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

Corentin Prié – AUDI AG – Sustainable Product Development
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

Source: Rogelj et al., 2018; Rockström et al (2017); update Zapf, Pengg, Büttler, Bach, Weindl (2019)
Do we currently measure the complete consequences of mobility?

Current legislation

"well-to-tank"  "tank-to-wheel"

"well-to-wheel"

"cradle to grave"

Source: AUDI AG 2018
Who wins the „LCA race“?

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

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)
  - 25 g CO₂-Äq./km
  - 35 g CO₂-Äq./km
  - Σ 60 g CO₂-Äq./km
  - Σ 153 g CO₂-Äq./km

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

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

![Graph](image)

*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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</thead>
<tbody>
<tr>
<td>Fossil fuels</td>
<td>Biofuels from crops</td>
<td>Audi e-fuels</td>
<td>Electricity based fuels</td>
</tr>
<tr>
<td><img src="image" alt="Fossil fuels" /></td>
<td><img src="image" alt="Biofuels from crops" /></td>
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</tbody>
</table>

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

- CO$_2$-reduction > 70% Well-to-Wheel
- No competition to food production
- 100% compatible with the infrastructure and ICE technologies
- Improved combustion properties

**Audi e-power**

**Audi e-hydrogen®**

**Audi e-gasoline®**
**Audi e-diesel®**

**Gas grid**

**BEV**

**FCEV**

**Diesel/Gasoline & Hybrid**

**Gas vehicle**
1. Renewable Green Energy

2. Electrical Energy

3. Synthetic Fuels

Chemical Synthesis

In the Audi Power-to-X process, renewable green energy is converted into synthetic fuels and chemicals. This process reduces the dependency on fossil fuels and contributes to a more sustainable mobility sector.

Quelle: Ineratac GmbH
But what is the worldwide potential of e-fuels when it comes to competing with fossil fuels?

Overview of e-fuel processes

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
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

- 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.

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

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

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

- 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.

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

### Potential photovoltaic energy

<table>
<thead>
<tr>
<th></th>
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<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>
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<tr>
<td>Germany</td>
<td>40</td>
<td>120</td>
<td>3,638</td>
</tr>
</tbody>
</table>

### Potential onshore wind energy

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
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
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: 17.557 TWh/a

Best Locations could cover the PtX demand of 23-33 Germanys!

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, 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

Full-load hours of fixed tilted PV panels in Morocco

Average wind speed in Morocco

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

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

Energy and material flow diagram for the PtG plant in Morocco

Overall efficiency: 48.2%

Energy flows:
- PV energy
- Wind energy
- Electricity
- Water
- Hydrogen
- SNG
- Heat
- CO₂
- Loss
- SNG after transport

Source: AUDI AG 2019, Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants - Mahdi Fasihi*, 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</th>
<th>SNG 1.58 €/kg SNG</th>
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<tr>
<td><strong>Cost of capital [%]</strong></td>
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<td><strong>PV</strong></td>
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<td>Full Load hours [h/a]</td>
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<td>LCOE [ct/kWh]</td>
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<td><strong>Onshore Wind</strong></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><strong>Overlapping PV7Wind [%]</strong></td>
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<td><strong>Full Load hours [h/a]</strong></td>
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<tr>
<td><strong>SWRO</strong></td>
<td>Cost of water [€/m³]</td>
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<td><strong>Electrolysis</strong></td>
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<tr>
<td>Cost of H₂ [€/kg H₂]</td>
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<tr>
<td><strong>DAC</strong></td>
<td>CO₂ costs [€/t CO₂]</td>
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<td><strong>FT / Meth.</strong></td>
<td>Capacity [MWₚM]</td>
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<tr>
<td>Full Load hours [h/a]</td>
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<td>Hydrocracking cost [ct/l e-diesel]</td>
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<td><strong>Transport costs [ct/l or ct/kg]</strong></td>
<td>4.2</td>
<td>32</td>
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<tr>
<td><strong>Overall investment [Mio.€]</strong></td>
<td>325</td>
<td>284</td>
</tr>
<tr>
<td><strong>Volume [l e-diesel] or [ton SNG]</strong></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. 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

35,000 vehicles
Fuel cost overview
Prognoses for 2030 before taxes

<table>
<thead>
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<th>Crude oil</th>
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<td>Electricity</td>
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</table>

- **Crude oil costs**
  - Gasoline: 0.69 €/l
  - Diesel: 0.64 €/l
  - Crude oil: 0.69 €/l

- **Renewable energy carriers costs**
  - eGasoline: 1.25 €/l
  - eDiesel: 1.27 €/l
  - eCNG: 1.93 €/kg
  - eH₂: 6.85 €/kg
  - Electricity: 0.19 €/kWh

**Not CO₂-neutral**

Source: Calculation AUDI AG verified in the range of international studies (Dena, Prognos, Agora, FVV, Frontier, Siemens, etc.)
Motivation: why e-fuels?

What is the worldwide potential of renewable energies?

What is the worldwide potential of e-fuels?

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
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:**

\[ E_{PV} \left( \frac{\text{KWh}}{a} \right) = \text{Irradiation} \left( \frac{\text{KWh}}{m^2a} \right) \times \text{Efficiency}_{PV} \times \text{Suitable Area} \left( m^2 \right) \]

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: 

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