

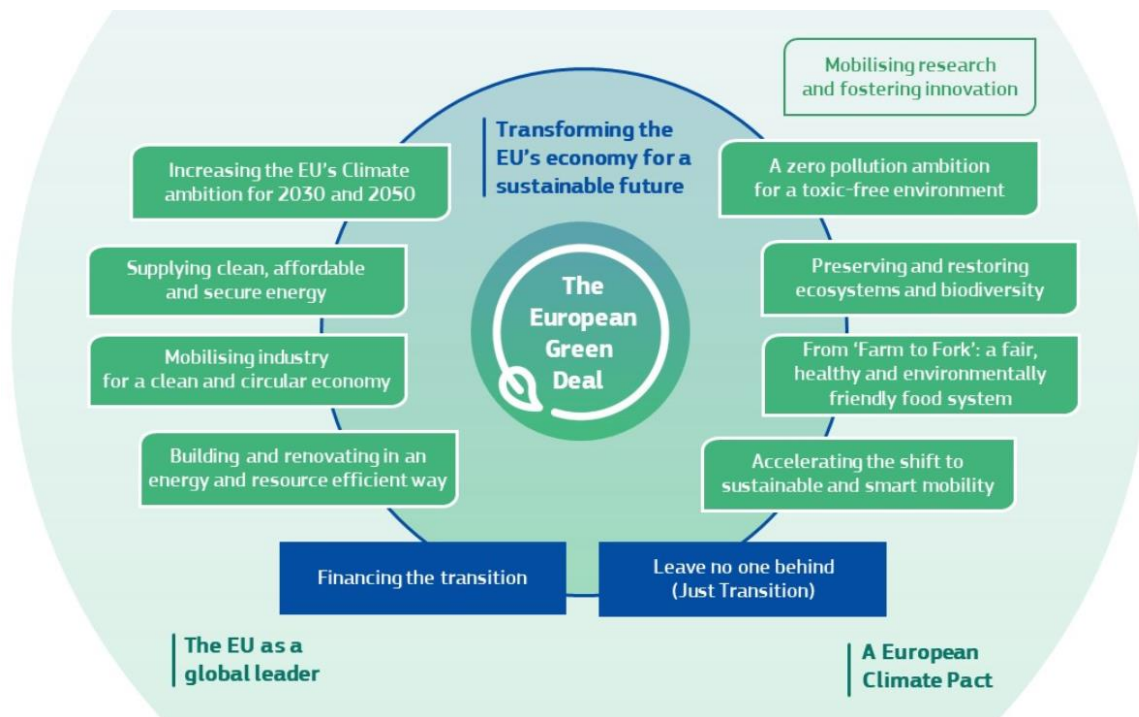
# Insights from Long-Term Energy Scenarios: The 100% Renewable Energy Opportunity



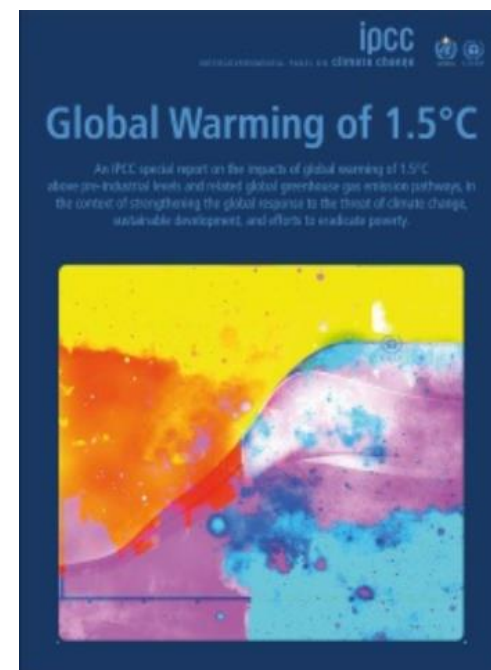
Open your mind. LUT.  
Lappeenranta University of Technology

Christian Breyer  
LUT University, Finland  
IAEE webinar  
November 23, 2020

## European Green Deal



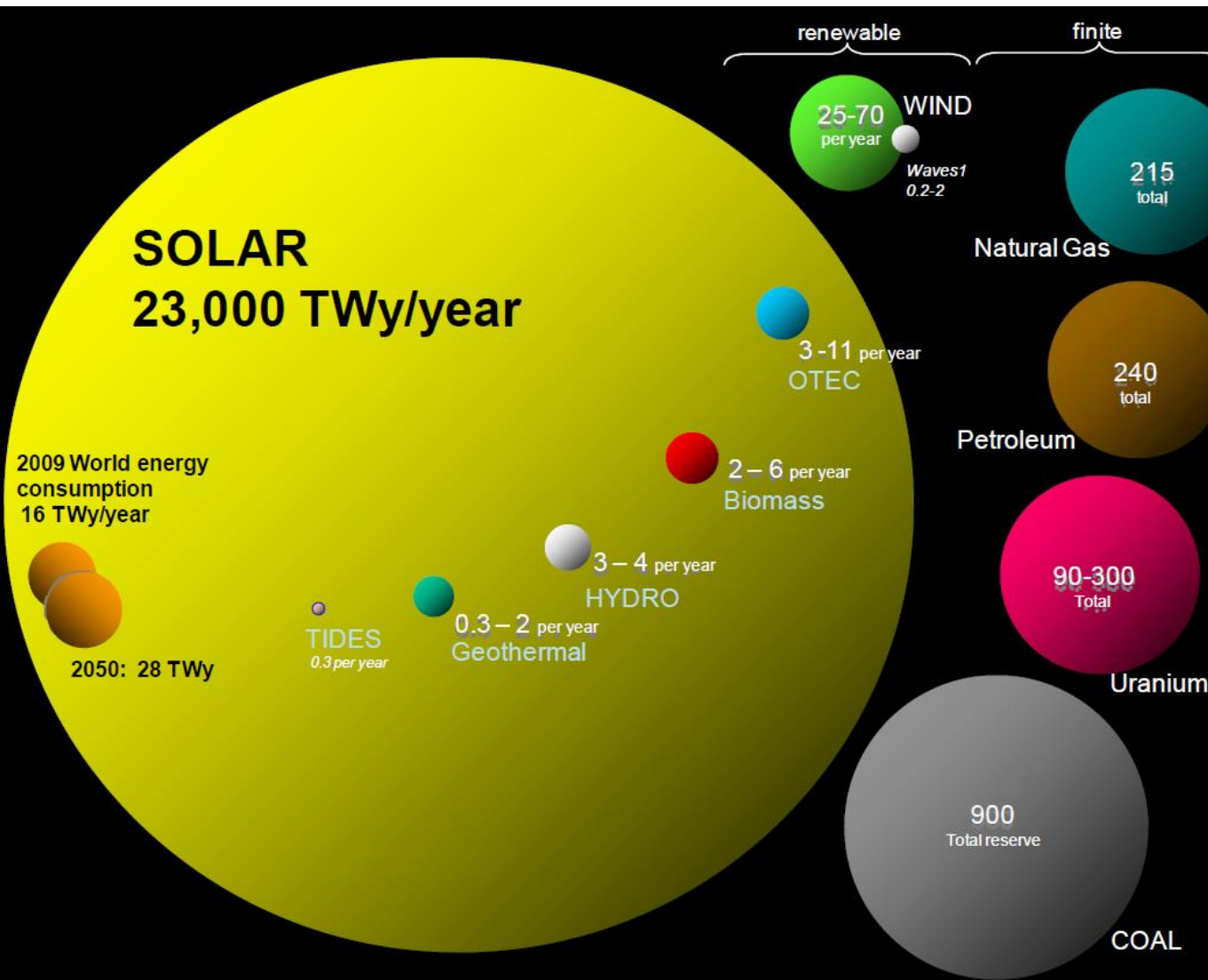
## Paris Agreement ("well below 2°C")



### 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



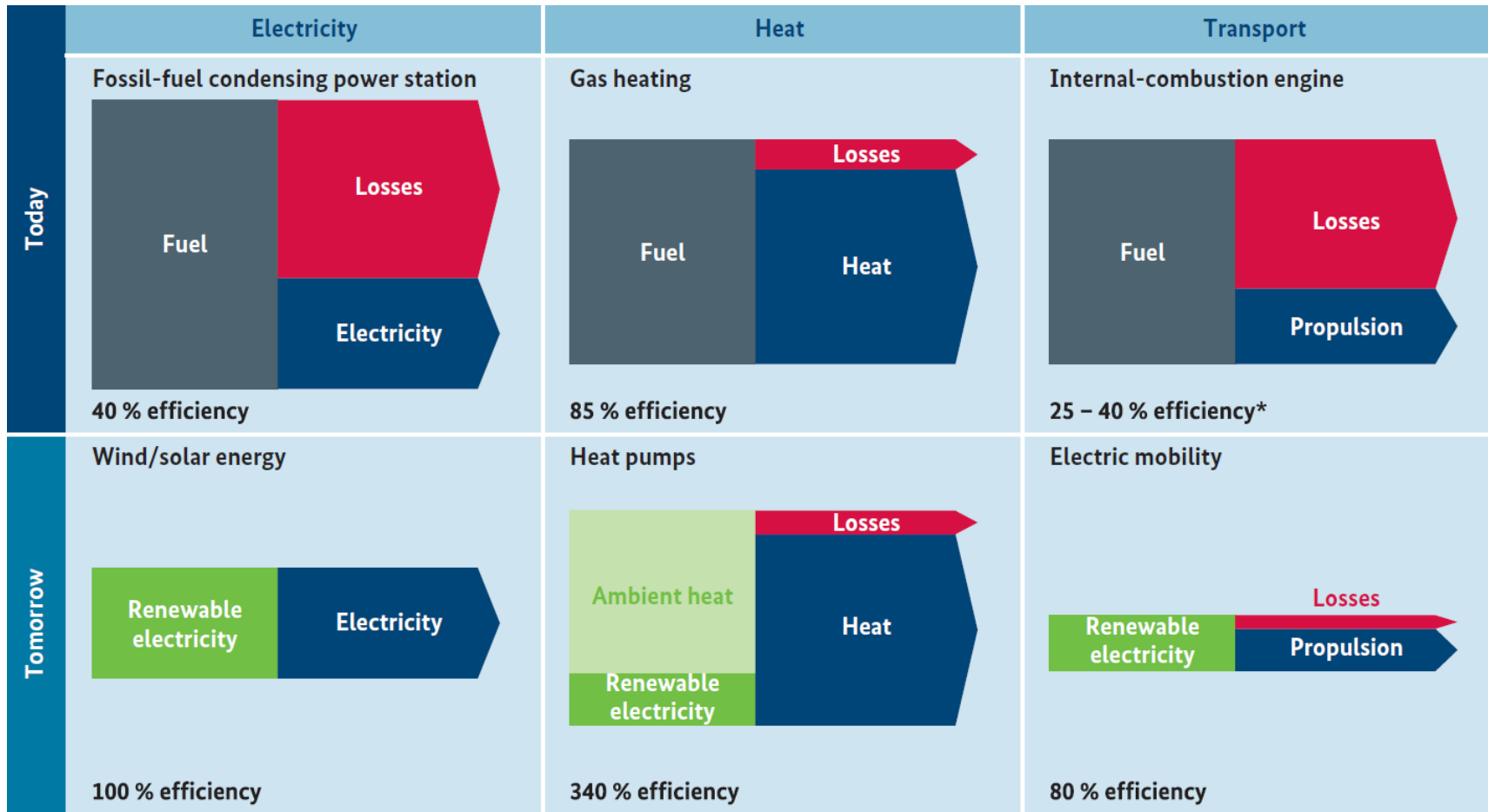
## Key insights:

- 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

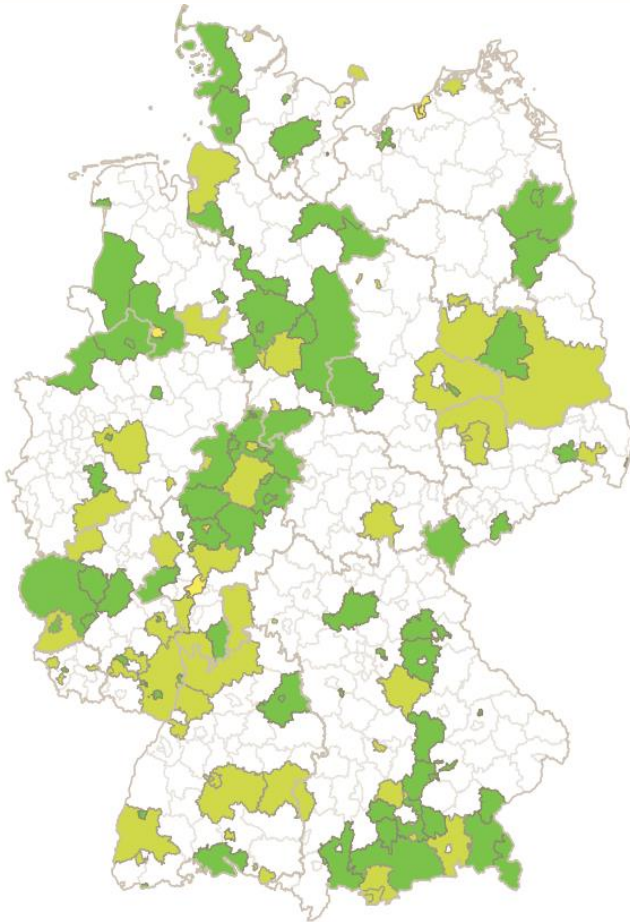
# Key Rationale for Electrification: Efficiency



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

# 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, ...

**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.waertsila.com), Walmart, ...

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

# Major Milestones on 100% RE Research

23 July 2015, Volume 191, Number 4199

SCIENCE

Progress

Energy Conversion, Storage, and Distribution

SCENARIOS FOR GREENHOUSE WARMING MITIGATION

ROBERT SMITHSON

Rothschilde University, Jerusalem 2  
P.O. Box 260, Tel-Aviv 61000, Israel

Energy and Resources

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

Robert Smithson

By choosing renewable sources such as wind, solar, and hydro, Denmark can meet its energy needs by the year 2050. The plan is outlined according to which solar and wind energy would supply Denmark's needs by the year 2050.

In its own right, the earth receives an immense amount of energy from the sun, and from other natural sources. This energy is available in a wide variety of forms, such as wind, solar, and hydro. The energy is available in a wide variety of forms, such as wind, solar, and hydro.

It is not the total amount of energy that is available, but the amount that is available in a form that is useful to us. The amount of energy that is available in a form that is useful to us is limited by the efficiency of the conversion process.

The IPCC Working Group II has broadly classified options for mitigation of the greenhouse warming associated with anthropogenic climate change. The options are divided into three categories: energy efficiency, energy conservation, and energy substitution.

2. BASIC ASSUMPTIONS AND DEMAND MODEL  
The scenario year 2050 is used to allow for a complete replacement of all fossil-fueled energy (except some hydro) with renewable energy. This requires a number of assumptions: high conversion efficiency, and the full conversion of energy into the service or product demanded. For all the scenarios, Table 1 gives the assumptions regarding population and land-use energy demand. The population conversion from the World Bank (1) and the 2050 values compared to the assumptions of high efficiency and renewable energy. The land-use energy demand is the maximum amount of energy that could be derived from the service actually demanded, using the best method and conversion equipment known today. The goal, which is 2050 has been achieved in all regions, is based on a basic and annual needs analysis made previously (1). It assumes that the Earth will be populated by a mixture of advanced and nonadvanced cities.

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

## Scenarien zur zukünftigen Stromversorgung

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



vorgelegt von: Dipl.-Phys. Gregor Czisch

Energy Revolution  
A Sustainable World Energy Outlook

IREC  
GREENPACK

APRIL 2019

DBU  
STATISTICS  
MERCATOR

## GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY

Power, Heat, Transport and Desalination Sectors

Study by  
LUT  
ENERGYMATCHGROUP

Sørensen, 1975

Sørensen, 1996

Czisch, 2005

Greenpeace, 2010

LUT/EWG, 2019

Lovins, 1976

Lund, 2007

Stern, 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

Renewable energy strategies for sustainable development

Henrik Lund\*

Department of Engineering and Physics, Aalborg University, Høegh-Holten 8, 9220 Aalborg, Denmark

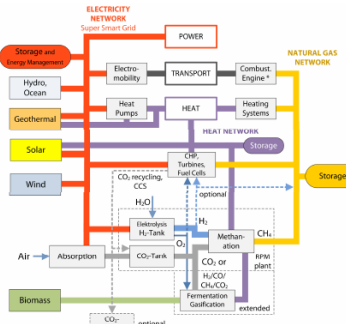
Abstract

This paper discusses the perspective of renewable energy (wind, wave and biomass) in the making of storage for a sustainable electricity system. Such storage options include pumped hydroelectric storage, energy storage in the form of compressed air, hydrogen, and other energy storage technologies. The paper discusses the perspective of renewable energy (wind, wave and biomass) in the making of storage for a sustainable electricity system.

Michael Sterner

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

Limiting global warming by transforming energy systems



Energy Policy 2011, 37(10):1188-1208

Contents lists available at ScienceDirect

Energy Policy

Journal homepage: [www.elsevier.com/locate/energy](http://www.elsevier.com/locate/energy)

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†

Abstract

This paper discusses the perspective of renewable energy (wind, wave and biomass) in the making of storage for a sustainable electricity system.

nature COMMUNICATIONS

ARTICLE OPEN

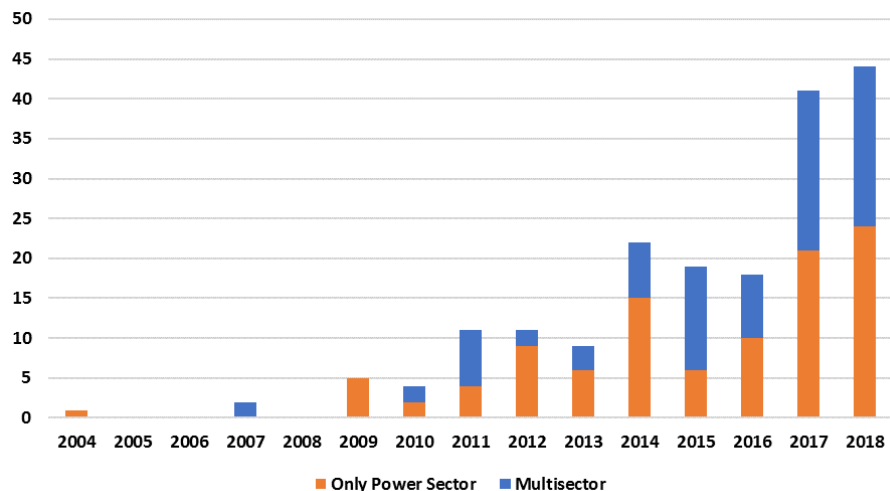
## Radical transformation pathway towards sustainable electricity via evolutionary steps

Denis Bogdanov\*, Armin Farber†, Kirilina Sedsova†, Aman Agrawal†, Michael Oden†, Armin Gatz†, Aptim Sorenson†, Larissa de Souza, Neal Sims, Robert†, & Christian Breyer†

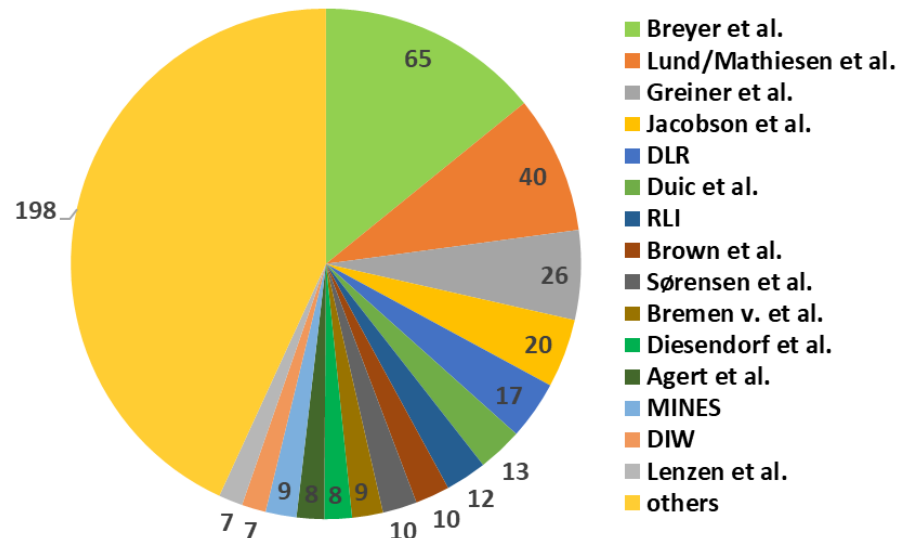
Abstract

This paper discusses the perspective of renewable energy (wind, wave and biomass) in the making of storage for a sustainable electricity system.

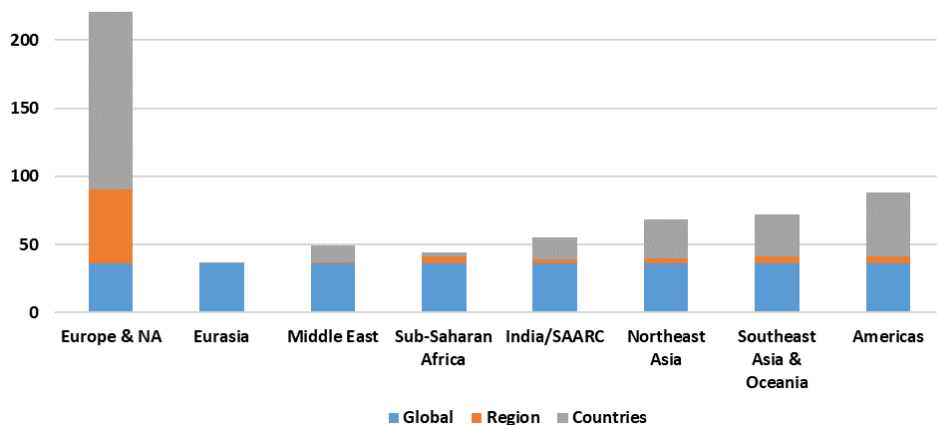
# 100% RE Articles in recent Years



Journal articles on 100% RE for regions



World Regions and Level of Detail

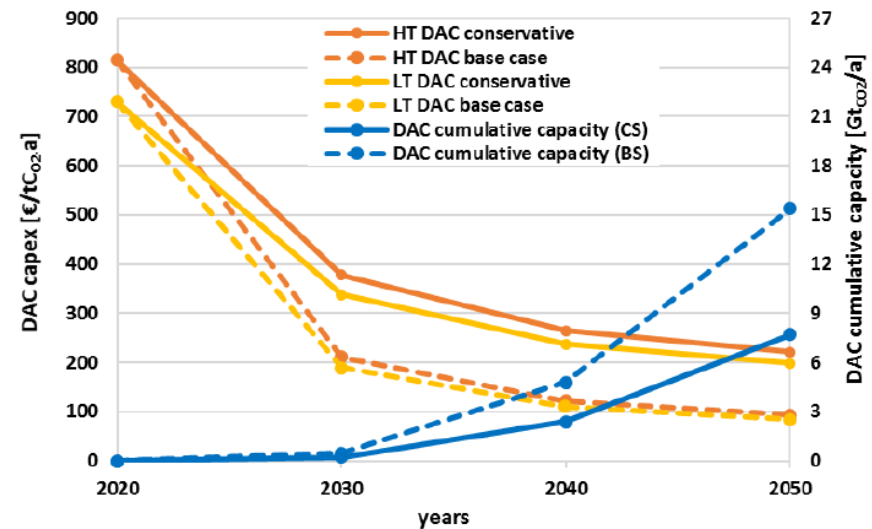
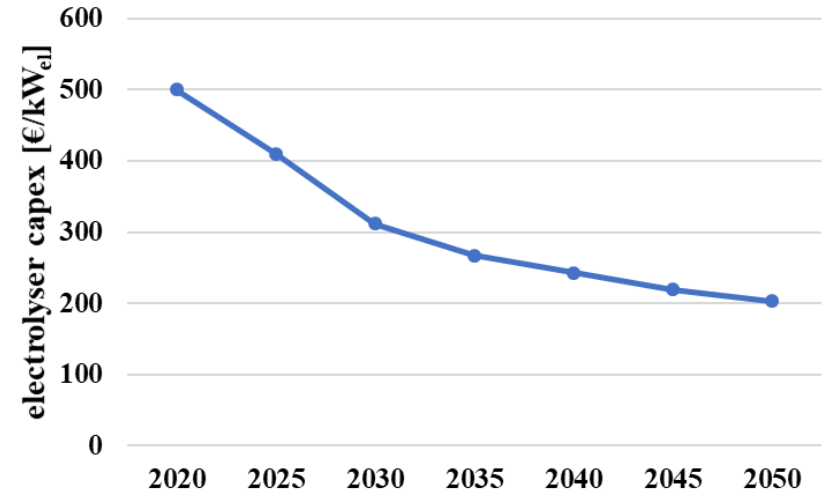
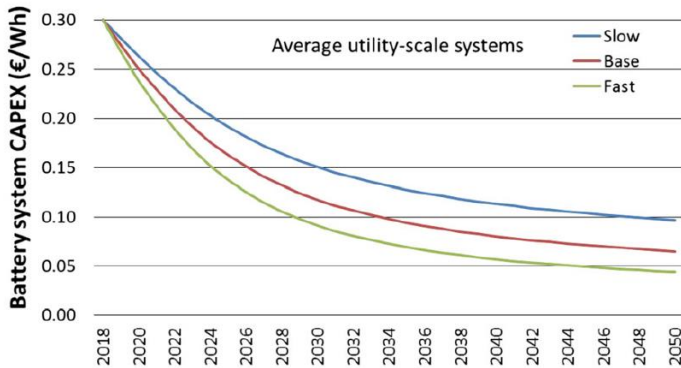
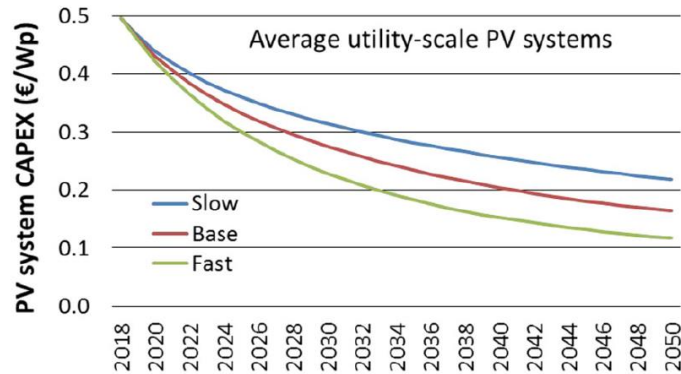


source: [Hansen, Breyer, Lund H., 2019. Energy, 175, 471-480](#)

## 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)

# Key Diagrams for massive PV induced Change



## Key insights:

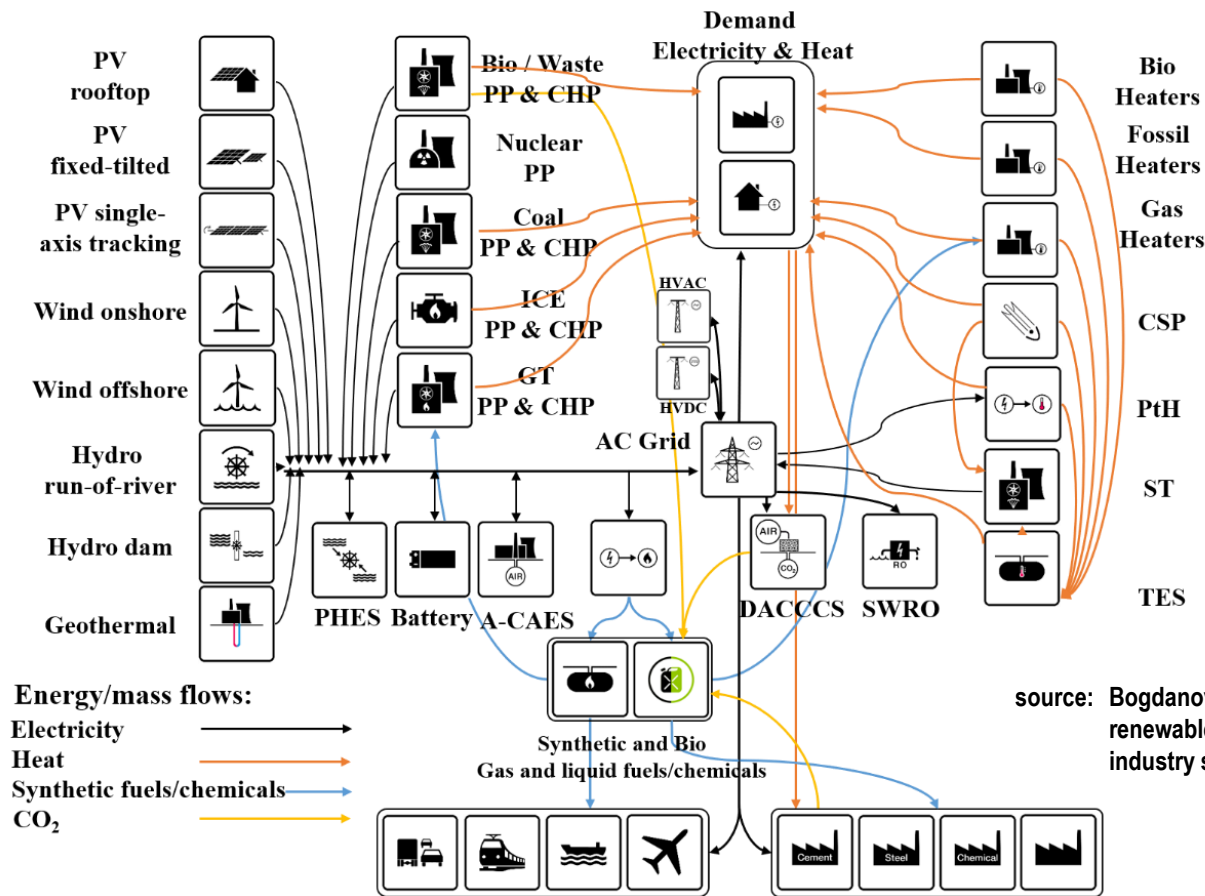
- massive continued cost decline for solar PV, wind, battery, electrolysers, CO<sub>2</sub> DAC
- massive pressure to eliminate all fossil fuels
- massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand

## 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](#)



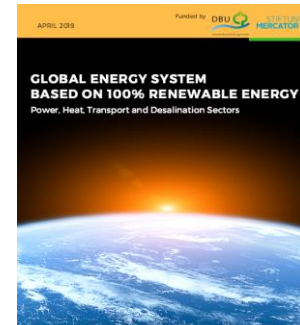
# LUT Energy System Transition Model



## recent reports



[link to report](#)



[link to report](#)

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

## Key features:

- **full hourly resolution**, applied in global-local studies, comprising about 120 technologies
- used for several major reports, in about 50 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (mobility, heat, fuels, chemicals, desalinated water, CO<sub>2</sub>)

# Renewables for the Power Sector



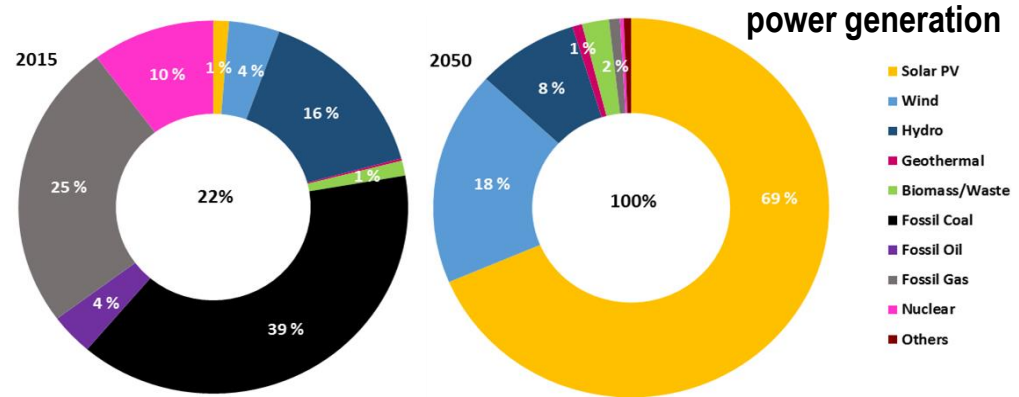
ARTICLE

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

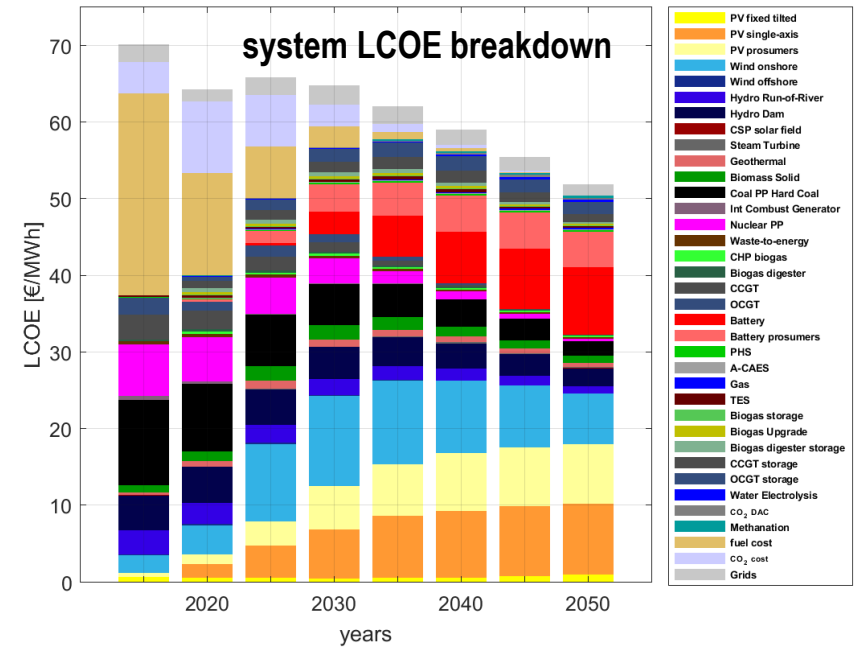
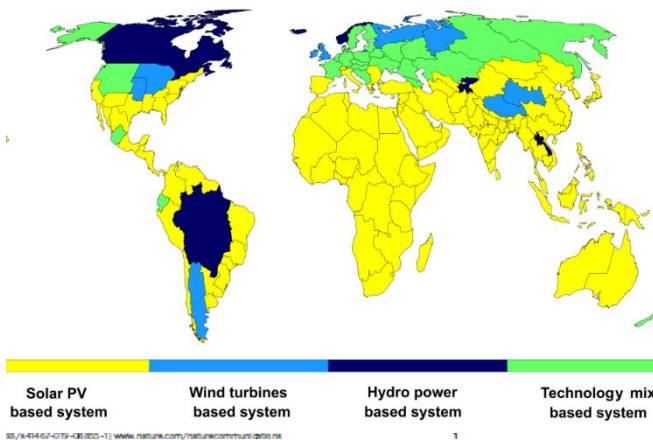
## Radical transformation pathway towards sustainable electricity via evolutionary steps

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>

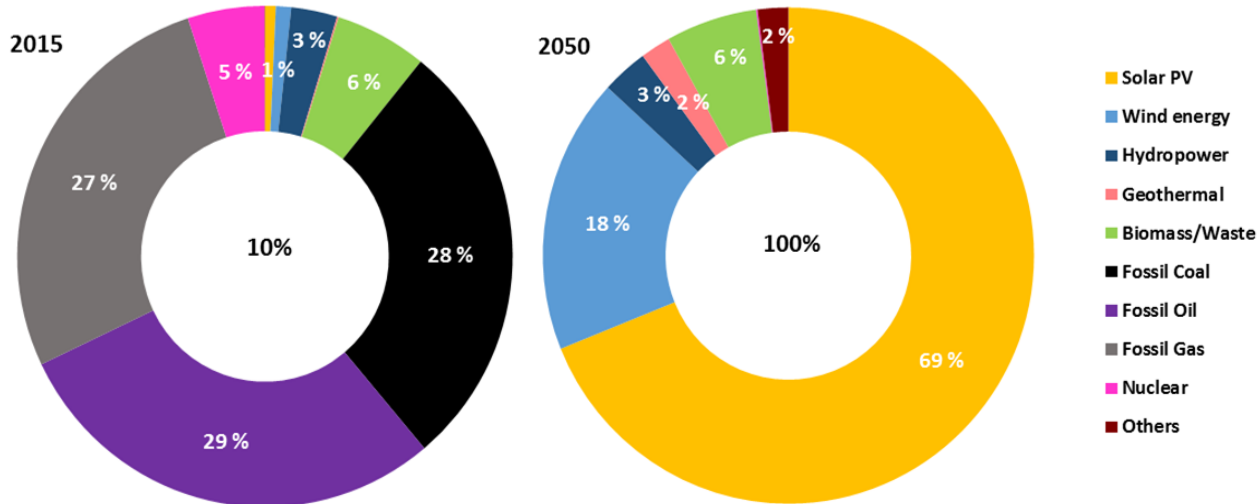
A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: greenhouse gas emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the 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.



- 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

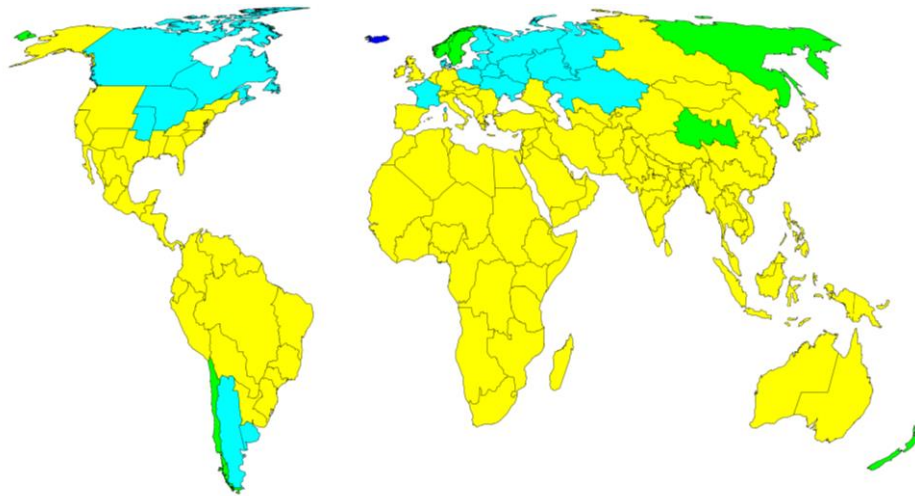


# Renewables for ALL energy demand (TPED)



## 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



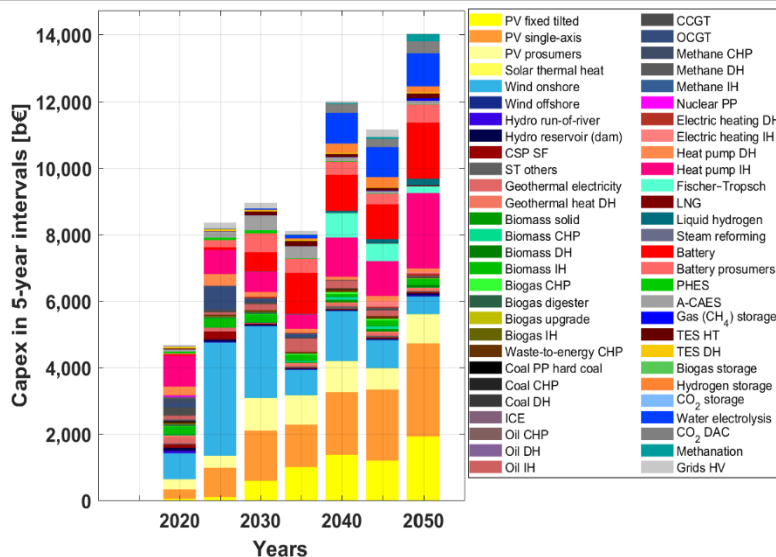
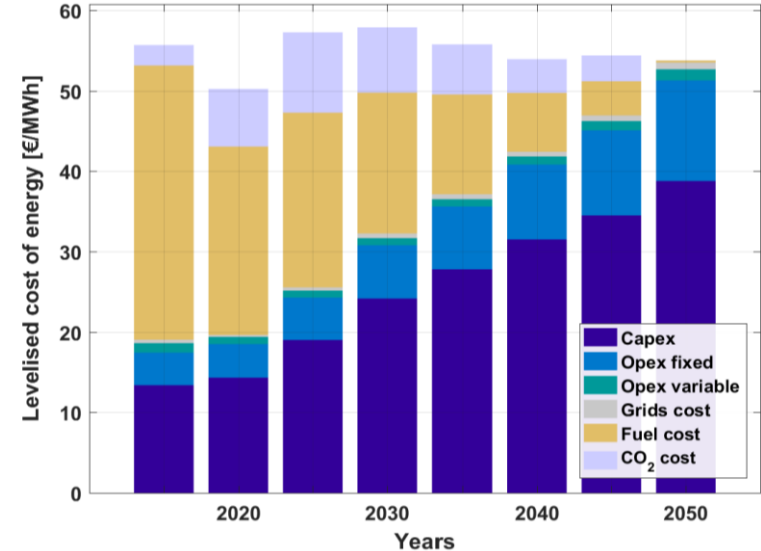
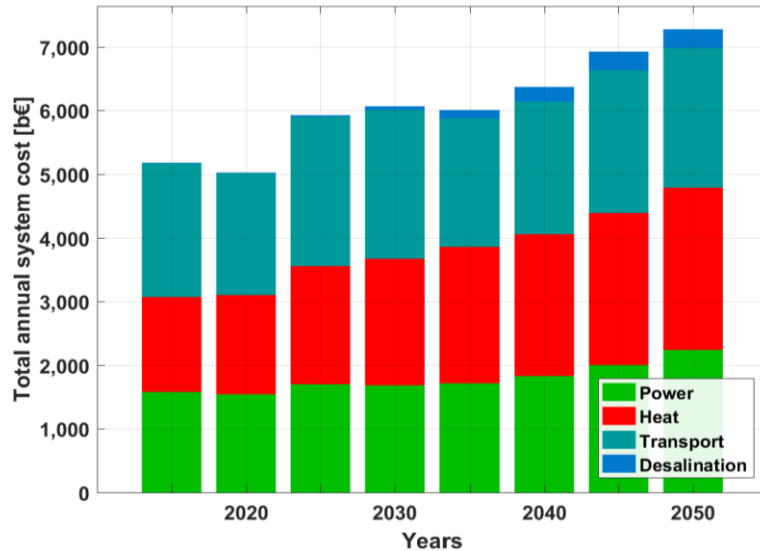
Solar PV based system

Wind turbines based system

Hydro power based system

Technologies mix based system

# Global: Energy System Cost

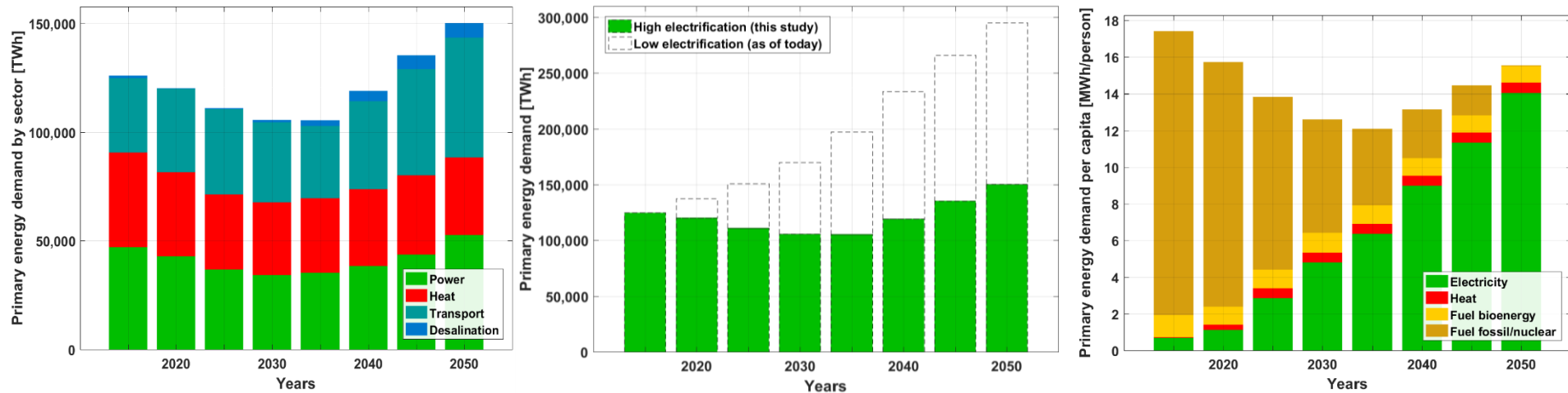


## Key insights:

- 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€



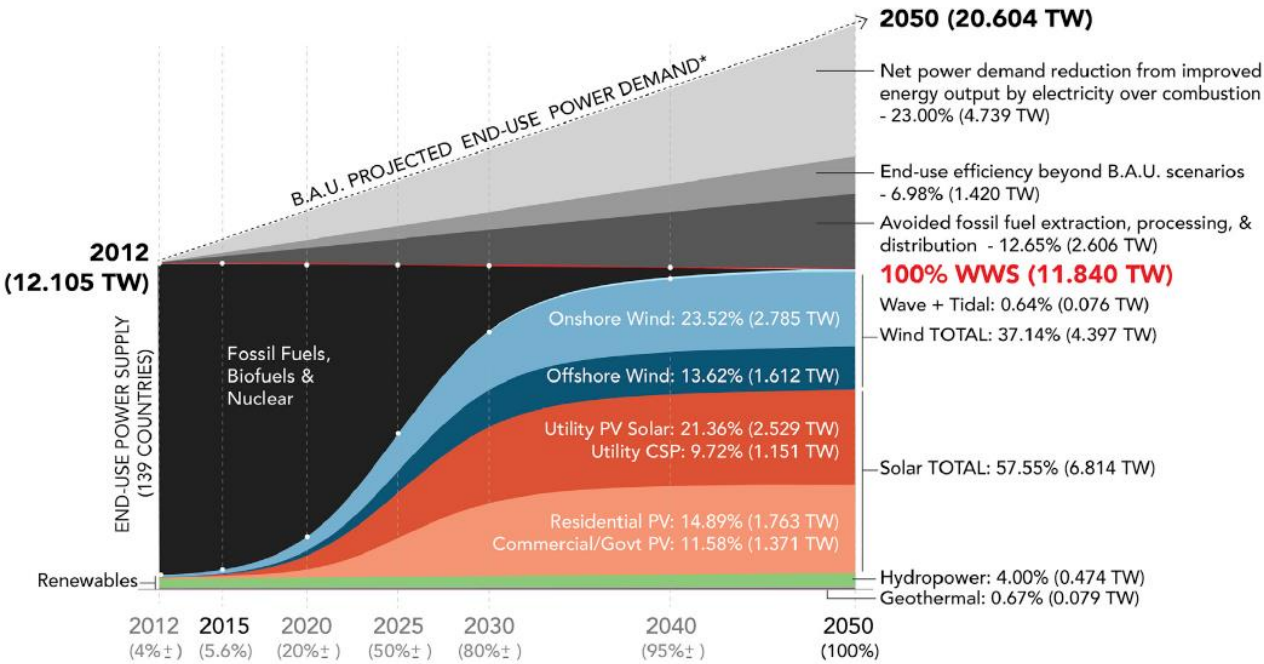
# Global: Energy Demand and Electrification



## Key insights:

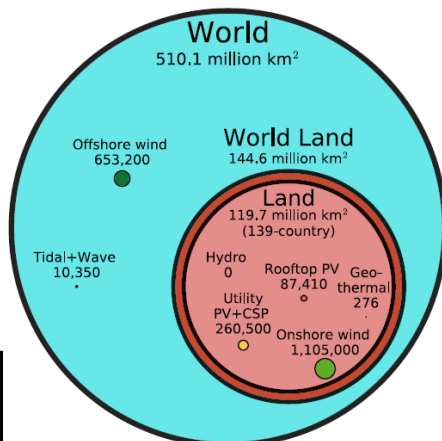
- A global compound average annual growth rate of about 1.0% in final energy demand drives the transition. This is composed by final energy demand growth for power and heat, desalinated water demand and transportation demand linked to powertrain assumptions. This leads to a comprehensive electrification, 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.

# Jacobson et al., 2017 – 2015 - 2050



## Projected Power Supply & Demand, 139 Countries

\*ENERGY FOR ALL USES INCLUDING ELECTRICITY, HEATING, TRANSPORTATION, INDUSTRY



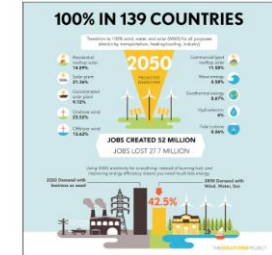
## Key insights:

- 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

Joule

CellPress

Article  
100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World



Mark Z. Jacobson, Mark A. Delucchi, Zack A.F. Bauer, ...  
Jingfan Wang, Eric Weimer,  
Alexander S. Yuzytskiy,  
jacobson@berkeley.edu

**HIGHLIGHTS**  
Roadmaps for 139 countries to use 100% wind-water-solar in all energy sectors

Roadmaps avoid 1.5°C global warming and millions of annual air-pollution deaths

Roadmaps reduce social cost of energy and create 24.3 million net long-term jobs

Roadmaps reduce power generation and increase worldwide access to energy

We develop energy roadmaps to significantly slow global warming and nearly eliminate air-pollution mortality in 139 countries. These plans call for electrifying all energy sectors (transportation, heating/cooling, industry, agriculture/forestry/fishing) and providing the electricity with 100% wind, water, and solar (WWS) power. Fully implementing the roadmaps by 2050 avoids 1.5°C global warming and millions of deaths from air pollution annually, creates 24.3 million net new long-term, full-time jobs, reduces energy costs to society, reduces power requirements 42.5%, reduces power generation, and increases worldwide access to energy.

Jacobson et al., Joule 1, 1-34  
September 2017 | DOI:10.1016/j.joule.2017.08.001  
http://dx.doi.org/10.1016/j.joule.2017.08.001

source: Jacobson et al., 2017. 100% Clean and Renewable Wind, Water, and

lut.fi

@Chris

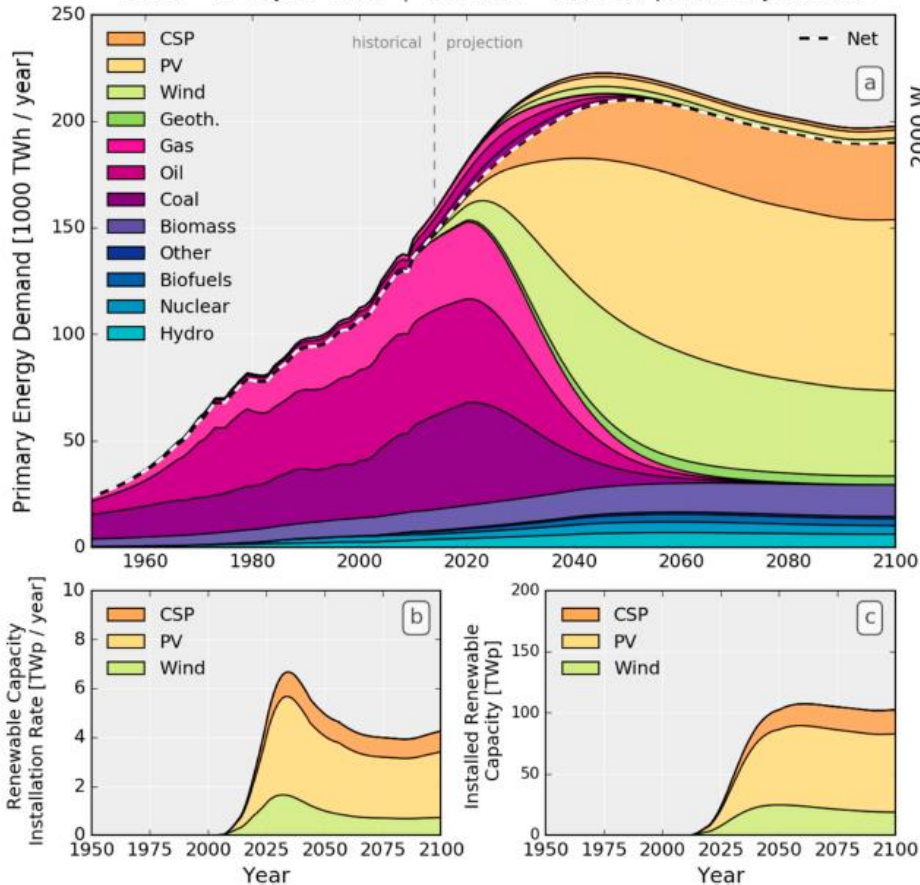
Sunlight All-Sector Energy Roadmaps for 139 Countries of the World, Joule 1, 1-14

# Sgouridis et al., 2016 – 2015 - 2100

## Detailed Sustainable Energy Transition Path

Fossil phase-out: 2020 - 2075 | Emissions cap: 990 GtCO<sub>2</sub>

EROEI = 20 in year 2014 | Demand = 2000 W / person in year 2100



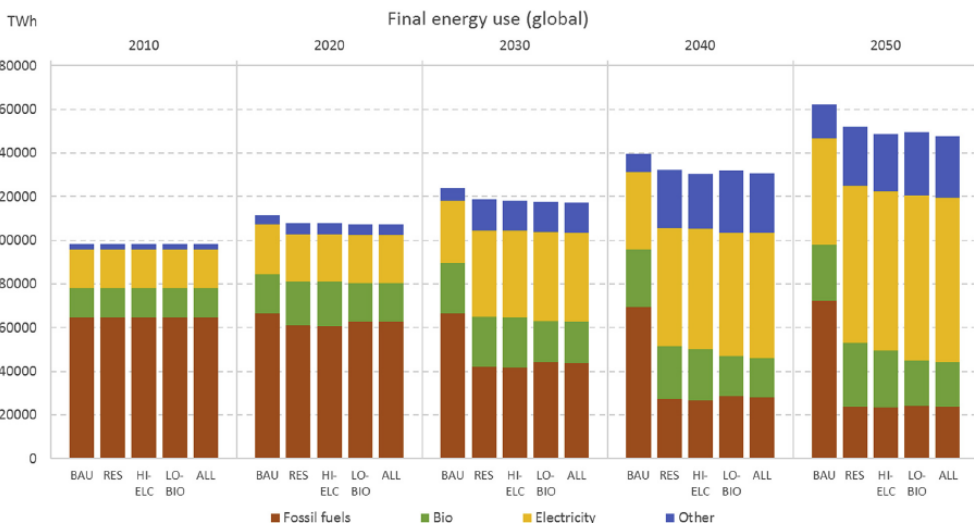
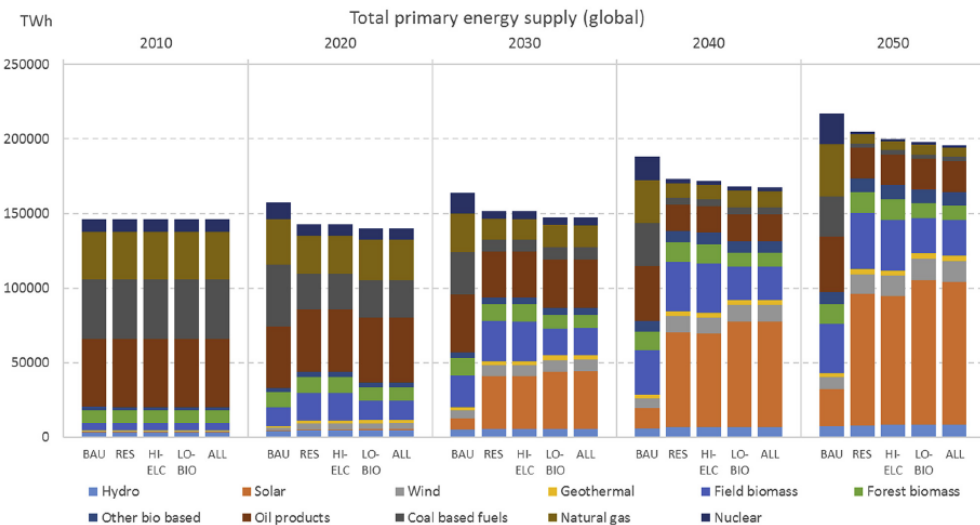
**Figure 1.** (a) SET-compliant primary energy supply evolution (in PWh) for providing 2000 W average net power per capita by 2100 to a population of 10.8 billion. Fossil fuel emissions comply with a 990 GtCO<sub>2</sub> cap peaking in 2020 and phased-out by 2075. The dashed line represents the net available energy while the values above it the energy investment in building and operating the energy system ('seed'). (b) RE portfolio installation rate profile (in TW<sub>p</sub> yr<sup>-1</sup>). (c) Installed RE capacity (in TW<sub>p</sub>).

### 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



# Pursiheimo et al., 2019 – 2010 - 2050



Renewable Energy 136 (2019) 1119–1129

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/rene

Inter-sectoral effects of high renewable energy share in global energy system

Esa Pursiheimo<sup>a</sup>, Hannele Holttinen, Tiina Koijanen

<sup>a</sup>VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT Espoo, Finland

ARTICLE INFO

ABSTRACT

Renewable energy future from energy coupling perspective is analyzed by using global energy system model. Energy system with high renewable share is examined by four scenarios differentiated by biomass potential and electric vehicle market share. For comparison, business-as-usual scenario with renewable free but without non-renewable energy exclusion is used. In renewable scenarios non-renewable energy sources are phased out by 100% for year 2050 and being model find cost-optimal path from 2010 to 2050. Results indicate that high renewable share poses major changes in each energy system sector, especially to power generation, industry and transportation. Substantial biomass utilization is required, and increased electrification of energy system, especially in industrial sector, is necessary with high penetration of solar and wind power. Solar photovoltaics (PV) reaches globally 39–44% share in primary energy and 75% share in electricity generation since positive development of PV technology drives especially power generation in Asia to solar power. This requires high capacity of power-to-gas technologies, which use electricity to produce synthetic fuel used in industrial and transport sectors, and electricity storage. Transition to renewable energy system mitigates CO<sub>2</sub> emissions by 90% from 2010 to 2050, even though the issue of non-CO<sub>2</sub> greenhouse gas emissions remains.

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1. Introduction

Commitment to Paris Climate Agreement [1] necessitates significant global greenhouse gas (GHG) emission reductions by year 2050 and utilizing renewable energy sources in the main tool for achieving this goal. In the national Non-Carbon Energy (NCE) research project transition scenarios and related paths to 100% renewable energy system (RES) from 2010 to 2050 have been investigated. This paper focuses on energy system effects of high renewable energy scenarios, at global level, with TIMES-VTT (The Integrated MARKET EFfect System) energy system model describing the entire global energy system.

In the NCE project, Lappeenranta University of Technology has studied in Ref. [2] and [3] the impact of high solar photovoltaics (PV) penetration and utilization of power-to-gas technologies on the global power generation sector. These studies are based on an hourly linear optimization model for the power generation sector in different global region. However, energy use sectors outside power generation are not included. Furthermore, in Ref. [3] benchmark for global energy transition scenarios in terms of solar PV market penetration is represented and this finding indicates that in scenario published so far solar PV share in power generation in year 2050 does not exceed 40%.

Transition to global energy system scenarios targeting year 2050 have been analyzed in several modelling exercises and a collection of these scenarios is examined in detail in Ref. [4]. These scenario analysis papers, utilizing several energy system models, concentrate mainly on climate change mitigation and therefore e.g. carbon capture and storage (CCS) technologies are utilized in several scenarios. Renewable global energy system is not de facto targeted in these scenarios, although high shares of renewables are achieved by year 2050 due to climate mitigation measures. Furthermore, since these analyses are implemented prior to year 2011, recent energy and cost evolution concerning solar power does not appear in these scenario studies. Obviously, several global energy system scenarios are also presented in Intergovernmental Panel on Climate Change (IPCC) report [5] mainly from climate change mitigation perspective.

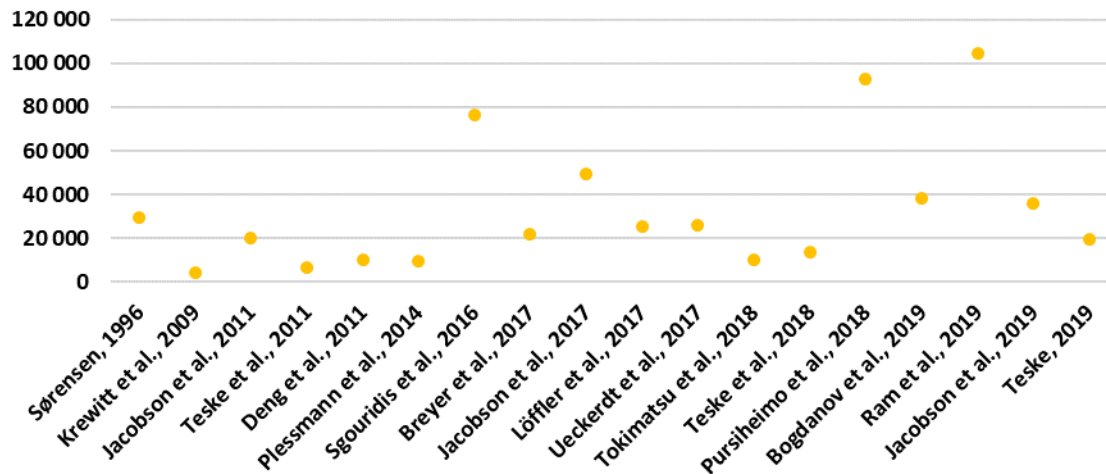
## Key insights:

- 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

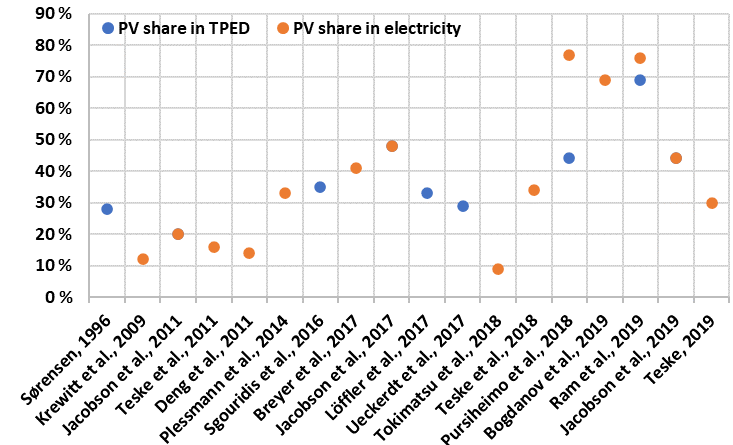


# Learnings for PV from Scenario Overview

PV generation [TWh] in global 100% RE scenarios by 2050



PV shares in global 100% RE scenarios by 2050

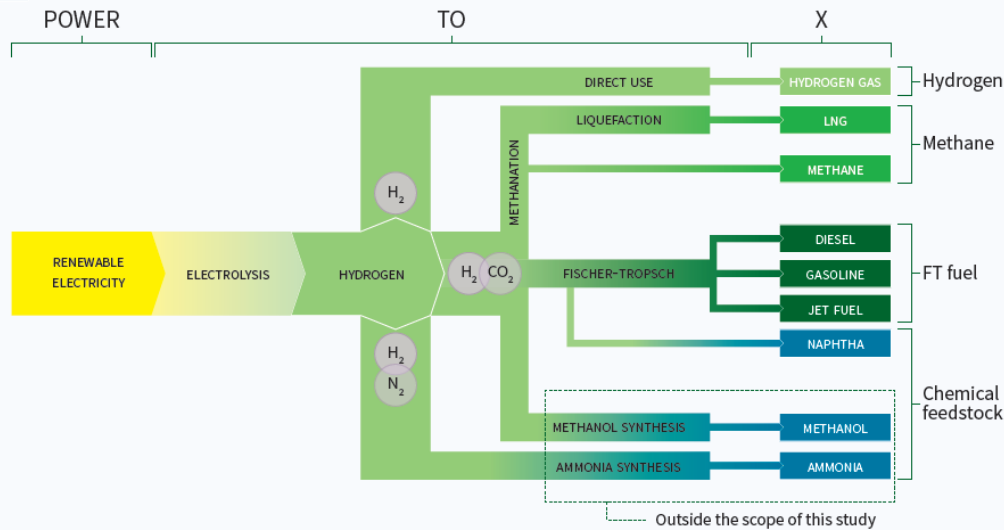


## Key insights:

- 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

## BOX 3. POWER TO HYDROGEN TO X



### Key insights:

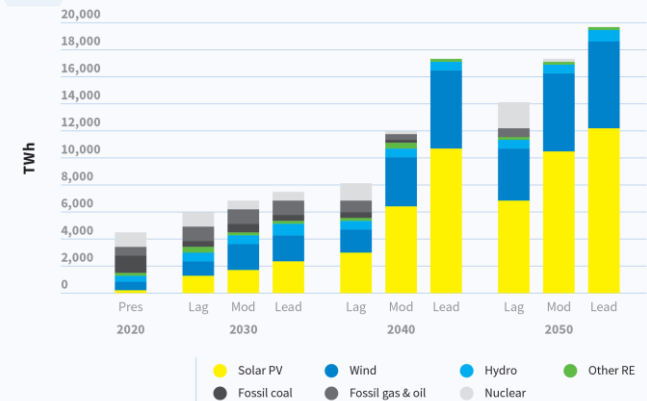
- Power-to-X comprises: Mobility, Fuels, Chemicals, Heat, Steel, Desalinated Water
- Hydrogen is ONLY required, where direct electrification fails, e.g. chemicals, fuels for aviation/ marine
- Power-to-X is an essential core element for least cost zero GHG emissions and a booster for solar PV demand



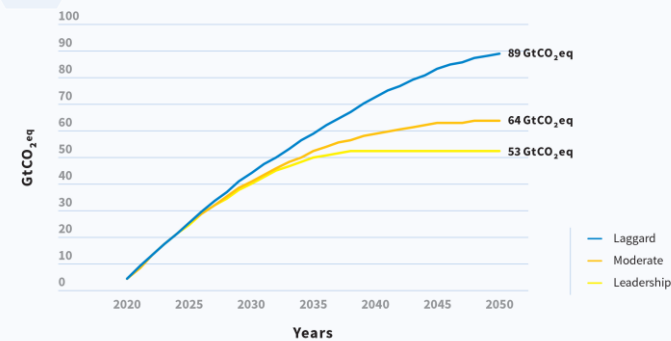
[link to report](#)

## Case: Sustainable Europe

### ELECTRICITY GENERATION

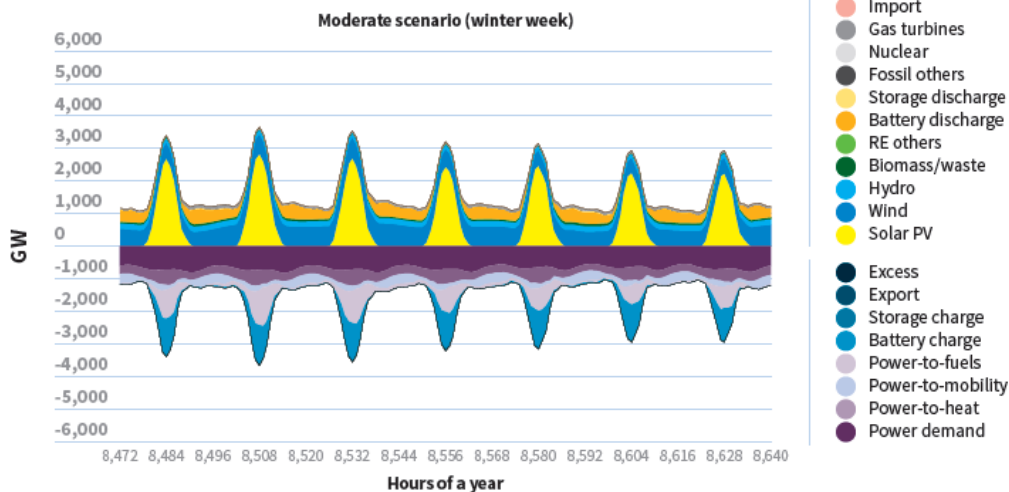
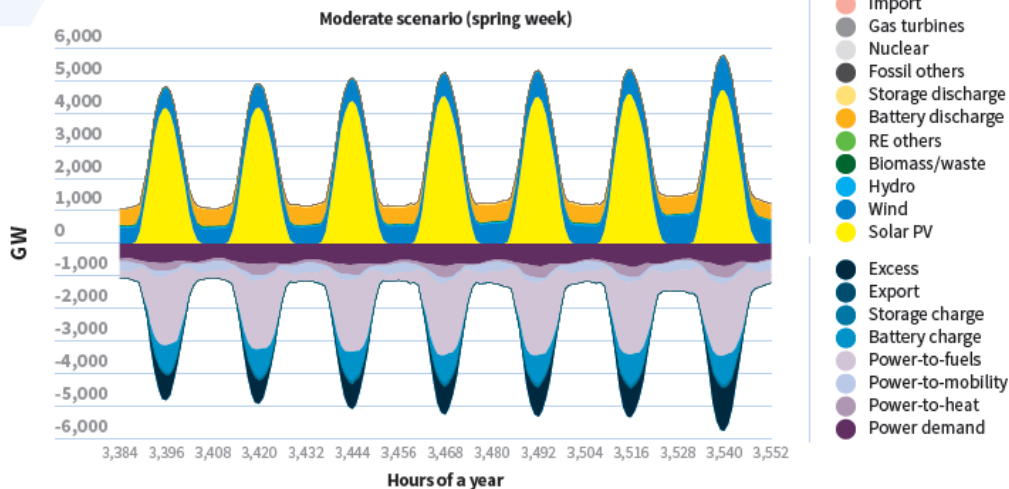


### CUMULATIVE GHG EMISSIONS



# Hourly Operation of the Energy System (Europe)

FIGURE 4.8 HOURLY OPERATION OF THE EUROPEAN ENERGY SYSTEM

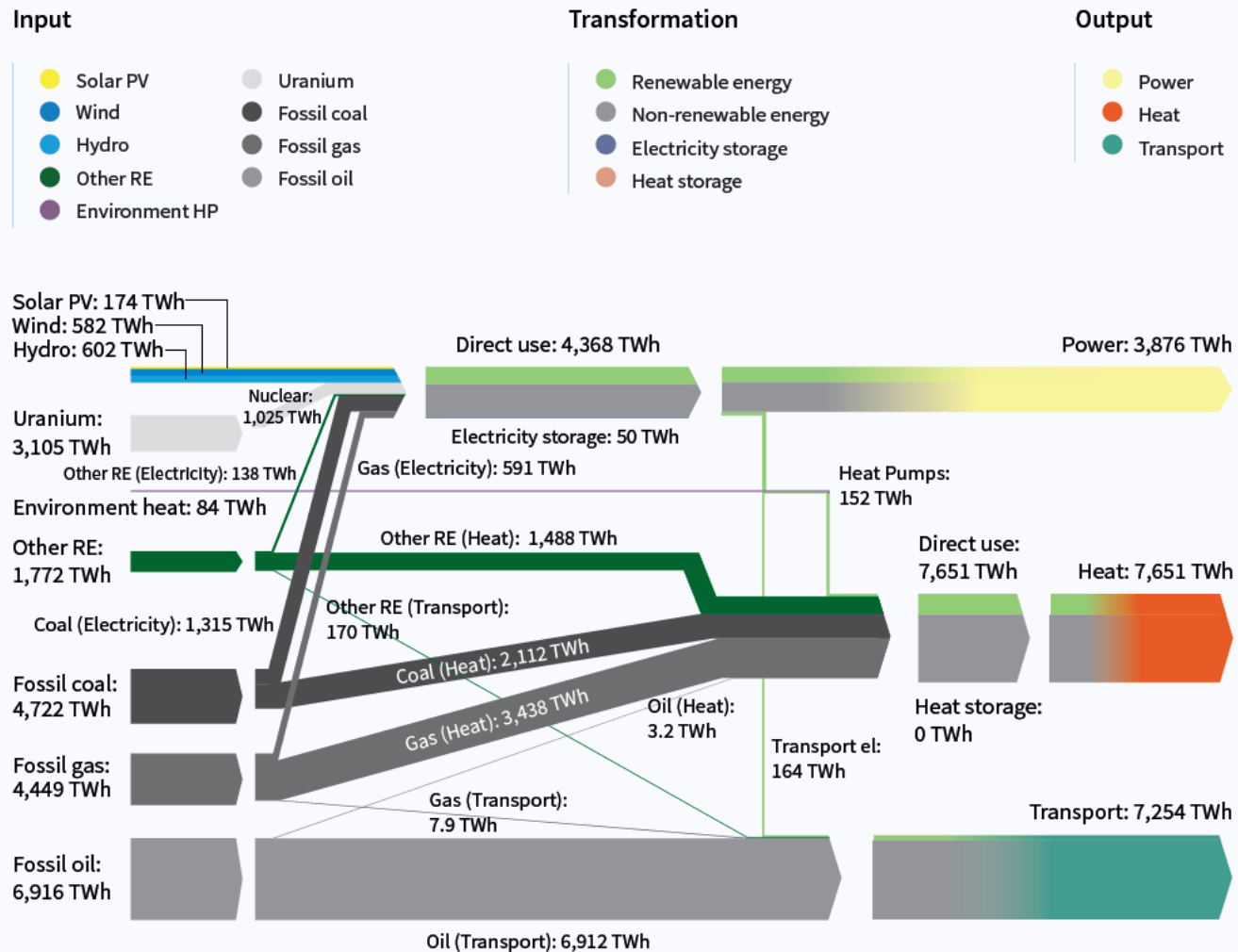


## Key insights:

- 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 electrolysers (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.

# Energy System Structure: Present (Europe)

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020

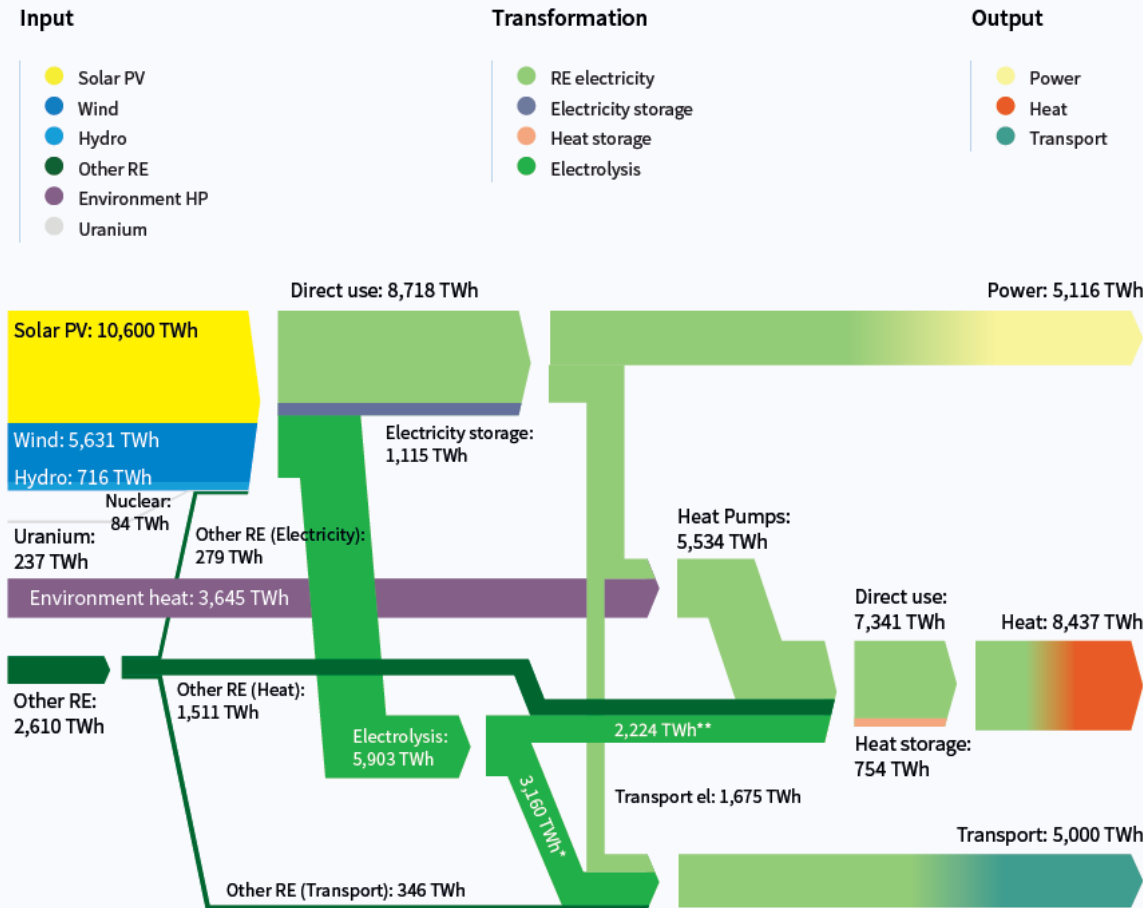


## Key insights:

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

# Energy System Structure: Future (Europe)

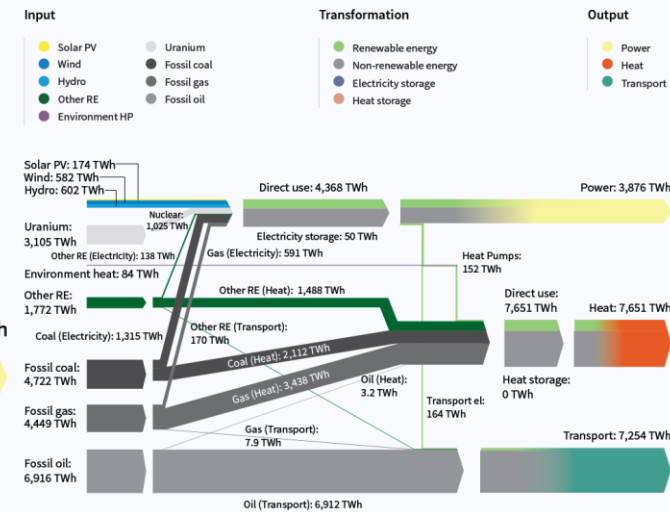
FIGURE 3.25 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN THE MODERATE SCENARIO IN 2050



\*RE synthetic fuels for transport.

\*\*RE synthetic fuels for heat, recovered heat.

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020



## 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

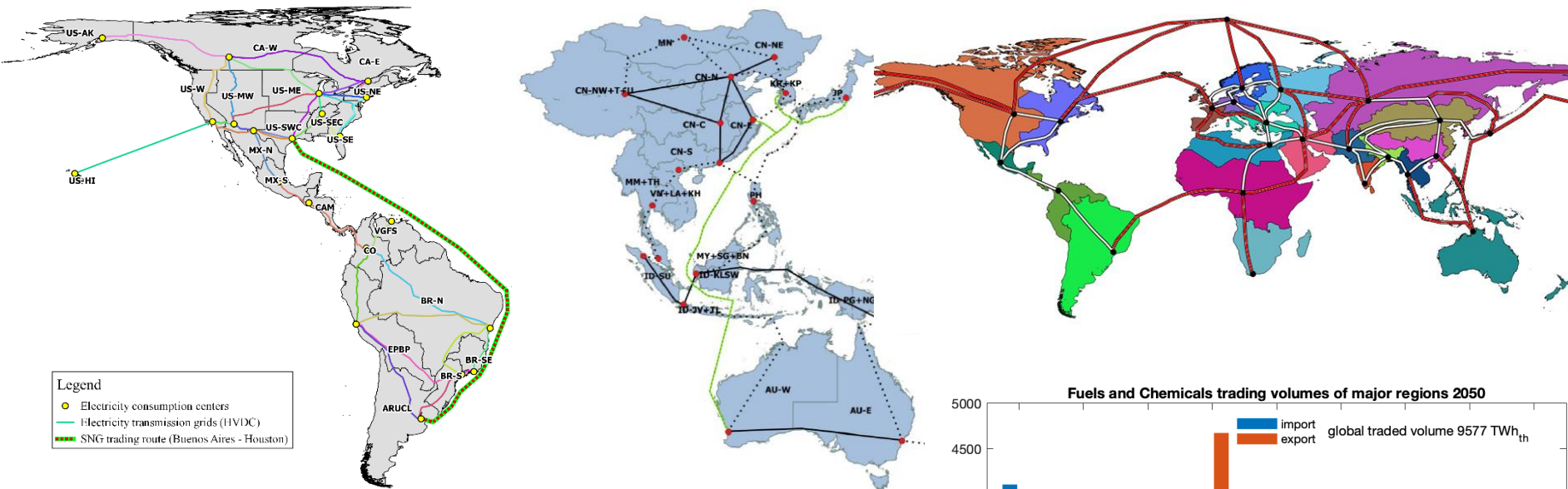
# Overview on transport sector transition

Source	Publication year	Unit	2015	2020	2025	2030	2035	2040	2045	2050	TFED share in 2050 *			
											fossils	biofuels	synfuels	electricity
this study	2019	TWh/a	31613	34799	35848	35609	33761	32177	31758	32542	0 %	1 %	63 %	35 %
Greenpeace [E]R	2015	TWh/a	-	26129	25599	25070	-	21808	-	19159	29 %	14 %	20 %	38 %
Greenpeace [E]R adv.	2015	TWh/a	-	25850	24897	23207	-	18020	-	14836	0 %	14 %	35 %	51 %
Teske, 1.5 °C	2019	TWh/a	30752	-	29411	25606	-	19604	-	17001	0 %	16 %	36 %	48 %
Teske, 2 °C	2019	TWh/a	30752	-	26142	20371	-	15919	-	14279	0 %	25 %	29 %	46 %
Jacobson et al.	2018	TWh/a	-	-	-	-	-	-	-	13113	0 %	0 %	33 %	67 %
Löffler et al.	2017	TWh/a	31298	32434	28910	24069	20258	16706	13326	10414	0	15 %	44 %	41 %
Pursiheimo et al.	2019	TWh/a	-	-	-	-	-	-	-	23480	0 %	30 %	33 %	37 %
García-Olivares et al.	2018	TWh/a	-	-	-	-	-	-	-	28383	n/a	n/a	n/a	n/a
WWF / Deng et al.	2011	TWh/a	29102	29598	28714	25940	24420	19533	17998	17741	0 %	74 %	0 %	26 %
World Energy Council	2016	TWh/a	-	31842	-	35471	-	37018	-	37169	77 %	15 %	2 %	6 %
DNV GL	2018	TWh/a	29513	30555	31945	31388	30555	28472	25694	25000	42 %	16 %	2 %	40 %
IEA, WEO NPS	2018	TWh/a	31308	-	36564	38530	40088	42065	-	-	90 %	6 %	0 %	4 %
IEA, WEO SDS	2018	TWh/a	31308	-	34250	33668	-	30703	-	-	73 %	13 %	0 %	14 %
Luderer et al. B200	2018	TWh/a	-	-	-	-	-	-	-	31945	32 %	29 %	18 %	21 %
Luderer et al. B800	2018	TWh/a	-	-	-	-	-	-	-	36110	47 %	26 %	12 %	15 %
Shell, Sky	2018	TWh/a	30812	33019	34989	34611	36290	37686	38837	40630	67 %	13 %	2 %	18 %
BP Energy Outlook	2019	TWh/a	29656	32564	34890	36053	37216	37099	-	-	89 %	7 %	0 %	4 %
ExxonMobil	2017	TWh/a	32530	-	36633	-	-	40736	-	-	94 %	4 %	0 %	2 %
US DoE EIA	2017	TWh/a	32823	33703	35168	37806	40736	44400	-	-	98 %	0% **	0 %	2 %

- 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](#)

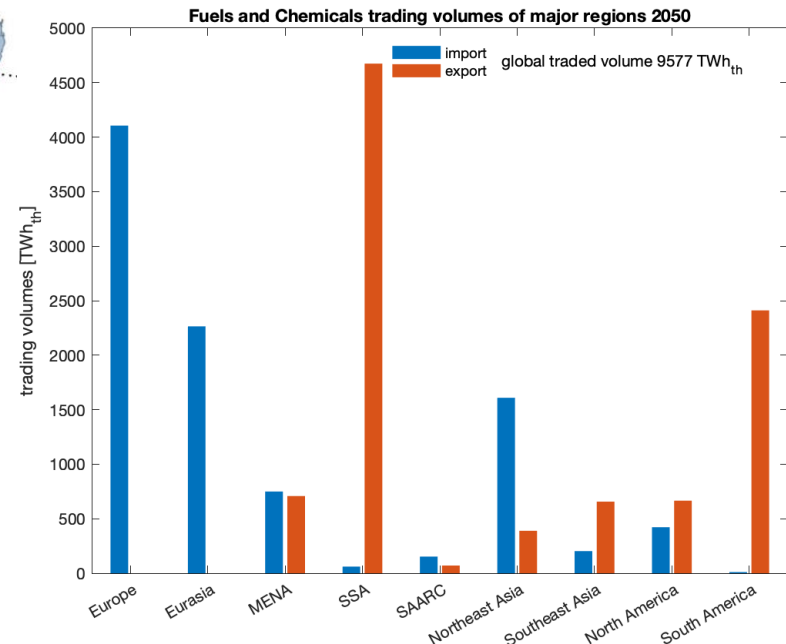
# Regional and Global Super Grids



Legend  
 ● Electricity consumption centers  
 — Electricity transmission grids (HVDC)  
 — SNG trading route (Buenos Aires - Houston)

## Key insights:

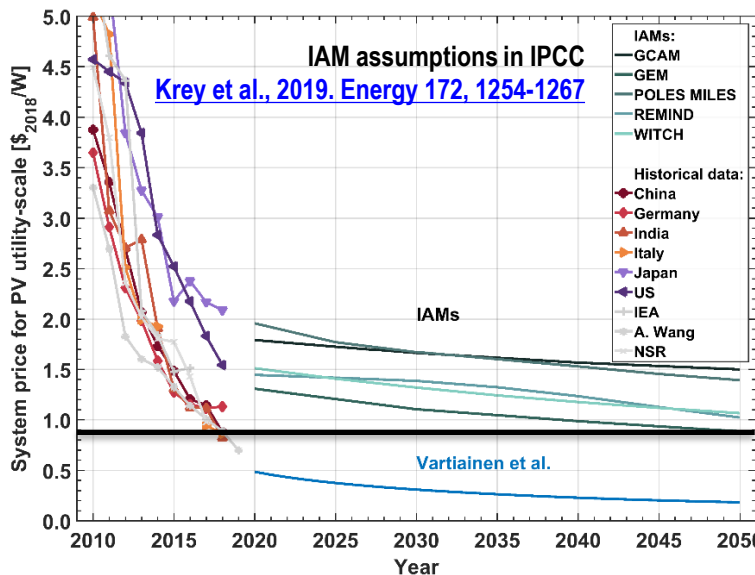
- What's the value add of very large Super Grids?
- Grids on a major region level (SAARC, Europe, etc.) reduce the system cost by about 10% by resource balancing, compared to state/ country level optimisation.
- The higher the solar PV share, the lower the balancing value.
- Integration beyond major 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

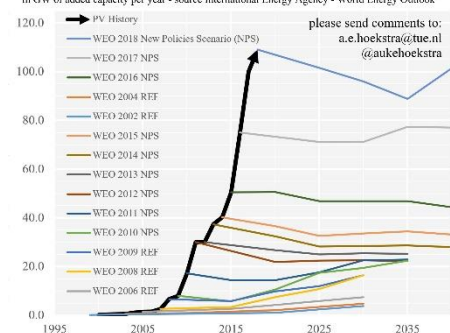
Heigel et al., 2019. *Science* 364(6443), 836-838

Vartiainen et al., 2020. *PIP* 28, 439-453

Breyer et al., 2018. *PIP* 26, 505-523

Breyer et al., 2017. *PIP* 25, 727-745

## Annual PV additions: historic data vs IEA WEO predictions



**RENEWABLE ENERGY**  
**Terawatt-scale photovoltaics: Transform global energy**  
Improving costs and scale reflect looming opportunities

**S**olar 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 reached 500 GW at the end of 2019, and an additional 300 GW of PV capacity is projected to be installed by 2025, helping us into the era of PV-lead PV. Over the next few decades, solar energy will drive the rapid decline of fossil fuels and the growth of renewable energy. The growth toward the scale PV has caught many observers, including many at the 2019 Davos Economic Summit. This has led to the challenge of achieving a 2°C or less increase in global average surface temperature by the end of the century. The 1.5°C target is now the goal for many. The challenge is to find a pathway to a low-carbon sustainable energy system, with solar energy as the main driver in the 21st century. The 21st-century energy system must be able to meet the global energy demand. For example, PV is expected to reach 10 TW by 2050. The growth of PV is expected to be 10 times the growth of wind energy. The growth of PV is expected to be 10 times the growth of wind energy. The growth of PV is expected to be 10 times the growth of wind energy.

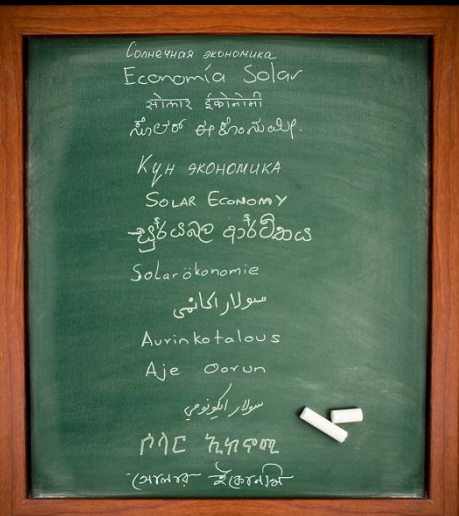
**RENEWABLE ENERGY**  
**RENEWABLE ENERGY**  
**RENEWABLE ENERGY**  
**RENEWABLE ENERGY**



# 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<sub>2</sub> 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!



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# 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, electrolyzers
- seasonal storage practically disappears and electrolyzers 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
- electrolyzers can effectively balance the power flows

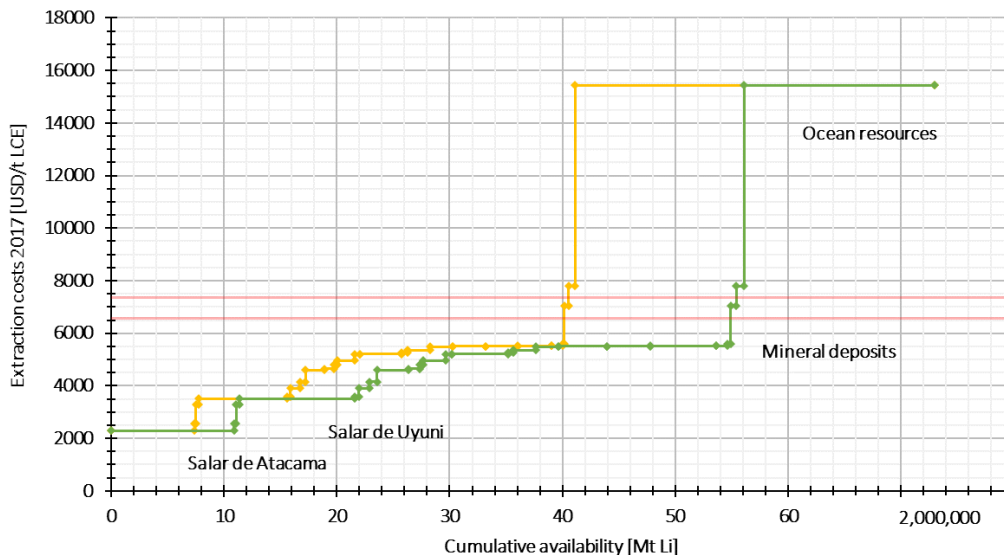
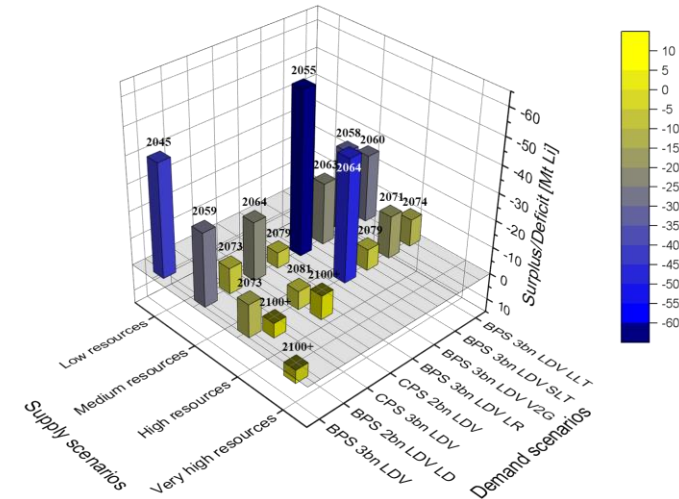
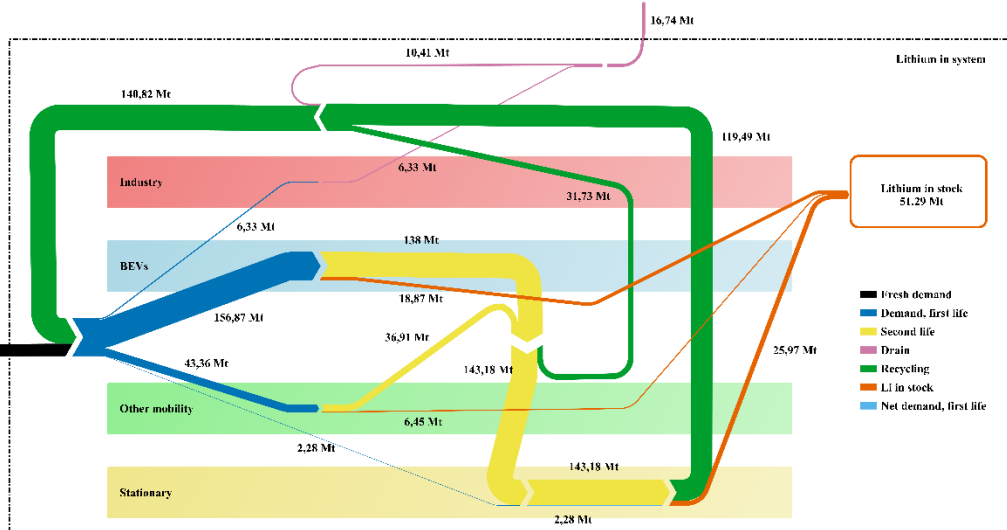
## Gap between the current speed of change and what needs to take to reach to 100% RE systems

- 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

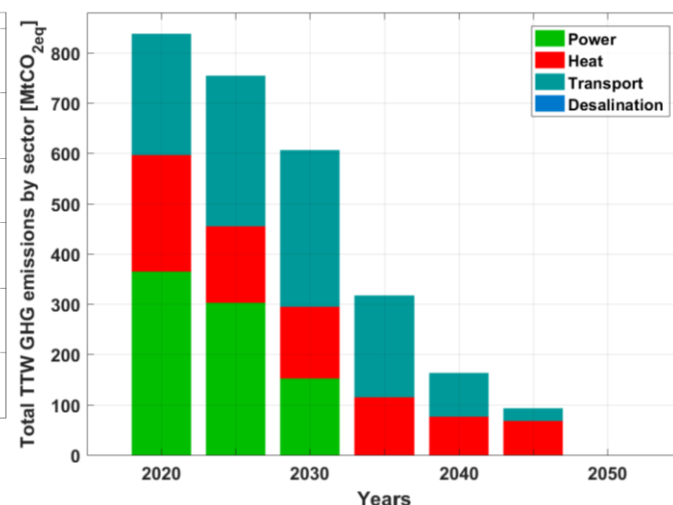
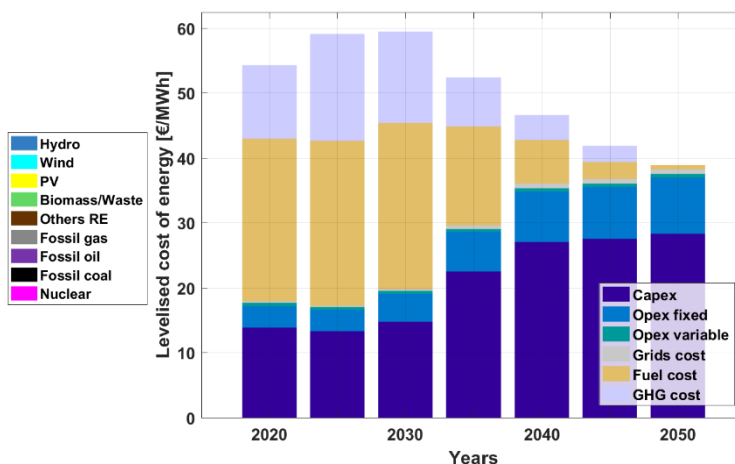
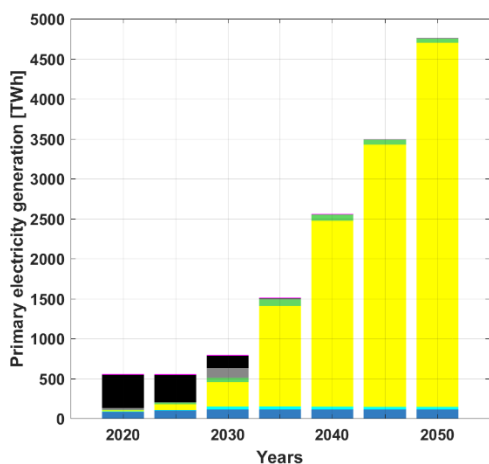
# Lithium – a potentially limiting raw material



## 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

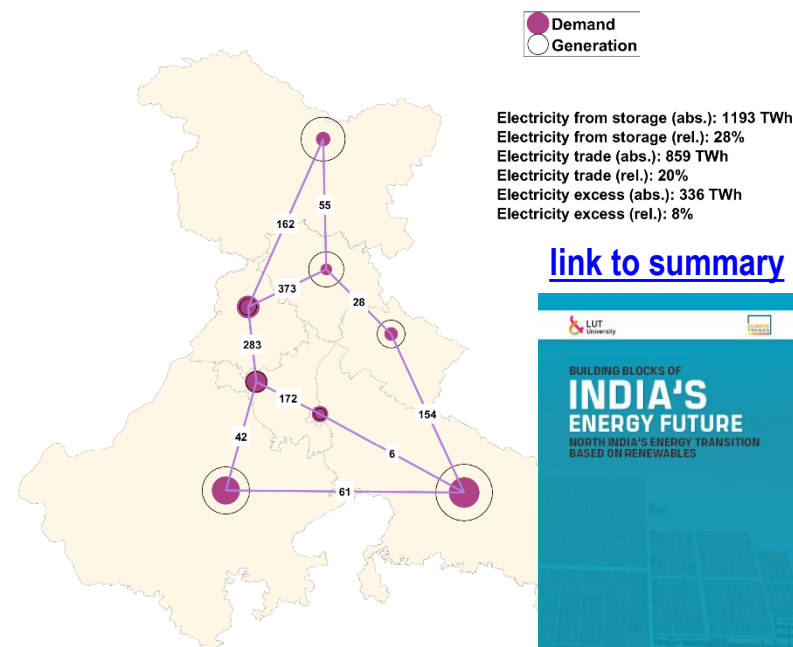
# India North and Delhi (power, heat, transport)



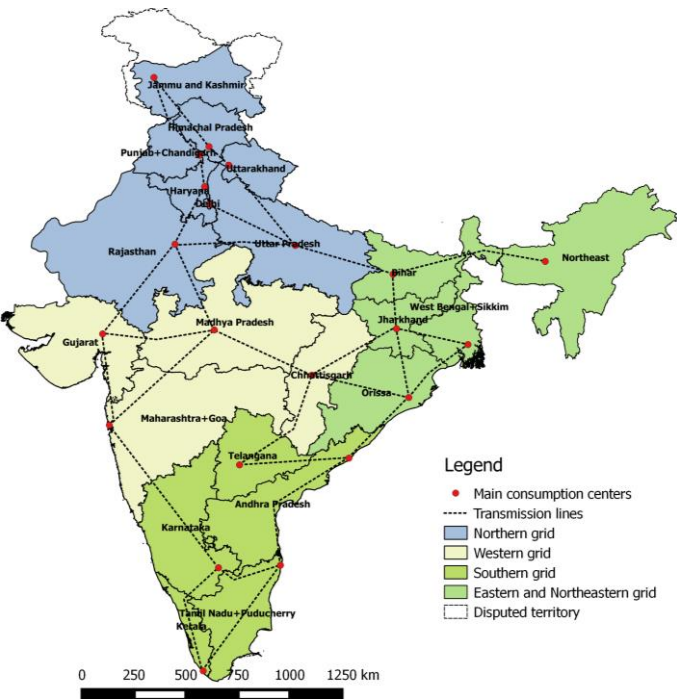
## Key insights:

- 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.

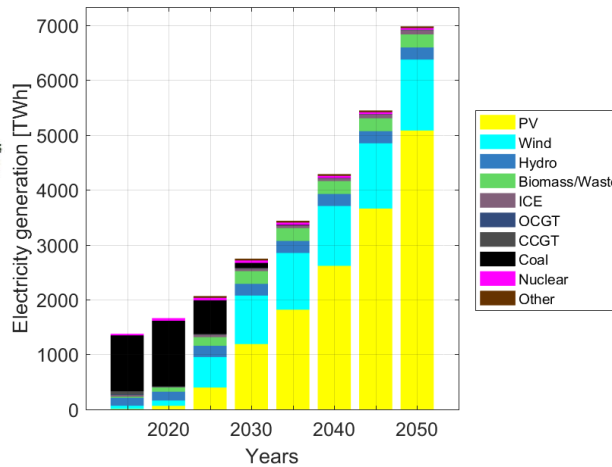
## Annual imported and exported electricity (TWh)



# India in state resolution (power sector)

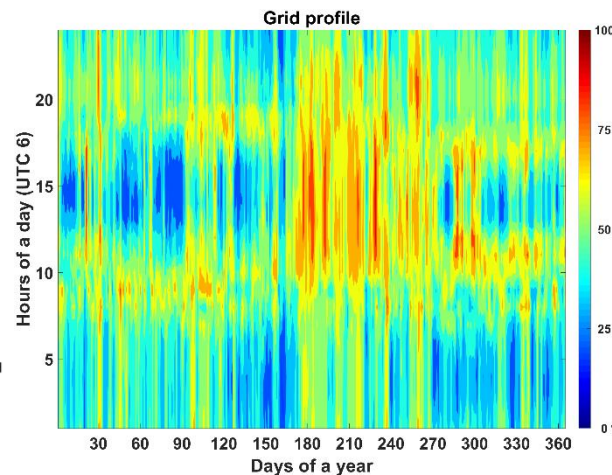
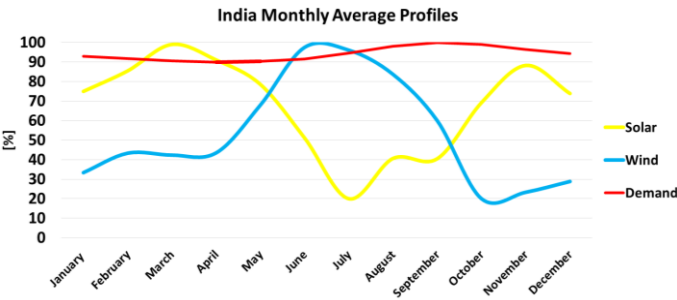


Legend  
 • Main consumption centers  
 - - - Transmission lines  
 Northern grid  
 Western grid  
 Southern grid  
 Eastern and Northeastern grid  
 Disputed territory



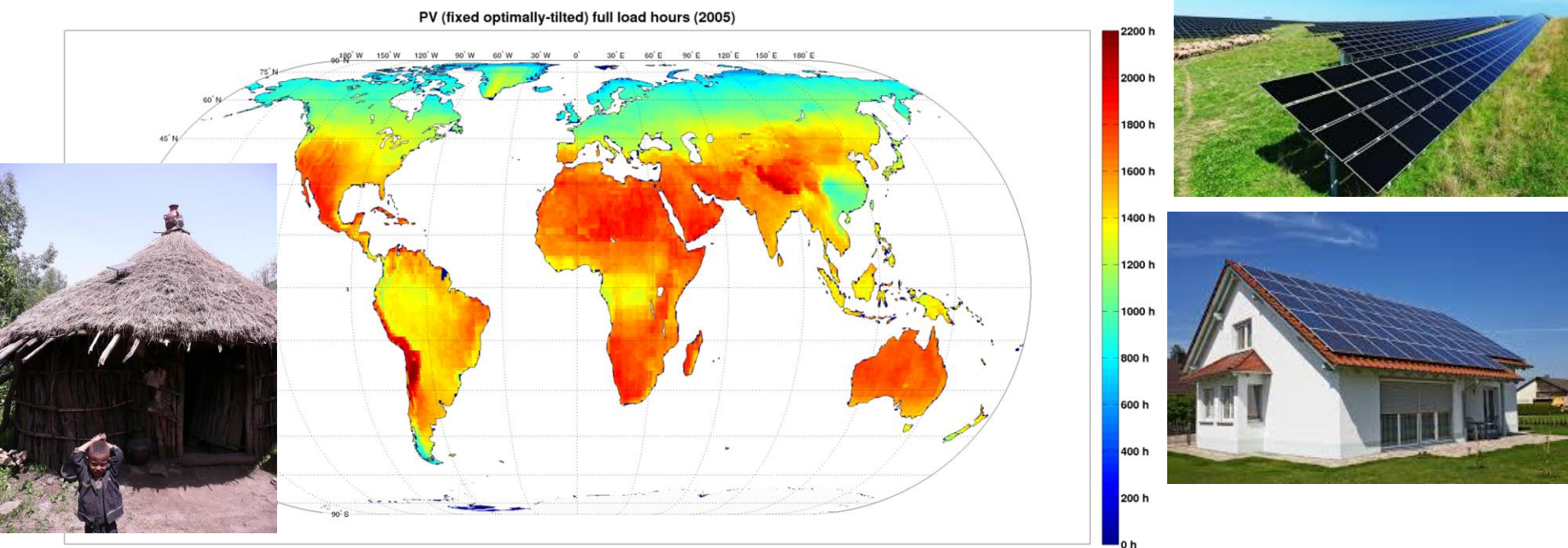
## Key insights:

- How to transition the most populated country in the 21<sup>st</sup> 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.



source: 22-states resolution not yet published. 10-regions interconnected results for India: [Gulagi et al., 2020. IET Renew Energy Gen 14, 254-262](#); [Gulagi et al., 2018. J of Energy Storage 17, 525-539](#)

# 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

