100% Renewable Electricity: how could it work and pathways to get there

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University of Lancaster, Energy Lancaster Seminar
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What is the Vision?

Neo-Carbon Energy: Future Energy System

Youtube link
Agenda

- Sustainability and Energy
- Major Constraints
- Key enabling technologies
- Focus: 100% Renewables for Europe
- Energy transition and other research
- Summary
Climate Change – Economics failed

“Climate Change presents a unique challenge for economics: it is the greatest and widest-ranging market failure ever seen.”

N. Stern, Economics of Climate Change, 2006
Spheres of Sustainability

Social-Environmental
- Environmental Justice
- Natural Resources Stewardship
- Locally & Globally

Environmental
- Natural Resource Use
- Environmental Management
- Pollution Prevention (air, water, land, waste)

Environmental-Economic
- Energy Efficiency
- Subsidies / Incentives for use of Natural Resources

Social
- Standard of Living
- Education
- Community
- Equal Opportunity

Economic
- Profit
- Cost Savings
- Economic Growth
- Research & Development

Economic-Social
- Business Ethics
- Fair Trade
- Worker’s Rights

Sustainability
Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

World Commission on Environment and Development, 1987
Agenda

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Constraint 1: Electricity (Energy) Demand

Global Demand Growth
2035: 35,000 TWh\text{el}
~2050: 55,000 TWh\text{el}
~2065: 90,000 TWh\text{el}

source: IEA, 2009; IEA, 2011; Breyer Ch., 2012

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Constraint 2: Climate Change

United Nations
Framework Convention on Climate Change

FCCC/CP/2015/L.9
Distr.: Limited
12 December 2015
Original: English

Conference of the Parties
Twenty-first session
Paris, 30 November to 11 December 2015
Agenda item 4(b)
Durban Platform for Enhanced Action (decision 1/CP.17)
Adoption of a protocol, another legal instrument, or an agreed outcome with legal force under the Convention applicable to all Parties

ADOPTION OF THE PARIS AGREEMENT

Article 2
1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:
   a. Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
   b. Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
   c. Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

Article 4
1. In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.
Constraint 2: Climate Change

![Graph showing emissions from fossil fuels and cement (GtCO2/yr) over time, with scenario categories for CO2eq emissions and historical emissions compared to projected emissions for 2030 and beyond.](Image)

Data: CDIAC/GCP/IPCC/Fuss et al 2014
Constraint 3: Diminishing Energy Fuels

Key insight:
- for decades too few new found oil fields
- no1 energy resource at its economic limits
- 3x higher price has not increased the oil production
- decline in oil production induces demand for gas/coal
Constraint 4: Energy Injustice

Global Access to Electricity Distribution

Constraint 5: Heavy metal emissions (cancer deaths)

Key insight:
- heavy metal emissions causing severe health damage are a tremendous and costly global health issue
- ~100 000 killed people globally per year (based on German results)
- ~400 000 killed people taking into account worse filter standards
- Ontario in Canada decided to phase-out coal due to very high subsidies in the health system (twice as high as the value of power)

source: PSI, Synapse; Greenpeace, 2013; IEA, 2013
Constraint 6: Energy Subsidies

Key insights:

• global energy subsidies are almost fully allocated for fossil (and nuclear) fuels
• fossil fuel subsidies are as large as global expenditures for the health sector
• RE would grow much faster if harmful fossil-nuclear subsidies would be phased-out
Constraint 7: Managing System Complexity

source:

- reasons for low efficiency and high costs
- complex value chains
- many energy conversion steps
"Energy security is the feature (measure, situation or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats."

- Availability
- Diversity
- Cost
- Technology & Efficiency
- Location
- Timeframe
- Resilience
- Environment
- Health
- Culture
- Literacy
- Employment
- Policy
- Military
- Cyber Security
Constraint 9: Ecological Footprint

Decarbonised power systems are desperately needed.

Historic Collapse Pattern (Jared Diamond)
- Over Exploitation of Resources
- Climate Change Impact
- Non Adaptive Social Behaviour
- Military Conflicts
- Structural Change in Trade Routes

Our performance is excellent, unfortunately under the wrong sign.

Source: Wackernagel, 2010; WWF, 2014
Agenda

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- Key enabling technologies
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- Summary
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 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
- 1st key enabling technology for survival of human civilization
Wind energy

Key insights:
- accessible in all world regions – no resource conflicts
- modular technology – off-grid, community turbines, large-scale
- already on low cost level – 3 – 8 €ct/kWh
- least cost electricity source in wind resource rich areas
- High full load hours due to 24/7 harvesting
- 2nd key enabling technology for survival of human civilization
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
- Extreme 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
- Flexibal seasonal storage option
- Global hydrocarbon downstream infrastructure usable
- Most difficult sectors to decarbonise can be managed with PtX (aviation, chemistry, agriculture, etc.)
- 4th key enabling technology for survival of humankind
Agenda

- Sustainability and Energy
- Major Constraints
- Key enabling technologies
- Focus: 100% Renewables for Europe
- Energy transition and other research
- Summary
Current status of the power plant mix

Key insights:
- new installations dominated by renewables
- nuclear as niche technology since 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
Key Objective

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 every sub-region of Europe,
- optimal operation modes for every element of the energy system,
- least cost energy supply for the given constraints.

LUT Energy model, key features
- linear optimization model
- hourly resolution
- multi-node approach
- flexibility and expandability
- enables energy transition modeling

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
- 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
Methodology

Full system

Renewable energy sources
- PV rooftop
- 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
Scenarios assumptions

Key data
- ~675 m population (2030)
- ~4450 TWh electricity demand (2030)
- ~715 GW peak load (2030)
- ~6.49 m km² area
- ~27.3 b m³/a water desalination demand (2030)
- ~265 TWh of non-energy industrial gas demand (2030)

20 regions
- NO: Norway
- DK: Denmark
- SE: Sweden
- FI: Finland
- BLT: Estonia, Latvia, Lithuania
- PL: Poland
- CRS: Czech Republic, Slovakia
- AUH: Austria, Hungary
- CH: Switzerland
- DE: Germany
- BNL: Belgium, Netherlands, Luxembourg
- BKN-W: Slovenia, Croatia, Bosnia & Herzegovina, Serbia, Kosovo, Montenegro, Macedonia, Albania
- BKN-E: Romania, Bulgaria, Greece
- UA: Ukraine, Moldova
- TR: Turkey, Cyprus

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Scenarios assumptions
Grid configurations

- Regional-wide open trade (no interconnections between regions/ countries)

- Area-wide open trade (country-wide grids are interconnected by HVAC or HVDC under given constraints*,**)

- Area-wide open trade with water desalination and industrial gas production

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Regional-wide open trade</th>
<th>Area-wide open trade</th>
<th>Area-wide open trade Des-Gas</th>
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<tbody>
<tr>
<td>PV self-consumption</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Water Desalination</td>
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<td></td>
<td></td>
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<tr>
<td>Non-energy Industrial Gas</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* existing transmission lines and planned ones according entso-e
** demand beyond 2030 capacity planning of entso-e fully on HVDC technology (70% underground cables, 30% overhead lines)

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
### Scenarios assumptions

#### Financial assumptions (year 2030)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capex [€/kW]</th>
<th>Opex fix [€/(kW·a)]</th>
<th>Opex var [€/kWh]</th>
<th>Lifetime [a]</th>
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<td>PV single-axis</td>
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<td>0</td>
<td>35</td>
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<td>Wind onshore</td>
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<td>25</td>
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<td>Hydro Run-of-River *</td>
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<td>Hydro dam *</td>
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<td>Geothermal energy</td>
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<td>Methanation</td>
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<td>Wood gasifier CHP</td>
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<td>Biogas CHP</td>
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<td>Water desalination</td>
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</tr>
</tbody>
</table>

**Generation costs**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy/Power Ratio [h]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>6</td>
<td>92</td>
</tr>
<tr>
<td>PHS</td>
<td>8</td>
<td>85</td>
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<tr>
<td>A-CAES</td>
<td>100</td>
<td>71</td>
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<tr>
<td>Gas storage</td>
<td>80*24</td>
<td>100</td>
</tr>
<tr>
<td>Battery</td>
<td>6</td>
<td>92</td>
</tr>
<tr>
<td>PHS</td>
<td>8</td>
<td>85</td>
</tr>
<tr>
<td>A-CAES</td>
<td>100</td>
<td>71</td>
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<tr>
<td>Water storage</td>
<td>80*24</td>
<td>100</td>
</tr>
<tr>
<td>Water electrolysis</td>
<td>84</td>
<td>77</td>
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<tr>
<td>Methanation</td>
<td>77</td>
<td>77</td>
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<tr>
<td>CCGT</td>
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<td>58</td>
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<td>OCGT</td>
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<td>43</td>
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<td>Gas storage</td>
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<td>100</td>
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<tr>
<td>Bio gasifier</td>
<td>40</td>
<td>40</td>
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<tr>
<td>Steam turbine</td>
<td>43</td>
<td>43</td>
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<tr>
<td>CSP collector</td>
<td>51</td>
<td>51</td>
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</table>

**CO₂ direct air capture consumes 225 kWh<sub>el</sub> and 1500 kWh<sub>th</sub> per ton of CO₂**

* hydro power plants older than 50 years are taken into account with refurbishment capex of 500 €/kW for 30 years
# Scenarios assumptions

## Financial assumptions (year 2030)

### Storage and transmission costs

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capex [€/kWh]</th>
<th>Opex fix [€/(kWh∙a)]</th>
<th>Opex var [€/kWh]</th>
<th>Lifetime [a]</th>
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<tr>
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<td>0.0002</td>
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<td>PHS</td>
<td>70</td>
<td>11</td>
<td>0.0002</td>
<td>50</td>
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<td>A-CAES</td>
<td>31</td>
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<tr>
<td>Gas storage</td>
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<table>
<thead>
<tr>
<th>Technology</th>
<th>Capex [€/(m³∙h)]</th>
<th>Opex fix [€/(m³∙h∙a)]</th>
<th>Opex var [€/(m³∙h)]</th>
<th>Lifetime [a]</th>
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<td>Water storage</td>
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<td>1.3</td>
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<table>
<thead>
<tr>
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<th>Opex fix [€/(m³∙h∙km∙a)]</th>
<th>Energy consumption [kWh/(m³∙h∙km)]</th>
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<td>Horizontal pumping</td>
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<td>Vertical pumping</td>
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<th>Opex fix [€/(kW∙km∙a)]</th>
<th>Opex var [€/kW]</th>
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<td>Transmission line DC</td>
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<table>
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<th>Technology</th>
<th>Capex [€/kW]</th>
<th>Opex fix [€/(kW∙a)]</th>
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<td>Converter station</td>
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*WACC = 7%*

**Note:**
- Distance in m for vertical pumping

**Notes:**
- **70% underground cables, 30% overhead lines**
Scenarios assumptions

Full load hours

<table>
<thead>
<tr>
<th>Region</th>
<th>PV fixed-tilted FLH</th>
<th>PV single-axis FLH</th>
<th>CSP FLH</th>
<th>Wind FLH</th>
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<tr>
<td>NO</td>
<td>882</td>
<td>1112</td>
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<td>DK</td>
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<td>BLT</td>
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<td>TR</td>
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<td>UA</td>
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<td>IS</td>
<td>819</td>
<td>1093</td>
<td>913</td>
<td>5019</td>
</tr>
</tbody>
</table>

FLH of region computed as weighed average of regional sub-areas (about 50 km x 50 km each):

- 0%-20% best “sub-areas” of region – 0.3
- 20%-30% best “sub-areas” of region – 0.2
- 30%-50% best “sub-areas” of region – 0.1

Scenarios assumptions
PV and Wind LCOE (weather year 2005, cost year 2030)
Scenarios assumptions
Generation profile (area integrated)

PV generation profile
Aggregated area profile computed using earlier presented weighed average rule.

Wind generation profile
Aggregated area profile computed using earlier presented weighed average rule.

Key insights:
- Seasonal complementary of PV and wind

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Scenarios assumptions
Load (area aggregated)

Synthesized load curves for each region

Total load (2030) - including the impact of prosumers (less load)

Key insights:
• PV self-consumption reduces the peak load and the gradients in the system
• Peak load reduced by 3% and electricity system demand by 14%

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
## Results

<table>
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<tr>
<th>2030 Scenario</th>
<th>Total LCOE</th>
<th>Primary LCOE</th>
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<th>LCOS</th>
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<th>Total ann. cost</th>
<th>Total CAPEX</th>
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<th>Generated electricity</th>
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<td>[€/kWh]</td>
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Des-Gas*,**

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<th>LCOS prosumer</th>
<th>Total ann. prosumer</th>
<th>Total PV prosumer</th>
<th>Generated electricity prosumer</th>
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<td>[€/kWh]</td>
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</table>

* additional demand 95% gas and 5% desalination
** LCOS does not include the cost for the industrial gas (LCOG)
*** integrated scenario, fully included in table above

Area integrated:

LCOW: 0.94 €/m³
LCOG: 0.04 €/kWh<sub>th,gas</sub>

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

Benefits of electricity and industrial gas sectors integration – Area-wide desalination gas

Key insights:
- integration benefits: decrease in total electricity demand and total annual levelized cost
- decrease in total capex by 6.8% (193 b€ absolute)

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Results
Import / Export (year 2030) – Area integrated

Key insights:
- Storage usage very limited, only 7% of total demand provided by storage
- Electricity trade limited, only 16% traded among regions
- Cost optimum includes 4% curtailed energy
- Net Importers: Sweden, Finland, Iberia, France, CRS, Benelux, AUH, Balkan-E, Balkan-W, Switzerland, Ukraine, Italy, Turkey
- Net Exporters: Norway, Denmark, Baltic, Poland, British Isles, Germany
- Balancing regions: France, Italy, Sweden

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Results
Total LCOE (year 2030) – Region-wide open trade total

Levelized Cost of Electricity (primary generation)

Average LCOE: 39.2 €/MWh

Source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Results

Total LCOE (year 2030) – Region-wide open trade prosumers

Levelized Cost of Electricity
(primary generation)

Average LCOE: 66.3 €/MWh

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

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

Levelized Cost of Electricity
(generation, curtailment, storage and transmission)

Average LCOE: 56.2 €/MWh

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 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

Levelized Cost of Electricity
(1rstary generation)

Average LCOE: 36.5 €/MWh

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 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

Levelized Cost of Electricity
(generation, curtailment, storage and transmission)

Average LCOE: 51.4 €/MWh

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
## Results
### Installed Capacities

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<td>Area-wide</td>
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<td>1238</td>
<td>432</td>
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<td>Area-wide</td>
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<td>979</td>
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<td>235</td>
<td>728</td>
<td>1056</td>
<td>148</td>
<td>1090</td>
<td>1238</td>
</tr>
</tbody>
</table>
Results

Resource utilization – area-wide open trade and area-wide desalination gas

Area-wide open trade

PV total capacity
979 GW

Area-wide open trade desalination gas

PV total capacity
1056 GW, +8%

Wind total capacity
617 GW

Wind total capacity
763 GW, +24%

Key insights:

- demand for offshore wind in North Sea region, significant capacity additions
- unused solar PV potential lower in cost than wind offshore
- resistance against new power lines will push solar PV in the system
- impact on PtG/ PtX not yet clear
Results
Regions Electricity Capacities – area-wide open trade

Area-wide open trade

Key insights:
• Area-wide scenario shows small share of system PV capacities in most of the regions, prosumers share is significant (especially in Nordic countries)
• Sunny conditions in Iberia and Mediterranean countries lead to significant share of PV single-axis
• >50% wind share in Baltic, Denmark, British Isles

Area-wide open trade desalination gas

Key insights:
• PV plays a major role in Area-wide desalination gas scenario for Central and Southern Europe
• PV single-axis and wind are the main sources of electricity for water desalination and industrial gas production
• resistance against new grids could drastically increase the PV share

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Results
Regions Electricity Generation – 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%)

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Results
Storage Capacities – Area-wide and area-wide open trade desalination gas

Key insights:
- Excess energy for area-wide open trade desalination gas lower than with independent sectors (from 141 TWh to 132 TWh, also relative shares of excess energy decrease from 3.2% to 2.2% of total generation).
- Existing PHS storage plays significant role
- Relative share of prosumer batteries increases significantly in integration scenario in Northern Europe
- Absolute storage capacities increase in Southern Europe and decrease in Central and Northern Europe when sectors are integrated

source: Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity, European Utility Week, Barcelona, November 15-17
Results
Storage Operation – area integrated

Breyer Ch., Child M., Koskinen O., Dmitrii B., 2016. A low-cost power system for Europe based on renewable electricity. European Utility Week, Barcelona, November 15-17
Results Visualisation

Global Internet of Energy: http://neocarbonenergy.fi/internetofenergy/#
# Overview on World’s Regions

<table>
<thead>
<tr>
<th>Regions</th>
<th>LCOE region-wide [€/MWh]</th>
<th>LCOE area-wide [€/MWh]</th>
<th>Integration benefit ** [%]</th>
<th>Storage * [%]</th>
<th>Regional grid trade* [%]</th>
<th>Curtailment [%]</th>
<th>PV prosumers* [%]</th>
<th>PV system * [%]</th>
<th>Wind * [%]</th>
<th>Biomass * [%]</th>
<th>Hydro* [%]</th>
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<td>3%</td>
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<td>22.0%</td>
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<td>22%</td>
<td>23%</td>
<td>3%</td>
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<td>53</td>
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<td>3.8%</td>
<td>9.9%</td>
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<td><strong>Europe</strong></td>
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<td><strong>51</strong></td>
<td><strong>11.2%</strong></td>
<td><strong>7%</strong></td>
<td><strong>16%</strong></td>
<td><strong>3%</strong></td>
<td><strong>18.1%</strong></td>
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<td>MENA</td>
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<td>Sub-Saharan Africa</td>
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<td>South America</td>
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<td>5%</td>
<td>12%</td>
<td>5%</td>
<td>12.1%</td>
<td>28.0%</td>
<td>10.8%</td>
<td>28.0%</td>
<td>21.1%</td>
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**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%)

* Integrated scenario, supply share annualised costs, results from older simulation
** sources: see [www.researchgate.net/profile/Christian_Breyer](http://www.researchgate.net/profile/Christian_Breyer)
Demand for solar PV (2030, integrated)

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<td>21668</td>
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</table>

source: [Breyer Ch., et al., 2016. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich, June 20-24](#) close to be accepted in a journal
Demand for solar PV

- 12.0 TWp demand for 100% RE and 2030 demand due to integrated scenario
- integrated scenario covers only about 45% of total primary energy demand (TPED)
- net zero constraint requires almost full electrification of all energy sectors
- almost all TPED can be electrified (except some industrial processes)
- 27.4 TWp demand for 100% RE and 2030 demand for full sector integration at about 41% solar PV contribution share

- 2030 TPED may be about 60% of TPED for 10 billion people on current European level
- 42 TWp demand by end of 21st century

- latest energy system transition modeling indicates a solar PV share increasing further for beyond 2030 cost assumptions, up to 80%, driven by low cost PV + battery

source: Breyer Ch., et al., 2016. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich, June 20-24 close to be accepted in a journal
Cost comparison of 'cleantech' solutions

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

Preliminary NCE results clearly indicate 100% RE systems cost about 50-70 €/MWh for 2030 cost assumptions on comparable basis

source: Breyer Ch., et al., 2016. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich, June 20-24

German Federal Constitutional Court decision on the accelerated nuclear power phase-out in Germany:

The court emphasised in its decision that phasing out of nuclear plants could be even accelerated for the common welfare, to protect life and health of the population, to protect the environment and future generations.

(The Federal Constitutional Court of Germany, 2016)

Why this should be different in other countries?
Agenda

- Sustainability and Energy
- Major Constraints
- Key enabling technologies
- Focus: 100% Renewables for Europe
- Energy transition and other research
- Summary
**Energy Transition Modeling: Saudi Arabia**

**Key insights:**
- energy system transition model for Saudi Arabia
- steady LCOE decline on energy system level driven by PV + battery
- beyond 2030 solar PV becomes more competitive than wind energy
- solar PV + battery finally runs the system more and more
- solar PV supply share in 2050 at about 81% (!!) as least cost

---

**source:** [Caldera U., et al., 2016. Integration of SWRO desalination in the power sector, based on PV and wind energy, for Saudi Arabia, 32nd EU PVSEC, Munich, June 20-24]
Energy Transition Modeling: Turkey

Key insights:
- energy system transition model for Turkey
- LCOE stays roughly stable and declines after 2040
- beyond 2030 solar PV becomes more competitive than wind energy
- solar PV + battery the most important system components
- solar PV supply share in 2050 at about 60% as least cost
- PV prosumers will play a very important role in Turkey

source: Kilickaplan A., Peker O., et al., 2016. The first electricity transition scenario for Turkey from now to 2050 for 100% renewables, SOLAR TR2016, Istanbul, December 7
Key insights:
• energy system transition model for Ukraine
• steady LCOE decline on energy system level driven by wind, PV, battery, PtG
• transition pushed first by wind energy, then PV (2050 share around 40%)
• coal and nuclear phase-out doable and system cost decline
• PV prosumers play a larger role beyond 2030 (further pushed by batteries)
• … we currently check 90 countries globally in the same style

source: Child M., Bogdanov D., Breyer Ch., 2016. Transition towards a 100% Renewable Energy System by 2050 for Ukraine. SEF-2016, Kiev, Ukraine, October 11
Energy Transition Modeling: India

Key insights:
- energy system transition model for India
- LCOE increase slightly (ex CO₂ cost) and then declines substantially
- solar PV becomes the dominating source of energy
- solar PV + battery the most important system components
- solar PV supply share in 2050 about 85% as least cost
- PV prosumers will play an important role in India

source: Gulagi A., Bogdanov D., Breyer Ch., 2017. The Demand For Storage Technologies In Energy Transition Pathways Towards 100% Renewable Energy for India, IRES 2017, Düsseldorf, March 14-16
Energy Transition Modeling: Iran

Key insights:
- energy system transition model for Iran
- steady LCOE decline on energy system level driven by PV + battery
- beyond 2030 solar PV becomes more competitive than wind energy
- solar PV + battery finally runs the system more and more
- solar PV supply share in 2050 at about 66% as least cost

source: Ghorbani N., Aghahosseini A., Caldera U., Breyer Ch., 2017. Transition to a 100% RE system and the role of storage technologies: A case study for Iran, IRES 2017, Düsseldorf, March 14-16
Key insights:
- energy system transition model for Nigeria
- stable LCOE in first periods then steady decline driven by PV + battery
- solar PV + battery finally run the system more and more
- PV prosumers become increasingly important
- solar PV supply share in 2050 at about 96% (!!) as least cost

source: Oyewo A.S., Aghahosseini A, Breyer Ch., 2017. Assessment of energy storage technologies in transition to a 100% renewable energy system for Nigeria, IRES 2017, Düsseldorf, March 14-16
Finland: 100% renewables by 2050

Key results:

- 100% Renewable Energy for Finland is possible by 2050
- business-as-usual and nuclear cases higher in cost
- Biomass, wind, solar PV and hydro are the key sources of energy
- For low biomass case, wind would be source no 1
- PV, wind and biomass CHP are highly complementary
- New jobs can be created
- Electric vehicles play a major role for the energy system

source: Child M. and Breyer Ch., 2016. Vision and Initial Feasibility Analysis of a Recarbonised Finnish Energy System, Renewable and Sustainable Energy Reviews, 66, 517-536; full slide set for 100% Renewables for Finland
Åland: 100% renewables by 2030

Key results:
- 100% Renewable Energy on Åland is possible by 2030 – and it can be lower in cost than the business-as-usual case
- Wind, biomass and solar PV are the key sources of energy (in this order)
- There are different possible pathways
- New jobs can be created
- Electric vehicles play a major role for the energy system
- Electric boats may be an economic opportunity for Åland

Europe: Aging power plants as opportunity

Key results:

• Transition close to zero emissions in Europe’s power sector can be achieved just by switching investments TODAY to renewables.
• Despite resistance and lobbying from certain groups, the transition towards sustainability is steady.
• Power plants are aging, and the current installations are increasingly shifting to renewables.
• Coal and nuclear investments are almost fully substituted by renewables, remaining fossil-nuclear investments seem to be policy failures.

Download:
Northwest Russian wind for Europe?

Key results:

- The wind potential in Northwest Russia is huge and electricity generation cost is low (30 €/MWh).
- The potential of offshore wind turbines with LCOE less than 50 EUR/MWh is around 2 GW for 2030 cost assumptions.
- Offshore wind generation in Europe is not cost competitive compared to local onshore wind generation and wind energy imports from Eurasia for 2030 cost assumptions.
- Due to high electricity transmission costs electricity import from Northwest Russia to European regions is higher in cost than local onshore wind generation.
- With the applied societal constrains on wind energy utilization (up to 4% of land area can be utilized for wind farms) local wind generation in European regions is not fully utilized. Only in case of much lower social acceptance of local wind power installations the demand for wind energy import may rise.
- Further example of challenging economics of very long (1500 – 2000 km) power lines.

download:
Bogdanov D. and Breyer Ch., 2016. Integrating the excellent wind resources in Northwest Russia for a sustainable energy supply in Europe, 15th Wind Integration Workshop, Vienna, November 15-17.
Can Australia become an energy source for Asia?

Key results:

- LCOE of the system in East Asia is between 52-61 €/MWh
- RE sources can cover electricity demand for power, SWRO desalination, RE-SNG local demand and exports
- Benefit due to interconnection of grids and integration of SEA and NEA is only marginal (1.2% cost reduction)
- Regions on the border benefit most from the integration
- Further example of challenging economics of very long (1500 – 2000 km) power lines
- PV is dominant mainly in SEA and wind plays a vital role in NEA
- Production of RE-SNG from the available electricity in Australia West creates benefit for China East and Japan
- Australia could become a hub for liquefaction of RE based SNG by utilizing the abundant solar and wind potential
- First example of beneficial long distance RE-LNG trading
- 100% RE system is more cost competitive than a nuclear-fossil option!

Integrated scenario

Regions electricity capacities

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Solar PV and Batteries show strong correlation

Key results:

- PV generation will be a major energy source in 100% RE based systems for all regions in the world
- The highest share of PV capacities and generation in the optimal mix is expected to be reached in the India/SAARC region
- PV and battery storage utilization are strongly correlated
- Correlation between PV capacities share and share of short-term storage in total generation reaches 0.92
- Correlation between system PV capacities share and battery storage share reaches 0.96.
- The relevance of short-term storage increases in the PV generation based energy systems and stays rather low in the wind energy based systems.

download:
Bogdanov D., Gulagi A., Breyer Ch., 2016. PV generation share in the energy system and battery utilisation correlation in a net zero emission world, 6th Solar Integration Workshop, Vienna, November 14-15
Synfuels production in Maghreb

Optimal annual generation potential

Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe – Renewable Energy Based Synfuels

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Synfuels production in Maghreb

Optimal annual generation potential

Optimal P4G annual generation potential for cost year 2040

Maghreb region = 33354 TWh
assuming 15% area limit for both PV and wind

Maghreb region = 38416 TWh
assuming 15% area limit for both PV and wind

1 barrel of P4G products (vol%)

Optimal annual generation potential for cost year 2040

Optimal P4G annual generation potential for cost year 2040

NEO CARBON

Fasihi M., et al., 2016. Long-Term Hydrocarbon Trade Options for Maghreb Core Region and Europe – Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World, SGEM Vienna Green 2016 Sessions, Vienna, November 2-5 close to be accepted in a journal
Agenda

- Sustainability and Energy
- Major Constraints
- Key enabling technologies
- Focus: 100% Renewables for Europe
- Energy transition and other research
- Summary
Summary

- Tremendous energy-related global problems induce collapse of global civilization – without drastic and fast change of our energy basis
- COP21 agreement in Paris is the first real attempt for survival of civilization
- Net zero emissions is equal to phase-out of all fossil fuels by 2050
- Sustainable resource basis is excellent
- Key enabling technologies are solar PV, wind energy, batteries, PtX
- Internet of Energy webtool allows an in-depth investigation of the dynamics
- 100% renewable energy system is a low cost solution
- Fossil CCS and nuclear energy not competitive based on full cost
- COP21 and 100% renewables create the largest business opportunity ever
- Net zero world does not mean a reduced standard of living but smart technologies
- The burning age ends, due to low efficiency and high societal costs
A WORLD ELECTRIFIED BY SOLAR AND WIND

KIITOS.