Decarbonization of the mobility sector: potential of Power-to-X technologies

Corentin Prié – AUDI AG – Sustainable Product Development

Source: CNBC
Motivation: why e-fuels?

What is the worldwide potential of renewable energies?

What is the worldwide potential of e-fuels?

Conclusions
Motivation: why e-fuels?

What is the worldwide potential of renewable energies?

What is the worldwide potential of e-fuels?

Conclusions
The targets resulting from the climate agreement of Paris are not sufficient to sustain our environment...

... and a responsible and fast response is essential in the transport sector which can only be possible by considering a large panel of options!

- CO₂ emissions have to be drastically reduced to have a chance stopping climate change
- The Volkswagen-Group needs to play a role of leader in the fight against climate change
- It implies a wide openness to all energy carriers and associated powertrain technologies
Do we currently measure the complete consequences of mobility?

Current legislation

vehicle manufacturing → fuel production → recycling

“well-to-tank“ → “tank-to-wheel“ → “cradle to grave“
Who wins the „LCA race“?

- **GASOLINE 1.0 TFSI (85KW)**: 25 + 24 + 104 = 153 g CO₂-Åq./km
- **CNG 1.4 g-tron (81KW)**: 29 + 23 + 89 = 141 g CO₂-Åq./km
- **BEV (85KW) 500km RW**: 49 + 56 = 105 g CO₂-Åq./km

**Assumptions:**
- Compact car (A3)
- NEDC
- All cars same range
- Lifetime 200,000 km
- Neglect recycling
- Fossil gasoline & CNG / EU electricity mix

**Source:** AUDI AG 2018
LCA race with green energy

- **e-gasoline 1.0 TFSI (85KW)**: 25 + 35 = 60 g CO₂-Äq./km
- **e-gas 1.4 g-tron (81KW)**: 29 + 20 = 49 g CO₂-Äq./km
- **e-power (85KW) 500km RW**: 49 + 1 = 50 g CO₂-Äq./km

**Assumptions:**
- Compact car (A3)
- NEDC
- All cars same range
- Lifetime 200.000 km
- Neglect recycling
e-gasoline / e-gas / wind energy

**Source:** AUDI AG 2018
Green energy – not powertrain - determines CO₂

- e-gasoline 1.0 TFSI (85KW):
  - g CO₂-Äq./km: 25, 35, 60, 153

- e-gas 1.4 g-tron (81KW):
  - g CO₂-Äq./km: 29, 20, 49, 141

- e-power (85KW) 500km RW:
  - g CO₂-Äq./km: 49, 1, 50, 105

Source: AUDI AG 2018
Evolution of fuels

<table>
<thead>
<tr>
<th>Gen. 0</th>
<th>Gen. 1</th>
<th>Gen. 2</th>
<th>Gen. 3</th>
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<tbody>
<tr>
<td>Fossil fuels</td>
<td>Biofuels from crops</td>
<td>Audi e-fuels</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Fossil fuels" /></td>
<td><img src="image" alt="Biofuels from crops" /></td>
<td><img src="image" alt="Audi e-fuels" /></td>
<td><img src="image" alt="Audi e-fuels" /></td>
</tr>
</tbody>
</table>

**Audi e-fuels** are advanced, renewable fuels of the 2\(^{nd}\) and 3\(^{rd}\) generation.
AUDI e-fuels enable the use of various powertrain technologies

- CO₂-reduction > 70% Well-to-Wheel
- No competition to food production
- 100 % compatible with the infrastructure and ICE technologies
- Improved combustion properties

Audi e-power → Electrolysis → H₂ → Methanation → CH₄ → Gas grid

- Audi e-hydrogen®
- Audi e-gasoline®
- Audi e-diesel®

BEV → FCEV → Diesel/Gasoline & Hybrid → Gas vehicle
But what is the worldwide potential of e-fuels when it comes to competing with fossil fuels?

Needed energies/material:
- Electricity (renewable)
- Water
- Carbon dioxide

Which regions could contribute to provide these energy sources?

What are their technical/financial potential?

Goal: Build a renewable energy landscape assigning technologies to regions

Overview of e-fuel processes

Source: DVGW-EBI, Engler-Bunte-Institut (KIT-EBI), Institut für Katalyseforschung und -technologie (KIT-IKFT) "Vergleichende Bewertung von PtX-Prozessen zur Bereitstellung von Kraftstoffen aus erneuerbaren Quellen", sl. 22
Content

1. Motivation: why e-fuels?
2. What is the worldwide potential of renewable energies?
3. What is the worldwide potential of e-fuels?
4. Conclusions
Energy generation potential of utility-scale PV power

**Solar energy density** \( \frac{\text{MWh}}{\text{km}^2 \text{a}} \) = \( \frac{\text{Solar energy output (MWh/a)}}{\text{Ground area (km}^2)} \)

- Largest potential producers: MENA countries with > 7,500 MWh/km²/a.
- Algeria alone could cover 5 times the current European electricity demand.
- Inside large countries, local potentials are hidden by country average values.

Source: AUDI AG 2019
Energy generation potential of onshore wind power

- Largest potential producers: Western Sahara with > 30,000 MWh/km²/a.
- MENA countries, the regions sharing the North Sea, as well as New Zealand, Chile, Argentina and Norway have a great wind potential.
- Denmark is currently a step ahead with a 44% rate of wind energy based electricity in the power grid.
- Again, inside large countries, local potentials are hidden by country average values.

Wind energy density \( \frac{MWh}{km^2/a} = \frac{Wind\ energy\ output\ (MWh/a)}{Ground\ area\ (km^2)} \)

Source: AUDI AG 2019
Potential renewable energies vs. energy demand

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>206,670</td>
<td>347,750</td>
<td>160,056</td>
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<tr>
<td>EU</td>
<td>1,050</td>
<td>19,500</td>
<td>18,583</td>
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<tr>
<td>USA</td>
<td>6,540</td>
<td>10,160</td>
<td>24,861</td>
</tr>
<tr>
<td>Germany</td>
<td>40</td>
<td>120</td>
<td>3,638</td>
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</tbody>
</table>

Sources: AUDI AG 2019, Dena „The potential of electricity-based fuels for low-emission transport in the EU, Dena Leitstudie „Integrierte Energiewende, BMWI, en:former, Statista
Content

» Motivation: why e-fuels?

» What is the worldwide potential of renewable energies?

» What is the worldwide potential of e-fuels?

» Conclusions
Worldwide PtX potential: Power full-load hours in 2030

Assumptions:
- Only sites with cumulative FLh higher than 3,000 are considered.
- Fixed tilted PV systems are not installed in 2030 (lower FLh).
- PV champions: Atacama Desert, Sahara Desert, Tibet (> 2,500 FLh).
- Wind champions: Patagonia, Tibet (6,000 - 5,500 FLh).
- Hybrid champions: Patagonia and Tibet (> 7,000 FLh).

Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer, Lappeenranta University of Technology
Worldwide PtX potential: Storage demand & excess electricity in 2030

The PV-Wind share has to be optimized according to LCOE/FLh.

Additional electricity costs for PtX depend on certain factors:

- Long distance to the coast, where PtX have to be introduced
- High storage costs in order to balance the system for lower electricity transmission cost, especially crucial with a high share of PV, such as Tibet.
- Excess electricity due to overlap and curtailments.

Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer, Lappeenranta University of Technology
Worldwide PtX potential: LCOE in 2030

- Top site 1-axis PV LCOE: Atacama Desert ~ €ct1.6/kWh.
- Top site Wind LCOE: Patagonia ~ €ct1.9/kWh.
- Top site hybrid PV-Wind LCOE: ~ €ct1.7-2.0/kWh.

Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer
Worldwide PtX potential: LCOE & LCOF in 2030

- Top site 1-axis PV LCOE: Atacama Desert ~ €ct1.6/kWh.
- Top site Wind LCOE: Patagonia ~ €ct1.9/kWh.
- Top site hybrid PV-Wind LCOE: ~ €ct1.7-2.0/kWh.
- Top sites could deliver electricity to PtX plants at €ct2.5-3.0/kWh.
- Assumption: CO₂ is supplied by a Direct Air Capture (DAC) plant.
- Top sites in the world could reach LCOF of €70-80/MWh in 2030.
- Additional cost to SNG cost for LNG value chain: €15-20/MWh.

Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer, Lappeenranta University of Technology

LCOE = Levelized Cost of Electricity  
LCOF = Levelized Cost of Fuel
Worldwide PtX potential vs. energy demand

Power generation potential in best areas for PtX in 2030
Potential Hybrid PV-Wind power plant: 31.435 TWh/a

PtX production potential in 2030: \textbf{17.557 TWh/a}

\textbf{Best Locations only} (< 10ct/kWh_{PtX})

<table>
<thead>
<tr>
<th>Country</th>
<th>EL 95</th>
<th>TM 95</th>
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<tbody>
<tr>
<td>Primary energy demand [TWh/a]</td>
<td>1,861</td>
<td>2,007</td>
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<tr>
<td>Renewable energy demand [TWh/a]</td>
<td>1,139</td>
<td>1,029</td>
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<tr>
<td>PtX-Demand [TWh/a]</td>
<td>533</td>
<td>744</td>
</tr>
</tbody>
</table>

Sources:
Dena, "The potential of electricity-based fuels for low-emission transport in the EU, Dena Leitstudie „Integrierte Energiewende, BMWI, Dmitrii Bogdanov, Mahdi Fasihi and Christian Breyer, \textit{Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants}
Simulation for an attractive spot in Morocco in 2030

- Wind and solar conditions both optimal → Hybrid PV-Wind power plant with 7,000 FLh
- Access to the ocean with a harbor located 20 km in the South (Agadir) → export is possible
- Water available from the ocean with additional desalination
- Desert region without natural or urban restraints

Chosen location

Source: Global Solar Atlas, Global Wind Atlas
Simulation for an attractive spot in Morocco in 2030

Water desalination (SWRO)

The Ashkelon SWRO desalination facility (IDE) produces 13% of Israel's domestic consumer demand: 100 million m$^3$/a, for $0.52/m^3$

Simulation for an attractive spot in Morocco in 2030

Energy and material flow diagram for the PtL plant in Morocco

Overall efficiency: 48.1%

Energy flows:
- PV energy
- Electricity (post-storage)
- Water
- Hydrogen
- Syncrude
- Heat
- CO₂
- Loss
- e-diesel

Simulation for an attractive spot in Morocco in 2030

Overall efficiency: 48.2%

Energy and material flow diagram for the PtG plant in Morocco

Source: AUDI AG 2019, Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants - Mahdi Fasih*, Dmitrii Bogdanov, Christian Breyer
## Simulation for an attractive spot in Morocco in 2030

<table>
<thead>
<tr>
<th>Assumptions H₂X</th>
<th>e-diesel 1.14 €/l (e)-diesel (^{(1)})</th>
<th>SNG 1.58 €/kg (SNG) (^{(1)})</th>
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<tr>
<td>Cost of capital [%]</td>
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<td>PV</td>
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<td>Full Load hours [h/a]</td>
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<td>Power capacity [MW]</td>
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<td>LCOE [ct/kWh]</td>
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<td>Onshore Wind</td>
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<td>Full Load hours [h/a]</td>
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<td>Power capacity [MW]</td>
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<td>LCOE [ct/kWh]</td>
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<td>LCOE [ct/kWh]</td>
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<td>SWRO</td>
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<td>Cost of water [€/m³]</td>
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<td>Capacity [MW]</td>
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<tr>
<td>Full Load hours [h/a]</td>
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<tr>
<td>Cost of (H_2) [€/kg (H_2)]</td>
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<td>DAC</td>
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<tr>
<td>(CO_2) costs [€/t (CO_2)]</td>
<td>83</td>
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<td>FT / Meth.</td>
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<td>Capacity [MW (PtX)]</td>
<td>48</td>
<td>55</td>
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<tr>
<td>Full Load hours [h/a]</td>
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<td>7,000</td>
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<td>Hydrocracking cost [ct/l (e)-diesel]</td>
<td>5.25 €/l (e)-diesel</td>
<td>-</td>
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<tr>
<td>Transport costs [ct/l or ct/kg]</td>
<td>4.2(^{(2)})</td>
<td>32(^{(2)})</td>
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<tr>
<td>Overall investment [Mio.€]</td>
<td>325</td>
<td>284</td>
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<tr>
<td>Volume [(l_{e-diesel}) or [ton (SNG)]</td>
<td>35,086,000</td>
<td>25,200</td>
</tr>
</tbody>
</table>

**Overall efficiency: 48 %**
for both \(PtL\) and \(PtG\) including transport to filling stations

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\(^{(1)}\) Cost at the gas station

\(^{(2)}\) Import shipping + pipeline and transport to gas stations

\(^{(3)}\) incl. local liquefaction, transport with LNG-tanker ship, regasification and gas grid expenses (Source: Agora 2018)

Source: AUDI AG 2019, Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants - Mahdi Fasih*, Dmitrii Bogdanov, Christian Breyer
Content

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- What is the worldwide potential of renewable energies?
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- Conclusions
Conclusions

Renewable energies have an extremely high potential in some regions → energy export to other markets with PtX energy carriers.

The main cost factors for PtX are the LCOE and the number of FLh for operating the PtX plant → a PV-Wind combination is often necessary to reach competitive costs.

PtX technologies have a high potential in terms of possible rising volume and cost decrease over time. A further PtG cost decline could be enabled by the development of the gas grid.

Morocco / Patagonia = 👍
Questions?
Back-UP: Decarbonization of the mobility sector: potential of Power-to-X technologies

Corentin Prié – AUDI AG – Sustainable Product Development
Energy generation potential of utility-scale PV power: Results

- Largest potential producers: Algeria, Saudi Arabia, and Libya with > 15,000 TWh/a.

- The largest PV power generation potential is measured in Northern Africa and the Middle East but the development of PtX facilities could strongly depend on the local political situation.

- Giant countries like Canada, the USA, China and Australia benefit from large bare spaces to install PV power plants.

- The potential of small countries is hidden by the surface difference with large countries.

Electric energy output: \( E_{PV} \left( \frac{kWh}{a} \right) = \text{Irradiation} \left( \frac{kWh}{m^2a} \right) \times \text{Efficiency}_{PV} \times \text{Suitable Area} \left( m^2 \right) \)

Source: AUDI AG 2019
Energy generation potential of onshore wind power: Results

- Largest potential producers: Algeria and Libya with > 30,000 TWh/a.

- Large countries like Canada, China, the USA and Russia could exploit bare areas to produce onshore wind energy.

- Countries with wide forests like in Central Africa and countries sharing the Amazon don’t have the space required to install onshore wind parks.

- The potential of small countries is hidden by the surface difference with large countries.

**Electric energy output:**

\[
E_{\text{Wind}}(\text{kWh a}^{-1}) = \frac{P_{W,el}}{A_G} \times A_{\text{suitable}} \times 8760
\]

Source: AUDI AG 2019
Energy generation potential of utility-scale PV power: Results

Potential annual energy output density of centralized PV in North America

Potential annual energy output density of centralized PV in Australia

Source: AUDI AG 2019
Energy generation potential of utility-scale PV power: Results

Potential annual energy output density of centralized PV in Russia

Source: AUDI AG 2019
Energy generation potential of utility-scale PV power: Results

Potential annual energy output density of centralized PV in China

Potential annual energy output density of centralized PV in Brazil

Source: AUDI AG 2019