Comparative assertion of battery electric cars with various alternatives

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Vergleichende Ökobilanz individueller Mobilität:

Elektromobilität versus konventionelle Mobilität mit Bio- und fossilen Treibstoffen

Hans-Jörg Althaus
Marcel Gauch

Life Cycle Assessment
Technologie

Dübendorf, Oktober

BEV1 BEV2
Outline of the presentation

Goal definition

Life Cycle Model

Life Cycle Inventory

Life Cycle Impact Assessment

Goal definition

Life Cycle Model

Life Cycle Inventory

Life Cycle Impact Assessment

Global Warming Potential kg CO2-Eq / km (substitution)
Goal & scope

Goal definition

- Compare driving in hypothetical near future battery electric cars with driving in modern (or near future) fossil or biofuel fuelled cars
- Cars representative for Golf class
- Provide background information to discuss the potential of electric mobility to improve environmental aspects of mobility
- Comparative LCA to be presented in public → critical review compulsory
Scope / Impact assessment methods considered

- **Human health damage:** Ecoindicator 99 H
  - Climate change: IPCC 2007
  - Toxic emissions: CML 01 HTP
  - Smog formation: CML 01 POCP

- **Damage to ecosystem:** Ecoindicator 99 H
  - Climate change: IPCC 2007
  - Land use / land use changes: CML 01 LUC
  - Eutrophication: CML 01 EP

- **Damage to resources:** Ecoindicator 99 H
  - Non renewable energy demand: CED fossil, nuclear
  - Exergy demand: CEDx metals, minerals
  - Resource dissipation: Loss of several scarce elements (kg)

- **Others**
  - Radioactive waste: Inventory (m³)
System boundaries

Environmental Impact

Emission

CO₂

Emission

Emission

Emission

Emission

Emission

Emission

Emission, Resources

Material Science & Technology

43rd LCA Discussion Forum, April 6, 2011, ETH Zurich
System boundaries
Scope / Life Cycle Model

- Functional unit: 1 vehicle kilometer (vkm) per year 2015

System boundary

EOL Processes
Foregound system

Materials
Production energy
Processes
Raw materials
Fuels
Electricity (use phase)

Chassis and body

Drive train

Electric
ICE diesel
ICE petrol

Hybrid, Petrol
Hybrid, LPG

Batteries

Energy demand and emissions

Road network

1 vehicle kilometer

43rd LCA Discussion Forum, April 6, 2011, ETH Zurich
Scope / End of Life Model

Aluminium

Sheet rolling

Cladding production

New scrap to recycling

Facade cladding element

Use phase (not in system)

3 products

Car part

De-construction

Old scrap to recycling

Old scrap to disposal

Landfill

Aluminium sheet
This LCA uses system expansion and substitution to avoid allocation
How is mobility modelled: Vehicle

Golf-Class vehicles with different (hypothetical) drive-trains

Conventional car

Body & glider
Axles, breaks, wheels, suspension, cockpit, A/C system, doors, entertainment, …

Drive train
Engine, gearbox, cooling system, fuel system, starter, exhaust, lubrication, …

Electric car

Body & glider
Axles, breaks, wheels, suspension, cockpit, A/C system, seats, doors, lights, entertainment, …

Drive train
Electric motor, gearbox, controller, charger, cables, cooling system, …

Battery
400 kg Li-ion battery (45 kWh)

Golf IV body, scaled to weight of Golf VI BlueMotion body

Golf IV, scaled to weight of Golf VI

Drivetrain from existing Brusa components

Scaled from existing KOKAM battery
How is mobility modelled: Energy consumption

- **Golf-Class vehicles with different (hypothetical) drive-trains**
  - Life time / mileage: 12 years / 150,000 km
  - Energy demand calculated: NEDC + real world addition
  - Break wear reduced for electric & hybrid cars
  - Maintenance: spare & wear parts. Batteries are replaced in every second electric vehicle
  - Use on Swiss road network

<table>
<thead>
<tr>
<th>Energy carrier / Drive train</th>
<th>Electricity¹</th>
<th>Diesel</th>
<th>Gasoline</th>
<th>Natural gas</th>
<th>Palmmeylester PME (Maleysia)</th>
<th>E85 from sugar cane² (Brazil)</th>
<th>Biogas (Swiss Kompogas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>20 kWh/100km 0.72 MJ/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug-In hybrid</td>
<td>Mix CH (80%) 16 kWh/100km 0.58 MJ/km</td>
<td>-</td>
<td>Hybrid (20%) 0.98 l/100km 0.31 MJ/km</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Hybrid</td>
<td>-</td>
<td>-</td>
<td>Euro 5 4.9 l/100km 1.56 MJ/km</td>
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<tr>
<td>ICE</td>
<td>-</td>
<td>Euro 5 4.9 l/100km 1.76 MJ/km</td>
<td>Euro 5 6.8 l/100km 2.17 MJ/km</td>
<td>Euro 5 6.3 m3/100km 2.17 MJ/km</td>
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<td>Euro 5 8.07 l/100km 2.17 MJ/km</td>
<td>Euro 5 6.3 m3/100km 2.17 MJ/km</td>
</tr>
</tbody>
</table>

¹: 6 generation scenarios (mix CH, mix UCTE, nuclear power CH, combined gas power UCTE, coal UCTE, PV CH)
²: Scenario with E85 from European waste wood

Golf BlueMotion → best in class!
Results: Global Warming Potential (GWP)

Global Warming Potential kg CO2-Eq / km (substitution)
Results: Ecoindicator 99 (H/A)

Not compliant to ISO!
Results: GWP and Ecoindicator 99 safeguards

**GWP**

- CH-PV
- UCTE-combined gas
- UCTE-Coal
- CH-nuclear
- CH-mix
- UCTE-mix
- Plug-in (80/20 CH-mix/gasoline)
- Gasoline
- Biogas
- Palmmethylester
- E85 sugar cane
- E85 waste wood
- Natural gas
- Diesel
- Gasoline

**El 99, Human health damage**

- CH-PV
- UCTE-combined gas
- UCTE-Coal
- CH-nuclear
- CH-mix
- UCTE-mix
- Plug-in (80/20 CH-mix/gasoline)
- Gasoline
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- Palmmethylester
- E85 waste wood
- E85 sugar cane
- Natural gas
- Diesel
- Gasoline

**El 99, Ecosystem damage**

- CH-PV
- UCTE-combined gas
- UCTE-Coal
- CH-nuclear
- CH-mix
- UCTE-mix
- Plug-in (80/20 CH-mix/gasoline)
- Gasoline
- Biogas
- Palmmethylester
- E85 waste wood
- E85 sugar cane
- Natural gas
- Diesel
- Gasoline

**El 99, Resource damage**

- CH-PV
- UCTE-combined gas
- UCTE-Coal
- CH-nuclear
- CH-mix
- UCTE-mix
- Plug-in (80/20 CH-mix/gasoline)
- Gasoline
- Biogas
- Palmmethylester
- E85 waste wood
- E85 sugar cane
- Natural gas
- Diesel
- Gasoline

43rd LCA Discussion Forum, April 6, 2011, ETH Zurich
Results: GWP and human health indicators

GWP

CML 01, Human toxicity potential

CML 01, photochemical oxidation potential

EI 99, Human health damage
Results: GWP and ecosystem indicators

**GWP**

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Global Warming Potential kg CO2-Eq / km (substitution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.05</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.10</td>
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<tr>
<td>Natural gas</td>
<td>0.15</td>
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<tr>
<td>E85 sugar cane</td>
<td>0.20</td>
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<tr>
<td>E85 waste wood</td>
<td>0.25</td>
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<tr>
<td>Palmmethylester</td>
<td>0.30</td>
</tr>
<tr>
<td>Biogas</td>
<td>0.35</td>
</tr>
<tr>
<td>Plug-in (80/20 CH-mix/gasoline)</td>
<td>0.20</td>
</tr>
<tr>
<td>UCTE-combined gas</td>
<td>0.25</td>
</tr>
<tr>
<td>UCTE-Coal</td>
<td>0.30</td>
</tr>
<tr>
<td>CH-nuclear</td>
<td>0.35</td>
</tr>
<tr>
<td>CH-mix</td>
<td>0.40</td>
</tr>
<tr>
<td>UCTE-mix</td>
<td>0.45</td>
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</tbody>
</table>

**CML 01, Land use**

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>CML01 Land use, normalized / km (substitution)</th>
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</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.005</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.010</td>
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<tr>
<td>Natural gas</td>
<td>0.015</td>
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<tr>
<td>E85 sugar cane</td>
<td>0.020</td>
</tr>
<tr>
<td>E85 waste wood</td>
<td>0.025</td>
</tr>
<tr>
<td>Palmmethylester</td>
<td>0.030</td>
</tr>
<tr>
<td>Biogas</td>
<td>0.035</td>
</tr>
<tr>
<td>Plug-in (80/20 CH-mix/gasoline)</td>
<td>0.020</td>
</tr>
<tr>
<td>UCTE-combined gas</td>
<td>0.025</td>
</tr>
<tr>
<td>UCTE-Coal</td>
<td>0.030</td>
</tr>
<tr>
<td>CH-nuclear</td>
<td>0.035</td>
</tr>
<tr>
<td>CH-mix</td>
<td>0.040</td>
</tr>
<tr>
<td>UCTE-mix</td>
<td>0.045</td>
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</table>

**CML 01, Eutrophication potential**

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>CML01 Eutrophication, normalized / km (substitution)</th>
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<tbody>
<tr>
<td>Gasoline</td>
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<td>UCTE-mix</td>
<td>0.045</td>
</tr>
</tbody>
</table>

**EI 99, ecosystem damage**

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Ecosystem damage, Ecoindicator 99 (H) pdf<em>m²</em>a / km (substitution)</th>
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</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.005</td>
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<tr>
<td>Diesel</td>
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</table>
Results: GWP and resource indicators

GWP

Cumulative energy demand, fossil

Cumulative energy demand, nuclear

Cumulative exergy demand, metals
Uncertainties
Variability of environmental impacts

Variability within Golf-Class

Vehicle mass
1.3 – 1.7 (1.48) [t]  
-12% / +14%

Vehicle composition
normal / light alu / light plastic  
100% / 138% / 171% CO₂-Eq  
(at constant weight)

Battery mass
250 – 450 (400) [kg]  
-37.5% / +12.5%

Battery mileage:
100-200 (150) [1’000 km]  
-33% / +33%

Vehicle mass
18 – 22 (20) [kWh/100km]
Efficiency (60-90 (82)%
18 – 26 (20) [kWh/100km]
Ancillary consumption
19 – 22 (20) [kWh/100km]
Overall
15 – 30 (20) [kWh/100km]
-25% / +50%

Vehicle mass
1.2 – 1.4 (1.23) [t]  
-3% / +14%

Global Warming Potential kg CO₂-Eq / km (substitution)
Variability of Global Warming Potential (GWP)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Worst Case</th>
<th>Baseline</th>
<th>Best Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-PV</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>UCTE-combined gas</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>UCTE-coal</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CH-nuclear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH-mix</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCTE-mix</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lightweight materialization for vehicle not included

Best case: 76 – 77%
Worst case: 126 – 145% of baseline

Global Warming Potential kg CO2-Eq / km (substitution)
Uncertainty of environmental impacts

- Uncertainty of battery production data

**Battery production data**
- Notter et al 2010: 52 kg CO₂/kWh
- Ishihara et al 2002: 75 kg CO₂/kWh
- Zackrisson et al 2010: 166 kg CO₂/kWh
- Frischknecht 2011: 123 kg CO₂/kWh

- Global Warming Potential kg CO₂-Eq / km (substitution)

- Road
- Vehicle w/o Li-Battery
- Li-ion Battery
- Non-exhaust emissions
- Exhaust emissions
- Fuel

= ecoinvent v2.2
Energy consumption in cell / battery production

- Notter et al / Ishihara et al: bottom up modelling of processes

- Energy demand measured or calculated from theoretical demand for e.g. heating.

- No allocation necessary
Production of a Li-Ion battery: Notter et al 2010

Brines → Li2CO3 → LiMn2O4 + binder + solvent → Al foil → PE foil → Cu foil → Graphite + binder + solvent → Ethylene carbonate + LiPF6

active electrode material

coating

winding/stacking

filling/sealing

assembly

Battery Pack

Enclosure

Electronics, BMS

Wires & Connectors

mining & refining of Al, Cu, Mn, C, ...

Li+ Ion battery: Notter et al 2010

Anode

Cathode

Separator

Electrolyte

Battery Pack

Production of a Li-Ion battery: Notter et al 2010

Main difference to other studies

Battery

0 20 40 60 80 100

CO2-Equivalents [%]

Lithium salt

Ethylene carbonate

Cathode

Rest cathode

Lithium manganese oxide

Aluminium

Separator

Anode

Rest anode

Graphite

Copper

Single cell

Battery pack

43rd LCA Discussion Forum, April 6, 2011, ETH Zurich
Variability Battery data: main differences

Energy consumption in cell / battery production

- Notter et al / Ishihara et al: bottom up modelling of processes
- Energy demand measured or calculated from theoretical demand for e.g. heating.
- No allocation necessary

- Zackrisson et al / Frischknecht: top down from producers
- Total energy demand from “sustainability report” of producer
- Allocation between various products of this producer by turnover and battery price

Main uncertainty with method

- Energy efficiency of processes
- Some processes might be lacking (e.g. energy demand for lighting)
Variability Battery data: main differences

- Notter et al / Ishihara et al: bottom up modelling of processes
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Graphic: Sustainability Report 2010, Maxell
Variability Battery data: main differences

Notter et al / Ishihara et al: bottom up modelling of processes
- Energy demand measured or calculated from theoretical demand for e.g. heating.
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Energy consumption in cell / battery production
Main uncertainty with method:
- Energy efficiency of processes
- Some processes might be lacking (e.g., energy demand for lighting)
Variability Battery data: main differences

Products:
Photographic paper
Disks
Videotapes
Alcaline batteries
Hard disks
Silver oxide batteries
DVD-R / Blue-ray discs
Shavers
CR batteries
Li-Cl batteries
Computer tapes
Lens units
Li-ion batteries for cell-phones
Head phones
Air-Zn-Batteries
Automatic urine sample systems
Batteries for Endoscopes
Tapes for wire connections
CR-batteries for sensors
Lenses for safety assurance

Energy demand / Sales
150 GWh electricity / 2.3 Ml oil
1 billion Euro

Makes sense if share of energy cost on product price is similar for all products

150 Wh/€ el.
2.3 ml/€ oil

75 kWh/kWh el.
11.5 l/kWh oil

Price:
500 €/kWh

Price:
Raw material cost
Energy cost
Capital cost
Marketing cost
Benefit
Variability Battery data: main differences

Energy consumption:

Investmenten für die Industrialisierung

Investment cost for battery production:
10’000 €/battery (ca. 30% of battery price!)

Energiespeicher: 500 M€ für 50 k Einheiten / Jahr

Üblicher Ansatz: Abschreibung der Investition nach einem Produktionsjahr
Anteil am Produkt: 10000 € / Stück

Investment cost for battery production:
10’000 €/battery (ca. 30% of battery price!)

Presentation Arno Mathoy (Brusa), 8.3.2011
Variability Battery data: main differences

Energy consumption in cell / battery production

- Notter et al / Ishihara et al: bottom up modelling of processes
  - Energy demand calculated from measured or theoretical demand for e.g. heating.
  - No allocation necessary

- Zackrisson et al / Frischknecht: top down from producers
  - Total energy demand from “sustainability report” of producer
  - Allocation between various products of this producer by turnover and battery price

Main uncertainty with method

- Energy efficiency of processes
- Some processes might be lacking (e.g. energy demand for lighting)

- Product prices might not correspond to energy consumption, especially if amortisation of infrastructure is important
## All results

<table>
<thead>
<tr>
<th>ICE fossil</th>
<th>E85 sugar cane</th>
<th>E85 waste wood</th>
<th>PME</th>
<th>Biogas</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>1.20E-07</td>
<td>3.66E-01</td>
<td>1.96E-01</td>
<td>8.23E-15</td>
<td>5.70E-15</td>
</tr>
<tr>
<td><strong>Worst case</strong></td>
<td>1.83E-07</td>
<td>6.61E-01</td>
<td>3.47E-01</td>
<td>1.18E-14</td>
<td>1.01E-14</td>
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<tr>
<td><strong>Best case</strong></td>
<td>1.72E-07</td>
<td>3.06E-01</td>
<td>1.64E-01</td>
<td>5.86E-15</td>
<td>5.24E-15</td>
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<td><strong>Worst case</strong></td>
<td>9.28E-08</td>
<td>3.50E-02</td>
<td>1.57E-01</td>
<td>4.79E-18</td>
<td>3.44E-18</td>
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<tr>
<td><strong>Baseline</strong></td>
<td>1.05E-07</td>
<td>4.41E-02</td>
<td>1.95E-01</td>
<td>4.91E-15</td>
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<td><strong>Worst case</strong></td>
<td>1.29E-07</td>
<td>6.22E-01</td>
<td>2.70E-01</td>
<td>5.16E-18</td>
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<td>6.41E-07</td>
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<td><strong>Best case</strong></td>
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<td>2.10E-01</td>
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<td>1.56E-02</td>
<td>1.04E-01</td>
<td>1.44E-01</td>
<td>5.58E-15</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td>1.12E-07</td>
<td>1.69E-02</td>
<td>1.17E-01</td>
<td>1.98E-01</td>
<td>6.03E-15</td>
</tr>
<tr>
<td><strong>Best case</strong></td>
<td>1.05E-07</td>
<td>1.17E-02</td>
<td>2.96E-01</td>
<td>1.62E-01</td>
<td>8.83E-15</td>
</tr>
<tr>
<td><strong>Best case</strong></td>
<td>1.26E-07</td>
<td>1.28E-02</td>
<td>3.66E-01</td>
<td>1.99E-01</td>
<td>9.85E-15</td>
</tr>
<tr>
<td><strong>Worst case</strong></td>
<td>1.99E-07</td>
<td>1.60E-02</td>
<td>5.06E-01</td>
<td>2.71E-01</td>
<td>9.40E-15</td>
</tr>
</tbody>
</table>
### All results

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Plug-in-hybrid (best case)</th>
<th>Plug-in-hybrid (worst case)</th>
<th>Electric (best case)</th>
<th>Electric (worst case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/50 CH-mix/gasoline</td>
<td>9.52E-08 - 1.16E-02</td>
<td>1.99E-01 - 1.18E-01</td>
<td>1.99E-01 - 1.18E-01</td>
<td>1.99E-01 - 1.18E-01</td>
</tr>
<tr>
<td>80/20 CH-mix/gasoline</td>
<td>9.42E-08 - 1.04E-01</td>
<td>1.86E-05 - 3.04E-01</td>
<td>1.86E-05 - 3.04E-01</td>
<td>1.86E-05 - 3.04E-01</td>
</tr>
<tr>
<td>UCTE-Mix</td>
<td>1.91E-07 - 1.60E-01</td>
<td>1.04E-01 - 1.04E-01</td>
<td>1.04E-01 - 1.04E-01</td>
<td>1.04E-01 - 1.04E-01</td>
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<tr>
<td>UCTE-gas</td>
<td>9.87E-08 - 1.91E-01</td>
<td>1.86E-05 - 1.04E-01</td>
<td>1.86E-05 - 1.04E-01</td>
<td>1.86E-05 - 1.04E-01</td>
</tr>
<tr>
<td>CH-PV</td>
<td>9.87E-08 - 1.91E-01</td>
<td>1.86E-05 - 1.04E-01</td>
<td>1.86E-05 - 1.04E-01</td>
<td>1.86E-05 - 1.04E-01</td>
</tr>
</tbody>
</table>

### Ecoindicator 99 (H)

- **Damage to human health** ([DALY / km]):
  - Plug-in-hybrid: 1.99E-01 - 1.18E-01
  - Electric: 1.99E-01 - 1.18E-01

- **Damage to ecosystem quality** ([PDF*m2*a / km]):
  - Plug-in-hybrid: 1.39E-01 - 1.18E-01
  - Electric: 1.39E-01 - 1.18E-01

- **Global warming potential** ([kg CO2-eq / km]):
  - Plug-in-hybrid: 8.27E-15 - 3.74E-15
  - Electric: 8.27E-15 - 3.74E-15

- **Human toxicity** ([1 / km]):
  - Plug-in-hybrid: 7.24E-18 - 4.41E-15
  - Electric: 7.24E-18 - 4.41E-15

- **Photochemical oxidation** ([1 / km]):
  - Plug-in-hybrid: 4.31E-09 - 9.59E-06
  - Electric: 4.31E-09 - 9.59E-06

- **Radioactive waste** ([m3 / km]):
  - Plug-in-hybrid: 6.27E-19 - 1.39E-15
  - Electric: 6.27E-19 - 1.39E-15

- **Cumulative energy demand nuclear** ([MJ-eq / km]):
  - Plug-in-hybrid: 1.31E-03 - 1.05E-02
  - Electric: 1.31E-03 - 1.05E-02

- **Cumulative energy demand fossil** ([MJ-eq / km]):
  - Plug-in-hybrid: 6.30E-02 - 1.09E-02
  - Electric: 6.30E-02 - 1.09E-02

- **Cumulative energy demand metals** ([MJ-eq / km]):
  - Plug-in-hybrid: 5.86E-02 - 1.06E-02
  - Electric: 5.86E-02 - 1.06E-02

- **Cumulative energy demand minerals** ([MJ-eq / km]):
  - Plug-in-hybrid: 9.58E-02 - 1.11E-02
  - Electric: 9.58E-02 - 1.11E-02

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**Note:** The table provides a summary of environmental impacts for different fuel types and technologies, focusing on key indicators such as Ecoindicator 99 (H) categories. The data includes both best and worst case scenarios for each category.
Conclusions

- Environmental impacts of electric mobility can be dominated by infrastructure or by operation depending on electricity source.

- Electric vehicles with sufficient battery capacity for “normal” use and a range extender for special use perform better than electric vehicles with larger batteries.

- Different data sources for carbon footprint of batteries can lead to different interpretations of carbon footprint of electric mobility.

- Variability of environmental impacts within the “Golf-class” is rather high (ca. 75% - 150% of baseline) and of the higher than difference to other technologies. → Specific vehicle demand for specific assessment!

- The ranking of vehicles with different drivetrains according to carbon footprint is completely different from the ranking according to other environmental impact indicators. → Carbon footprint is not sufficient as environmental performance indicator!
Thank you

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