Energieträger für die Mobilität der Zukunft:
Dekarbonisierung, Versorgungssicherheit und Kosten

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With contributions by G. Pareschi (ETH Zürich)
Worüber wollen wir heute sprechen?

• CO₂-Emissionen – wie viel trägt die Schweiz bei?
• Anteil der Mobilität am Energiesystem und Klimawirkung
• Zwei Wege zur “Dekarbonisierung” des Verkehrs
• E-Mobilität: wieviel Elektrizität braucht es? Aus welchen Quellen?
• Synthetische Treibstoffe: woher? Zu welchem Preis?
Energy and climate policy: the “Trilemma”

Net-Zero CO₂
(and minimization of other environmental impact)

Security of Energy Supply
(Diversification, Share of imports)

Competitiveness
(of industry) / fair access to energy services

→ Partially conflicting goals
→ Optimization required

Alignment with international regulations /
currently: CH-energy expenditures ~4% of GDP
Every tonne of CO$_2$ adds to global warming

The near linear relationship between the cumulative CO$_2$ emissions and global warming for five illustrative scenarios until year 2050.

Likelihood of staying within temperature increase:
- 17%
- 50%
- 83%

Cumulative emissions to likely (67%) stay within 1.5°
Cumulative emissions to likely (67%) stay within 2°

Sources: IPCC AR6 WG1
Relevance of Transportation for the Swiss CO$_2$ Emissions

Total 2019: 43 MtCO$_2$/y

- Cars 25%
- Buses 1%
- LDV Vans 3%
- HDV Trucks 4%
- Int. Aviation 13%
- Other 2%
- Industry 11%
- Services 8%
- Residential 18%
- Energy sector 8%
- Other 2%

Example of expected increase in transportation service demand:

Sources: BAFU, Greenhouse gas emissions of Switzerland 1990-2019

Example of expected increase in transportation service demand:

Sources: ARE 2016, Intraplan 2015
If we have 20-50 years, why is immediate action imperative?

1.5° net-zero target
2.0° net-zero target

In addition:
- Power plants → 20-50 years
- Buildings → 30-100 years
- Industrial processes → > 20 years
- Roads, Grids, Refineries → 50-100 years

- Huge need for investments in infrastructure!
- Invest in decarbonizing incumbent assets!

Data for cars from Held et al. (2021): European Transport Research Review, vol. 13, art. 9
Data for ships from Held et al. (2021): 7th Internat. Symposium on Ship Operations, Management, & Economics

Prof. K. Boulouchos
How can we reduce CO$_2$-emissions?

→ (the four R’s – strategy)

1. **Reduce** (efficiency increase)
2. **Remove** (sequestration)
3. **Replace** (i.e. non-carbon energy carriers)
4. **Recycle**
Two complementary “Replace” strategies

A. Directly electrify what is possible:
   • Cars
   • Light-duty road
   • Low-temperature heating (heat pumps)

B. Use “Net-zero” CO₂ chemical energy carriers elsewhere:
   • Heavy-duty road
   • Aviation
   • Seasonal electricity storage (?)
   • High-temperature industrial process heat (?)
   • (Shipping)
Electricity Balance today and in 2050

However, the situation in Winter requires imports in the order of 9 TWh (compared to today’s 5 TWh)

Quelle: EP2050+, Szenario ZERO Basis
We anticipate that in the future we will need in addition about:

28 $\text{TWh}_{\text{chem}}$ of e-fuels ($\sim 80\%$ vs total fossil fuels currently), to be imported:

- 21 $\text{TWh}_{\text{kerosene}}$ for aviation*
- 7 $\text{TWh}_{\text{H2}}$ for heavy-duty freight transport*

which require:

$$21 \cdot 2.7^\dagger + 7 \cdot 1.8^\dagger = 70 \text{TWh}_{\text{electricity}}$$

For comparison the domestic Swiss electricity demand in 2050 will be in the same order of 70 TWh.

*Both of which may change in the future because of 1) increase in demand and 2) improved efficiency (but with the former stronger than the latter)

$^\dagger$Today’s electricity-to-fuel factor lies between 1.8 (hydrogen) and 2.7 (liquid hydrocarbons). Source: B. Stolz, M. Held (2021) accepted in *Nature Energy.*
What would we need to produce 70 TWh of electricity?

<table>
<thead>
<tr>
<th></th>
<th>Full-load hours</th>
<th>Peak capacity</th>
<th>CAPEX $ / kW_{peak}</th>
<th>Lifetime years</th>
<th>LCOE $ / kWh</th>
<th>Annualized costs power generation bill. $</th>
<th>Annualized costs electricity to e-fuel* bill. $</th>
<th>Total annualized costs bill. $</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV in Switzerland</td>
<td>1’000</td>
<td>70 GW</td>
<td>1’100</td>
<td>25</td>
<td>0.09</td>
<td>6.0</td>
<td>29.8</td>
<td>35.8</td>
</tr>
<tr>
<td>PV in Middle East</td>
<td>2’500</td>
<td>28 GW</td>
<td>750</td>
<td>25</td>
<td>0.02</td>
<td>1.6</td>
<td>11.0</td>
<td>12.6</td>
</tr>
<tr>
<td>Off-shore Wind EU</td>
<td>4’000</td>
<td>18 GW</td>
<td>3’200</td>
<td>25</td>
<td>0.09</td>
<td>6.1</td>
<td>6.4</td>
<td>12.5</td>
</tr>
<tr>
<td>On-shore Wind</td>
<td>5’300</td>
<td>13 GW</td>
<td>1’500</td>
<td>25</td>
<td>0.03</td>
<td>1.9</td>
<td>4.4</td>
<td>6.3</td>
</tr>
<tr>
<td>Patagonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>7’000</td>
<td>10 GW</td>
<td>7’000</td>
<td>50</td>
<td>0.11</td>
<td>7.5</td>
<td>3.0</td>
<td>10.5</td>
</tr>
</tbody>
</table>

*Excluding costs for transport

Compare to current ~6 bill. CHF spent for importing transportation fuel!

Preliminary results G. Pareschi (LAV ETHZ)
Current costs of generating e-fuels via different paths

$ / \text{litre}_{\text{e-fuel}}^*$

$\text{PV in Switzerland}$

$\text{PV in Middle East}$

$\text{Off-shore Wind EU}$

$\text{On-shore Patagonia}$

$\text{Nuclear}$

*Excluding costs for transport

Preliminary results G. Pareschi (LAV ETHZ)
Projected costs in 2050 for production and transportation of e-fuels

Source: PtX-Atlas: Weltweite Potenziale für die Erzeugung von grünem Wasserstoff und klimaneutralen synthetischen Kraft- und Brennstoffen
A fair cost-comparison of transport fuel imports to Switzerland

<table>
<thead>
<tr>
<th></th>
<th>2017 CHF</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. fuel cost at wholesale</td>
<td>~ 0.5 CHF / l</td>
<td>~ 1.3 CHF / l</td>
<td></td>
</tr>
<tr>
<td>Transport fuel imports</td>
<td>82 TWh</td>
<td>28 TWh*</td>
<td></td>
</tr>
<tr>
<td>Expenditure for importing chemical fuels</td>
<td>~ 4.1 bill. CHF</td>
<td>~ 3.6 bill. CHF</td>
<td></td>
</tr>
<tr>
<td>GDP</td>
<td>713 bill. CHF</td>
<td>969 bill. CHF</td>
<td></td>
</tr>
<tr>
<td>% of GDP</td>
<td>~ 0.6 %</td>
<td>~ 0.4 %</td>
<td></td>
</tr>
</tbody>
</table>

*However, passenger cars and LDV would consume ~17 TWh of additional electricity, which – with a wholesale market price of 0.05 CHF/kWh – would make 0.85 bill. CHF. That makes a total of 4.45 bill. CHF which is less than 0.5% of GDP.

→ But keep in mind that hard-to-decarbonize sectors will be hit anyhow by CO₂ prices, if they remain based on fossil fuels!

→ Let’s start investing in e-fuels immediately to accelerate learning and reach cost parity!
Schlussfolgerungen & Ausblick

• Dekarbonisierung des Energiesystems ist dringend nötig.

• Mobilität stellt in der Schweiz diesbezüglich die grösste Herausforderung dar.

• Autos und Lieferwagen/Busse können durch inländische Stromproduktion bedient werden, aber Importe von etwa 10 TWh werden im Winterhalbjahr erforderlich sein (2050).

• Langstreckenverkehr ist Schlüsselfaktor – Bedarf an neuer Infrastruktur und sehr hohen Investitionen. Importe von erneuerbaren Treibstoffen werden (in 2050) etwa 20% der gesamten heutigen fossilen Importe bzw. 35% der Treibstoffimporte betragen.

• Politik und Wirtschaft müssen sich früh genug und schnell genug um Finanzierung diese Investitionen und Kooperationsabkommen mit verschiedenen Ländern (Diversifizierung) sorgen.
Danke schön
Relevance of Transportation for Final Energy Demand and CO₂ Emissions

Total: 229 TWh / y

- Households: 63 TWh
- Industry: 42 TWh
- Services: 37 TWh
- Transportation: 87 TWh

Or 48% of all domestic CO₂ emissions!!

Sources: BFE, Schweizerische Gesamtennergiestatistik 2019
Drivers behind CO₂ growth... and CO₂ reduction
The case of Switzerland

\[ \text{CO}_2 = \text{Population} \cdot \frac{\text{GDP}}{\text{cap}} \cdot \frac{\text{Energy}}{\text{GDP}} \cdot \frac{\text{CO}_2}{\text{Energy}} \]

“The S-curve”
Historical cumulative emissions condemn early industrialized countries

- Many countries (mainly OECD, incl. Switzerland) have already depleted their fair share of cumulative CO₂ emissions!
- These countries should immediately stop emitting CO₂ and compensate the excess cumulative CO₂ with 31 trill. € (assuming 50 €/tCO₂)
- Or 77% of their combined GDP!

The big question from a systemic viewpoint:
Electrify end-use sectors or decarbonize electricity generation first?

Switching from Coal to Gas (feasible today for ~50 €/tCO₂) saves 6 GtCO₂

Roughly equivalent to all emissions from road transport, which however requires 300-600 €/tCO₂ to be electrified!

Source: elaborations based on Cox et al. (2020)
Climate effect of different car propulsion technologies

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>2017 - Ecoinvent</th>
<th>2040 - Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional combustion car</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Hybrid car</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Plug-in hybrid car</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Electric car</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Fuel-cell hydrogen car</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Electricity grid carbon intensity (kg CO₂e / kWh)

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Benefits of sharing the ownership of electric vehicles

Assuming 5 out of 250 driving days a year are unserved in both private and shared ownership models.

~100 replaced private cars to maximise benefits...

... with ~70 shared cars

G. Pareschi et al. (2021), Seizing the low-hanging benefits of shared electric vehicles, In preparation for submission
Walking time to find a car to share

G. Pareschi et al. (2021), Seizing the low-hanging benefits of shared electric vehicles, In preparation for submission