1MG11: FUEL CELL VEHICLES
Part 2: Applications

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References

- Les Piles à Combustibles http://www.annso.freesurf.fr/index.html#plan
- Fuel cell org: www.fuelcell.org
Comparison of FC and ICE
Efficiency of FC vs ICE

- High electrical efficiency:
  - FC efficiency is about 50 to 60% with the perspective of further improving the performance, nearly no limitations
  - ICE: effective efficiency of 20 to 25% in road vehicle in urban and highway driving conditions, limited by Carnot efficiency

- Efficiency in terms of nominal power:
  - FC: efficiency is nearly independent of the size of the FC
  - ICE: minimum and maximum size to achieve satisfactory performance

- Cogeneration favored with FC
Efficiency of FC vs ICE

- Number of conversion steps to produce electricity
  - FC: single stage process
  - ICE: at least two stages: 1/ combustion and thermodynamic conversion 2/ generator
CO$_2$ emissions of FC and ICE

- Reduction of CO$_2$ emissions and pollutants
  - FC have a higher energy efficiency
  - ICE exhaust emissions produces CO$_2$, CO, NO$_x$, sulfur oxides SO$_x$ (acid rains) and unburnt hydrocarbon (HC) (cancer risk)
  - Hydrogen FC emits solely steam water
  - Methane FC (CH$_4$) are characterized by a reduction of CO$_2$, CO, HC, and NO$_x$ emissions
**CO₂ emissions of FC and ICE**

- Reduction of CO₂ emissions and pollutants
  - Nowadays inconvenient: H₂ is produced from fossil fuels so they yield indirect CO₂ emissions: Research to find new production paths of H₂ (biomass for instance)
  - FC are fitting the hydrogen route as an alternative energy vector and on the impetus of Hydrogen as corner stone for decentralized production
  - Allows for a low carbon society, weakly dependent on fossil fuels in centralized production using poly generation schemes
  - FC allows valorizing renewable energy sources (geothermal, hydroelectricity, wind energy....)
Advantages of FC

- Higher energy conversion efficiency
- Low emissions or even zero emissions ($\text{NO}_x$, $\text{SO}_2$, PM, CO)
- Silent operation
- Reliability
- Reduced maintenance
- Flexibility in usage
- Efficiency is high even for low rate of power generation
Future trends

- Domestic applications: non centralized production of electricity
- Applications in transports: road vehicle and urban transports such as busses, cars, bikes,...
- Partial substitution of heavy batteries in mobile applications: Mobile phones, PC, portable electronics, cameras...

To this end, it is necessary to further improve the robustness, the durability and the cost!
Advantages of FC

FOR STATIONARY APPLICATIONS

- High electrical efficiency, nearly independent of the size of the power plant
- FC close to consumers (decentralized energy production)
- Cogeneration is easier (electricity + heat / air conditioning)
- High overall efficiency
- Electricity supply of isolated sites
- Circumvent the necessity to develop expensive and difficult high voltage transmission lines
Advantages of FC

FOR MOBILE APPLICATIONS

- Compared to traditional vehicle based on ICE:
  - Better environmental score
    (Higher conversion efficiency, emissions reduction)
  - Reduction of noise

- Compared to electric vehicles equipped with batteries
  - Longer range because of higher specific energy
  - Improvement of available power
  - Easier refueling
Problems of Fuel Cells

- Fuel:
  - Hydrogen storage (high pressure or low temperature)
  - Liquid fuel: reforming
  - Distribution network

- Presently, one is just moving the emissions
- Robustness and reliability of fuel cells
- Cost is still high

Shell Hydrogen Refueling Station (HRS) in Reykjavik to fuel the Fc busses involved in ECTOS demonstration program since 2003
Applications
Market of stationary applications
Market of stationary applications
Mobile applications

- **Niche markets:**
  - Electric bikes, golf karts, two wheelers...

- **Automobile:**
  - Market is slowly taking off
  - Fuel cell powered vehicle: market after 2020, probably 2030
  - Electric supply of electric vehicles and hybrid electric vehicles
  - Hybrid vehicles: Series hybrid vehicle with a fuel cell prime mover
  - Strongly related to the availability of $\text{H}_2$ network and hydrogen refueling stations
  - Storage problems
  - Fuel technology: PEMFC
Mobile applications

**Bus:**
- Few dozens of fuel busses fabricated up to now (44 in Europe). Several have been operated in demonstration and prestige projects.
- Marketing restricted because of the availability of large power fuel cells (200 kW) and by the cost (~1.5 M€)
- Fuel cell technologies: PEMFC
- Fuel: compressed gas

**Military vehicles:**
- UAV (unmanned planed)
- Submarines
- etc.
Fuel cell powered vehicles

Validated solution
Reliable and robust
Efficient is moderate (no electricity storage)
Fuel cell powered vehicles: PAC2FUTURE

Fuel cell

H2

Fuel Cell Controller And Chopper

Electric motor

Fuel cell
Advantages:

- Advantages of pure battery electric vehicles:
  - Zero emission mode
  - Silent operation
  - Large torque at low speed
  - Comfort during urban driving conditions

Disadvantages:

- Important voltage variation of power supply with current output
- Requires a good quality power electronics and a complex control systems to carry out the energy management
- Hydrogen storage
  - Limitation of range
  - Careful manipulation, e.g. refueling
  - Volume constraints
Fuel cell powered hybrid vehicles

- Based on series hybrid architecture
  - Battery or supercap power storage system levels the energy demand
  - Improvement of vehicle performance
  - Braking energy recovery
  - Downsizing of the fuel cell
- Pure H₂ or dual energy systems (electric network + H₂)
- H₂ production and retail network ?
- H₂ stockage ⇒ reduction of the range
Mercedes Story


Necar II

Necar 4

Necar 4a

Necar 3

Necar 5

Jeep Commander 2

Go cart
Mercedes NECAR 1, 2, 3
Mercedes NECAR 5

- Prototype released in 2005
- 5 seats
- Fuel: Ballard® Mark 900 of 75 kW
- Maximum speed: 150 km/h
- Fuel: methanol from on board reforming provided by XCELLSIS
Ford FCV HEV
Ford FCV HEV

- Fuel Cell: Ballard Mark 902 Fuel Cell with high reliability, designed for a better maintenance and easier fabrication. Output power 85 kW (117 CV).
- Integrated powertrain combining a converter, an electric motor and differential / gear box
- Batteries: made of 180 batteries « D », placed between the rear seats and the hydrogen reservoir
- Reservoir containing four kilos of compressed hydrogen
- Maximum speed: 125 km/h
Toyota FCHV-4

- Series Hybrid architecture
- Fuel cell power: 90 kW
- Batteries: NiMH
- Hydrogen storage: Compressed gaseous H₂ @ 250 bars
- Electric motor: Permanent magnets synchronous machine: 80 kW / 260 Nm
- Top speed > 150 km/h
- Range: 250 km
Honda Clarity

Performance:
- Max speed: 100 mph ~ 140 km/h
- Acceleration: 0-60 mph (96 km/h) : 10 sec
- Curb weight: 1625 kg

Honda Clarity

- Electric motors: Synchronous Permanent Magnets with output power 100 kW / max torque: 256 Nm
- Fuel cell: PEM type V-flow (patent by Honda) 100 kW
- Li-ions batteries: 288 V (capacity?)
- Suspensions: Double wishbone at front / Five points suspension at rear
- Range: 240-270 miles
- Leasing cost: 600 $ per month
# Honda Clarity

## Powertrain

<table>
<thead>
<tr>
<th>Drive method</th>
<th>Front-wheel drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>AC synchronous electric motor (permanent magnet)</td>
</tr>
<tr>
<td>Max. output (kW [HP])</td>
<td>100 [134]</td>
</tr>
<tr>
<td>Max. torque (N·m [kg·m])</td>
<td>256 [26.1]</td>
</tr>
<tr>
<td><strong>Fuel cell stack</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>PEMFC (Proton Exchange Membrane Fuel Cell)</td>
</tr>
<tr>
<td>Max. output (kW)*</td>
<td>100</td>
</tr>
<tr>
<td><strong>Lithium-ion battery</strong></td>
<td>Voltage (V)*</td>
</tr>
<tr>
<td>Voltage (V)*</td>
<td>288</td>
</tr>
</tbody>
</table>

## Fuel

<table>
<thead>
<tr>
<th>Type</th>
<th>Compressed hydrogen gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>High-pressure hydrogen tank</td>
</tr>
<tr>
<td>Tank capacity (L)</td>
<td>171</td>
</tr>
<tr>
<td>Max. pressure when full (MPa)</td>
<td>35</td>
</tr>
</tbody>
</table>
## Honda Clarity

<table>
<thead>
<tr>
<th>Technology</th>
<th>Example Car</th>
<th>Gas mileage</th>
<th>Well-to-Wheel Efficiency</th>
<th>Well-to-Wheel CO₂ Emissions</th>
<th>0 to 60 mph Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>Tesla Roadster</td>
<td>110 Wh/km</td>
<td>1.15 km/kWh</td>
<td>46.1 g/km</td>
<td>3.9 sec</td>
</tr>
<tr>
<td>Gasoline Engine (Turbo 6-cy)</td>
<td>Porsche Turbo</td>
<td>22.0 mpg</td>
<td>0.22 km/mJ</td>
<td>328.2 g/km</td>
<td>4.2 sec</td>
</tr>
<tr>
<td>Gasoline Engine (V12)</td>
<td>Ferrari 550 Maranello</td>
<td>11.7 mpg</td>
<td>0.12 km/mJ</td>
<td>617.1 g/km</td>
<td>4.7 sec</td>
</tr>
<tr>
<td>Gasoline Engine (V8)</td>
<td>Chevrolet Corvette</td>
<td>25.0 mpg</td>
<td>0.25 km/mJ</td>
<td>288.8 g/km</td>
<td>4.8 sec</td>
</tr>
<tr>
<td>Gasoline Engine (VTEC 4-cy)</td>
<td>Honda Civic VX</td>
<td>51.0 mpg</td>
<td>0.52 km/mJ</td>
<td>141.6 g/km</td>
<td>9.4 sec</td>
</tr>
<tr>
<td>Diesel Engine (4-cyl)</td>
<td>VW Jetta Diesel</td>
<td>50.0 mpg</td>
<td>0.48 km/mJ</td>
<td>152.1 g/km</td>
<td>11.0 sec</td>
</tr>
<tr>
<td>Natural Gas Engine (4-cyl)</td>
<td>Honda CNG</td>
<td>36.0 mpg</td>
<td>0.32 km/mJ</td>
<td>186.0 g/km</td>
<td>12.0 sec</td>
</tr>
<tr>
<td>Hybrid (3-cyl Gas/Electric)</td>
<td>Toyota Prius</td>
<td>55.0 mpg</td>
<td>0.56 km/mJ</td>
<td>131.3 g/km</td>
<td>10.3 sec</td>
</tr>
<tr>
<td>Hydrogen Fuel Cell</td>
<td>Honda FCX</td>
<td>64 miles/gallon</td>
<td>0.35 km/mJ</td>
<td>151.7 g/km</td>
<td>15.8 sec</td>
</tr>
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</table>

### Well-to-Wheel Carbon Dioxide Emissions

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### 0 to 60 mph Acceleration

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<th>Acceleration (Sec)</th>
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</table>
The Mirai’s cruising range is on par with a conventional gasoline-fueled vehicle, letting you enjoy day trips without stopping.

* Toyota measurements based on JBD test cycle performance, as measured by Toyota when refueling at a hydrogen station supplying hydrogen at a pressure of 30 MPa, under the SAE J2601 Standard conditions (ambient temperature 20°C, Hydrogen tank temperature when fueled 13 MPa). Different amounts of hydrogen will be consumed if time of refueling is extended, the trip is long-distance, conditions at hydrogen stations differ, and the cruising range will therefore also differ accordingly. It is estimated that cruising range of approximately 700 km can be achieved when fueled at new hydrogen stations scheduled to begin operations after FY2016. Possible cruising range may vary considerably due to usage conditions (weather, traffic congestion, etc.) and driving methods (constant speed, air conditioning, etc.).

Toyota Mirai
Released in 2015 (Japan)

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
Fuel cell vehicle: case studies
Fuel cell vehicle: case studies

EV advantage

FCV advantage

TOYOTA estimation:
150 km, Joint study on a Portfolio of Powertrains for EU, 2010: 140 km

Source: Toyota
Development of MIRAI

**FC stack**
- Innovative flow channel structure and Electrodes of cells for higher output
  Output/volume; 3.1kW/L

**High pressure hydrogen tank**
- The light weight structure of carbon fiber reinforced plastic enabled Storage; 5.7 wt%*

Humidifier less
- Internal circulation

FC boost converter
- Reduced number of cells in FC stack
- Common use of hybrid units

*Hydrogen mass/Tank mass

FC main components developed in-house to achieve world leading performance
TOYOTA Mirai

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
TOYOTA Mirai

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
TOYOTA Mirai

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
TOYOTA Mirai

Complex geometries! → Thermal management??

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
TOYOTA Mirai

Manual assembly!

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
TOYOTA Mirai

- Challenges:
  - Materials with given properties
  - Mass manufacturing of components?
  - Stacking?
  - Mass manufacturing of devices?

http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/index.html
Toyota FCHV-Bus 1/2

- Hybrid series configuration
- Fuel cells: 2 fuel cells of 90 kW
- Batteries: NiMH
- Hydrogen storage: compressed $\text{H}_2$ compressed @ 250 bars
- Electric motor: PM synchronous machine
Mobile applications: niche markets
Motor bikes and electric bikes
Fuel Cell busses

Programme CUTE: clean Urban Transport
NEBUS de Daimler Benz
Mobile applications
Market for portable equipment

- PC, GSM, etc.
- Mainly based on Direct methanol Fuel Cells
Many thanks for your kind attention

All the best in your future professional life