</sup>, Larissa de Souza Nogueira Sarmadpour<sup>a</sup>, Christian Wehner<sup>a</sup>

A transition towards being entirely sustainable in global energy systems based on renewable energy resources can require several growing blocks to harness society's collectively-generated power intensities, heterogeneous climate conditions, and the increasing of critical energy transitions. However, the optimal structure of future systems and justified transition pathways are still open questions. This research describes a grand, 100% renewable electricity system, which can be achieved by 2050, and the ways required to reach a realistic transition that prevents societal disruption. Modeling results show that a carbon neutral electricity system can be built in all regions of the world, even in an increasingly hostile world. This radical transformation will require stable but revolutionary changes for the next 30 years, and will lead to sustainable and affordable power globally.

# 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 %.

# 100% RE for Power Sector



## ARTICLE

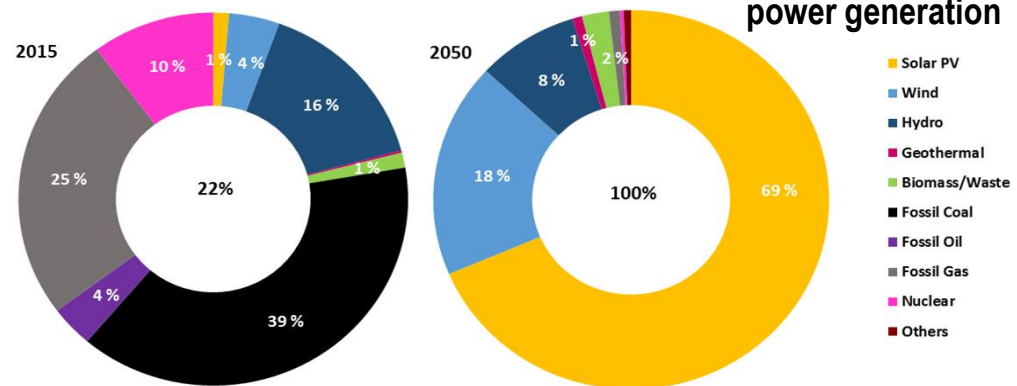
<https://doi.org/10.1038/s41467-019-0885-1>

OPEN

## Radical transformation pathway towards sustainable electricity via evolutionary steps

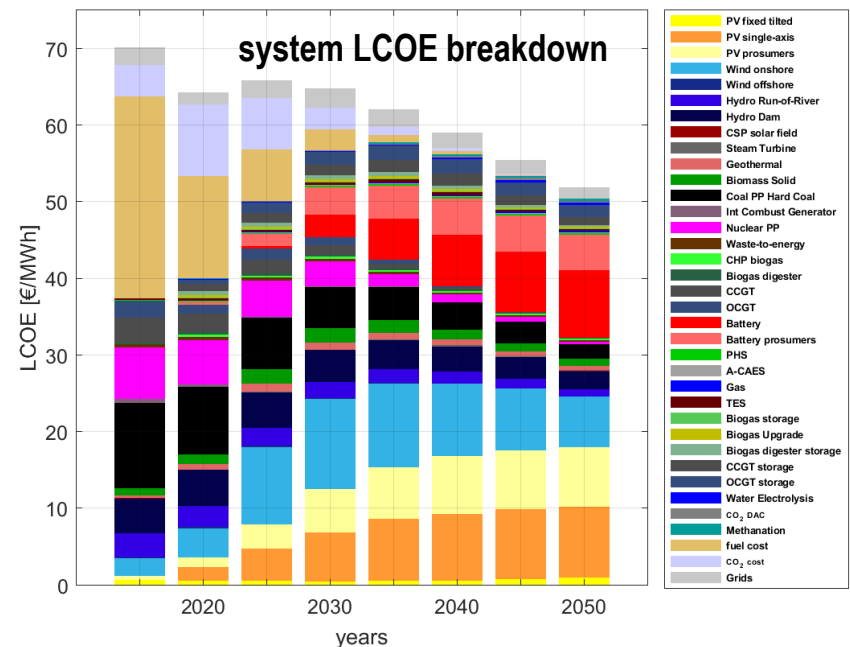
Dmitrii Bogdanov<sup>1</sup>, Javier Farfan<sup>1</sup>, Kristina Sadovskaia<sup>1</sup>, Arman Aghahosseini<sup>1</sup>, Michael Child<sup>1</sup>, Ashish Gulagi<sup>1</sup>, Ayobami Solomon Oyewo<sup>1</sup>, Larissa de Souza Noel Simas Barbosa<sup>2</sup> & Christian Breyer<sup>1</sup>

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.

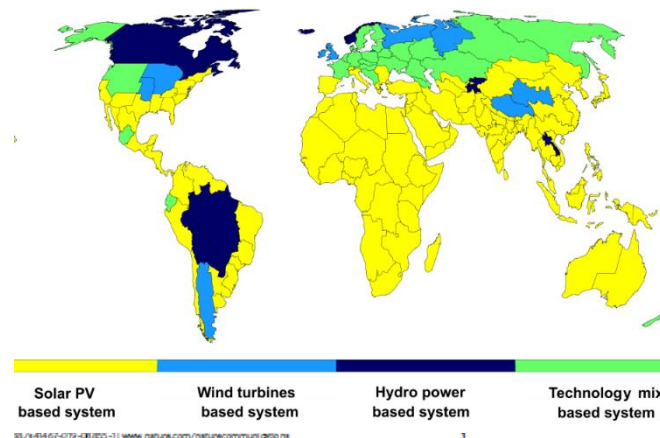


power generation

- Solar PV
- Wind
- Hydro
- Geothermal
- Biomass/Waste
- Fossil Coal
- Fossil Oil
- Fossil Gas
- Nuclear
- Others



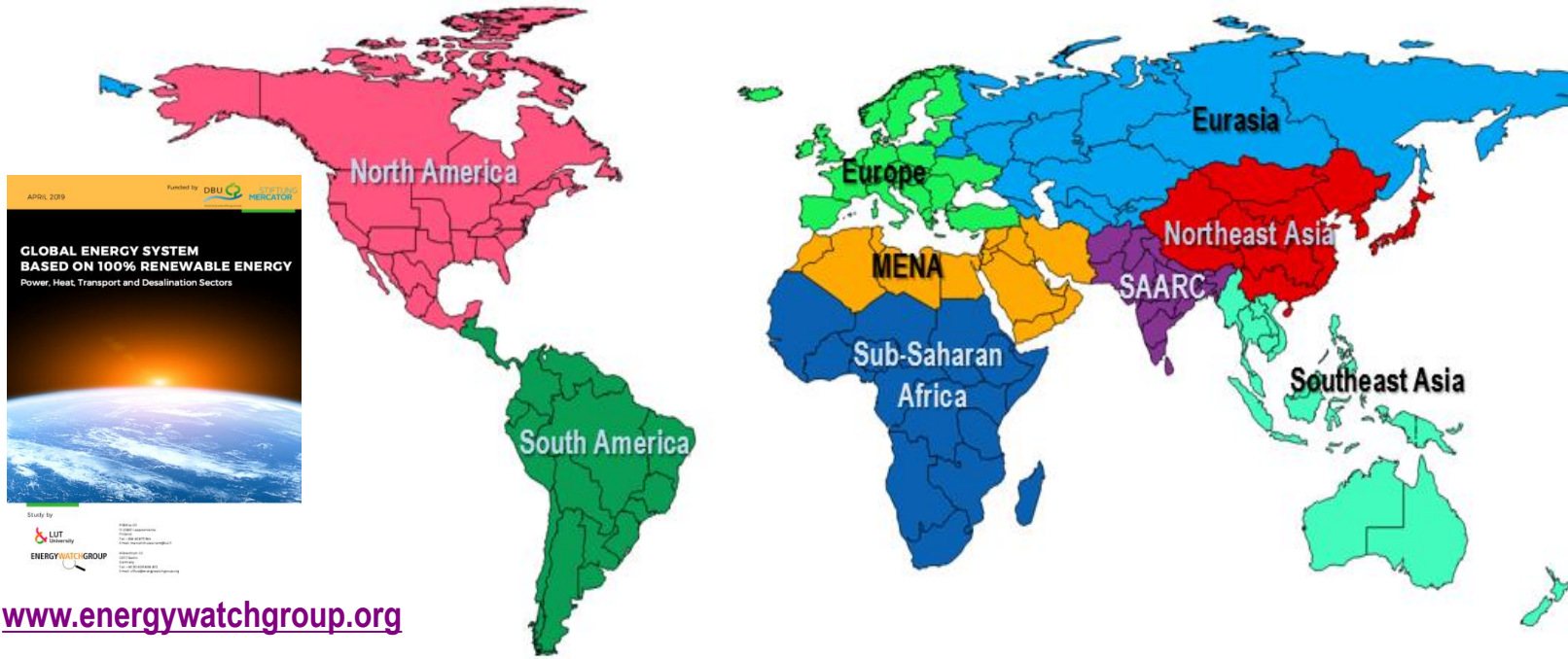
- PV fixed tilted
- PV single-axis
- PV prosumers
- Wind onshore
- Wind offshore
- Hydro Run-of-River
- Hydro Dam
- CSP solar field
- Steam Turbine
- Geothermal
- Biomass Solid
- Coal PP Hard Coal
- Int Combust Generator
- Nuclear PP
- Waste-to-energy
- CHP biogas
- Biogas digester
- CCGT
- CCGT
- Battery
- Battery prosumers
- PHS
- A-CAES
- Gas
- TES
- Biogas storage
- Biogas Upgrade
- Biogas digester storage
- CCGT storage
- CCGT storage
- Water Electrolysis
- CO<sub>2</sub> DAC
- Methanation
- fuel cost
- CO<sub>2</sub> cost
- Grids



10.1038/s41467-019-0885-1 | www.nature.com/naturecommunications



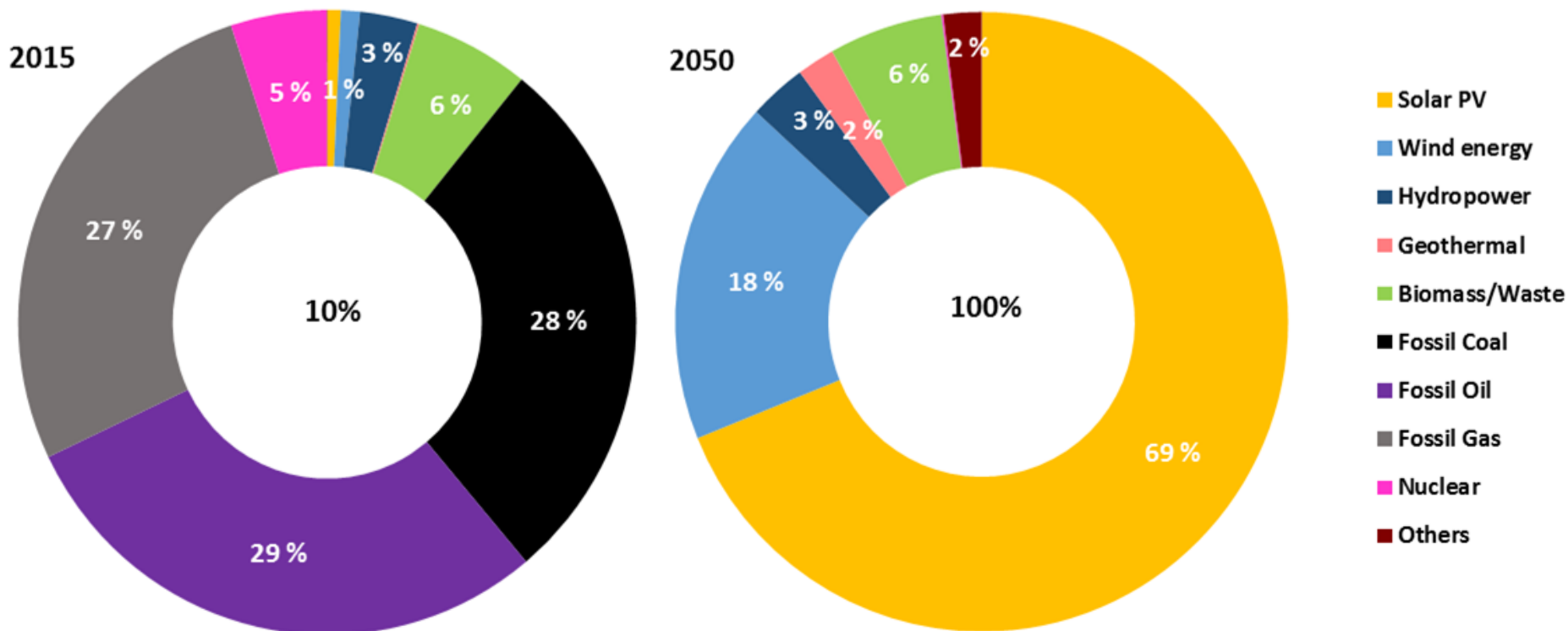
# Global Overview



- 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



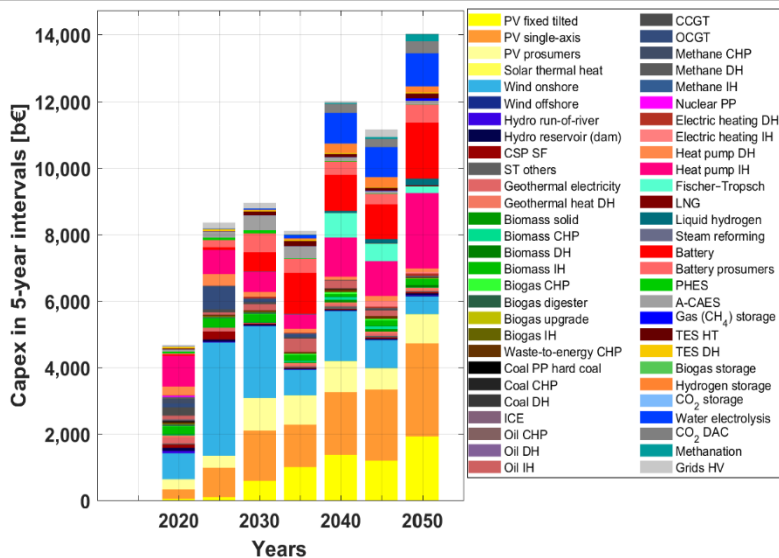
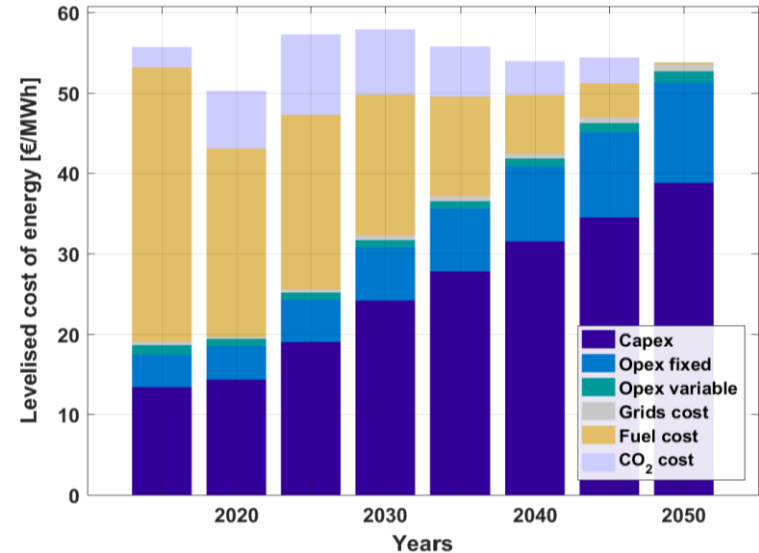
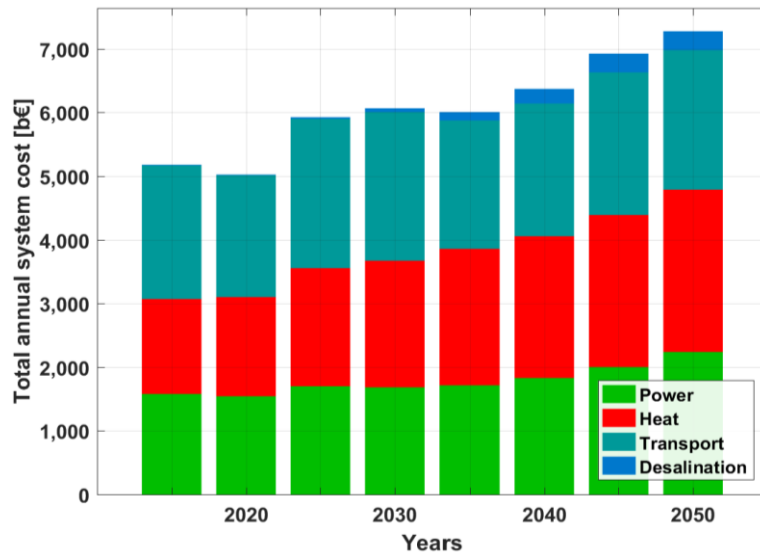
# Total Primary Energy Demand Shares



## 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

# Energy System Cost



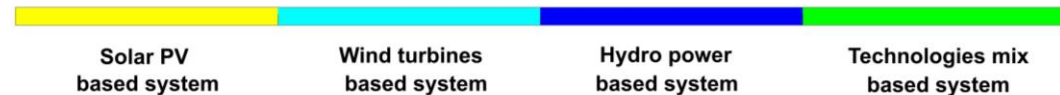
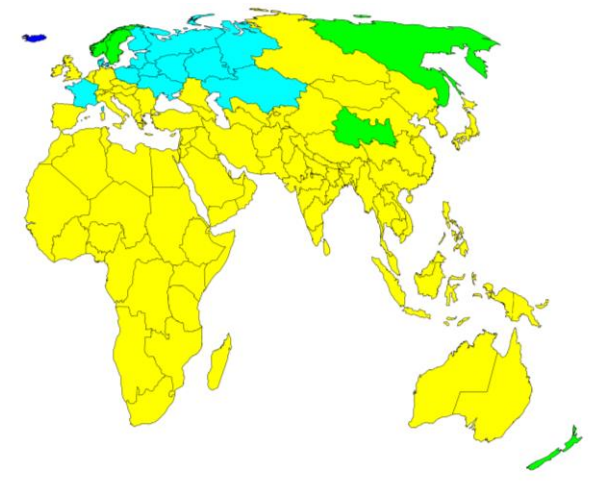
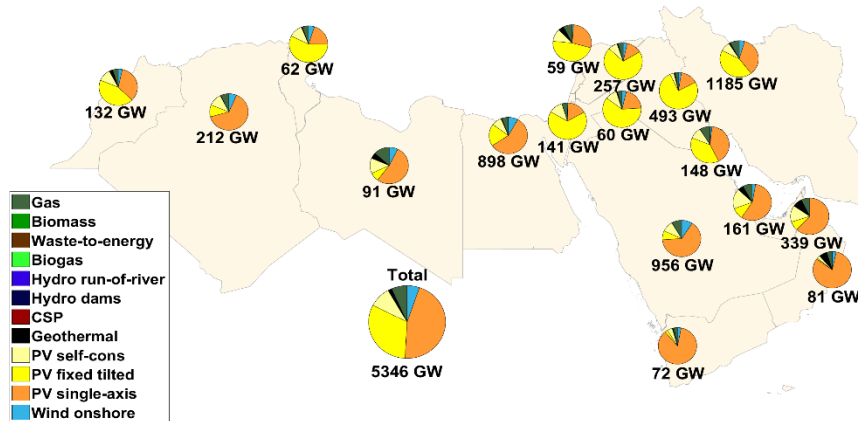
## Key insights:

- 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€

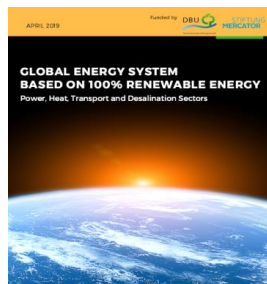


# Regional Variation in 2050

Regional electricity capacities



[www.energywatchgroup.org](http://www.energywatchgroup.org)

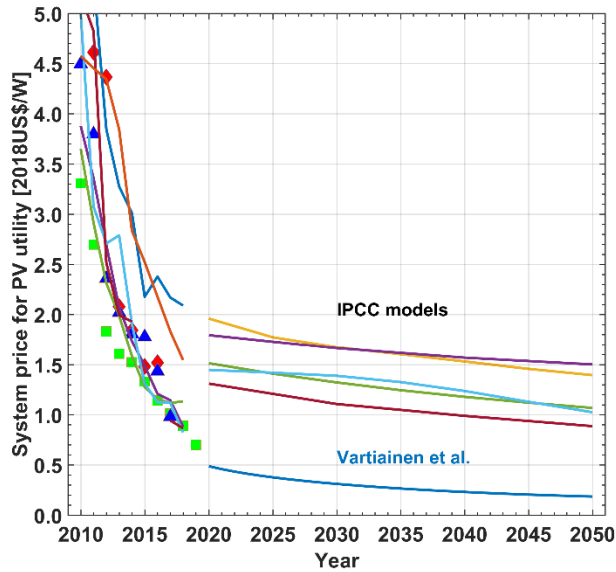


## Key insights:

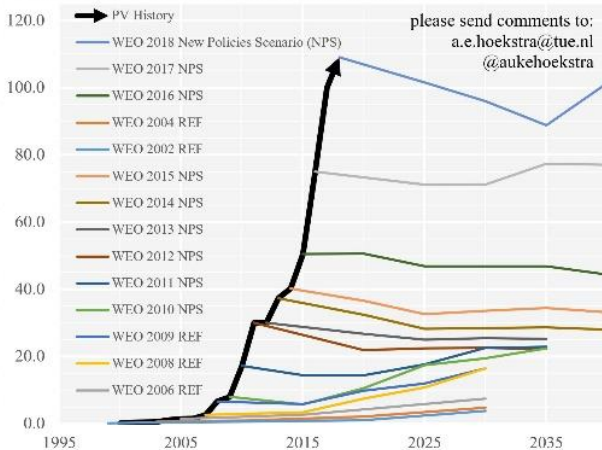
- Solar PV dominates most of regions around the world and particularly in the Sun Belt
- Wind energy drives systems in the Northern and Southern hemispheres with excellent wind conditions and lacking seasonal solar energy
- Some regions are further complemented with hydropower to form a mixed system



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



Annual PV additions: historic data vs IEA WEO predictions  
In GW of added capacity per year - source International Energy Agency - World Energy Outlook



please send comments to:  
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@aukehoekstra

**Models used by IPCC:**  
 POLES MILES  
 GCAM4.2 ADVANCE  
 WITCH GLOBOIM 4.4  
 REMIND 1.6  
 GEM E3

**Historical data:**  
 IEA  
 A. Wang  
 NSR

**IRENA:**  
 China  
 Germany  
 India  
 Italy  
 Japan  
 US

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 EA, 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 with batteries is needed

Received: 8 July 2019 | Revised: 26 July 2019 | Accepted: 5 August 2019  
 DOI: 10.1002/epi.1319

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

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Correspondence: Eero Vartiainen, Forum Growth Oy, P.O. Box 100, FI-00101 Espoo, Finland. Email: eero.vartiainen@fgm.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 expenditure (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 Malta 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 Malta 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 leverage have a relatively smaller impact on future PV LCOE.

INSIGHTS

POLICY FORUM

### Terawatt-scale photovoltaics: Transform global energy

Improving costs and scale reflect looming opportunities

By Nancy M. Haeg, Harry Abuter Jr., Teresa Barnes, Christian Breyer, Anthony Burrill, Yixi Ming Chang, Stefan De Wolf, Bernhard Dismann, David Feldman, Stefan Glens, Joo Chul-Gyeong Goh, David Hothorn, Heli Hovinen, Kari Kallio, Ken Kropp, Sarah Kutz, Sylvère Lee, Robert Margolis, Kofi Mambura, Aid Meit, Wyatt K. Metzger, Malah Madhala, Mogens Nils, Sofia Novak, Sam Nouri Peters, Steven Phillips, Thomas Reddy, Andre Richter, Dong Sun, Seidman Sabara, Roger Schickman, Masahiro Shimizu, Wim Sijm, Ron Shinar, J. J. Van der Stoep, Marlon Trigo, William Tress, Yusef Ueda, Joo Won Lee, August, Pierre Vanlaere, Matthias Verter, Holly Warren, Mary Worsar, Masaharu Yamaguchi, Andrew W. Bell

**Abstract**  
 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 on an estimated 500 GW at the end of 2018, and an ordered additional 500 GW of PV capacity is projected to be installed by 2022–2023, bringing us into the era of TW-scale PV. Given the speed of change in the PV industry, both in terms of continued dramatic cost decreases and manufacturing-scale increases, the growth toward TW-scale PV has caught many observers, including many of us (1), by surprise. Two years ago, we focused on the challenges of achieving 3 to 10 TW of PV by 2030. Here, we envision a future with >10 TW of PV by 2030 and 30 to 50 TW by 2050, providing a majority of global energy. PV would be not just a key contributor to electricity generation but also a central contributor to all aspects of the global energy system. We discuss implications and challenges for complementary technologies (i.e., energy storage, power-to-gas, liquid fuels, desalination, grid integration, and multiple sector electrification) and summarize what is needed in research in PV performance, reliability, manufacturing, and recycling.

**DECREASING COSTS, INCREASING ELECTRICITY**  
 Global average PV module selling prices have decreased by more than two orders of magnitude in the last 10 years (2). In California, the fraction of electricity generated from combined utility and residential PV increased from less than 1% in 2010 to ~1% in 2018 (3). These data plus lead to questions about the next stages of growth, with critical focusing on challenges related to the variable nature of PV. Some research suggested that with current electricity generation operating practices, the value of PV will decrease as PV penetration increases. More recent analysis has identified how changes in operational practices of the existing generation fleet and PV systems themselves could enable much higher levels of PV in the electricity generation system. California is already implementing some of these operational practices, enabling an unmet utility-scale PV plant curtailment to stabilize around 1 to 2%. However, if renewable electricity generation continues to increase rapidly without substantial storage and/or load shifting, then curtailment could increase. The challenge is to develop low-cost operational strategies and complementary technologies to accommodate the growing fraction of renewable generation.

Electricity demand could be increased through increased electrification (see the second figure, gray shaded area), including in heating, transportation, desalination, and industrial sectors. A growing body of research concludes that decarbonization of electricity followed by electrification of almost all parts of the energy system is a least-cost pathway for a low-carbon sustainable energy system, with many possible scenarios for PV growth (e.g., see the second figure, solid blue curves). But there are multiple ways to transform the global energy system. For example, PV operates at a much lower fraction of the total generation mix in the World Energy Outlook 2018 Sustainable Development Scenario, in which power generation is largely decarbonized (see the second figure, blue dashed box).

**THE TOTAL ENERGY ECONOMY**  
 Tracking a minority share of solar in the total energy economy presents opportunities and challenges at the system level and for research in technologies in related sectors.

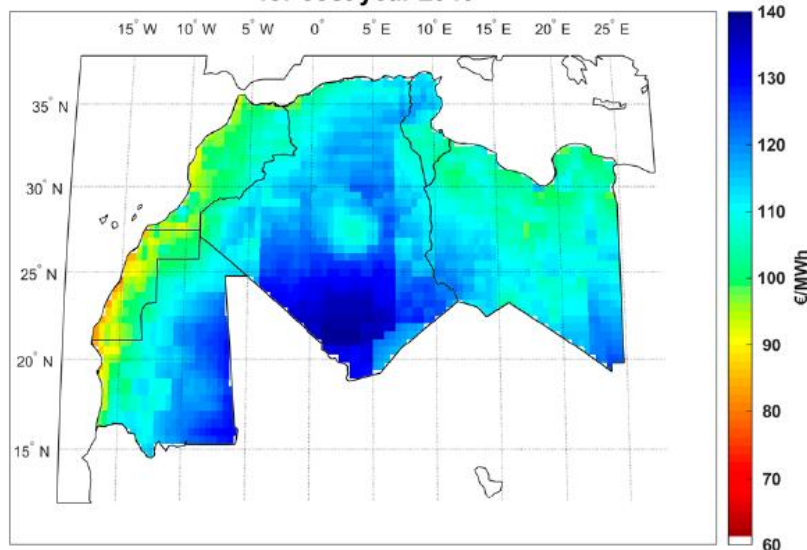
**Grid integration**  
 Geographic and technology diversity and managing the supply-demand balance over large geographic footprints could help smooth some of the variability of solar resources, especially in locations where nighttime wind electricity can complement daytime solar electricity and where high-voltage transmission lines can be available. Such approaches may be especially effective in managing short-term variability, improved solar forecasting already helps to reduce uncertainty in predicting solar output (4).

Increasing the flexibility of the remaining generation portfolio would be helpful. First-

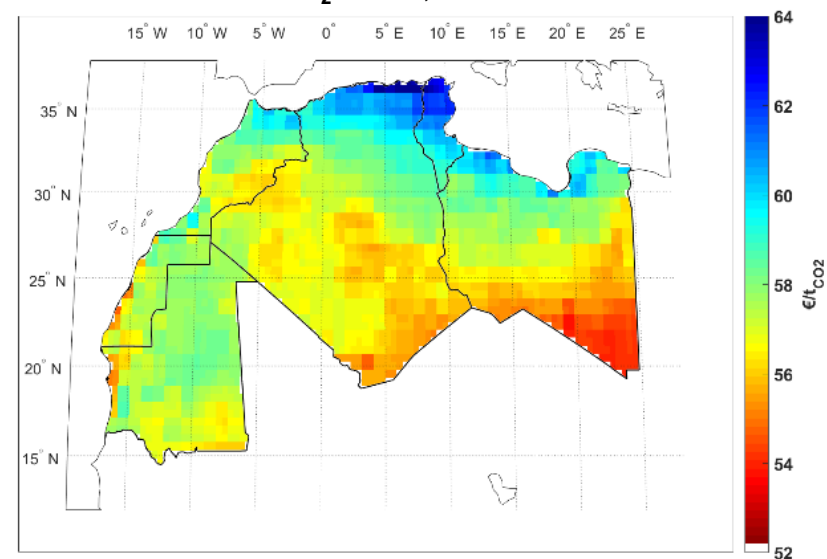
## Key insights:

- 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<sub>2</sub> emissions (DACCS) may be a new business opportunity on the horizon

Cost of Synthetic Liquid Fuels  
for cost year 2040



Levelised cost of CO<sub>2</sub> Direct Air Capture (LCOD)  
for PtCO<sub>2</sub> onsite, in 2050

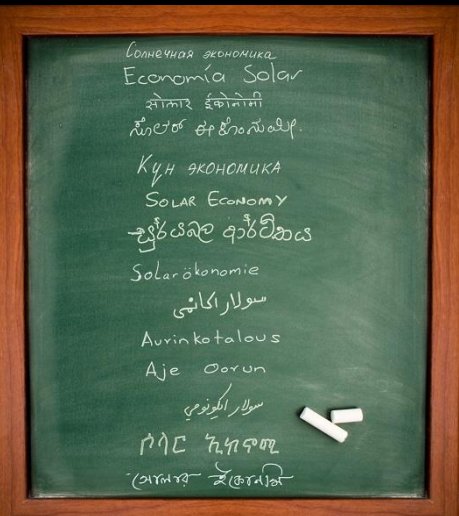


## Key insights:

- **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<sup>nd</sup> 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<sub>2</sub> direct air capture units, H<sub>2</sub>-to-X synthesis and desalination



# Thank you for your attention ... ... and to the team!



**NEO  
CARBON  
ENERGY**

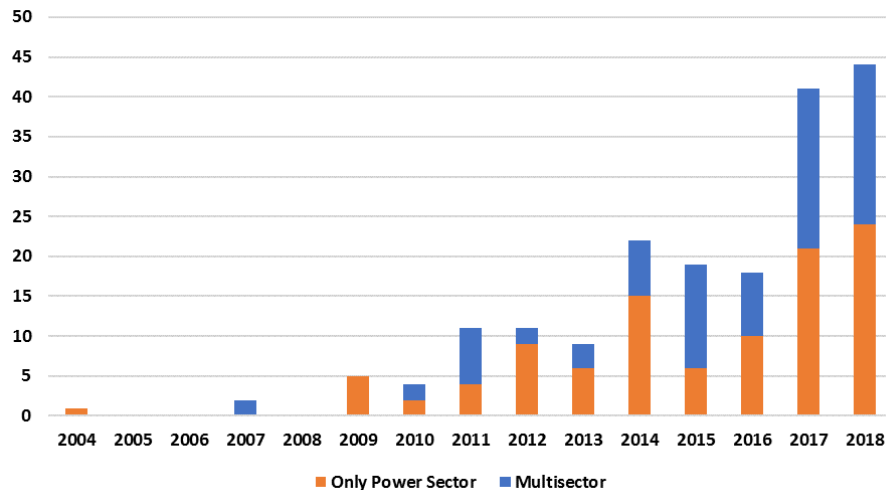
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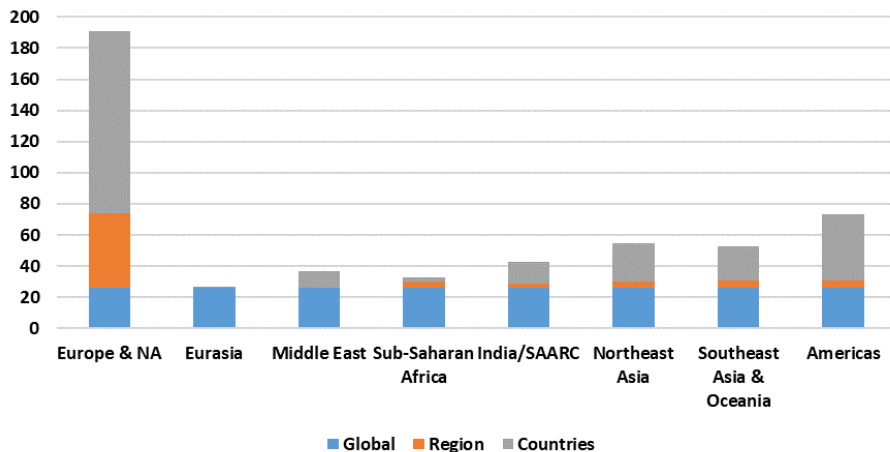


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# 100% RE articles in recent years

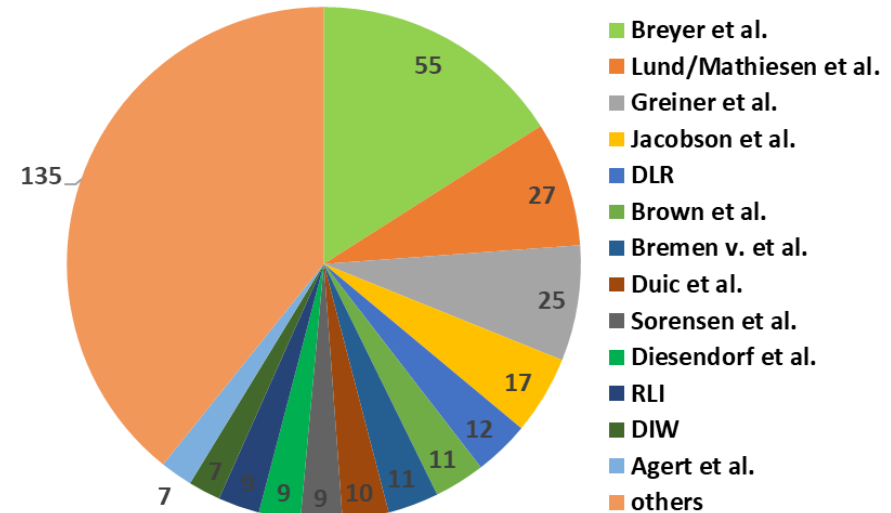


## World Regions and Level of Detail



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

## Journal articles on 100% RE for regions



## 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)