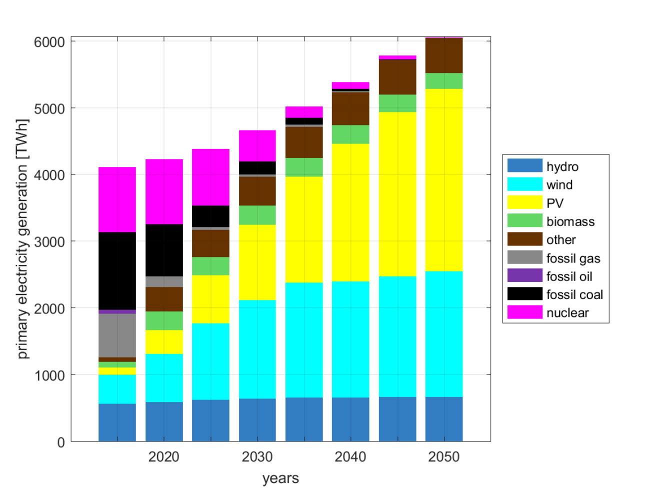

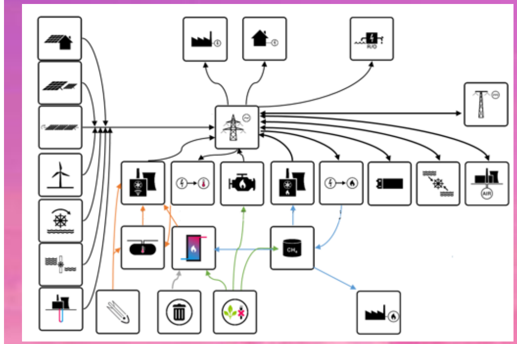

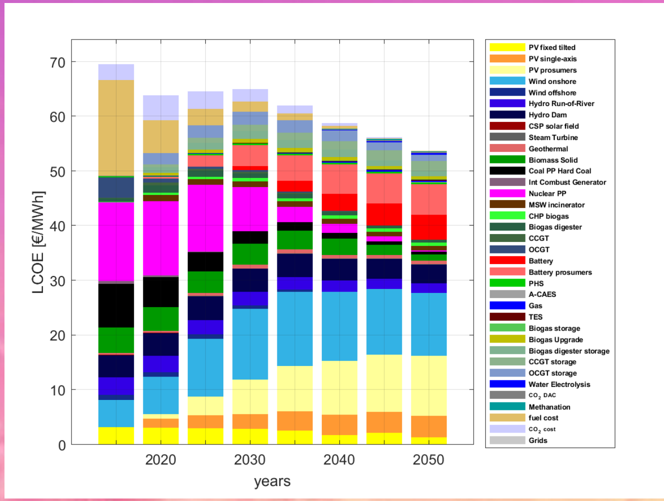

100% RENEWABLES IN EUROPE

NEO CARBON ENERGY

Christian Breyer
Lappeenranta University of Technology, Finland

PhotoVoltaic
EUROPEAN TECHNOLOGY & INNOVATION PLATFORM

PV Manufacturing in Europe Conference
European Technology & Innovation Platform - Photovoltaic
Brussels, May 19 2017

Agenda

- Global Scenarios / Current Status in Europe
- LUT Energy System Model
- 100% Renewable Power Sector – Overnight
- 100% Renewable Power Sector – Transition
- Summary

We witness the start of the Solar Age

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RENEWABLE ENERGY MAGAZINE
At the heart of clean energy journalism

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panorama

Global solar investment to be higher than coal, gas and nuclear combined in 2017

Wednesday, 17 May 2017

Robin Whitlock

Declining project costs are driving investment towards renewables as the industry continues to transition to more decentralised and intelligent energy systems, finds a report by Frost & Sullivan.

The report, by Frost & Sullivan's Energy & Environment team, examines the continued rise of renewable energy systems around the world. Global Power Industry Outlook, 2017, a new analysis from Frost & Sullivan's Power Generation Growth Partnership Service programme, examines power market trends, including installed capacity, investment, and regional growth across coal-fired, gas-fired, nuclear, hydro, solar PV, wind and biomass power.

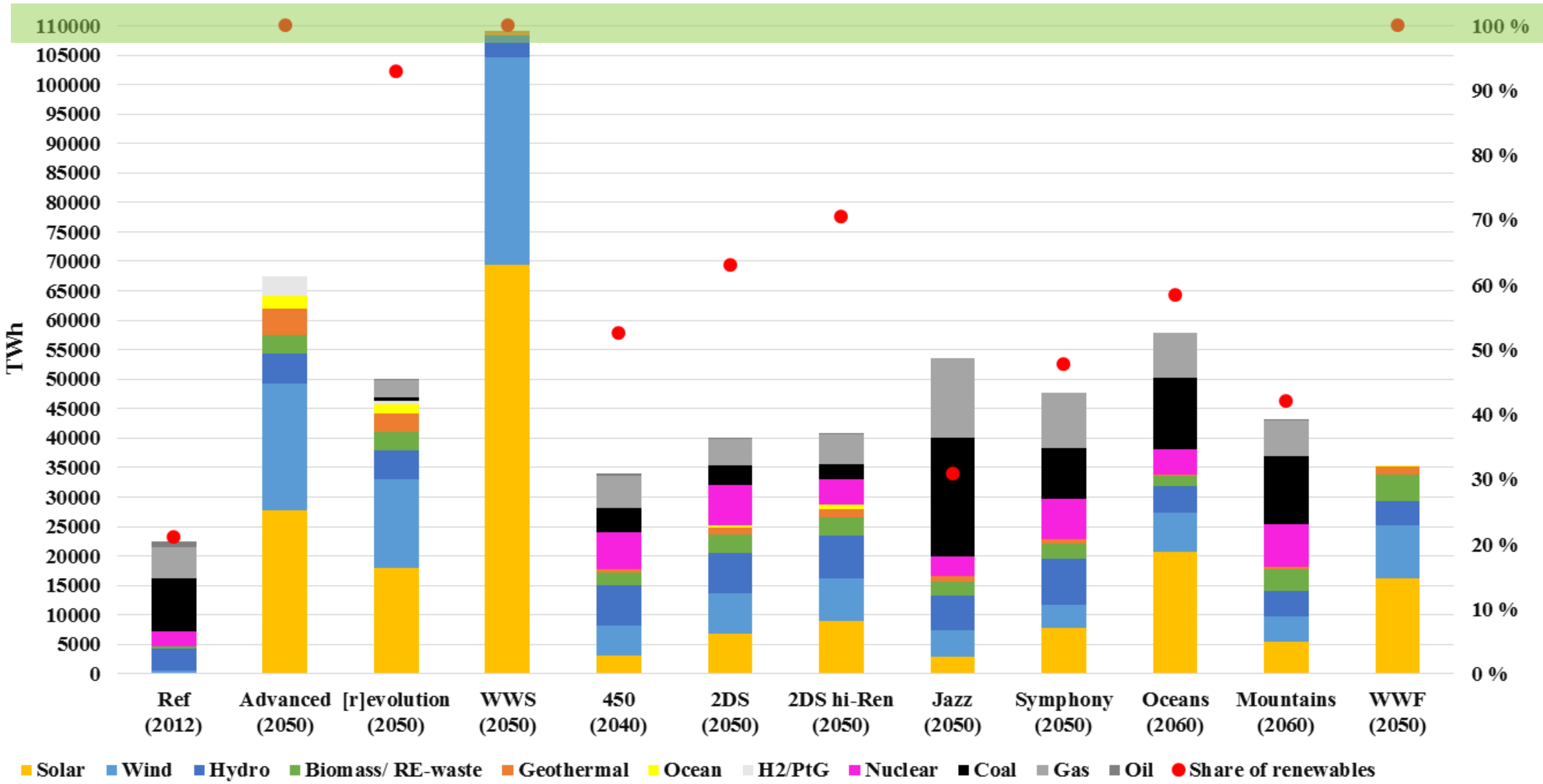
Prices for both solar and wind continue to decline enabling a boom in investment in renewable energy at the expense of traditional power generation. Lower project costs and continued regulatory support for renewable energy in key markets will see global renewable power investment reach $243.1 billion in 2017, with solar photovoltaic (PV) the fastest growing segment, followed by wind power. By 2020, non-hydro renewables will account for 65 percent of global power investment.

Comments:

- **Most global energy scenarios do not yet see that reality**
- **LUT results clearly indicate a solar century and PV as the key energy technology**
- **Europe will follow that global trend, depite of good wind (and weak policies)**

NEO CARBON ENERGY

Global Energy Scenarios: Selected Overview

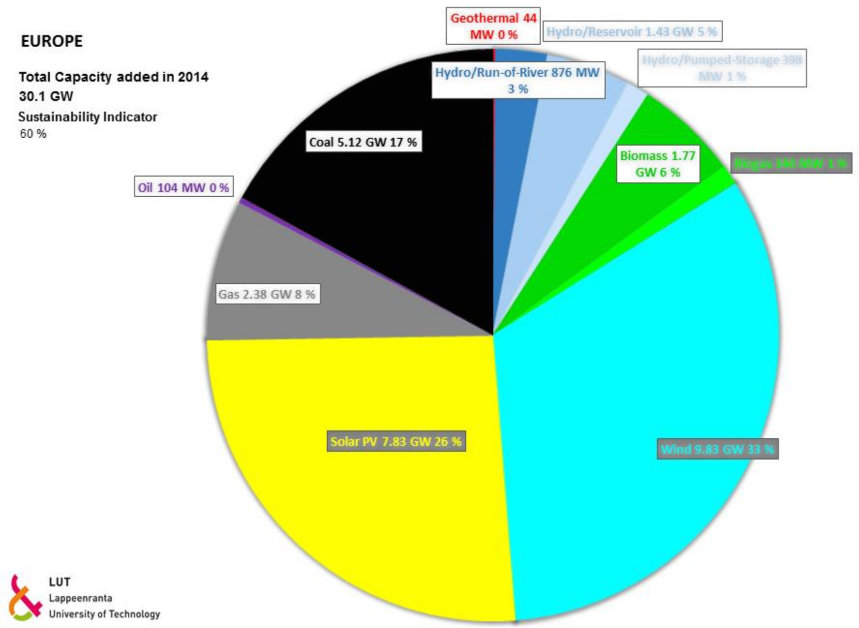


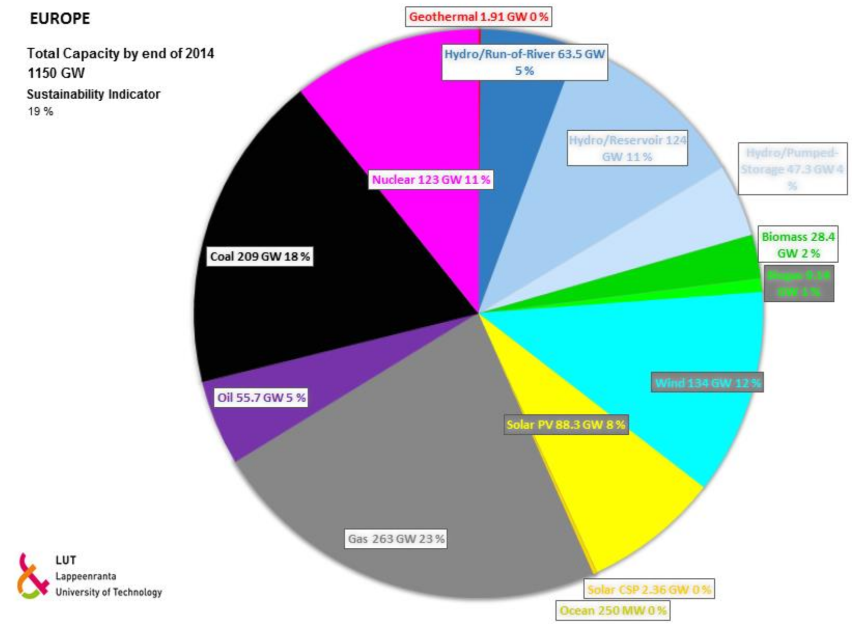
Key insights:

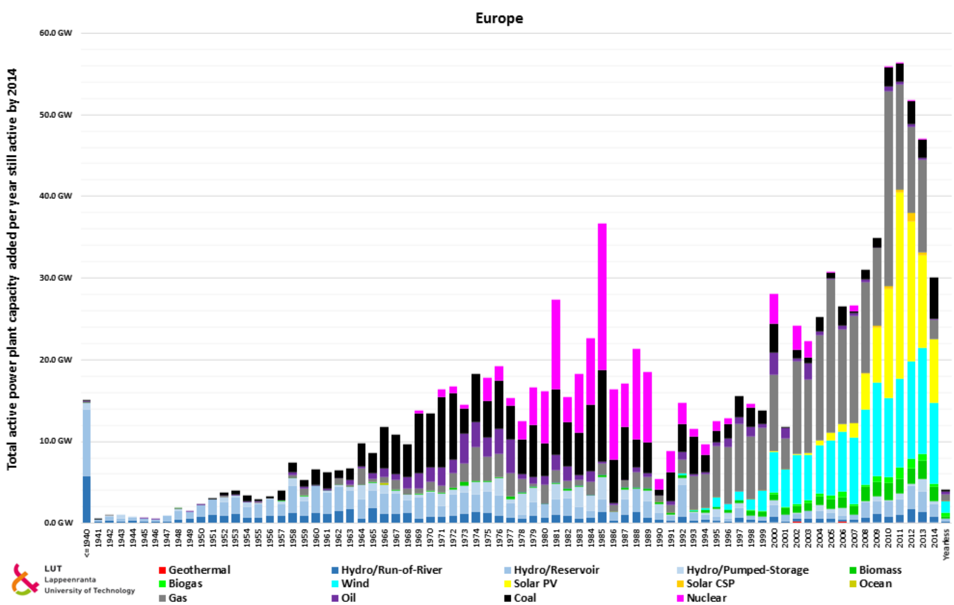
- 100% RE: Greenpeace, WWF, Jacobson et al.: demand strongly deviates, PV and wind dominated, no hourly resolution
- IEA, WEC, Shell: not COP21 compatible, high nuclear shares, low solar shares, no hourly resolution

source: Child M., Koskinen O., et al., 2017. Sustainability Guardrails for Energy Scenarios of the Global Energy Transition, submitted

Current status of the power plant mix







Key insights:

- new installations dominated by renewables
- nuclear as niche technology for years
- still some new coal capacities
- overall trend very positive

source:

Farfan J. and Breyer Ch., 2017. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator; J of Cleaner Production, 141, 370-384

Farfan J. and Breyer Ch., 2017. Aging of European Power Plant Infrastructure as an Opportunity to evolve towards Sustainability, International Journal of Hydrogen Energy, in press

Agenda

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- 100% Renewable Power Sector – Transition
- Summary

LUT Energy System Model

Full system

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Renewable energy sources

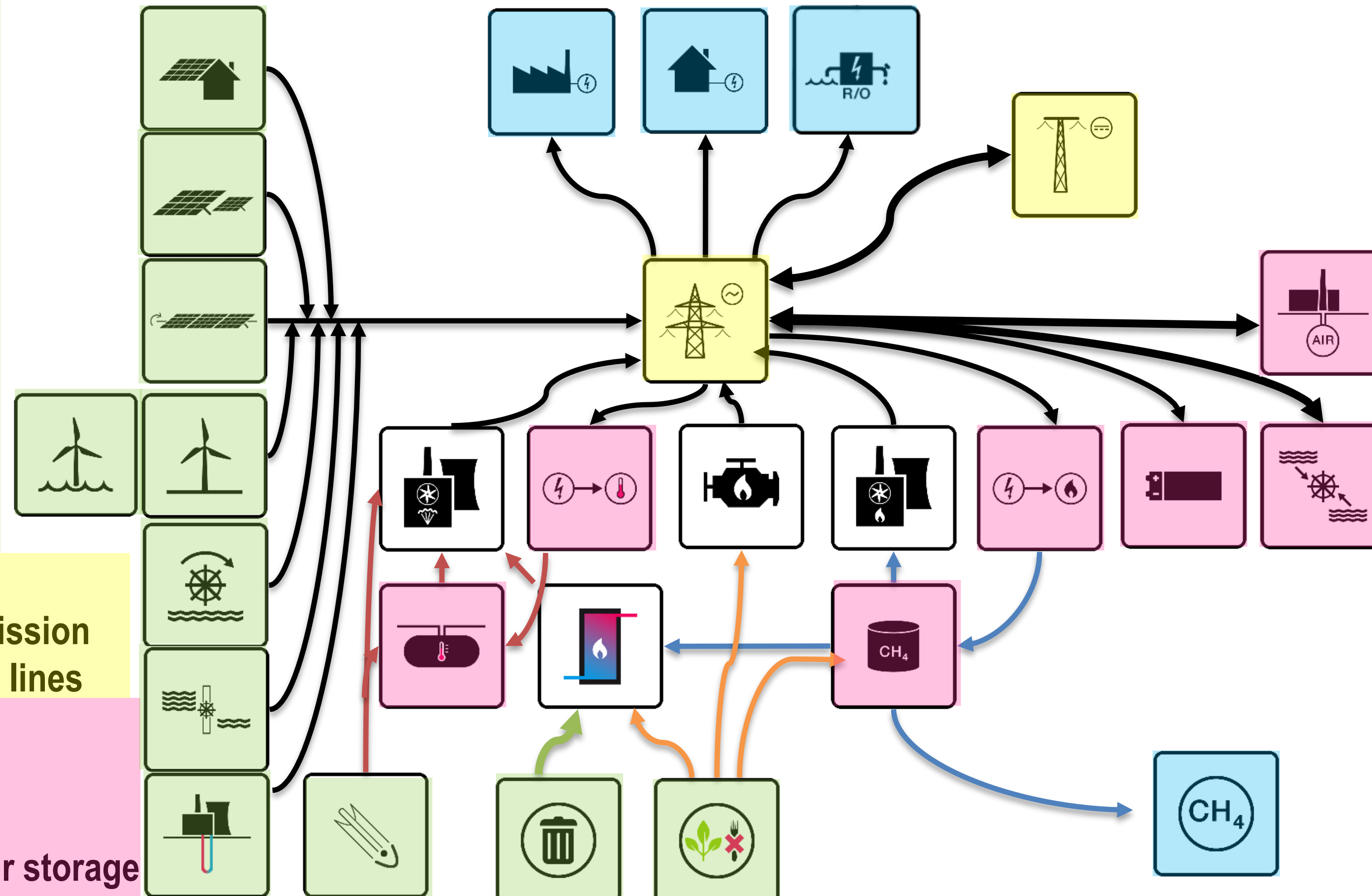
- PV rooftop (RES, COM, IND)
- PV ground-mounted
- PV single-axis tracking
- Wind onshore/ offshore
- Hydro run-of-river
- Hydro dam
- Geothermal energy
- CSP
- Waste-to-energy
- Biogas
- Biomass

Electricity transmission

- node-internal AC transmission
- interconnected by HVDC lines

Storage options

- Batteries
- Pumped hydro storage
- Adiabatic compressed air storage
- Thermal energy storage, Power-to-Heat
- Gas storage based on Power-to-Gas
  - Water electrolysis
  - Methanation
  - CO_2 from air
  - Gas storage



Energy Demand

- Electricity
- Water Desalination
- Industrial Gas

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LUT Energy System Model

Key Objectives

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Definition of an optimally structured energy system based on 100% RE supply

- optimal set of technologies, best adapted to the availability of the regions' resources,
- optimal mix of capacities for all technologies and world structured into 145 sub-regions globally,
- optimal operation modes for every element of the energy system,
- least cost energy supply for the given constraints.

Input data

- historical weather data for: solar irradiation, wind speed and hydro precipitation
- available sustainable resources for biomass and geothermal energy
- synthesized power load data
- non-energetic industrial gas and water desalination demand
- efficiency/ yield characteristics of RE plants
- efficiency of energy conversion processes
- capex, opex, lifetime for all energy resources
- min and max capacity limits for all RE resources
- nodes and interconnections configuration

LUT Energy System model, key features

- linear optimization model
- hourly resolution
- multi-node approach
- flexibility and expandability
- enables energy transition modeling
- overnight scenarios
- energy transition scenarios in 5-year steps

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LUT Energy System Model

publications peer-reviewed

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- **Examples of research with LUT energy model published in peer-reviewed journals (10 in total)**

Breyer et al., 2017

Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2017)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2885

BROADER PERSPECTIVES

On the role of solar photovoltaics in global energy transition scenarios

Christian Breyer[1]*, Dmitrii Bogdanov[1], Ashish Gulagi[1], Arman Aghahosseini[1], Larissa S.N.S. Barbosa[2,3], Otto Koskinen[1], Maulidi Barasa[1], Upeksha Caldera[1], Svetlana Afanasyeva[1], Michael Child[1], Javier Farfan[1] and Pasi Vainikka[2]

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ABSTRACT

The global energy system has to be transformed towards high levels of sustainability in order to comply with the COP21 agreement. Solar photovoltaic (PV) offers excellent characteristics to play a major role in this energy transition. The key objective of this work is to investigate the role of PV in the global energy transition based on respective scenarios and a newly introduced energy transition model developed by the authors. A progressive group of energy transition scenarios present results of a fast growth of installed PV capacities and a high energy supply share of solar energy to the total primary energy demand in the world in the decades to come. These progressive energy transition scenarios can be confirmed. For the very first time, a full hourly modelling for an entire year is performed for the world, subdivided in 145 sub-regions, which is required to reflect the intermittent character of the future energy system. The model derives total installed solar PV capacity requirements of 7.1–9.1 TWp for the electricity sector (as of the year 2015) and 27.4 TWp for the entire energy system in the mid-term. The long-term capacity is expected to be 42 TWp and, because of the ongoing cost reduction of PV and battery technologies, this value is found to be the lower limit for the installed capacities. Solar PV electricity is expected to be the largest, least cost and most relevant source of energy in the mid-term to long-term for the global energy supply.

KEYWORDS
PV demand; battery demand; energy transition scenario; hourly resolution; 100% renewable energy

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1. MOTIVATION

Further development of human welfare is at a crossroads. For several decades, humankind has needed the capacity of more than one planet Earth [1], and 50% of this need is due to the resource exploitation and emissions of the energy system. Access to (diminishing) energy resources [2] have caused in the past and will cause in the future dramatic economic, social, political and military conflicts. Poverty in the world needs to be tackled [3,4] for a still growing world population [5]. The only pathway to manage all these different major problems is a transition [6] towards a fully sustainable energy system, one that is able to cover accelerated growth in demand for energy.

The two key resources for very large scale renewable energy (RE) harvesting are the wind resource and the direct solar resource. The two major solar technologies are solar photovoltaics (PV) and concentrating solar thermal power (CSP), although the future cost competitiveness of CSP is more and more questioned [7]. Solar PV is the fastest growing energy technology in the world [8] and reached a level of 50 GW of new capacity added annually. Financial renewable energy experts expect installations to grow to 80 GW annually (2020), 143 GW (2030) and 206 GW (2040) [7]. The International Energy Agency (IEA) lags behind by projecting annual installations of 37.1 GW (2013–2020), 32.6 GW (2020–2025), 33.6 GW (2025–2030), 34.4 GW (2030–2035) and 33.2 GW (2035–2040) in its New Policies Scenario [9,10], which is not only in

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Gulagi et al. ,2017

sustainability MDPI

Article

Can Australia Power the Energy-Hungry Asia with Renewable Energy?

Ashish Gulagi *, Dmitrii Bogdanov, Mahdi Fasihi and Christian Breyer

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Academic Editor: Arnulf Jäger-Waldau
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Abstract: The Paris Agreement points out that countries need to shift away from the existing fossil-fuel-based energy system to limit the average temperature rise to 1.5 or 2 °C. A cost-optimal 100% renewable energy based system is simulated for East Asia for the year 2030, covering demand by power, desalination, and industrial gas sectors on an hourly basis for an entire year. East Asia was divided into 20 sub-regions and four different scenarios were set up based on the level of high voltage grid connection, and additional demand sectors: power, desalination, industrial gas, and a renewable-energy-based synthetic natural gas (RE-SNG) trading between regions. The integrated RE-SNG scenario gives the lowest cost of electricity (€52/MWh) and the lowest total annual cost of the system. Results contradict the notion that long-distance power lines could be beneficial to utilize the abundant solar and wind resources in Australia for East Asia. However, Australia could become a liquefaction hub for exporting RE-SNG to Asia and a 100% renewable energy system could be a reality in East Asia with the cost assumptions used. This may also be more cost-competitive than nuclear and fossil fuel carbon capture and storage alternatives.

Keywords: East Asia; Australia; 100% renewable energy; power-to-gas; synthetic natural gas; grid integration; system optimization; economics

1. Introduction

In December 2015, the annual Conference of Parties (COP) 21 held in Paris, also known as the Paris Agreement [1] was an action-driven event with several concreate achievements [2]. The conference presented several political and business leaders with the opportunity to take the critical decisions needed to keep the average global temperature rise to no more than 1.5 or 2 °C, which finally requires net zero greenhouse gas emissions shortly after the middle of this century [1]. According to Schellnhuber et al. [3], the 2 °C limit is economically achievable due to rapidly falling costs of renewable energy, particularly solar PV, but is constrained by politics. It is observed that change is happening in energy supply for a lot of countries, but this needs to happen faster. The region of interest for this research is East Asia, which is comprised of Northeast Asia and Southeast Asia, the latter including Australia and New Zealand.

Energy is a key driver for social and economic development, particularly in developing countries where many people have no access to basic forms of energy. Many developing countries have programs to electrify the non-electrified population and at the same time maintain a high level of economic development. Thus, the demand for electricity is growing very fast, particularly in East Asia. According to Taggart [4], leading up to 2050, East Asia—comprised of China, Japan, the ASEAN states, and Australia—will become the world's largest economy. To keep up with economic development and improve living conditions, there will be a rapid increase in energy needs, which will put our climate at risk, as the energy sector is one of the main sources of greenhouse gas

Sustainability **2017**, *9*, 233; doi: 10.3390/su9020233 www.mdpi.com/journal/sustainability

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Bogdanov and Breyer, 2016

Energy Conversion and Management 112 (2016) 176–190

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Energy Conversion and Management

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

ELSEVIER

North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options

CrossMark

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Keywords:
100% renewable energy
North-East Asia
Energy system optimization
Grid integration
Power-to-gas
Storage

ABSTRACT

In order to define a cost optimal 100% renewable energy system, an hourly resolved model has been created based on linear optimization of energy system parameters under given constrains. The model is comprised of five scenarios for 100% renewable energy power systems in North-East Asia with different high voltage direct current transmission grid development levels, including industrial gas demand and additional energy security. Renewables can supply enough energy to cover the estimated electricity and gas demands of the area in the year 2030 and deliver more than 2000 TW h_{th} of heat on a cost competitive level of 84 €/MW h_{el} for electricity. Further, this can be accomplished for a synthetic natural gas price at the 2013 Japanese liquefied natural gas import price level and at no additional generation costs for the available heat. The total area system cost could reach 69.4 €/MW h_{el}, if only the electricity sector is taken into account. In this system about 20% of the energy is exchanged between the 13 regions, reflecting a rather decentralized character which is supplied 27% by stored energy. The major storage technologies are batteries for daily storage and power-to-gas for seasonal storage. Prosumers are likely to play a significant role due to favourable economics. A highly resilient energy system with very high energy security standards would increase the electricity cost by 23% to 85.6 €/MW h_{el}. The results clearly show that a 100% renewable energy based system is feasible and lower in cost than nuclear energy and fossil carbon capture and storage alternatives.

1. Introduction

Fast economic growth in the North-East Asian region provoked an extensive rise in electricity demand, based mainly on fossil fuel utilization, in the last decades [1]. Increasing ecological and social problems are caused by the fossil fuel based energy system, including increased anthropogenic pressure on nature in general [2] and an ongoing destruction of ecosystems all around the world [3]. This anthropogenic pressure leads in particular to climate change [4], which will have a dramatic negative impact on the economy on a global scale, as concluded by Stern [5]. Harmful and costly consequences of coal-based air pollution [6] have to be further taken into account for the full societal cost of energy supply. These issues drive the idea for a renewable energy (RE) based system development up to 100% RE [7] and the discussion of its competitiveness on a global scale [8] and in a rather distributed manner [9]. It is feasible that RE based systems can decrease the anthropogenic footprint [10] in particular since the most important RE technologies show a continued strong growth and the large majority of countries in the world have introduced respective policies [11].

Scenarios of energy systems based on very high shares of RE had been already discussed for several countries and regions. Connolly and Mathiesen [12] showed for the case of Ireland in an hourly modeling that 100% RE is technically feasible and economic affordable. Henning and Palzer [13] discussed that a 100% RE system for the sectors electricity and heat is technically doable and the cost are comparable to the current energy system, also based on hourly resolution. Thellufsen and Lund [14] pointed out that energy efficiency measures in the electricity and heat sector can even generate positive synergies for 100% RE for the example of Denmark. Critz et al. [15] emphasized that demand response measures help to integrate a high penetration of renewables into the existing system and that it can reduce the overall cost for the case of Hawaii. Huber et al. [16] found on the case of the ASEAN region that a well balanced mix of renewable resources and a geographic integration of a larger region is required for balancing high shares of RE.

Komoto et al. [17] proposed very large scale solar photovoltaic power plants for North-East Asia pointing out that excellent renewable resources of a large unpopulated region, such as the Gobi desert, can be utilized for a very large region by applying a

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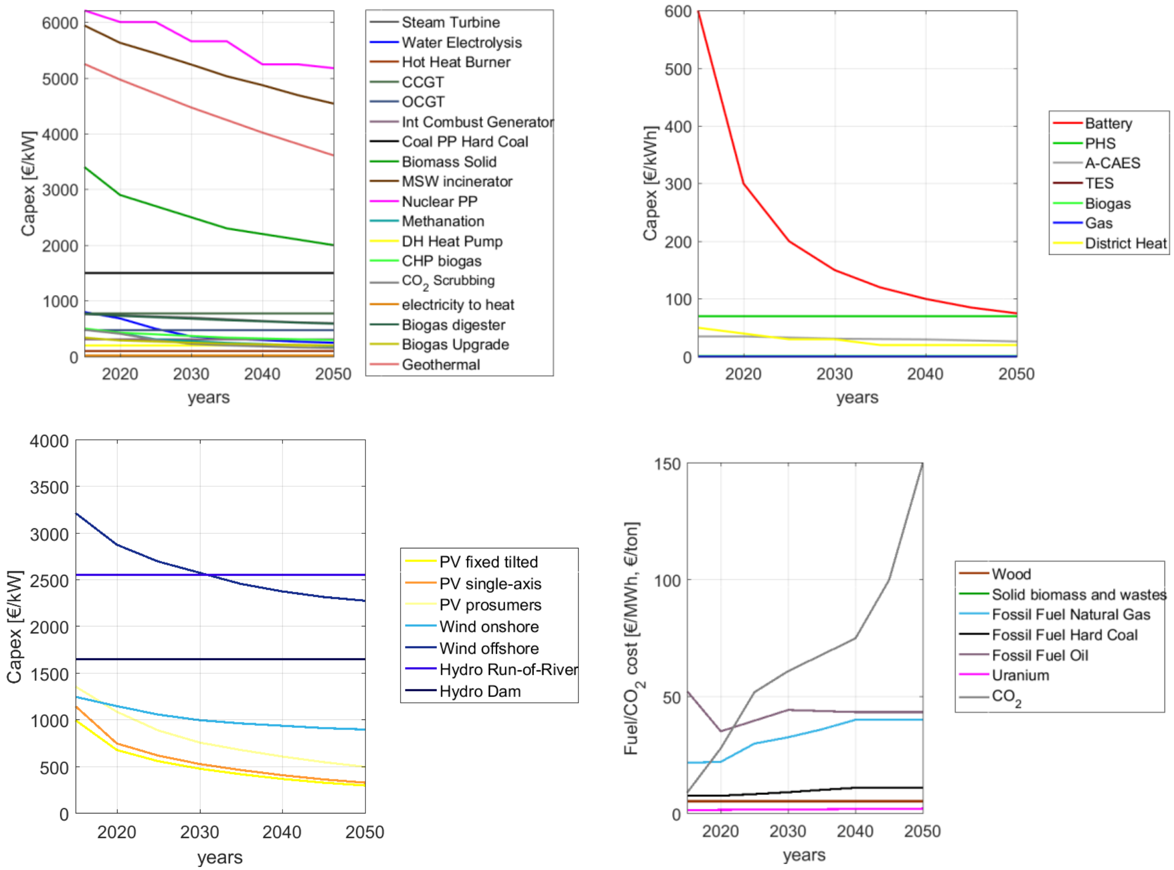
NEO CARBON ENERGY

LUT Energy System Model

Data – Financial Assumptions

- Capex variation based on learning curves
- Least cost power plant capacities based on
  - Cost
  - Efficiency of generation and storage
  - Power to energy ratio of storage
  - Available resource
- WACC is set to 7% for all years
- Fuel costs
  - 47.3 €/MWh_{th} for oil (~100 USD/bbl in 2020 and ~+2.1%/a)
  - 22.2 €/MWh_{th} for gas (in 2020 and ~+3.0%/a)



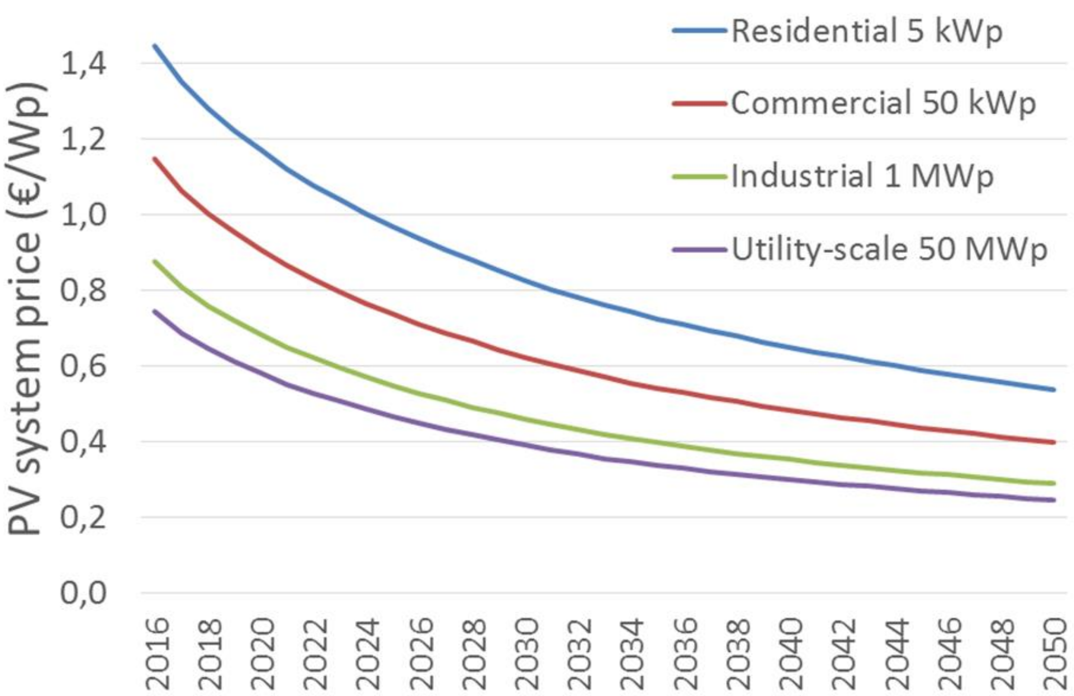
Variation in capex from 2015 – 2050 for all power plant components utilised by model. Detailed capex, fixed opex, efficiency and power to energy ratio numbers are presented at end of slide set

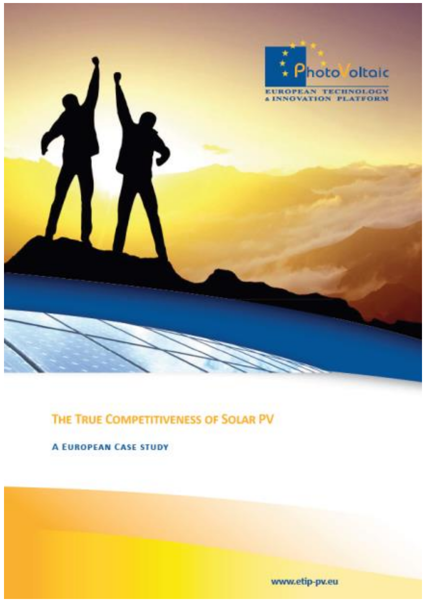
NEO CARBON

source: Gulagi A., et al., 2017. The Demand for Storage Technologies in Energy Transition Pathways Towards 100% Renewable Energy for India, IRES, Düsseldorf

LUT Energy System Model

Data – Financial Assumptions: PV update





source: ETIP-PV, 2017. The True Competitiveness of Solar PV – A European Case Study

- capex variation based on learning curves, market growth
- PV capex has been continuously too high in own work during the last 10 years
- PV most important in energy transition scenarios, hence very good capex understanding required
- now split into 5 types of PV segments (rooftop RES/ COM/ IND, ground-mounted fixed, tracking)

NEO CARBON ENERGY

Agenda

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Results: Global view for Overnight 2030

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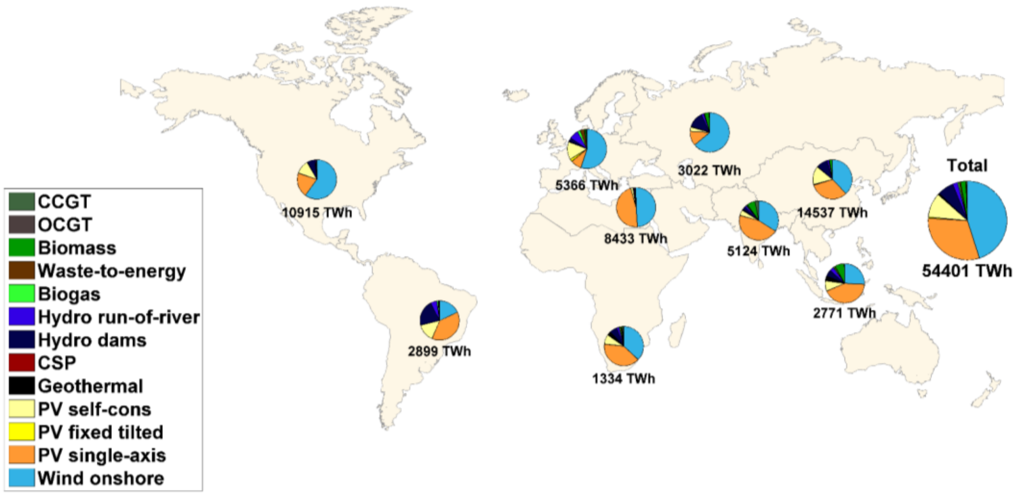

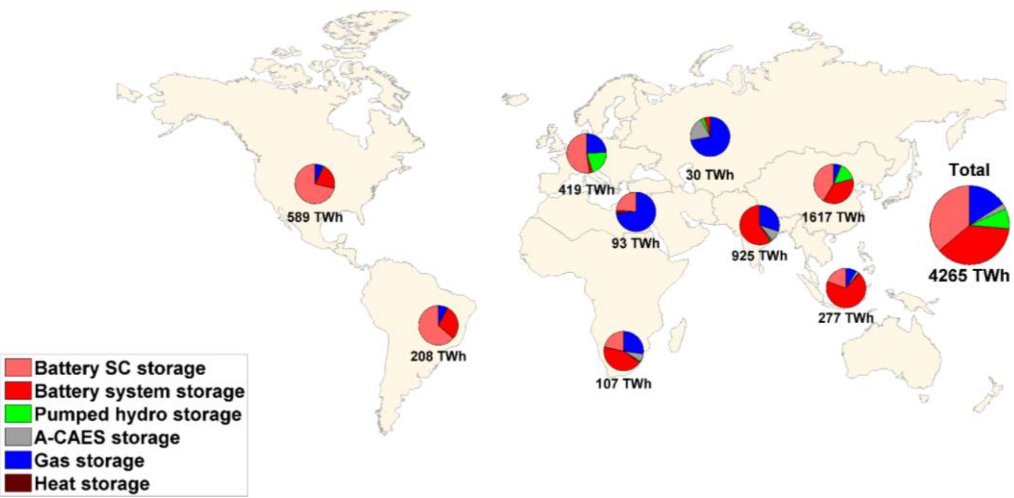

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source: Breyer Ch., Bogdanov D., et al., 2017. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, Progress in Photovoltaics

Scenarios assumptions

Generation profile (area integrated) for Europe

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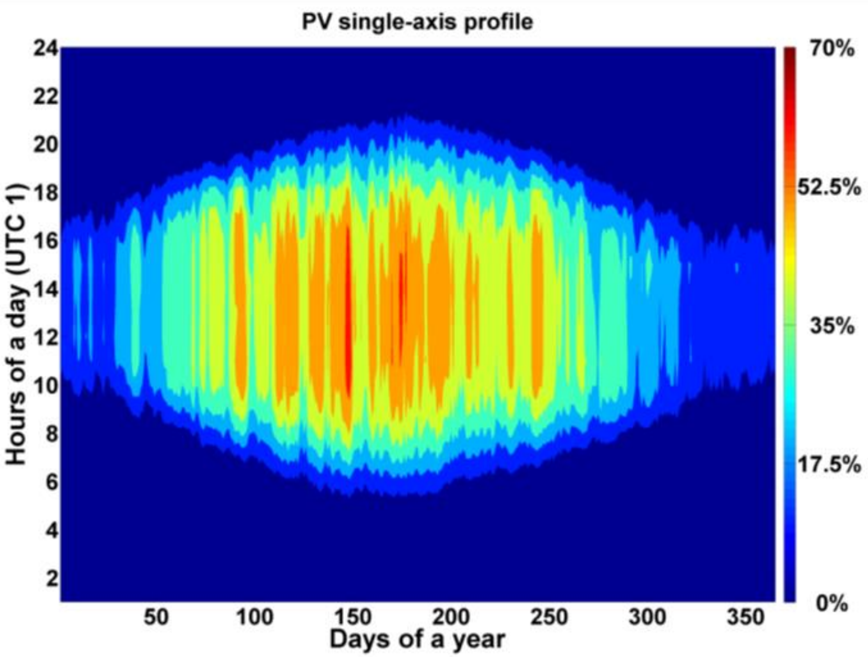
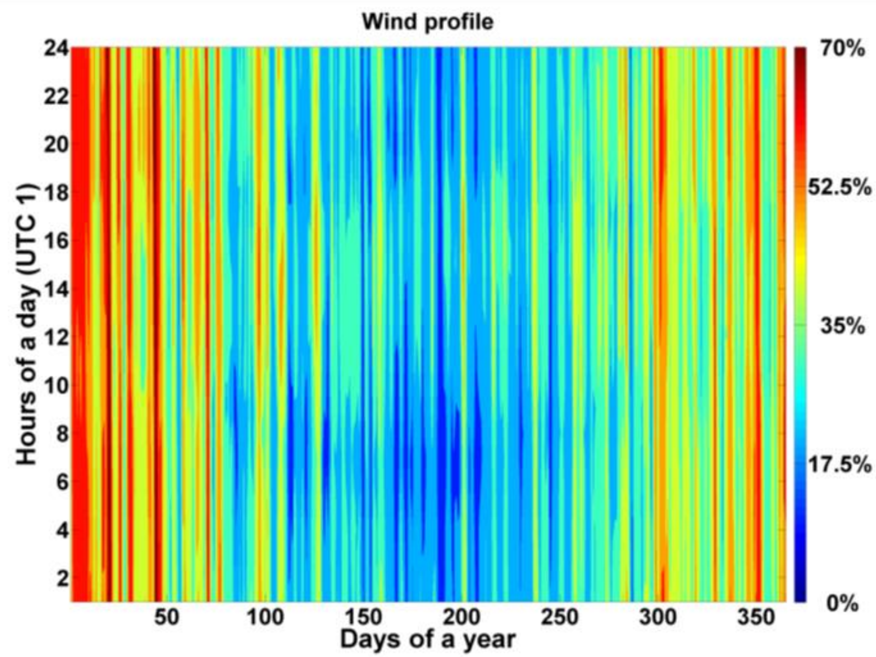
PV generation profile

Aggregated area profile computed using earlier presented weighed average rule.

Wind onshore generation profile

Aggregated area profile computed using earlier presented weighed average rule.





Key insights:

- seasonal complementary of PV and wind

NEO CARBON

Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

source: Breyer Ch., Child M., et al., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17

Results

Regions Electricity Generation and Storage (year 2030) – area-wide open trade

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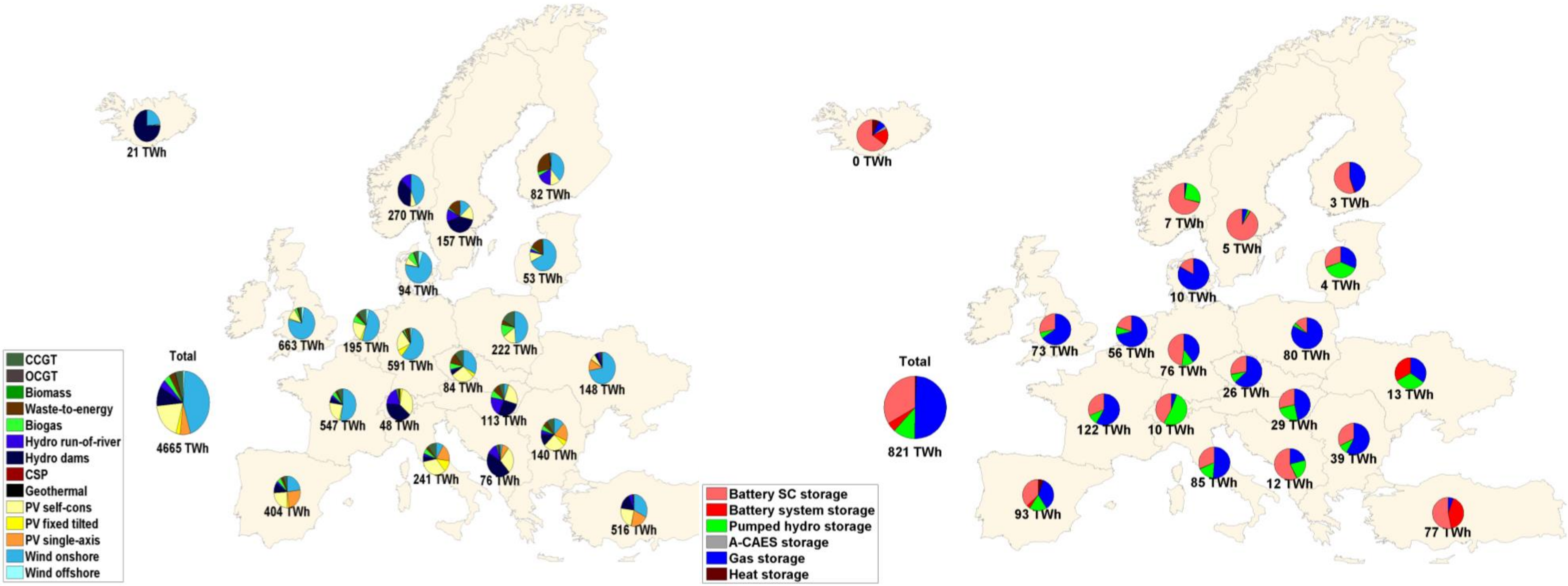
Area-wide open trade



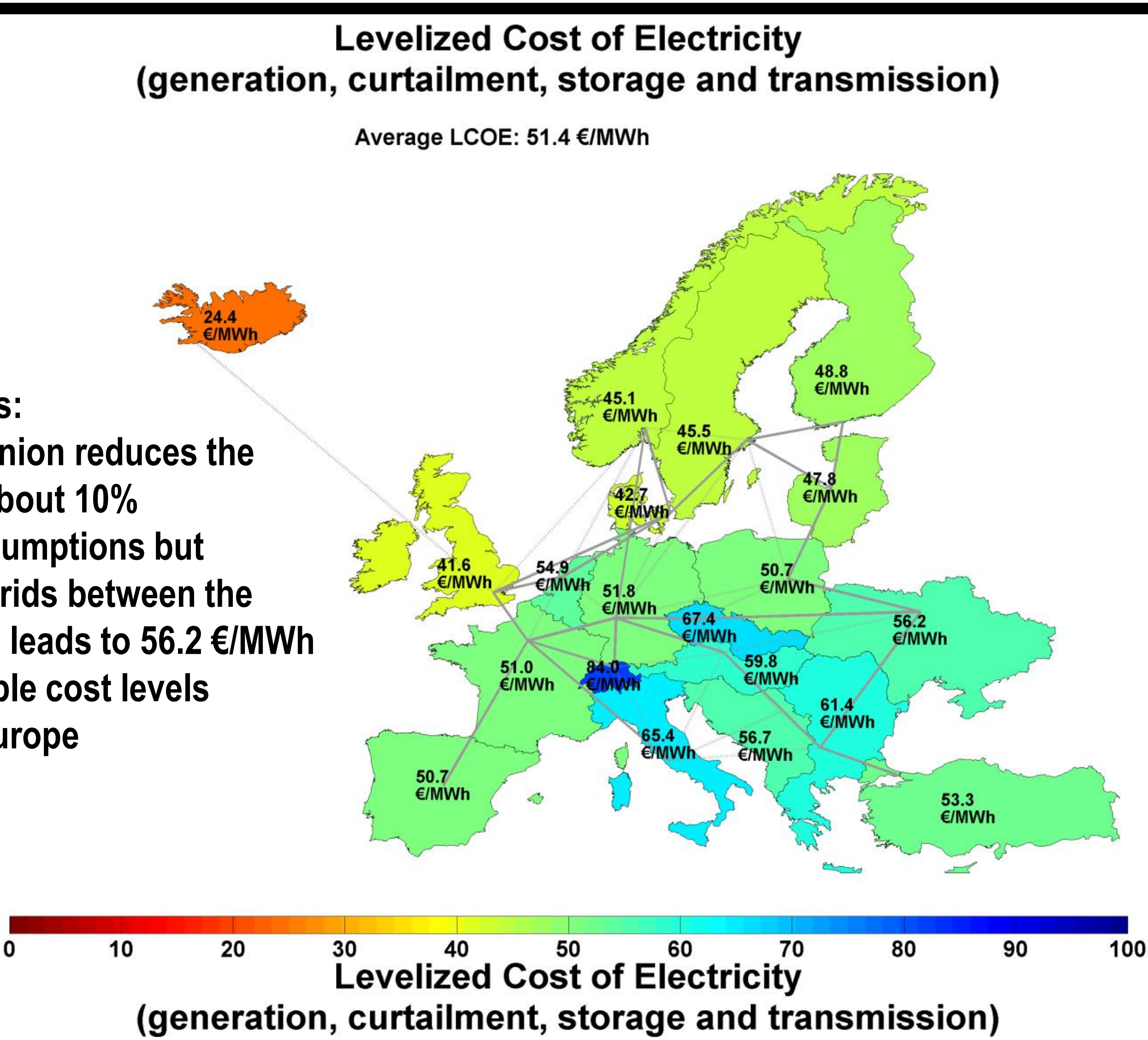
Key insights:

- significant role of hydropower generation in Nordic countries, Austria, Switzerland, Balkan East, Turkey
- solar PV represents approximately 29% of total energy generation
- >50% wind share in Baltic, Germany, Benelux, Denmark, British Isles, France, Ukraine
- wind has largest role in total generation across regions (48-50%)
- existing PHS storage plays significant role
- relative share of prosumer batteries increases in integration scenario in several regions

source: Breyer Ch., Child M., et al., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17

Results

Total LCOE (year 2030) – Area-wide open trade total



Key insights:

- Energy Union reduces the cost by about 10%
- same assumptions but without grids between the countries leads to 56.2 €/MWh
- comparable cost levels across Europe

source: Breyer Ch., Child M., et al., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17

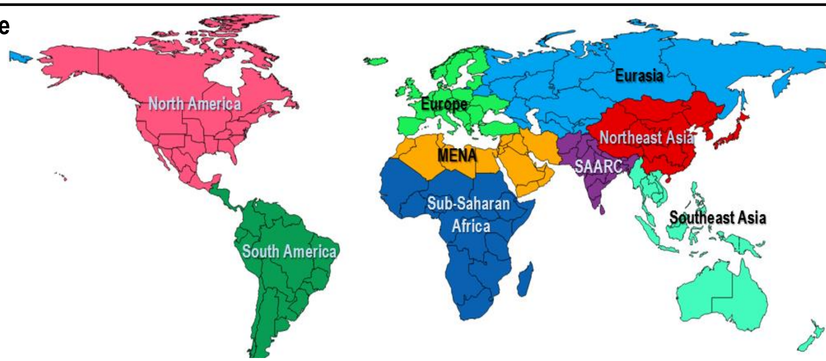
Overview on World's Regions: Overnight 2030

Regions	LCOE region-wide [€/MWh]	LCOE area-wide [€/MWh]	Integra-tion benefit ** [%]	Storage * [%]	Regional grid trade* [%]	Curtail-ment [%]	PV prosu-mers* [%]	PV system * [%]	Wind * [%]	Biomass * [%]	Hydro* [%]
Northeast Asia	63	56	6.0%	7%	10%	5%	16.4%	35.4%	40.9%	2.9%	11.6%
Southeast Asia	67	64	9.5%	8%	3%	3%	7.2%	36.8%	22.0%	22.9%	7.6%
India/ SAARC	72	67	5.9%	22%	23%	3%	6.2%	43.5%	32.1%	10.9%	5.4%
Eurasia	63	53	23.2%	<1%	13%	3%	3.8%	9.9%	58.1%	13.0%	15.4%
Europe	56	51	11.2%	7%	16%	3%	18.1%	11.1%	51.7%	6.4%	14.1%
MENA	61	55	10.8%	<1%	10%	5%	1.8%	46.4%	48.4%	1.3%	1.1%
Sub-Saharan Africa	58	55	16.2%	4%	8%	4%	16.2%	34.1%	31.1%	7.8%	8.2%
North America	63	53	10.1%	1%	24%	4%	11.0%	19.8%	58.4%	3.7%	6.8%
South America	62	55	7.8%	5%	12%	5%	12.1%	28.0%	10.8%	28.0%	21.1%

* Integrated scenario, supply share
** annualised costs, results from older simulation

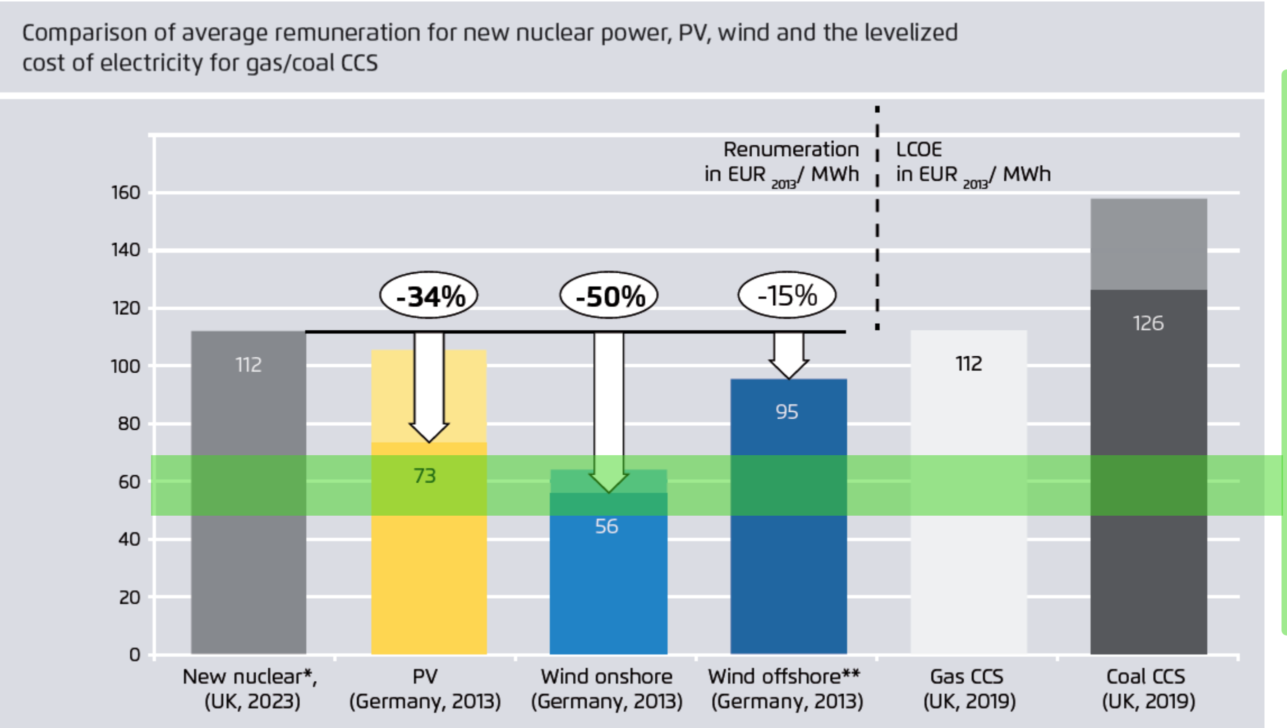
Key insights:

- 100% RE is highly competitive
- least cost for high match of seasonal supply and demand
- PV share typically around 40% (range 15-51%)
- hydro and biomass limited the more sectors are integrated
- flexibility options limit storage to 10% and it will further decrease with heat and mobility sector integration
- most generation locally within sub-regions (grids 3-24%)



sources: see www.researchgate.net/profile/Christian_Breyer

Cost comparison of ’cleantech’ solutions



Preliminary NCE results clearly indicate 100% RE systems cost about 55-70 €/MWh for 2030 cost assumptions on comparable basis

source: Breyer Ch., Bogdanov D., et al., 2017. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, Progress in Photovoltaics

Key insights:

- PV-Wind-Gas is the least cost option
- nuclear and coal-CCS are too expensive
- nuclear and coal-CCS are high risk technologies
- 100% RE systems are highly cost competitive

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source: Agora Energiewende, 2014. Comparing the Cost of Low-Carbon Technologies: What is the Cheapest option; Grubler A., 2010. The costs of the French nuclear scale-up: A case of negative learning by doing, Energy Policy, 38, 5174

Agenda

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Energy Transition Modeling: Europe

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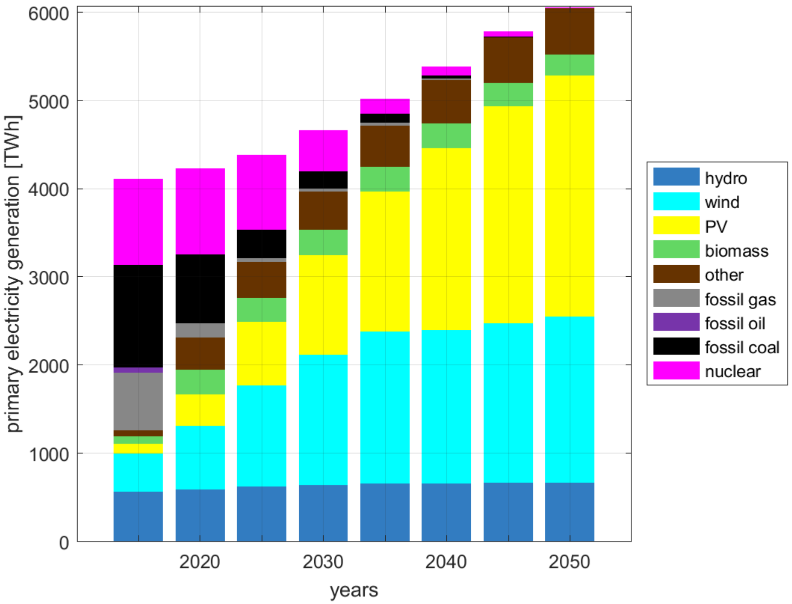

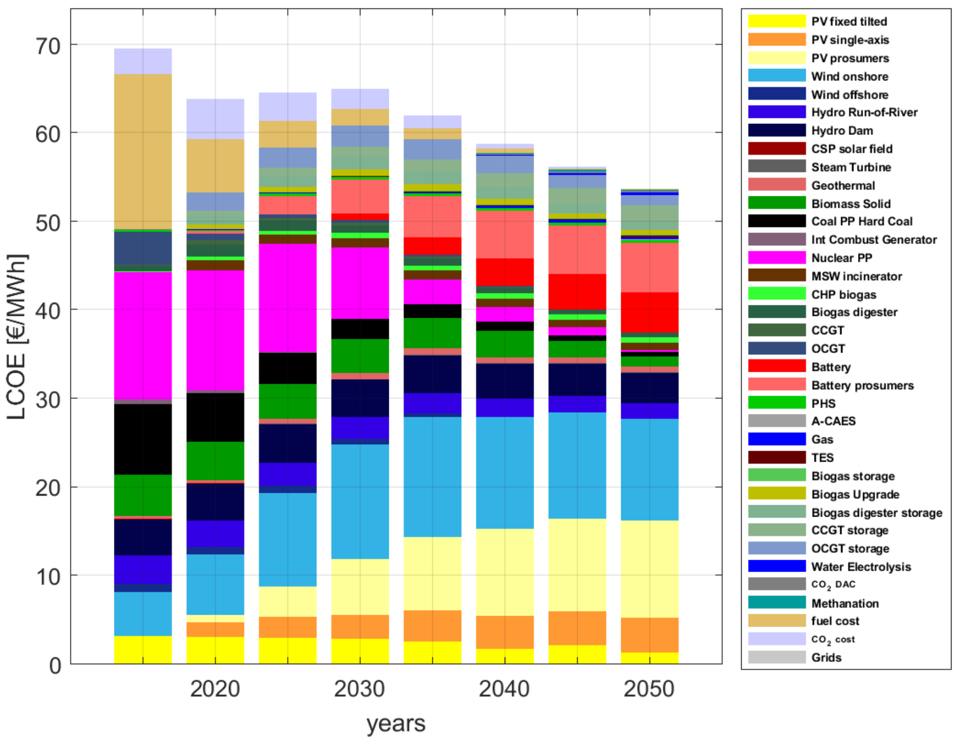

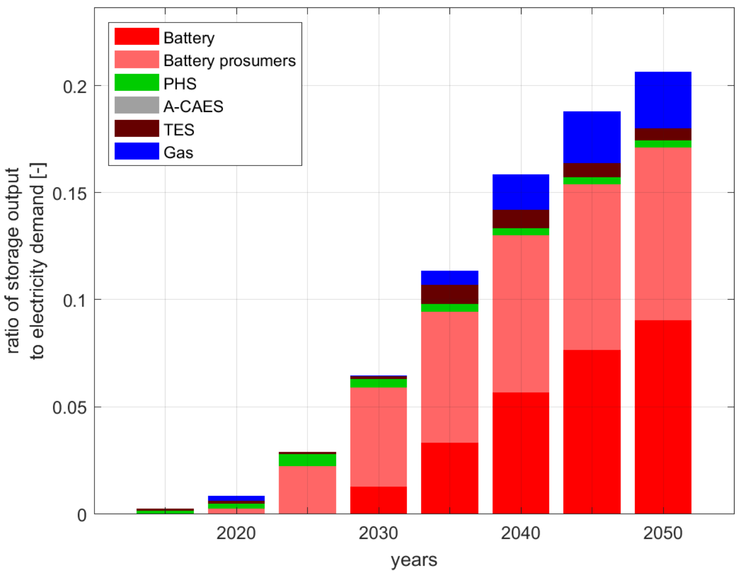

Key insights:

- energy system transition model for 145 regions forming 92 countries
- results here are for Europe (in limits of IS, PT, TR, UA, EE, FI)
- LCOE decline on energy system level driven by wind/PV + battery
- beyond 2030 solar PV grows much more than wind energy
- wind and PV + battery finally run the system more and more
- solar PV supply share in 2050 at about 45% as least cost
- capacities in 2050: solar PV of ~2000 GWp and wind of ~600 GW
- LCOE of 54 €/MWh are further reduced to 46 €/MWh for 2050 cost

Energy Transition Modeling: Europe

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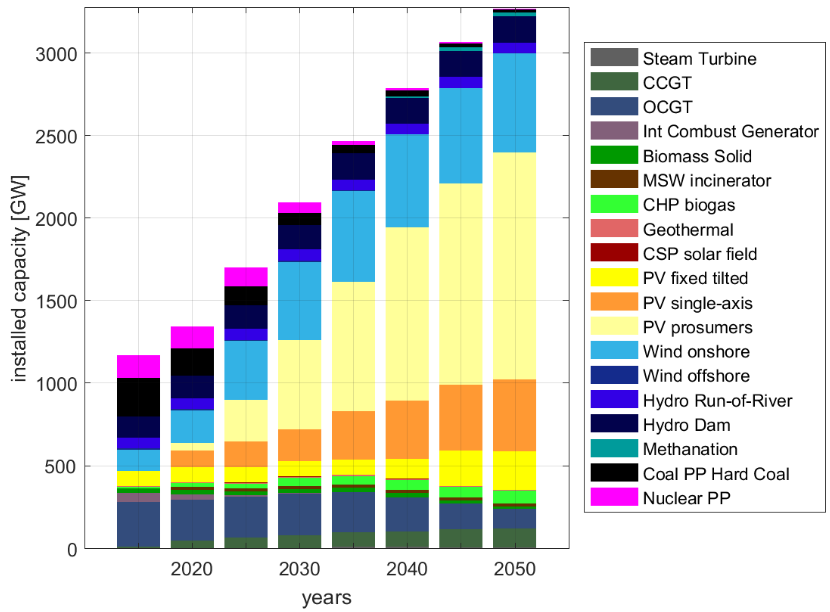
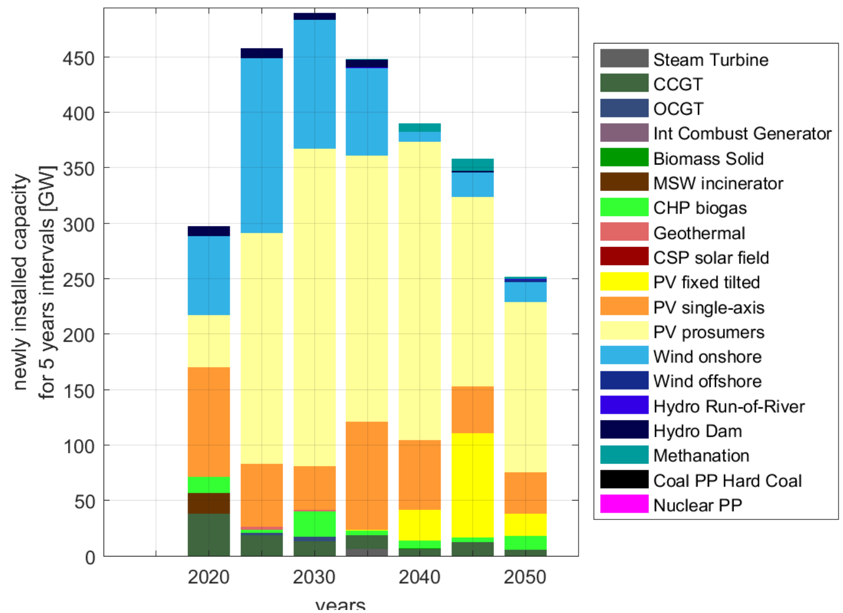
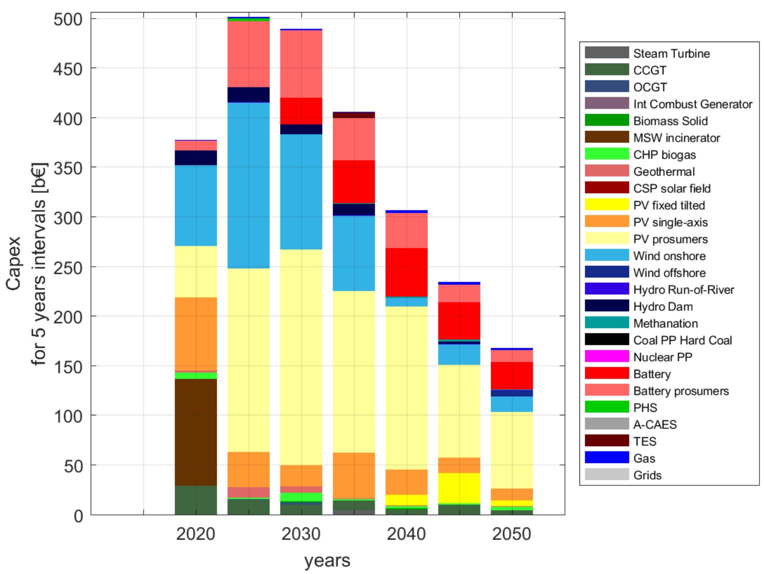
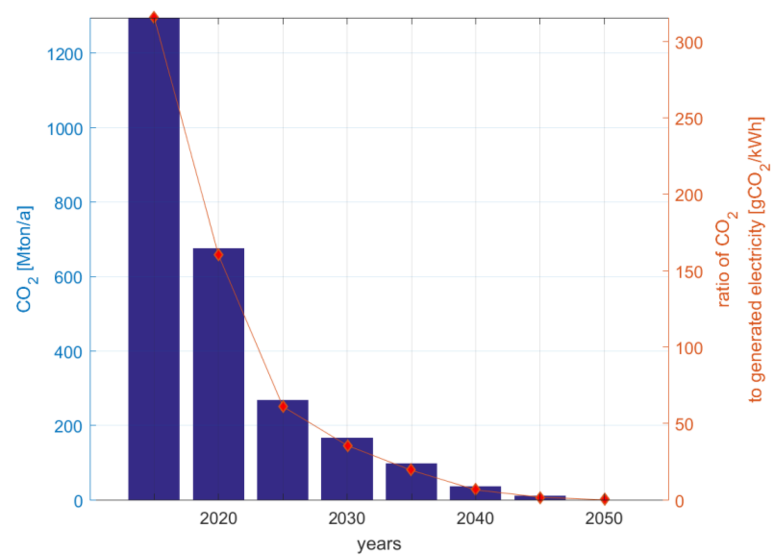






Sector



Energy Transition Modeling: Global and Europe

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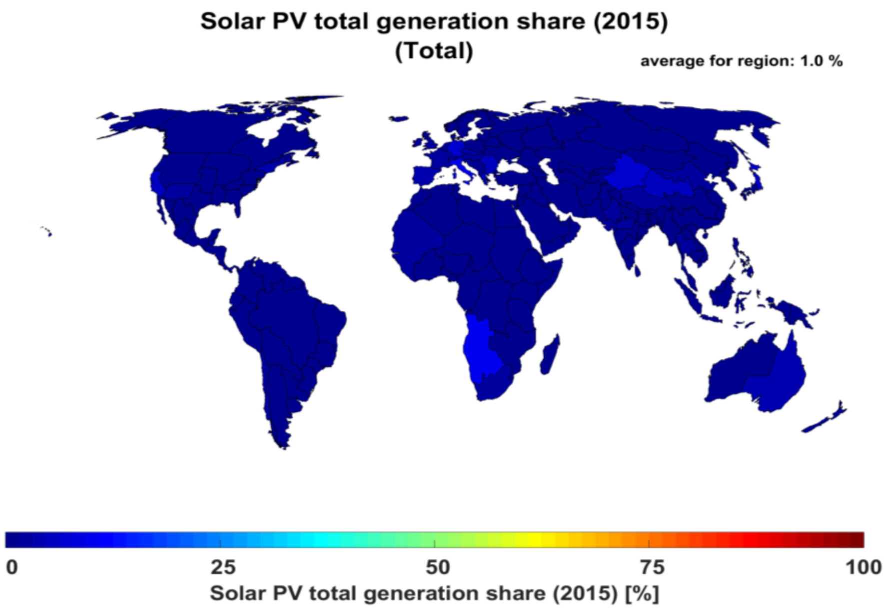
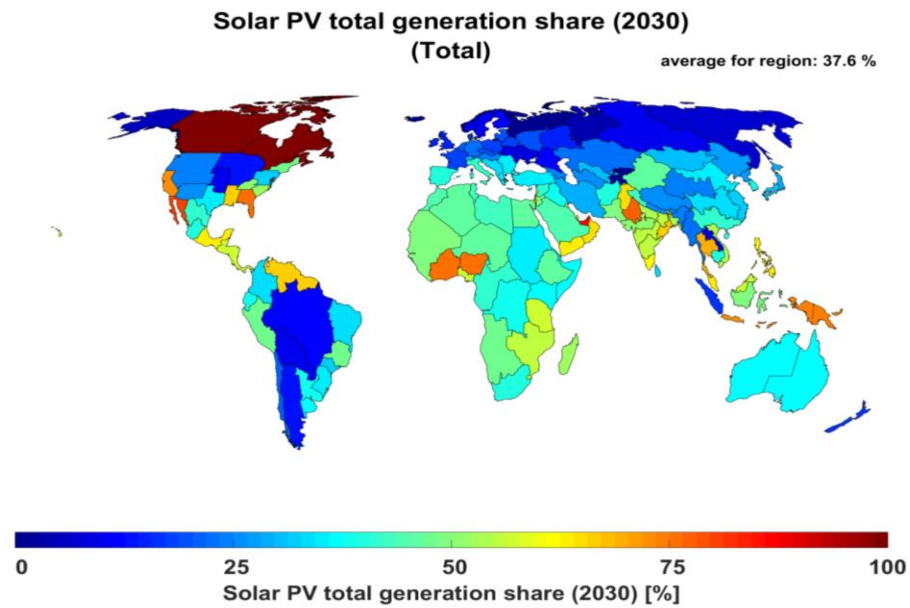
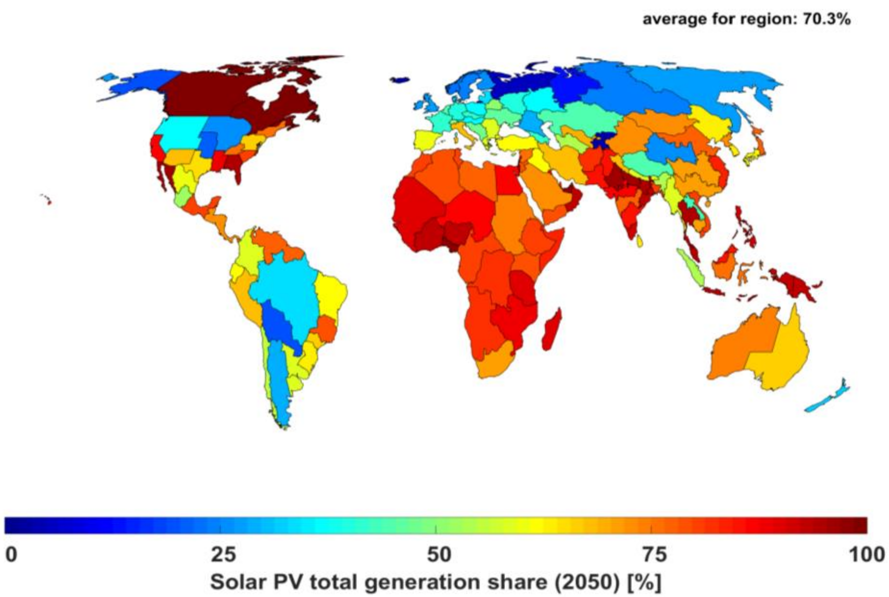


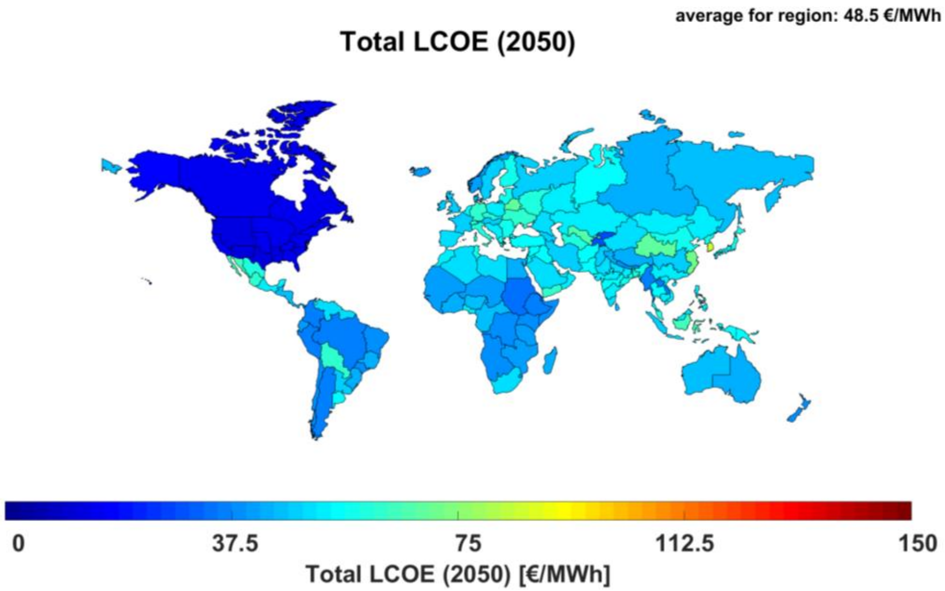


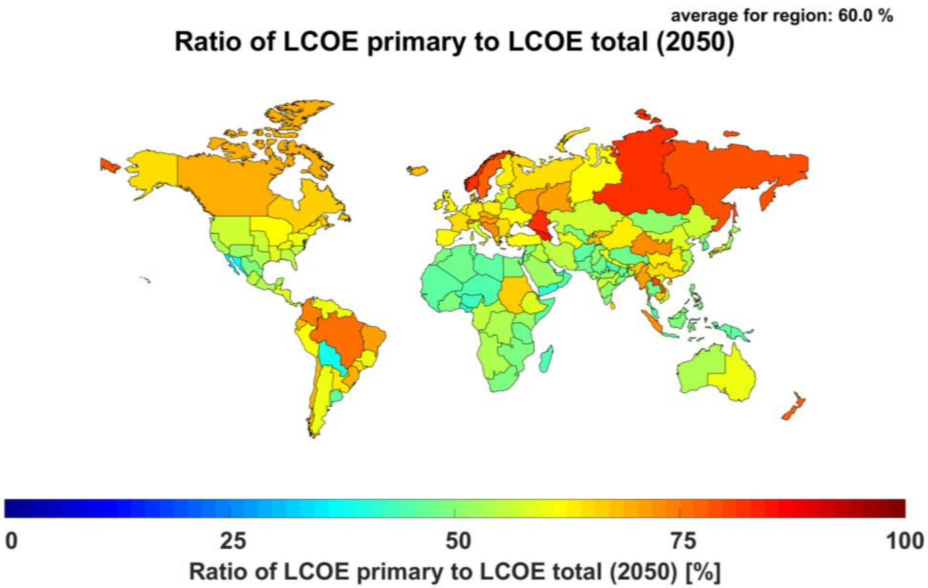


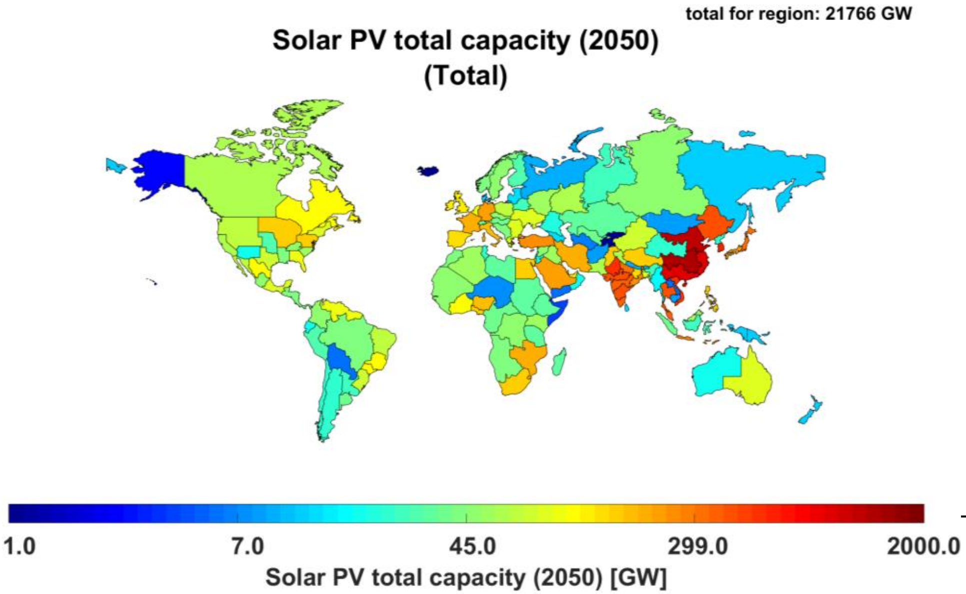
Key insights:

- 1.0% electricity share by 2015
- Strong growth till 2030 would be possible
- By 2050 solar PV could be the dominating source of electricity
- Canada is still in progress for simulations
- Countries in the Sun Belt would be almost fully dominated by solar PV, e.g. Africa, India, Southeast Asia, Central America
- Regions of strong seasons and excellent wind show lower PV values, as well as the few hydro power and geotherrmal regions
- solar PV supply share in 2050 at about 70% (!!) as least cost

Energy Transition Modeling: Global and Europe







Key insights:

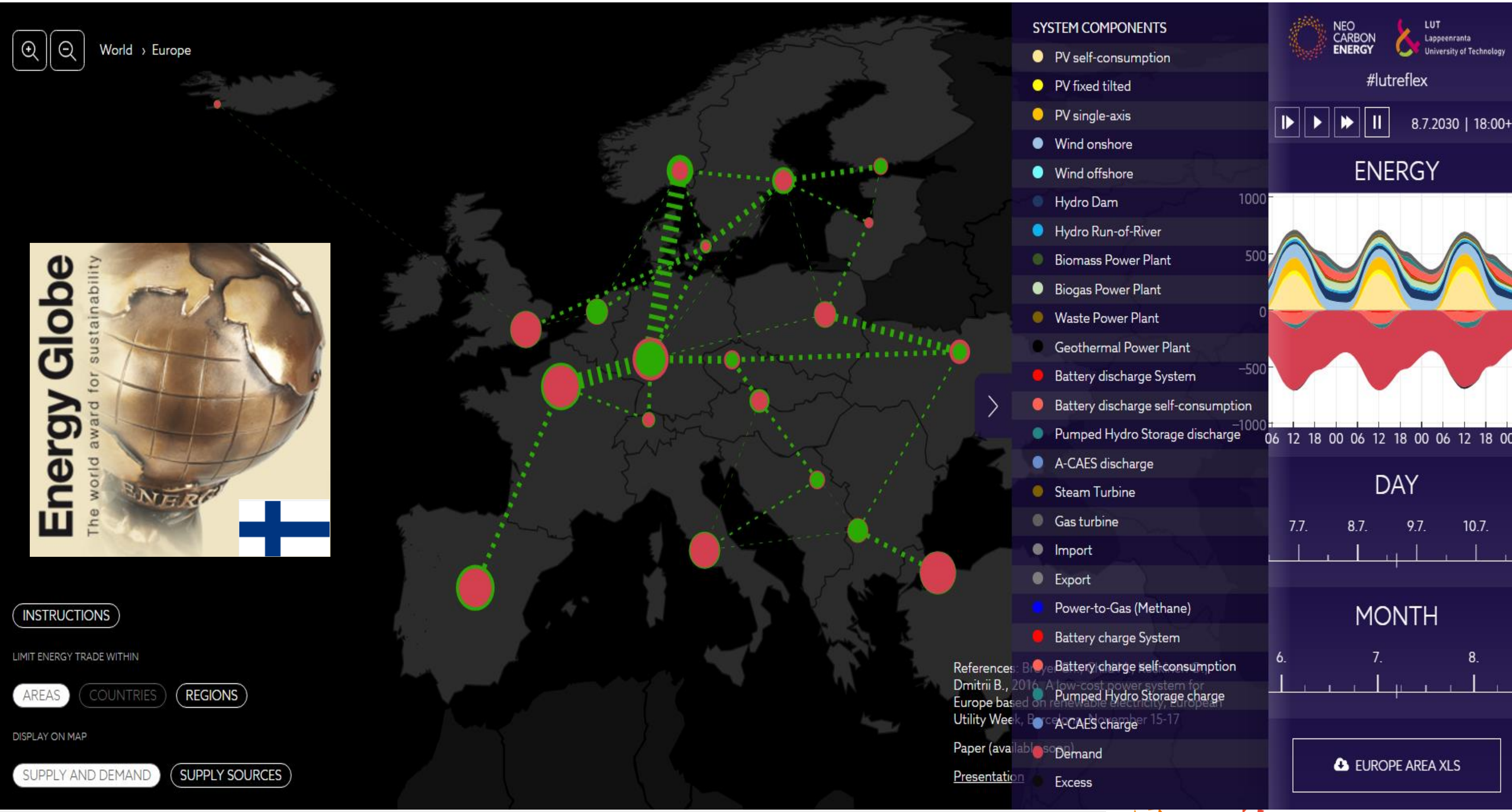
- Total LCOE by 2050 around 50 €/MWh (incl. generation, storage, curtailment, some grid cost)
- 60% ratio of primary generation cost to total LCOE
- Total PV installed capacity around 22 TWp (ONLY for today's power sector)

Global Internet of Energy

Global Internet of Energy: http://neocarbonenergy.fi/internetofenergy/#

Global Internet of Energy: Europe

Global Internet of Energy: http://neocarbonenergy.fi/internetofenergy/#



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Summary

- Total LCOE on a European average is around 54 €/MWh for 100% RE in 2050 (incl. generation, curtailment and storage) – further reduced to 46 €/MWh for 2050 cost
- Solar PV share can reach about 45% by 2050 in electricity supply (equal to ~2000 GWp)
- Battery investments enable a high solar PV share, driven by prosumers
- Sector integration and Energy Union further decreases the cost
- Wind energy may not grow anymore much after 2030-2040
- Seasonal variations are the key reason for keeping wind energy in the system
- 100% RE system is more cost competitive than a nuclear-fossil option!

Personal note:

- Policy failures caused the loss of almost all European manufacturing capacities for the number 1 global energy technology in this century
- This unacceptable status has to be fixed, asap.

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

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The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14.

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

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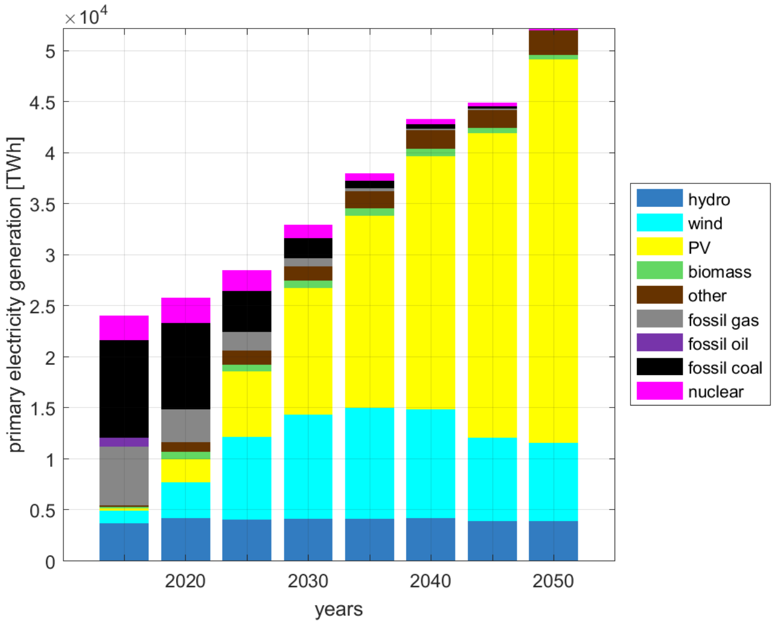
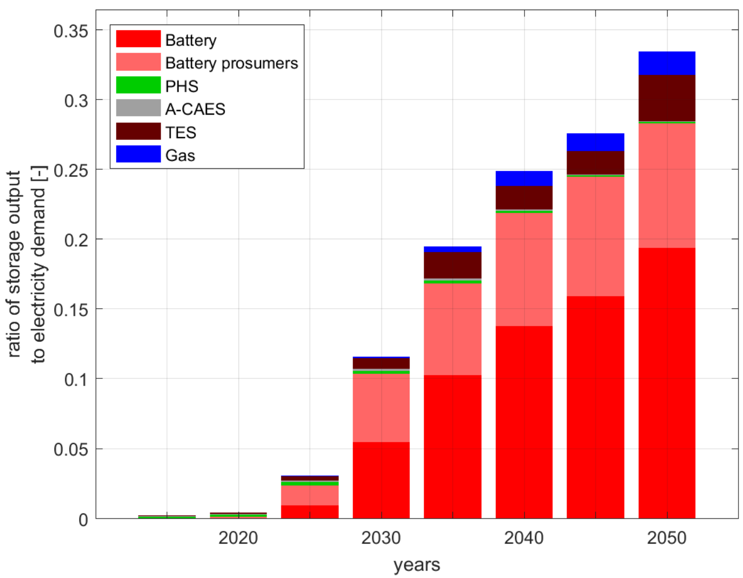
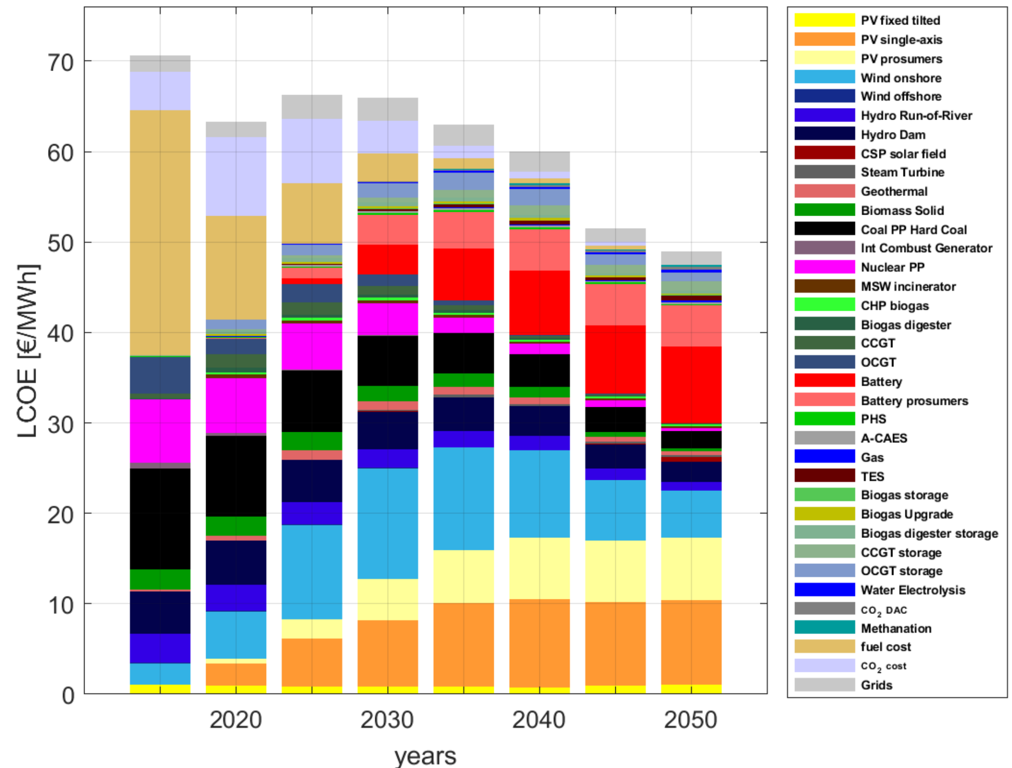
Back-up Slides

Energy Transition Modeling: Global







Key insights:

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Sector

Energy Transition Modeling: Global

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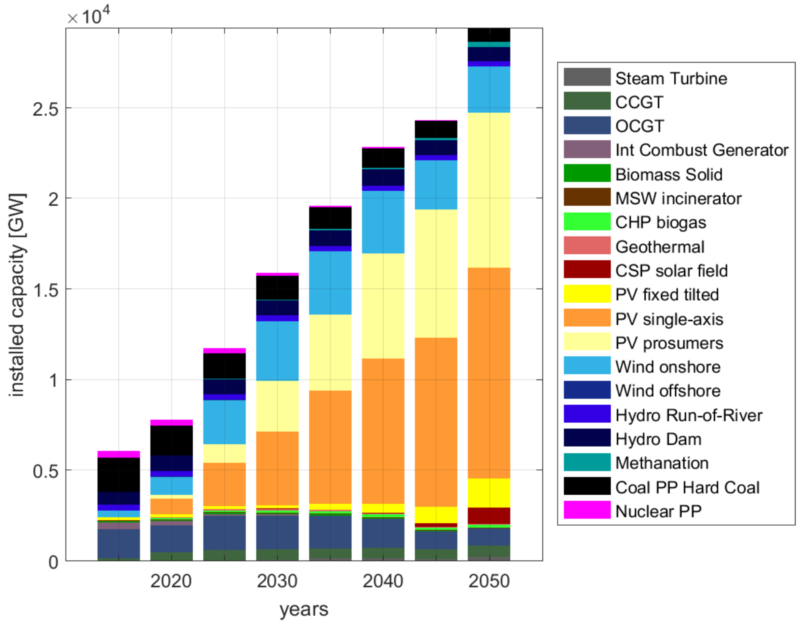
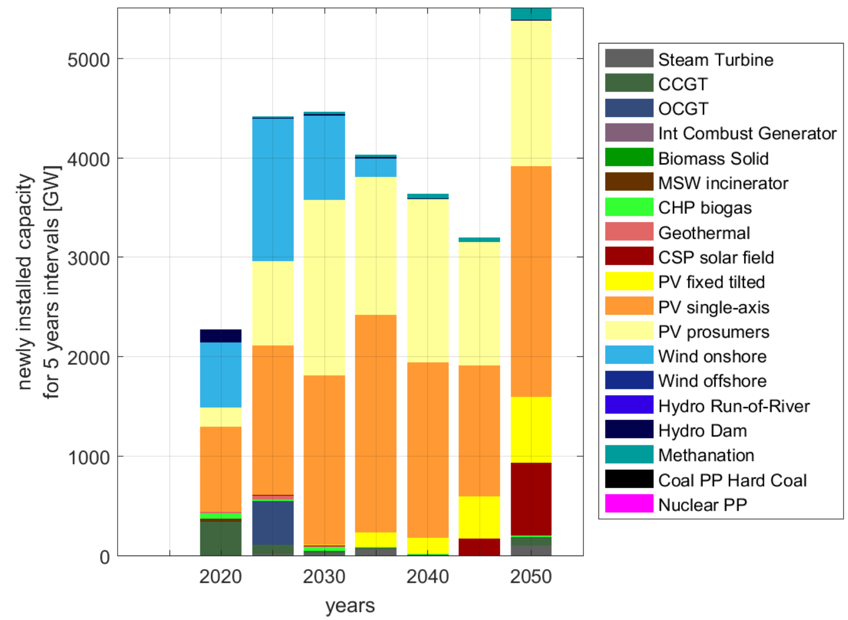
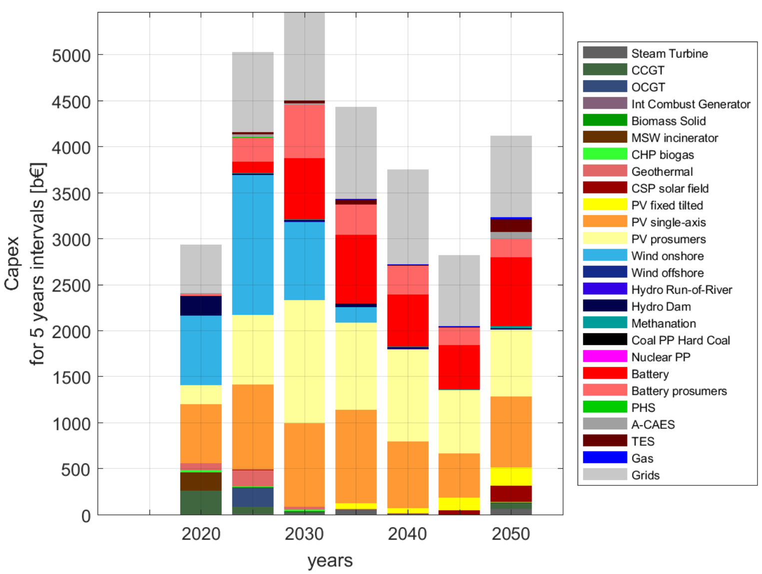
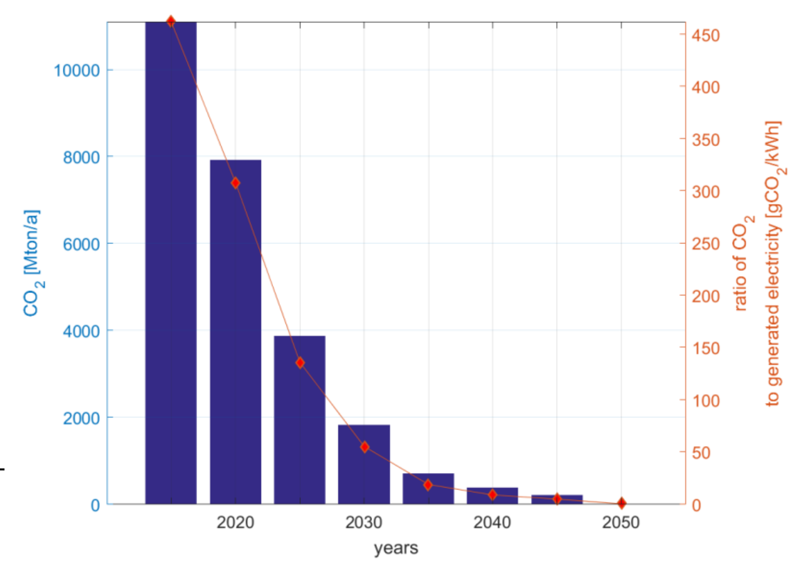






Sector



Temporal Resolution in Global Scenarios

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Table 1. Energy storage in global scenarios.

Study (year)	Energy storage assessment	Temporal resolution	Remarks	Type of study
IEA WEO Special (2015)	Total demand of 400 GW by 2050. Increasing level of variable renewables requires conventional power plants, energy storage and demand response.	Yearly*	Renewable share in primary energy grows from 1% (2013) to 5% (2030), excl. hydro and bio. Energy storage could alleviate transmission constraints. Solar and wind power are given an availability factor based on hourly generation and load profiles. *Power generation curve based on hourly data	Report [21]
BP Energy Outlook 2035 (2015)	-	1+ years	Intermittency seen as constraint for RE growth	Report [28]
Statoil Energy Perspectives (2015)	Intermittency of solar and wind power is overcome with energy storage, smart-grids and natural gas turbines	1+ years	10% RE (excl. hydro and bio) in primary energy in 2040	Report [31]
Troendle (2014)	Europe 150 TWh (3.8% of the el. demand), Australia 13 TWh (4.9%), South America 45 TWh (4.3%), North America 113.8 TWh (2.2%), New Zealand 2.4 TWh (5.4%), Asia 172 TWh (1.9%), Africa 35.7 TWh (5.6%)	Hourly	100% renewable el. system, Europe 70/30 PV/Wind power ratio, 10% excess production capacity results in 50% storage reduction	Dissert. [23]
Plessman et al. (2014)	RPM 1960 TWh, Thermal energy storage 73.6 TWh, Battery 1.5 TWh	Hourly	100% renewable el. system with 2020 cost and 2010 demand basis, 50/50 PV/Wind power ratio	Article [22]
ExxonMobil The Outlook for Energy 2040 (2014)	-	1+ years	Gas-fired power plants seen necessary back-up for wind and solar	Report [29]
MIT Energy and Climate Outlook 2050 (2014)	-	1+ years	Fossil fuels and nuclear account for 91% of primary energy in 2050	Report [27]
IEA-PVPS (2013)	On-grid storage can be faster than grid reinforcement, thus essential for completing a VLS-PV project in time	1+ years	PV and VLS-PV provide 22 – 25% of global primary energy need in 2100. PV capacity 133 TW in 2100, of which 50% is VLS.	Book [33]
Shell New Lens (2013)	H2 infrastructure for storing and transporting energy implemented after 2020	1+ years	Primarily reformed from gas, by 2060 60% of passenger cars use electricity and H2 as fuel	Report [36]
WEC World Energy Scenarios (2013)	Storage seen as solution to intermittency of RE	Seasonal and day-night	26% renewable el. generation in 2050 (symphony scenario, excl. hydro and bio)	Report [32]
Aboumahboub (2012)	Restricted grid scenario: 60 TWh energy storage or 130 TWh in case costs are reduced 40%	Hourly**	Near 100% renewable share in el. sector 2050, 60 – 80% of produced el. inter-regionally transported. Storage can reduce transcontinental transmission capacity from total of 10 TW to 7 TW. **The total year is represented by 6-13 weeks	Dissert. [24]
IIASA GEA (2012)	Storage one solution for accommodating over 20 – 50% renewable el. generation	5 years	30 – 75% share of RE in primary energy by 2050, in some regions over 90%	Report [10]
SEI Global Scenarios (2012)	Storage will be key to achieve high renewable el. penetration	Yearly	28% RE share in primary energy in 2050 (excl. hydro and bio)	Report [34]

Key insights:

- no global report exists in full hourly resolution
- all kinds of flexibility cannot be modelled without proper temporal resolution:
  - resource complementarity
  - supply side management
  - demand side management
  - grids
  - storage
  - sector coupling
- three global energy system modeling publications had hourly resolution: two dissertations and the first article of Plessman & Breyer et al.
- having no detailed global scenario in proper temporal resolution is a major failure of the energy system modeling community in discussing the climate change mitigation options

source: Koskinen O. and Breyer Ch., 2016. Energy Storage in Global and Transcontinental Energy Scenarios: A Critical Review, Energy Procedia, 99, 53-63

NEO CARBON ENERGY

100% RE Scenarios: Country to Global

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Listed by Heard et al., 2017. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems, RSER

Mason et al. [9,104]	2010, 2013	J	New Zealand
Australian Energy Market Operator (1) [8]	2013	R	Australia (NEM–only)
Australian Energy Market Operator (2) [8]	2013	R	Australia (NEM–only)
Jacobson et al. [112]	2015	J	USA
Wright and Hearps [60]	2010	R	Australia (total)
Fthenakis et al. [133]	2009	J	USA
Allen et al. [27]	2013	R	UK
Connolly et al. [19]	2011, 2014	J	Ireland
Fernandes and Ferreira [119]	2014	J	Portugal
Krajacic et al. [20]	2011	J	Portugal
Esteban et al. [17]	2012	J	Japan
Budischak et al. [118]	2013	J	USA - PJM Interconnection
Elliston et al. [22]	2013	J	Australia (NEM–only)
Lund and Mathiesen [16]	2009	J	Denmark
Cosic et al. [11]	2012	J	Macedonia
Elliston et al. [75]	2012	J	Australia (NEM–only)
Jacobsen et al. [18]	2013	J	USA - New York State
Price Waterhouse Coopers [10]	2010	R	Europe and North Africa
European Renewable Energy Council [26]	2010	R	EU27
ClimateWorks [116]	2014	R	Australia
World Wildlife Fund [108]	2011	R	Global
Jacobsen and Delucchi [24,25]	2011	J	Global
Jacobson et al. [113]	2014	J	California
Greenpeace (Teske et al.) [15]	2012, 2015	R,J	Global

NEO CARBON ENERGY

100% RE Scenarios: Country to Global

Missing in Heard et al., 2017:

Blakers et al.	2012	J	Southeast Asia & Australia
Huber et al.	2015	J	ASEAN
Bussar et al.	2014, 2015	J	EU-MENA
Grossmann et al.	2014	J	Americas
Scholz	2012	D	Europe & North Africa
Rasmussen et al.	2012	J	Europe
ECF	2010	R	Europe & North Africa
Czisch	2005	D	Europe, North Africa
Troendle	2014	D	Europe
Aboumahboub	2012	D	Global
Matthew & Patrick	2010	R	Australia
Henning & Palzer	2014	J	Germany
ADEME	2015, 2016	R	France
Plessmann et al.	2014	J	Global
Child & Breyer	2016	J	Finland
Bogdanov & Breyer	2015, 2016	J	Northeast Asia
Gulagi et al.	2017	J	Southeast Asia
Barbosa et al.	2017	J	South America
Breyer et al.	2017	J	Global
Barbosa et al.	2016	J	Brazil
Plessmann & Blechinger	2017	J	EU28
Gulagi et al.	2017	J	East Asia
WWF	2015	R	Uganda
Aghahosseini et al.	2016	C	North America
Aghahosseini et al.	2016	C	MENA
Bogdanov & Breyer	2015	C	Eurasia
Gulagi et al.	2016	C	India/ SAARC
Barasa et al.	2016	C	Sub-Saharan Africa

Oyewo et al.	2017	C	Nigeria
Caldera et al.	2016	C	Saudi Arabia
Aghahosseini et al.	2016	C	Iran
Ghorbani et al.	2017	C	Iran
Child et al.	2017	C	Ukraine
Gulagi et al.	2017	C	India
Lu et al.	2017	J	Australia
Gils & Simon	2017	J	Canary Islands
UBA	2010, 2013	R	Germany
SEI	2009	R	Europe
UBA	2014	R	Germany, Europe
Breyer et al.	2014	R	Germany
Teske et al.	2016	R	Australia
Turner et al.	2013	J	Australia
Moeller et al.	2014	J	Berlin-Brandenburg
Mathiesen et al.	2015	J	Denmark
Lund et al.	2011	R	Denmark
Child et al.	2017	J	Åland

Please send me more documents, in case you think one is missing: journal articles, reports, dissertations, conference papers

100% RE Scenarios: Country to Global

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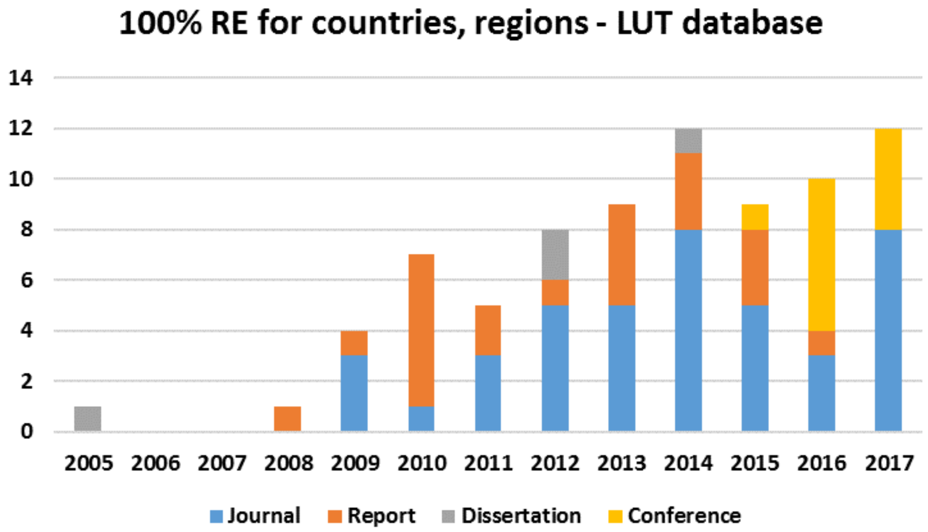
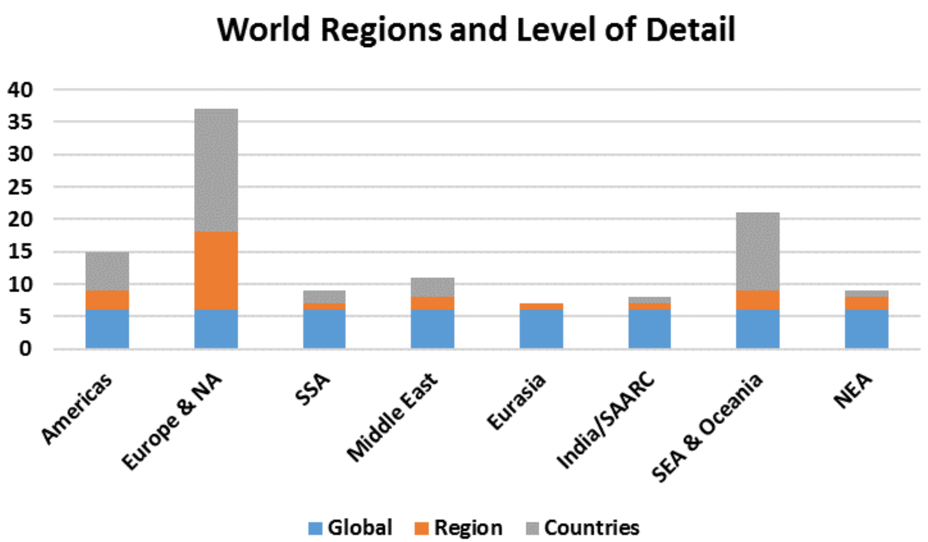


Key insights:

- rather new field of research
- several papers are expected to miss
- good coverage in journals
- not much research on global level
- most major world regions are not yet covered
- Europe seems to be understood best (region and country-wise)
- Australia shows highest country records (10)
- most countries are still ’terra incognita’

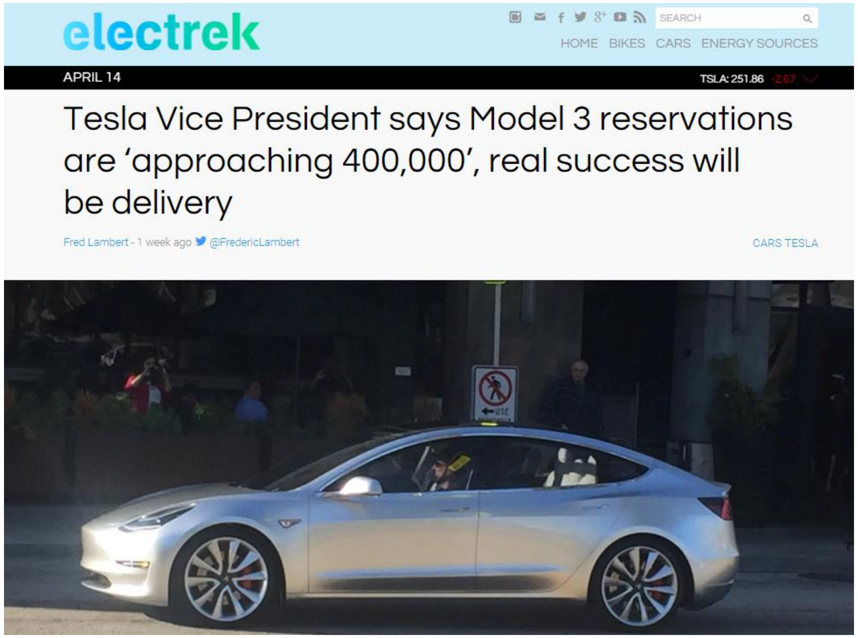


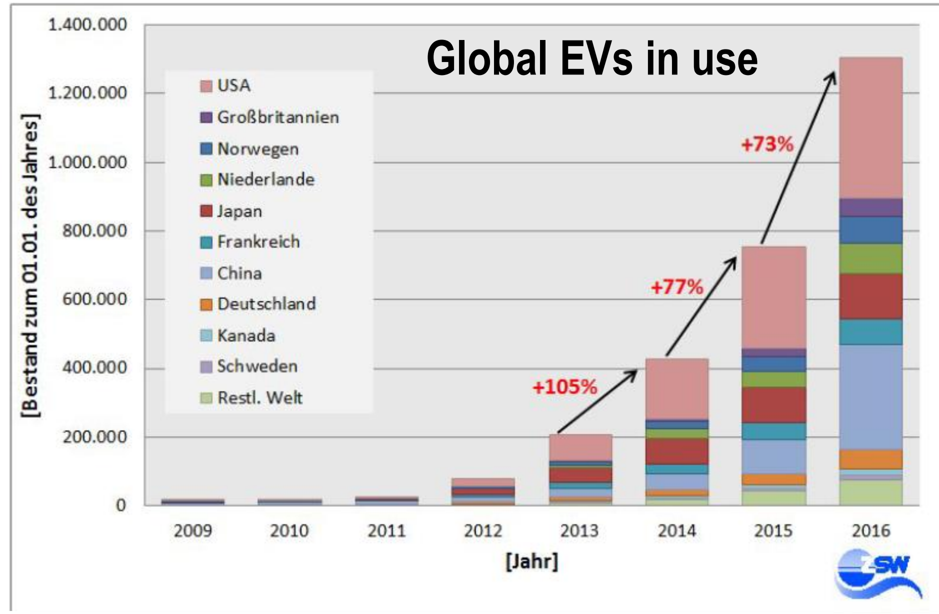
Special comments:

- Jacobson et al. produce country results, but non-hourly analysis leads to respective results
- Breyer et al. are currently working on 145 regions, aggregated to 92 countries in full hourly resolution and energy transition in 5-year steps for 100% RE in 2050 for power sector

NEO CARBON ENERGY

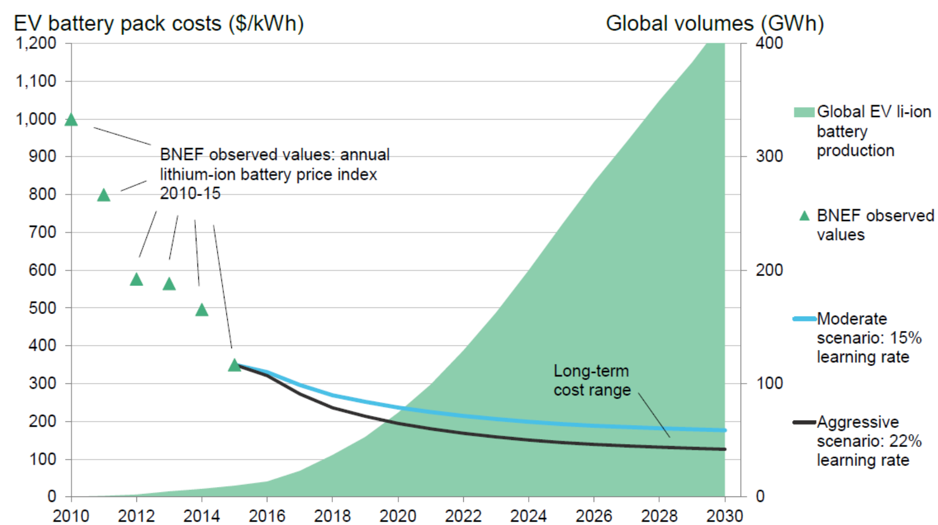
Batteries and EVs – Very high dynamics



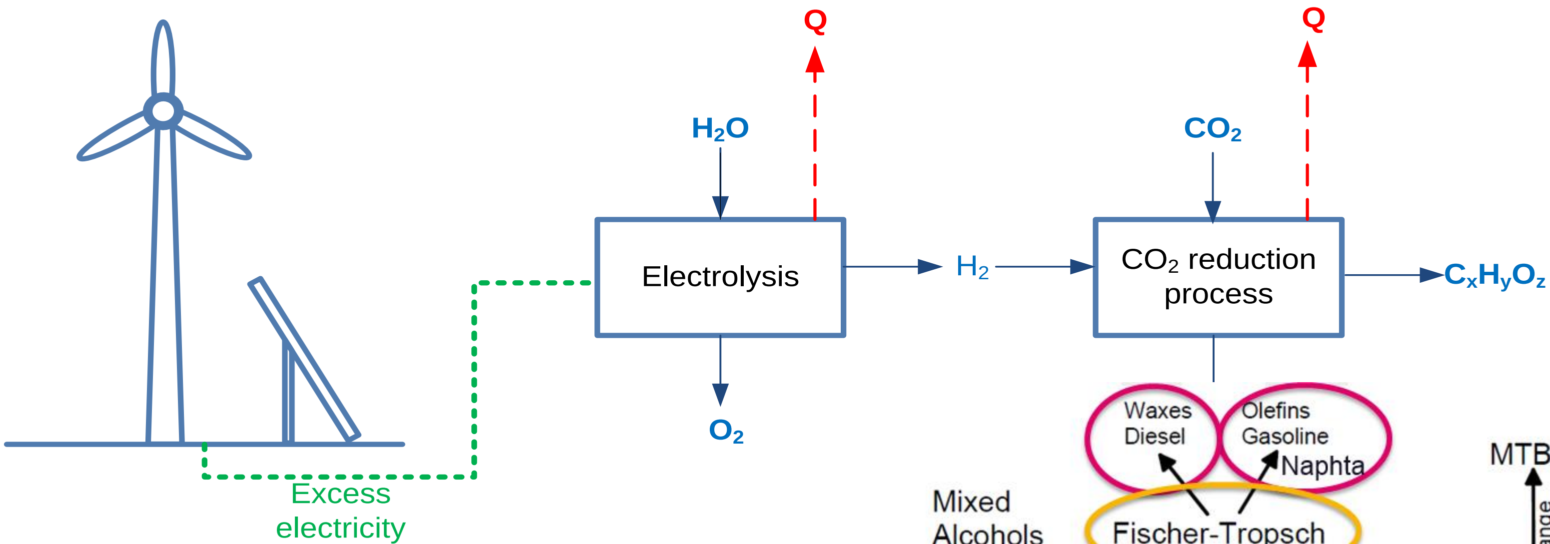


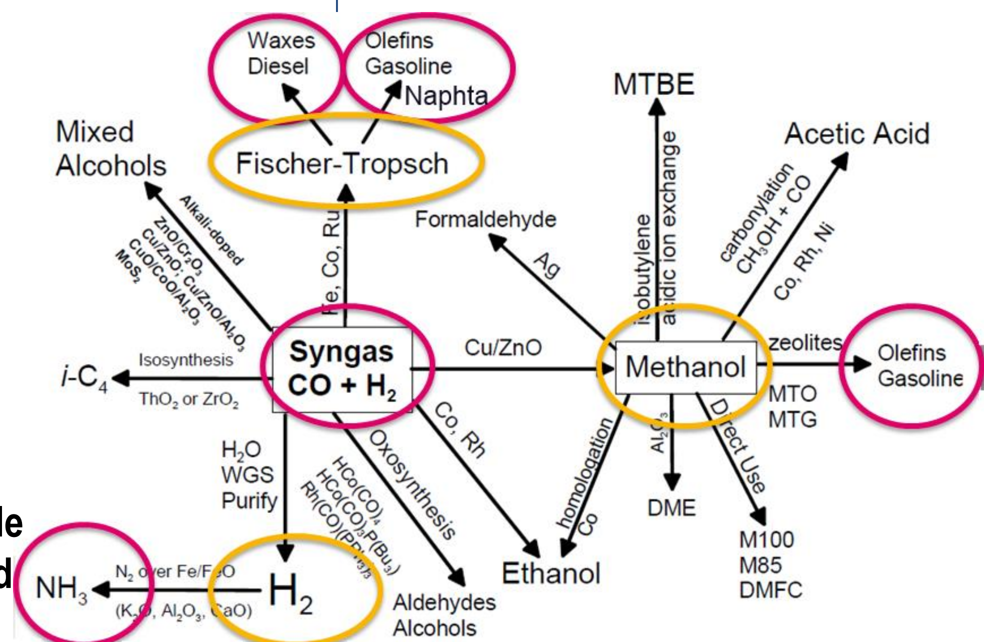
Key insights:

- Batteries convert PV into flexible 24/7 technology
- Batteries show same high learning rates as PV
- Highly module technology – phone to storage plant
- Extremely fast mobility revolution (fusion of renewables, modularity, digitalization, less complex)
- high growth rates – fast cost decline
- least cost mobility solution from 2025 onwards
- Key reason for collapse of western oil majors
- 3rd key enabling technology for survival of humankind



Power-to-X – covering hydrocarbon demand





Key insights:
- **PtX enables sustainable production of hydrocarbons**
- **Ingredients: electricity, water, air**
- **w/o PtX COP21 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, ect.)**
- **4th key enabling technology for survival of humankind**

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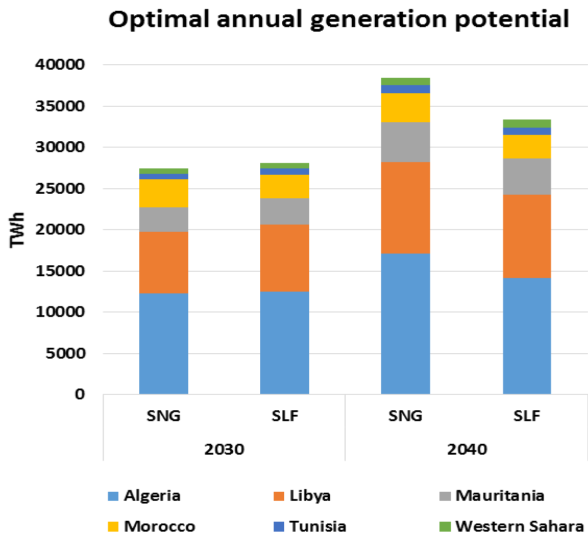
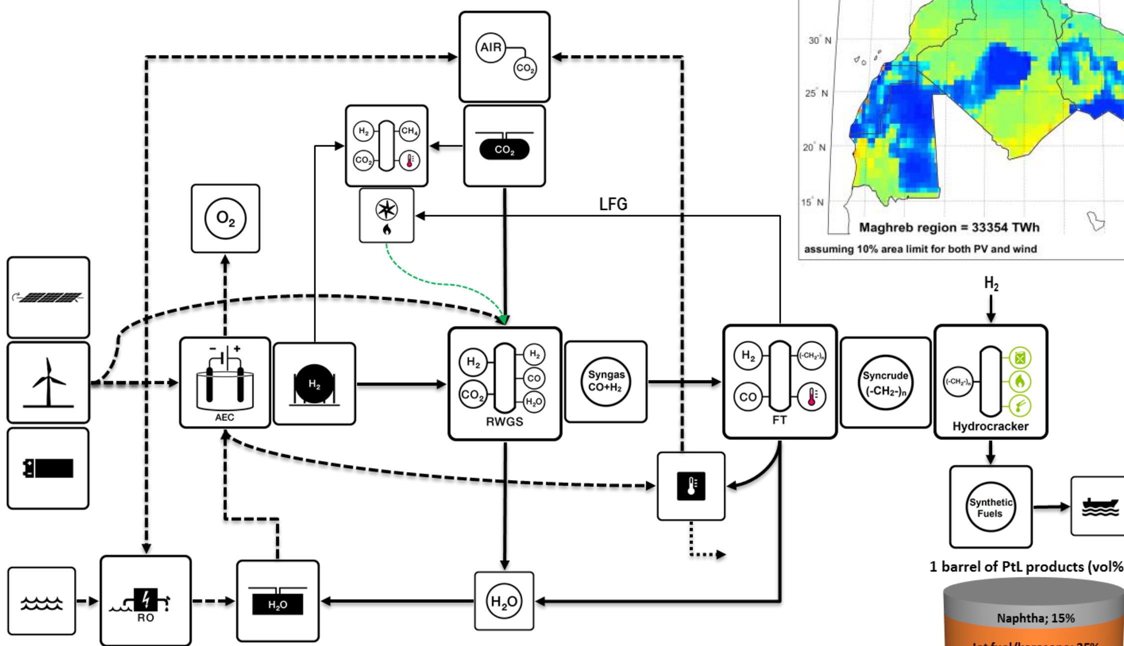
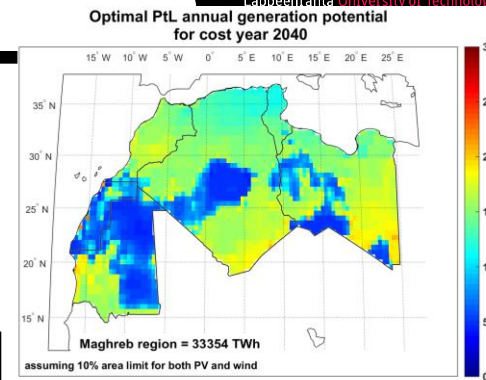
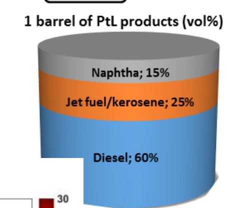
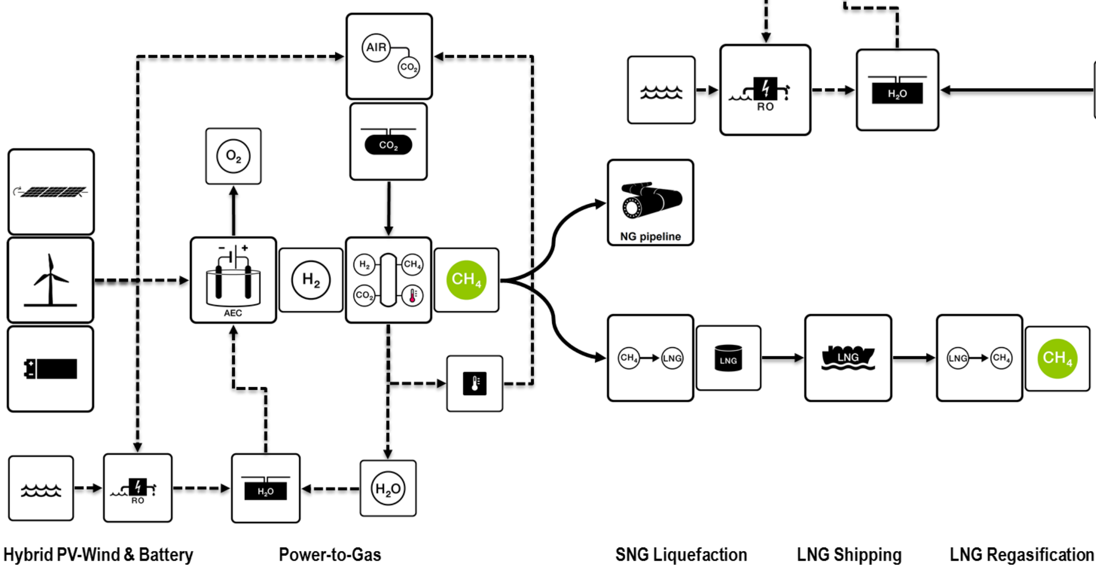
Synfuels production in Maghreb

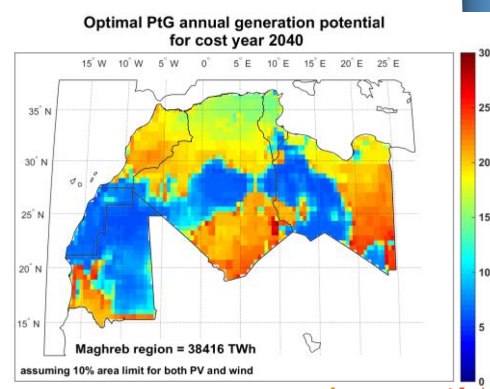












NEO CARBON

source: Fasihi M., et al., 2017. Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe – Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World, Sustainability, 9, 306