Energy Sources for EVs: Fuel Cell and? - or? Batteries

Peter Prenninger
AVL List GmbH
CONTENT

- Fuel cell systems for automotive applications
- Braking energy recovery – general powertrain requirements
- Fuel cell – battery – hybrids for passenger car application
- Fuel cell – battery – hybrids for commercial transport applications
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FUEL CELLS FOR AUTOMOTIVE APPLICATION

Proton Exchange/Polymere Electrolyte Membrane Type
- High efficiency particularly at partload (>> 50%)
- Pure H2 as fuel
- Operating temperature < 100 °C
- Main challenges: costs and durability

High-Temperature PEMFC
- Operating temperature 120-180 °C
- No humidification & water management
- Limited CO tolerance – coupling with fuel reformer feasible
- Power density currently < standard PEMFC

Solid Oxide Fuel Cell (SOFC)
- Operating temperature > 650 °C
- O-Ion conductor – suitable for various fuels
- Simple system also if Diesel fuelled
- Main challenge: durability, corrosion, integration
TYPICAL FC SYSTEM EFFICIENCIES

- Higher relative power demand of auxiliaries of lower power systems
- Decreasing efficiency of lower power systems
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TYPICAL MID-CLASS CAR (REFERENCE CASE)

- Weight: 1470 kg during test
- Wheelbase: 2,7 m
- Peak propulsion power: 80 kW
- Drag coefficient: 0,31
- Frontal area: 2,25 m²
- Time for 0-100 km/h: <12 s
- Top speed: 180 km/h
BRAKE POWER IN NEDC

Power Distribution in NEDC (Vehicle: ALTANKRA-standard)

Power Range [kW]

Share of Cycle Time [%]

Pmin=-26kW
Pmax=36kW

Relevant for recuperation!
BRAKE POWER IN ARTEMIS CYCLES

Power Distribution in ARTEMIS (Vehicle: ALTANKRA-standard)

Artemis driving cycle

- Relevant for recuperation!

Power Range [kW]

<table>
<thead>
<tr>
<th>Power Range [kW]</th>
<th>Share of Cycle Time [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>von -105 bis -95</td>
<td>von -95 bis -85</td>
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<tr>
<td>von -45 bis -35</td>
<td>von -35 bis -25</td>
</tr>
<tr>
<td>von -25 bis -15</td>
<td>von -15 bis -5</td>
</tr>
<tr>
<td>von -5 bis +5</td>
<td>von +5 bis +15</td>
</tr>
<tr>
<td>von +15 bis +25</td>
<td>von +25 bis +35</td>
</tr>
<tr>
<td>von +35 bis +45</td>
<td>von +45 bis +55</td>
</tr>
</tbody>
</table>

Pmin=-105kW
Pmax=55.01kW
TYPICAL PASSENGER CAR POWERTRAIN

Low Voltage DC Bus (12V)
SYSTEM REQUIREMENTS FOR HYBRIDIZATION
TYPICAL FC POWERTRAIN FOR CARS
BATTERY AS COMMON ELEMENT IN HEV!
BRAKE ENERGY RECOVERY IN NEDC

Reference car (1470 kg test weight, 80 kW peak power)

- Normalized energy demand for driving approx. 45 MJ/100 km in NEDC – independent of powertrain architecture and type!

- Normalized braking energy approx. 12 MJ/100 km in NEDC – independent of powertrain architecture and type!

- Full recovery of braking energy would reduce the overall energy consumption by 27%

- Hybrids – either ICE or FC based – make use of this potential!
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DEGREE OF HYBRIDIZATION: ICE-HEV

Hybrid

= Combination Combustion Engine and E-Motor
Conventional Starter & Generator
1 - 4 kW

Belt Driven Starter-Generator
2 - 8 kW

Integrated Starter-Generator
4 - 30 kW

Combined Hybrid / Powersplit
20 - >80 kW

Example: Toyota Prius II
- E-Motor 1: 50 kW / 500 V
- E-Motor 2: ≈25 kW / 500 V
- Engine idle off at standstill
- Torque assist during acceleration
- Regenerative braking
- Continuous variable transmission
- Electric driving
Hybrid

= 
FC-System and Battery

- FC vehicle = EV!
- Higher battery capacity needed for fast FC system start-up – synergy in view of brake energy recovery!
- Peak power of battery determined by target brake energy recovery!
- Full FC powertrain if FC system peak power = maximum driving power
Hybrid = FC-System and Battery

Capacity

Range Extender FC Powertrain
- FC system peak power < power of traction motor
- Driving range with battery > 5 km
- Typical battery capacity > 2 kWh

Full FC Powertrain
- FC system peak power = power of traction motor
- Driving range with battery only < 5 km
- Typical battery capacity < 2 kWh

DEGREE OF HYBRIDIZATION: ICE-HEV
FC-BATTERY HYBRID VEHICLE

- Test and Validation of components
- Demonstration of FC-Battery Hybrid Powertrain
HYLITE POWERTRAIN CONCEPT

- energy management unit
- PEFC system 15kW net
- gas. H2 tank
- battery pack NiMH, 8kW

Diagram:
- DC/DC
- DC/AC
- VMU
- ASM
- R D N P

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TYPICAL FC SYSTEM EFFICIENCIES FOR REFERENCE VEHICLE
FC & BATTERY-FC-HYBRID EFFICIENCIES

NEDC Powertrain Efficiency [%]

- Pure FC Powertrain: 80 kW
  Efficiency: 52% (Potential future improvement >60%)

- Battery-FC Powertrain: P_{FC} = 80 kW, P_{Batt} = 25 kW
  Efficiency: 55%

- Battery-FC Powertrain: P_{FC} = 40 kW, P_{Batt} = 40 kW
  Efficiency: 54%

- Battery-FC Powertrain: P_{FC} = 15 kW, P_{Batt} = 65 kW
  Efficiency: 51%

Efficiency Improvement!
FURTHER ADVANTAGE OF FC-BATTERY HYBRID

Assumption (incl. Improvements):

- Battery system power density approx. 1.5 kW/kg
- Battery system energy density approx. 100 Wh/kg and 60% usable SOC range
- Net energy demand of EV powertrains (with recuperation) approx. 0.14 kWh/km
- Pure battery driving range = plug in hybrid function!
BATTERY RANGE OF BATTERY-FC-HYBRID

Battery Range [km]

- Pure FC Powertrain
  - 80 kW

- Battery-FC Powertrain
  - $P_{FC} = 80$ kW
  - $P_{Batt} = 25$ kW
  - $E_{Batt} = 1.5$ kWh

- Battery-FC Powertrain
  - $P_{FC} = 40$ kW
  - $P_{Batt} = 40$ kW
  - $E_{Batt} = 4$ kWh

- Battery-FC Powertrain
  - $P_{FC} = 15$ kW
  - $P_{Batt} = 65$ kW
  - $E_{Batt} = 6.5$ kWh
Fuel cell systems for automotive applications

Braking energy recovery – general powertrain requirements

Fuel cell – battery – hybrids for passenger car application

Fuel cell – battery – hybrids for commercial transport applications
HT-PEM POWERED FORKLIFT - SIMULATION STUDY

Recorded a 5h load profile with a standard forklift at AVL facilities

- Process simulation of a 20kW HT-PEM fuel cell system (fuel: diesel)
- Simulation of the HTPEM system through the recorded load profile
- Comparison of the ICE powertrain with the fuel cell powertrain

| Electric Motor Efficiency | 85% |
| Battery Efficiency       | 90% |
| Fuel Cell Efficiency     | Simulated Curve |
| IC Engine Efficiency     | Recorded map |
| Hydraulic Pump           | 90% |
| Hydraulic Motor          | 90% |
| Battery Size             | 12,000 kJ |
| LHV of Diesel            | 42500 kJ/kg |

Forklift used for simulation study

FC-battery hybrid powertrain

Recorded load profile (frequency chart)
HT-PEM MAIN POWER FOR FORKLIFT

Why HT-PEM?

- Membrane: Polybenzimidazole doped with phosphoric acid
- Temperature: 120-180°C
- CO tolerance: ~1mol% @ 160°C
- No humidification
- No liquid water issues

Electrical Net Efficiency

Facts:
- Fuel: Diesel
- $P_{\text{net}}=20\text{kW}$
- $P_{\text{gross}}=23.9\text{kW}$
- $\eta_{\text{elec}}=24\%$
- $CD=0.75\text{A/cm}^2$
- $CV=0.53\text{V}$
- Diesel=$8.5\text{L/h}$
- Water=$12.2\text{L/h}$

CD…current density, CV…cell voltage
Fuel cell powertrain advantages:

- Significant increase of overall efficiency
- Significant reduction of noise
- Most likely faster working movements due to the electric motor and hence reduced working time
- Recuperation of breaking energy
- No charging times (as for electrical forklifts)
- Moveably power supply of DC or AC power (power socket possible, incl. DC/AC inverter)
- No environmental concerns (leakages) due to the elimination of the hydraulic system
• 40% fuel consumption reduction (2.9L, 0.56L/h)

• Battery needed for recuperation of energy!

• Factors of improvement:
  ✓ Very high fuel cell partload efficiency
  ✓ Recuperation of braking and lowering of fork
SOFC-APU VEHICLE INTEGRATION STUDY

- Air supply and filter
- SOFC-APU
- Vehicle cooling circuit
- Battery
- ICE exhaust from TC
- Air conditioning circuit

ICE...Internal Combustion Engine
TC...Turbocharger
Diesel SOFC APU

- Air conditioning and truck electrification during parking
- Cabin heating and engine pre-heating/conditioning

### HYBRID FC-BATTERY SYSTEM FOR HD-TRUCK

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
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<tbody>
<tr>
<td>Net Stack Power</td>
<td>3kW</td>
</tr>
<tr>
<td>Gross Stack Power</td>
<td>3.8kW</td>
</tr>
<tr>
<td>Efficiency @ max Load</td>
<td>33%</td>
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<tr>
<td>Reforming Temp.</td>
<td>800°C (ATR)</td>
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<tr>
<td>Weight</td>
<td>70kg</td>
</tr>
<tr>
<td>Volume</td>
<td>70L</td>
</tr>
<tr>
<td>Power Density</td>
<td>45W/kg</td>
</tr>
</tbody>
</table>
SOFC APU System Integration

- 1 kW SOFC APU Proof-of-concept
- SOFC stack from TOFC
- High dynamics in „self-sustained“ mode
- System efficiency > 35%
- Full hot box system integration
“Fuel Cell Vehicles” are EVs and ideally suited for recovery of brake energy – high voltage and high power board net available!

Well designed architecture of a FC-battery hybrid powertrain improves overall system efficiency

Battery provides plug-in function (bi-directional!)

FC-battery powertrain provides additional benefits for customer – on-site high power electricity supply in LD vehicles

Combination of FC-system and battery improves availability of former pure-battery off-road vehicles

FC-APU in HD trucks offers additional benefits compared to energy supply based on pure battery solutions

Electric powertrains, batteries and fuel cells are natural allies!
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