European Fuel Cell and Hydrogen Summer School JESS 2, 17 - 28 Sept 2012, Crete

- **Vehicle Applications.**
- **Technology Introduction**
- **Markets,market development,**

Professor Dr. Ferdinand Panik

University of Applied Science Esslingen
Germany

A) Vehicle Applications.Technology
Introduction

1. Fuel Cell Vehicles
    - 1.1 Status
    - 1.2 Development Programs
    - 1.3 Perspectives

2. Fuel Cell Vehicle Systems
    - 2.1 Hydrogen Supply
    - 2.2 Air Supply
    - 2.3 Cooling System
    - 2.4 Reformer Technology

3. Fuel Cell Drive Trains
    - 3.1 Architecture
    - 3.2 Packaging
    - 3.3 Components

4. Simulation
    - 4.1 Introduction
    - 4.2 Control Strategy
    - 4.3 Results

1. Fuel Cell Vehicles / Status

Eight Automotive Companies presented their FCVs of the Second Generation in the "Test the Future Tour" in May 2009 from San Diego to Vancouver in May 2009

1. Fuel Cell Vehicles / Status

California Fuel Cell Partnership "Test the Future Tour 2009"

Daimler	GM	
Hyunday	Kia	Honda
Toyota	Volkswagen	Nissan

(http://www.hydrogenroadtour.com/participants/daimler)

(http://www.hydrogenroadtour.com/participants/gm)

(http://www.hydrogenroadtour.com/participants/hon

(http://www.hydrogenroadtour.com/participants/Hyundai)

(http://www.hydrogenroadtour.com/participants/kia)

(http://www.hydrogenroadtour.com/participants/niss

(http://www.hydrogenroadtour.com/participants/toyota)

(http://www.hydrogenroadtour.com/node/123)

Toyota FCHV 2008

The **2008 TOYOTA FCHV** represents the advancement on the FCHV-4 prototype, which underwent 18 months and over 80,000 miles of real-world testing in California and Japan. On December 2, 2002, Toyota began leasing FCHVs in the US and Japan. The TOYOTA FCHV has a remarkable balance of high efficiency and a luxury car-like smooth, quiet ride.

Year: 2008
PSI: 10,000
Kilograms: ~ 6 kg
Range in Miles: 491 miles
Max Power: 90 kW
Max Torque: 192 lb-ft
Max Speed: 96 mph

KIA FCEV 2009

The **2009 KIA Borrego FCEV** is the company's second generation in development. This vehicle, based on the gasoline/diesel version of the same name, is built on a small preproduction line. Borrego FCEVs are being tested in the United States and Korea. With this vehicle, KIA is closer to making fuel cell vehicles available for consumers.

Year: 2009
PSI: 10,000
Kilograms: 7.9 kg
Range in Miles: 426 miles
Max Power: 110kW
Max Torque: 300Nm
Max Speed: 100 mph

Honda FCX Clarity 2009

In 2008 Honda began limited production of an all new fuel cell car, "FCX Clarity" targeted primarily for leasing to private individuals. This newest generation powerplant features an advanced Honda "V-Flow" fuel cell stack that is 30% lighter, 20% smaller, offers 100 KW output, and a power/density improvement of 50%. Driving range has been increased 9% from 210 to 240 miles, using 5,000 psi gaseous hydrogen. With sub-freezing startup temperatures as low as -22F, it is a practical vehicle for a wide range of real-world applications. Honda continues research on hydrogen refueling solutions right-sized for individual vehicle at-home refueling.

Year: 2009
PSI: 5,000
Kilograms: 3.9 kg
Range in Miles: 240 miles
Max Power: 100kW
Max Torque: 189 lb.-ft
Max Speed: 100 mph
Fuel Economy: 60 city/60 hwy (m/kg)

Honda FCX Clarity "WORLD GREEN CAR 2009"

Propulsion
Fuel Cell Hybrid
PEMFC developed by Honda: 100 kWe

1 Front motor: 80 kW
2 rear in-wheel motors: 25 kW each
all with regenerative braking

Storage
Two CGH2 tanks @ 35 MPa: 4 kg
Range ~ 400 km
Top speed 160 km/h, limited

Structure
Light weight Body+Chassis concept

General Development Scenario

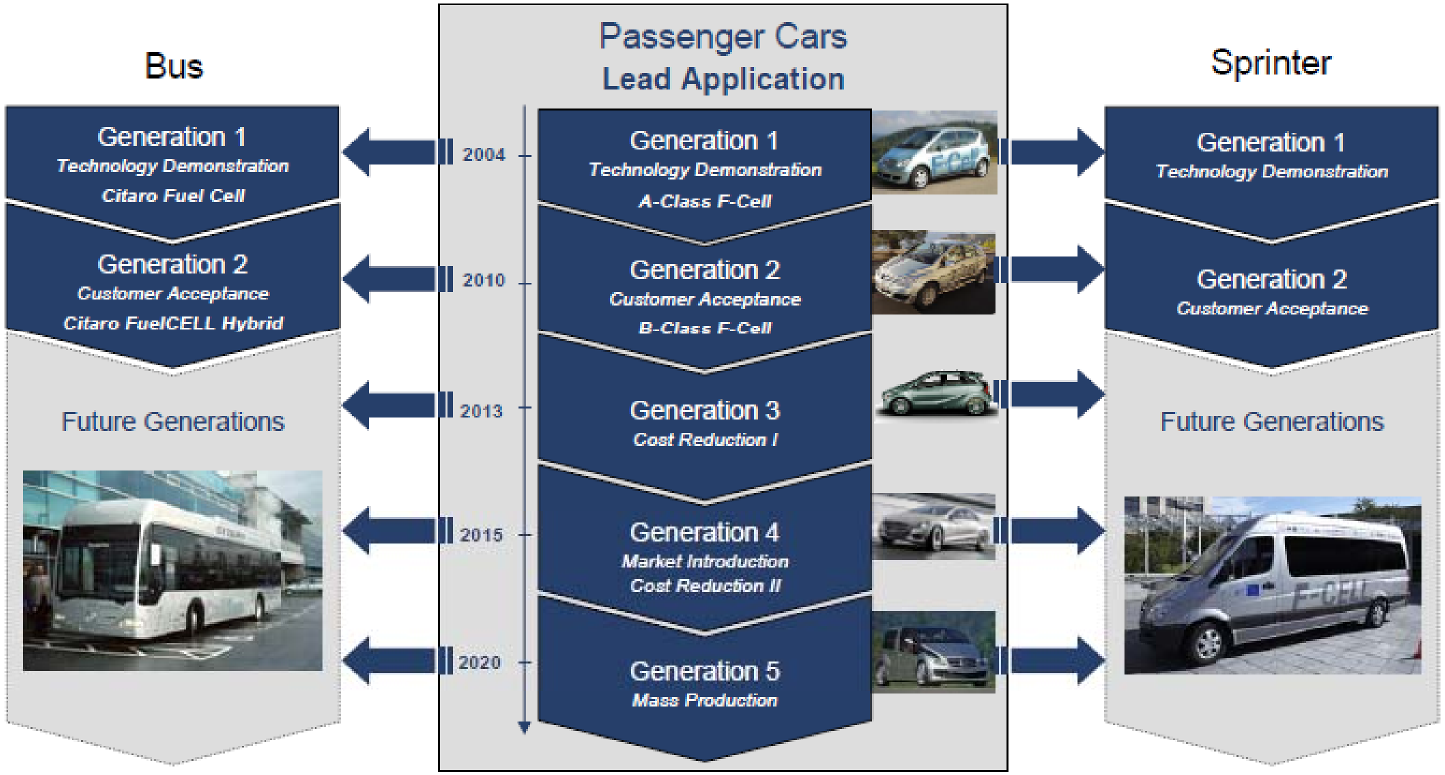
In order to build up a robust product strategy for the future, automotive and energy companies are preparing themselves towards a broader portfolio of drive-trains and fuels which may consist of five steps:

- Optimization of Combustion Engines
- Improvement of Conventional Fuels
- Introduction of Fuel Efficient Hybrid Vehicles
- Introduction of Renewable Fuels
- Introduction of Fuel Cells and Hydrogen as a Fuel

Fuel Cells and Hydrogen are positioned last in a row of innovations because of the disruptive changes required, and because of the fact, that the current technological barriers and costs preclude it from being considered as a short or mid-term solution.

Nevertheless, because of their strategic importance, significant investments were done already and will be done in research, development and demonstration programs by the industry and governments.

The Five Generation Development Program of the Automotive Companies: Example Daimler



Daimler is dedicated to commercialize fuel cell vehicles

Source: Daimler

1. Fuel Cell Vehicles / Development

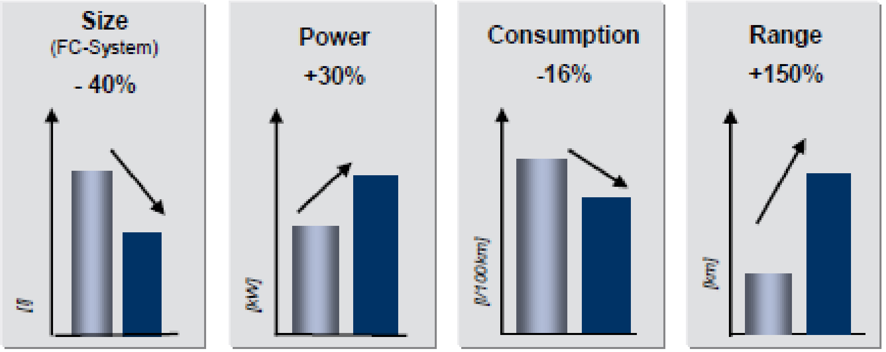
Transition to the next Generation of FCV: B Class F-CELL

A Class F-Cell
Generation 1

2004 – 2009
Controlled fleet demonstration

B Class F-CELL
Generation 2

from 2010
Large fleet demonstration



B-Class F-CELL:

- Higher stack lifetime (more than 2000 h)
- Increased power (65 kW → 100 kW)
- Higher reliability
- Longer range (160 km → 400 km)
- Freeze start ability below 0°C
- Li-Ion battery

Source: Daimler

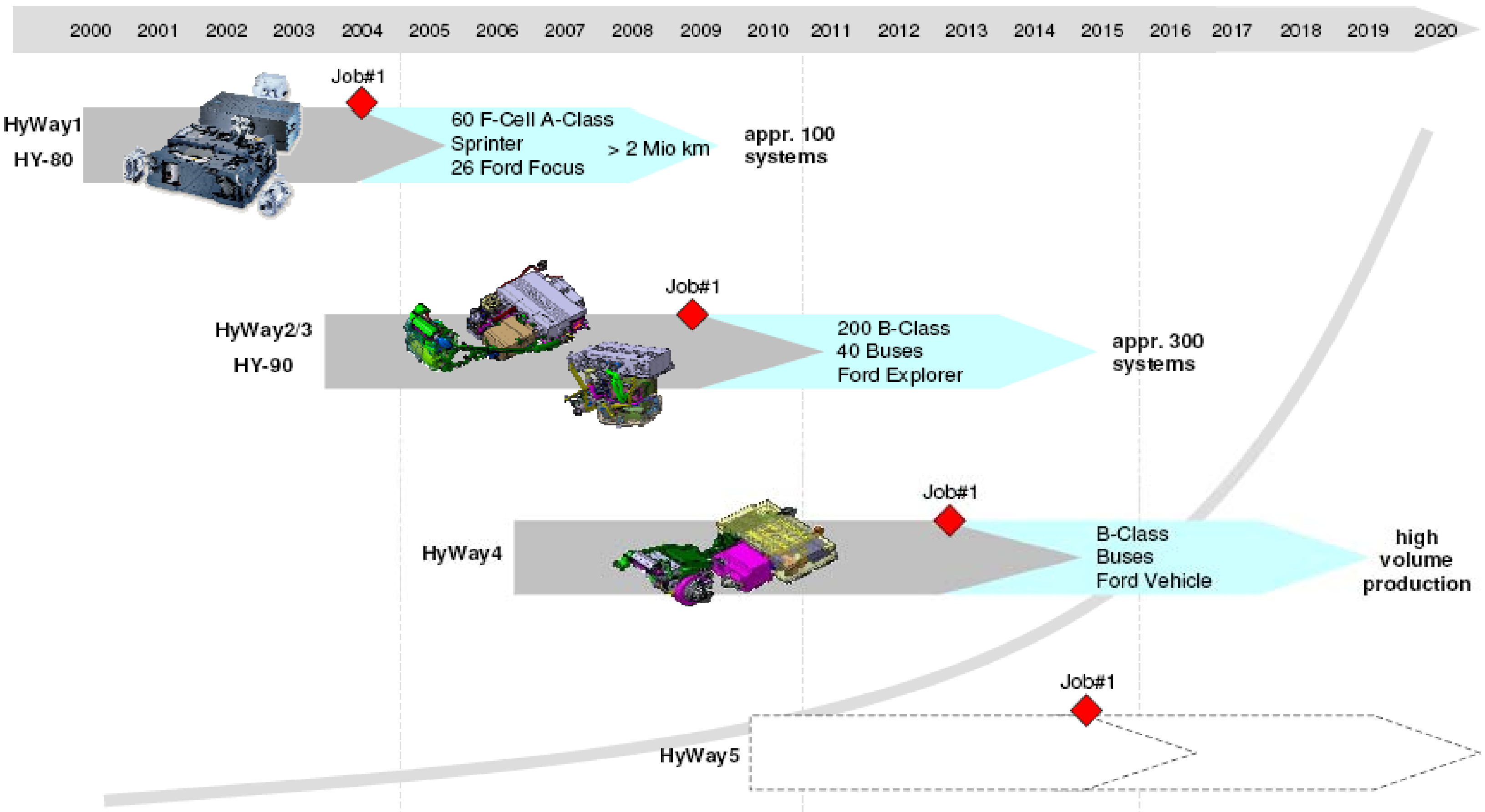
1. Fuel Cell Vehicles / Development

Daimler Fuel Cell Vehicle World tour 2011

1. Fuel Cell Vehicles / Development

The FC Systems Product Development Program:

The third and fourth Generation for 2013 and 2016 are already underway: Example Daimler



Source: NuCellSys

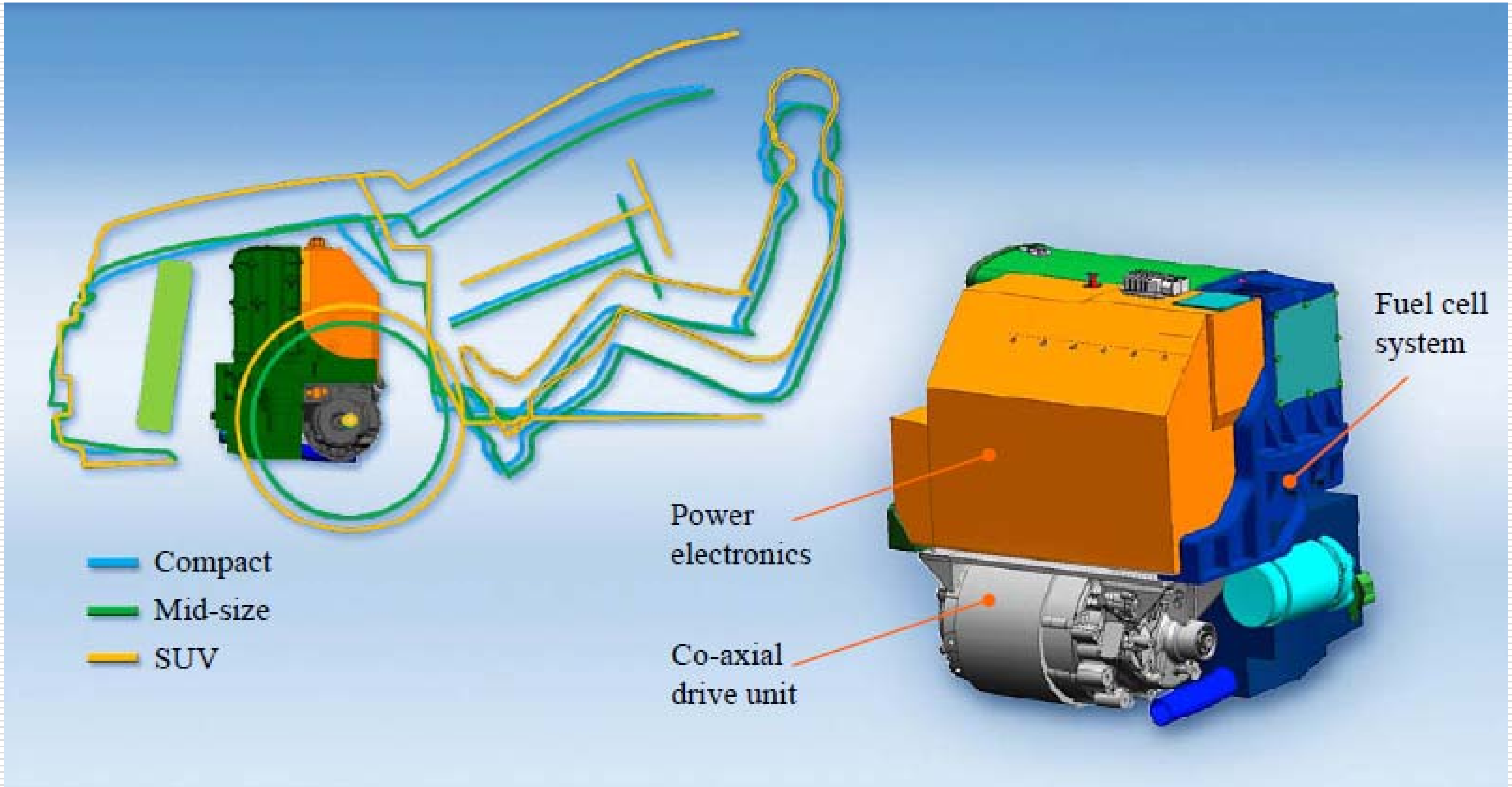
Development Steps of the GM Fuel Cell Program

	HydroGen4 	Next Generation 
Net power	93 kW	85-92 kW
Max excursion temp	86°C	95°C
Durability	1,500 h	5,500 h
Cold operation	Start from -25°C	Start from -40°C
Mass	240 kg	< 130 kg
Sensors / actuators	30	≤ 15
Stack subsystem: Plates UEA	Composite 80 g platinum / FCS	Stamped stainless steel < 30 g platinum / FCS
Air subsystem & humidification	Tube-style humidifier Sensor-based RH control	GM designed humidifier Model-based RH control
Design integration	Semi-integrated	Highly integrated for thermal performance

Source: GM

GM- Next Generation Fuel Cell System

Flexible for various vehicle applications



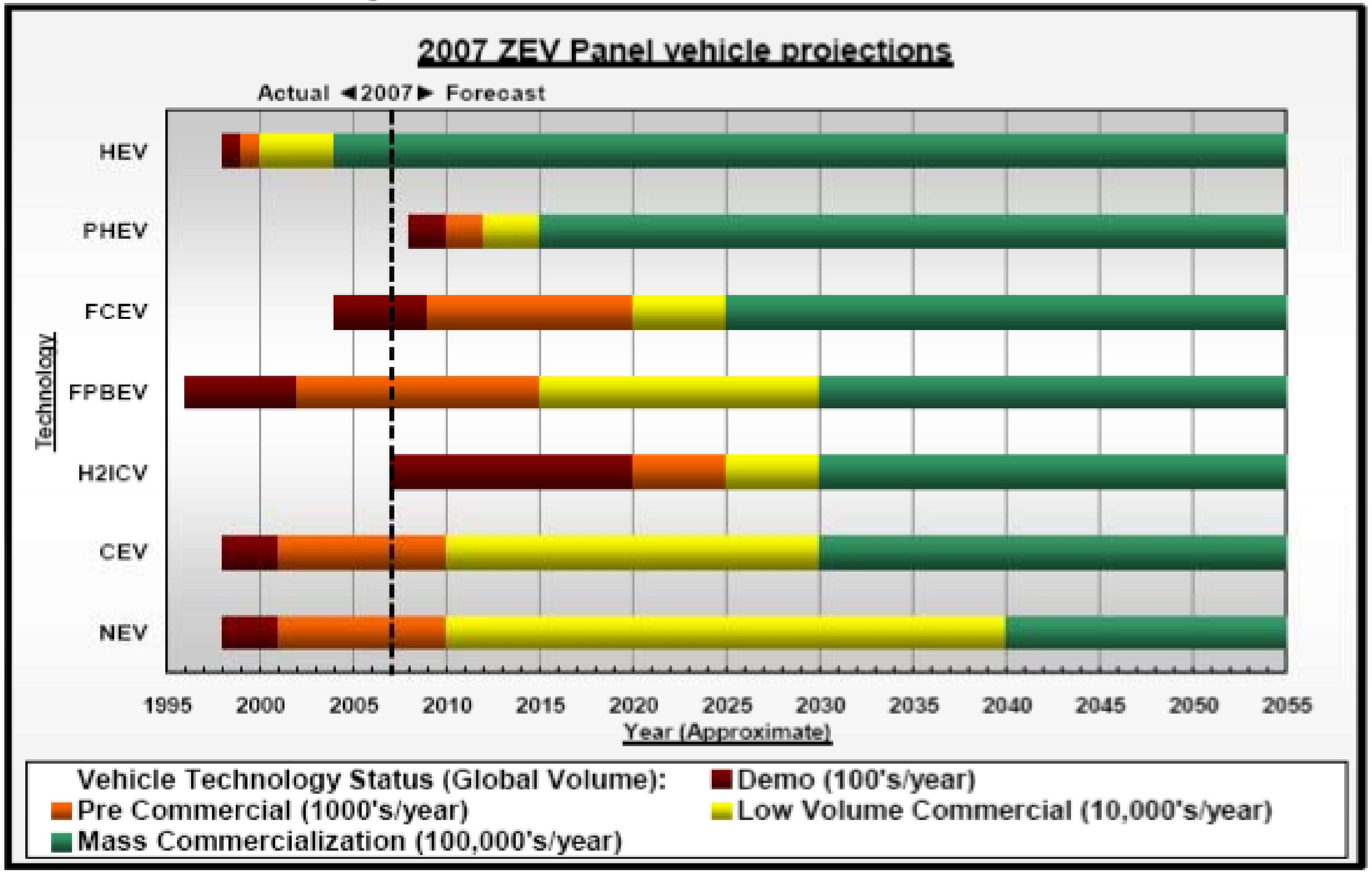
Source: GM

1. Fuel Cell Vehicles / Perspectives

Fuel Cell Vehicles: Expected Mass Production from 2025 on

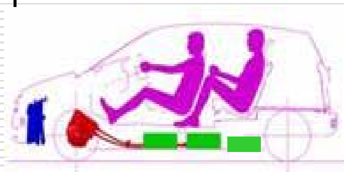
(ZEV Panel March 2007)

Projected Achievement of Global Volumes



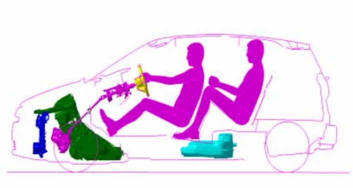
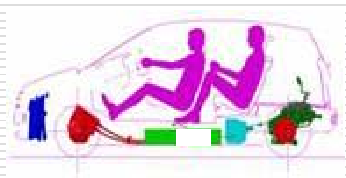
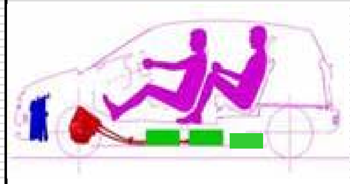
HEV= Hybrid EVs; PHEV= Plug-In HEVs; FCEV= Fuel Cell EVs; FPBEV= Full Power Battery EVs; H2ICV= Hydrogen Internal Combustion Engine Vehicles; CEV= City EVs; NEV= Neighborhood EVs

Mass and Volumes of drive train for a range of 500km (B-Class in NEDC)

Drive Train	Diesel	Plug-In (Range-Extender)	E vehicle	FC vehicle
Positioning in vehicle				
Energy storage and mass	Tank 45kg	Tank, battery (14,6 kWh) 180kg E-Range from battery = 70km	Battery (100 kWh) 830kg	H2-Tank, battery (1,4kWh) 131kg E-Range from battery = 2-5km
Energy conversion and mass	ICE, transmission 215kg	E-Motor, transmission, converter ICE, generator, converter 275kg	E-Motor, transmission, converter 147kg	E-Motor, converter, transmission, HV DC/DC FC System (HW4) 276kg
Drive train mass	**257kg** 	**455kg** 	**977kg** 	**407kg** 
Drive train volume	125 l	319l	1000 l	480l

Source: Daimler

Mass and Volume of drive train for a range of 500km (B-Class in NEDC)

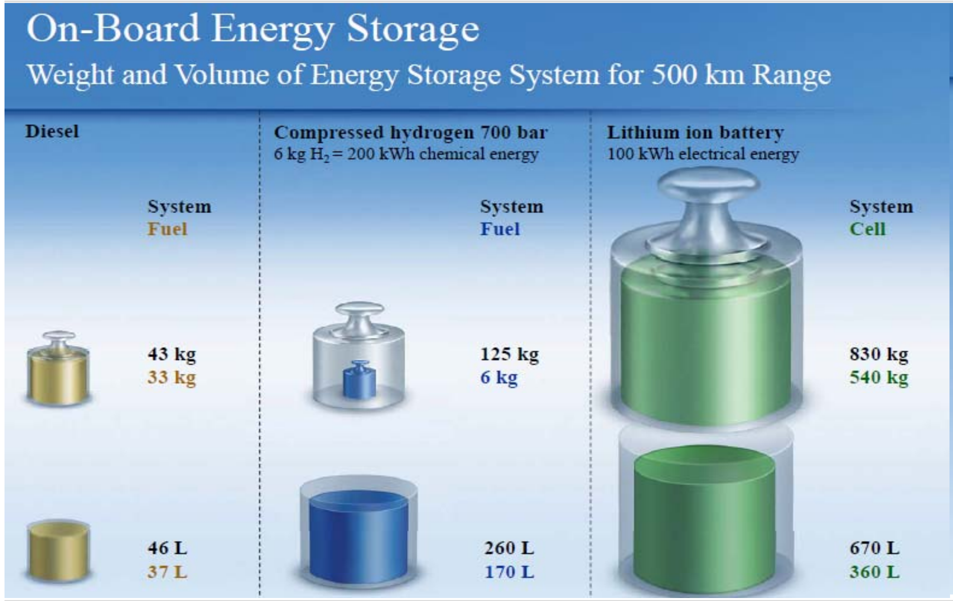
Drive Train	Diesel	Plug-In (Range-Extender)	E vehicle	FC vehicle
Positioning in vehicle				
Energy storage and mass	Tank 45kg	Tank, battery (14,6 kWh) 180kg E-Range from battery = 70km	Battery (100 kWh) 830kg **Batterie (40kWh =200km) 330kg**	H2-Tank, battery (1,4kWh) 131kg E-Range from battery = 2-5km
Energy conversion and mass	ICE, transmission 215kg	E-Motor, transmission, converter ICE, generator, converter 275kg	E-Motor, transmission, converter 147kg	E-Motor, converter, transmission, HV DC/DC FC System (HW4) 276kg
Drive train mass	**257kg** 	**455kg** 	**977kg** **455kg**  	**407kg** 
Drive train volume	125 l	319l	**500l**	480l

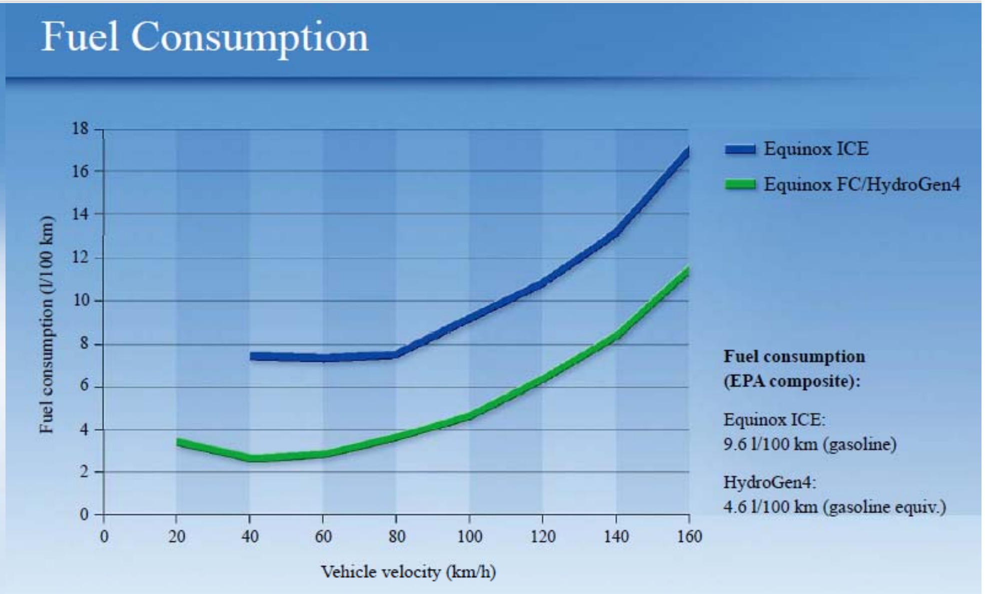
Source: Daimler

1. Fuel Cell Vehicles / Perspectives

Why Fuel Cell Vehicles?

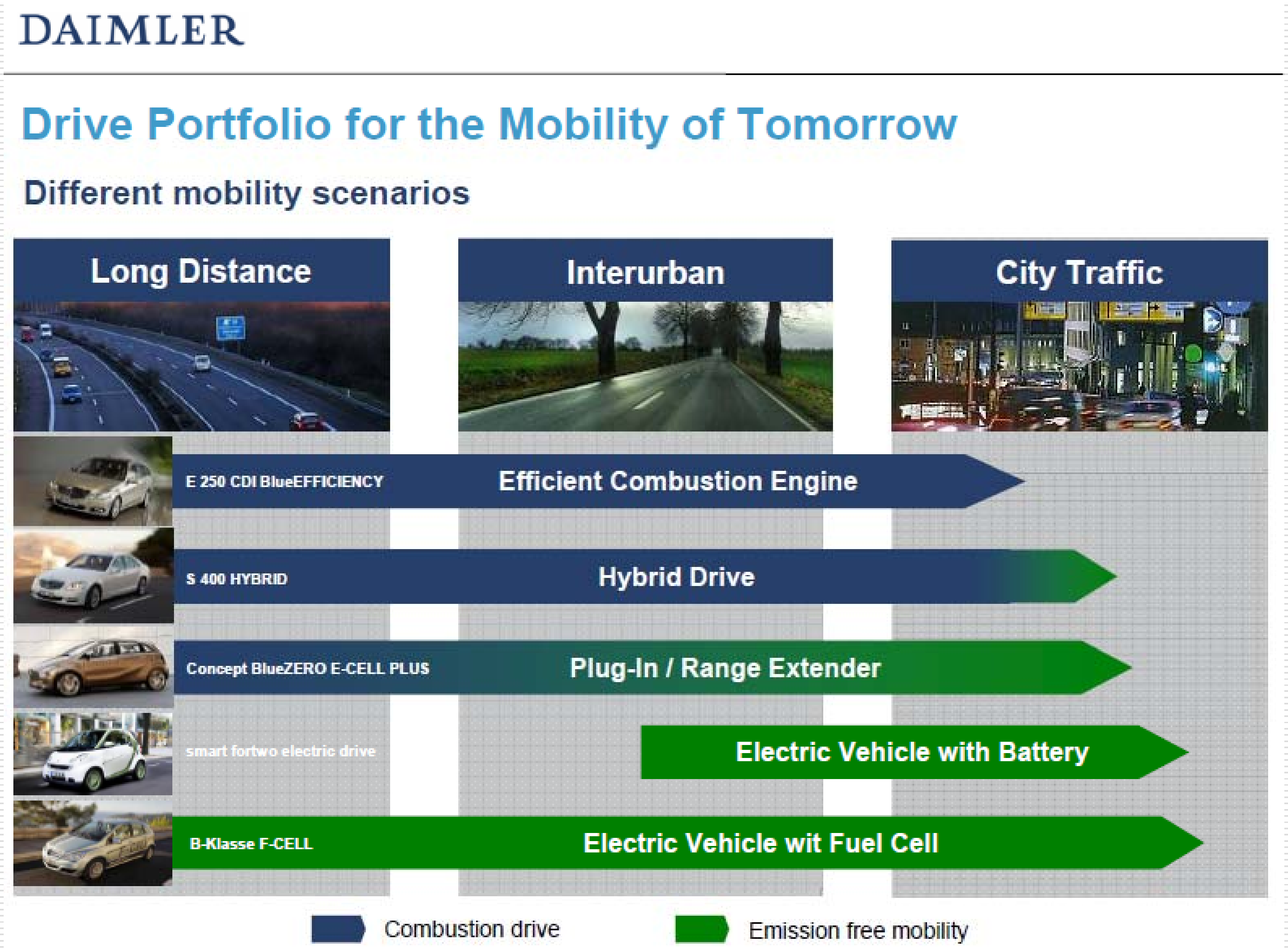
- Zero Emissions
- High Efficiency
- Low Noise
- High Ranges
- Good Performance
- Fast Refueling
- Potential for Zero GHG
- Renewable Feedstock Variability
- Use of Hydrogen as Future Energy Carrier
- Acceptable Packaging Characteristics





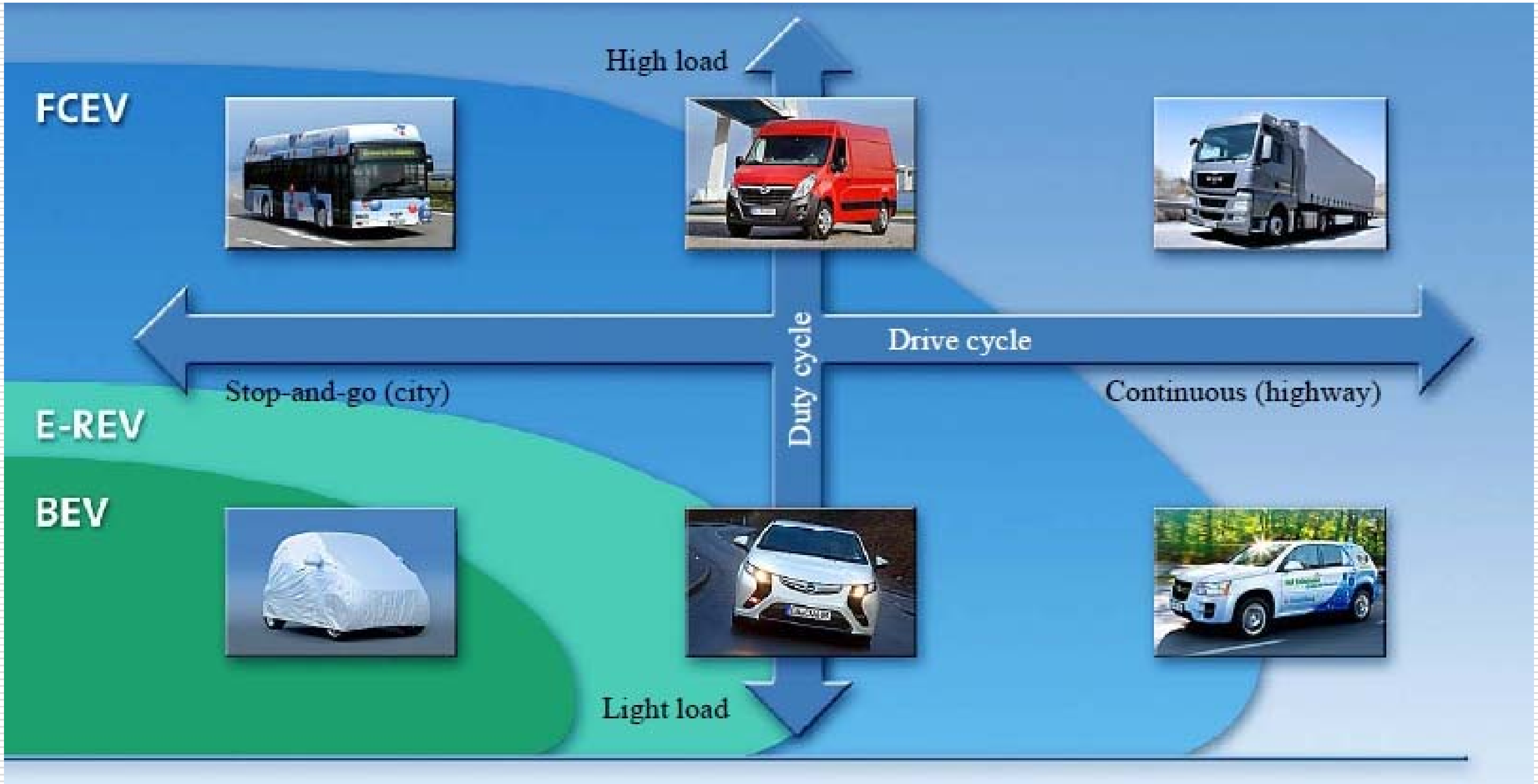
Source: GM

1. Fuel Cell Vehicles/ Perspectives



Source: Daimler

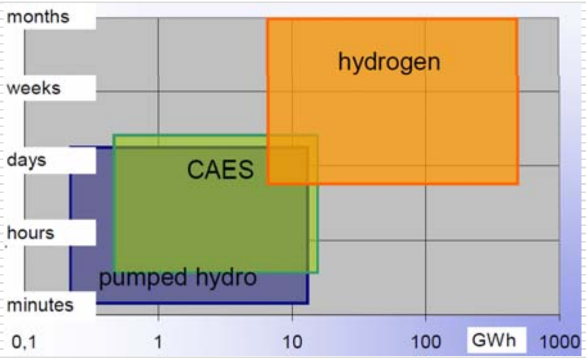
GM: Application Map for Future Vehicle Technologies

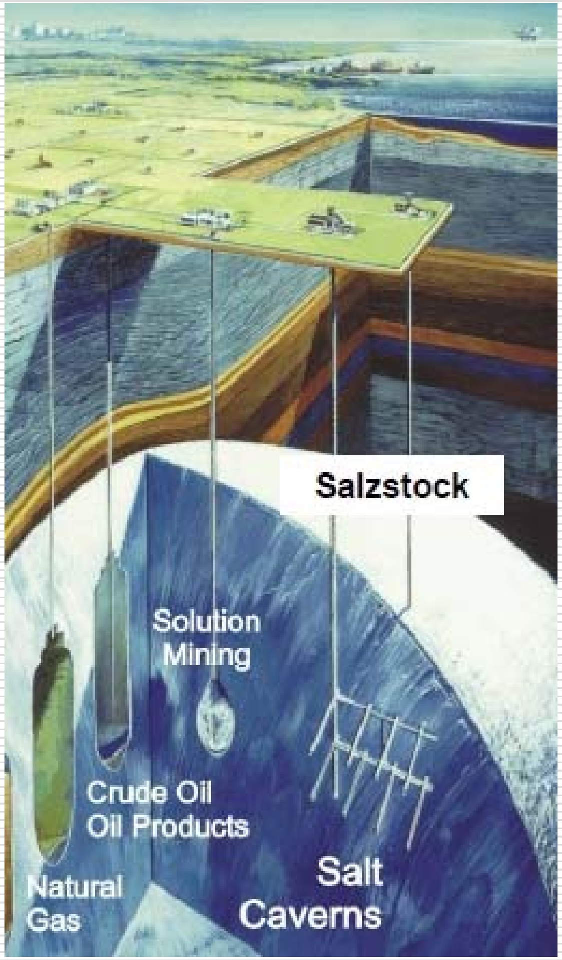


Source: GM

Hydrogen as Storage for Fluctuating Renewable Energy

- Hydrogen systems offer great potential for leveling out fluctuating energy: electrolysers may use excess electricity
  - compressed H_2 can be stored in caverns
  - due to its high gravimetric storage density, H_2 is a superior medium for storing expected large volumes of fluctuating energy
- Transportation has to be seen as part of an integrated energy system





source: KBB Underground Technologies

Mobil Applications, Demos and Practical Work

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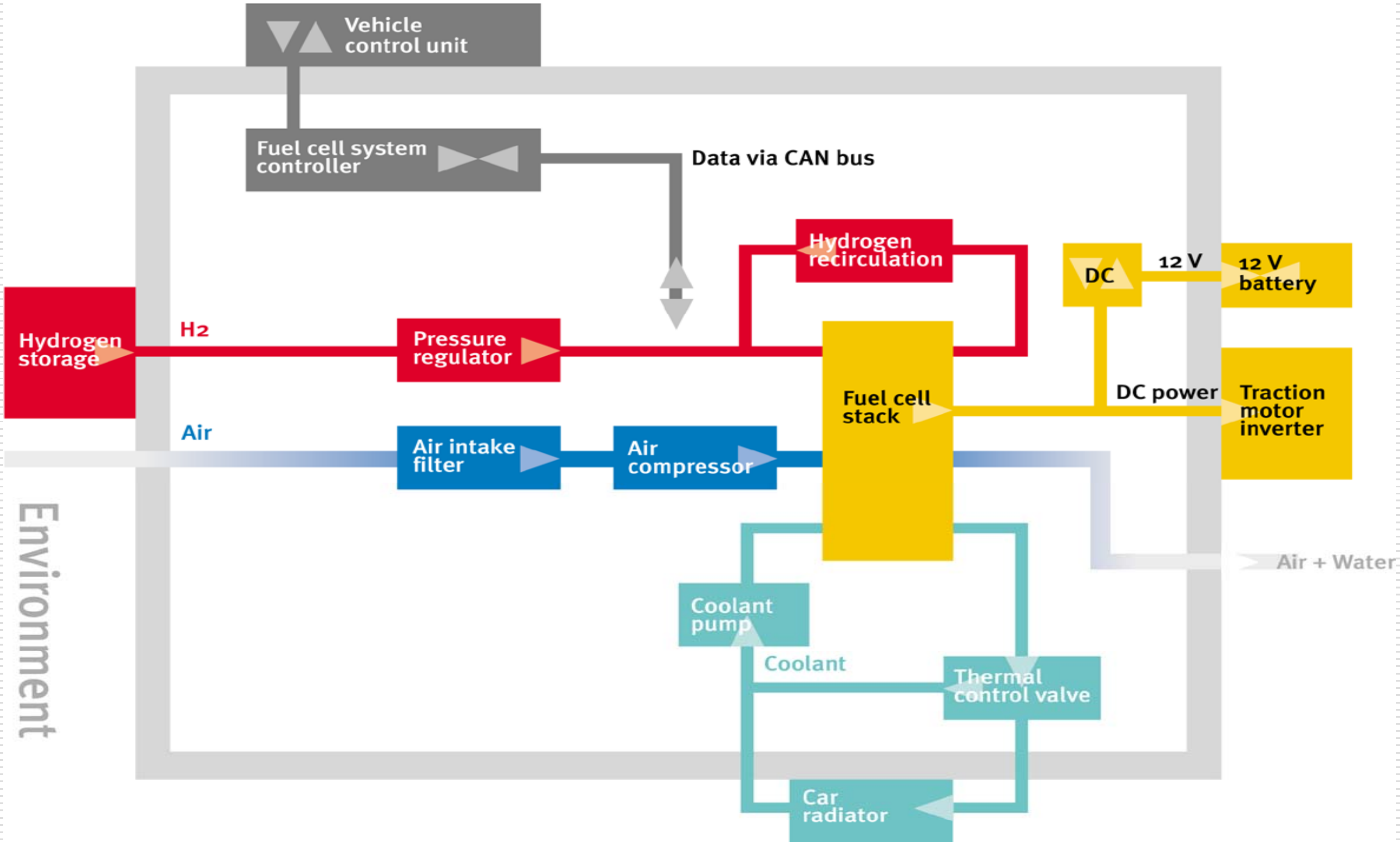
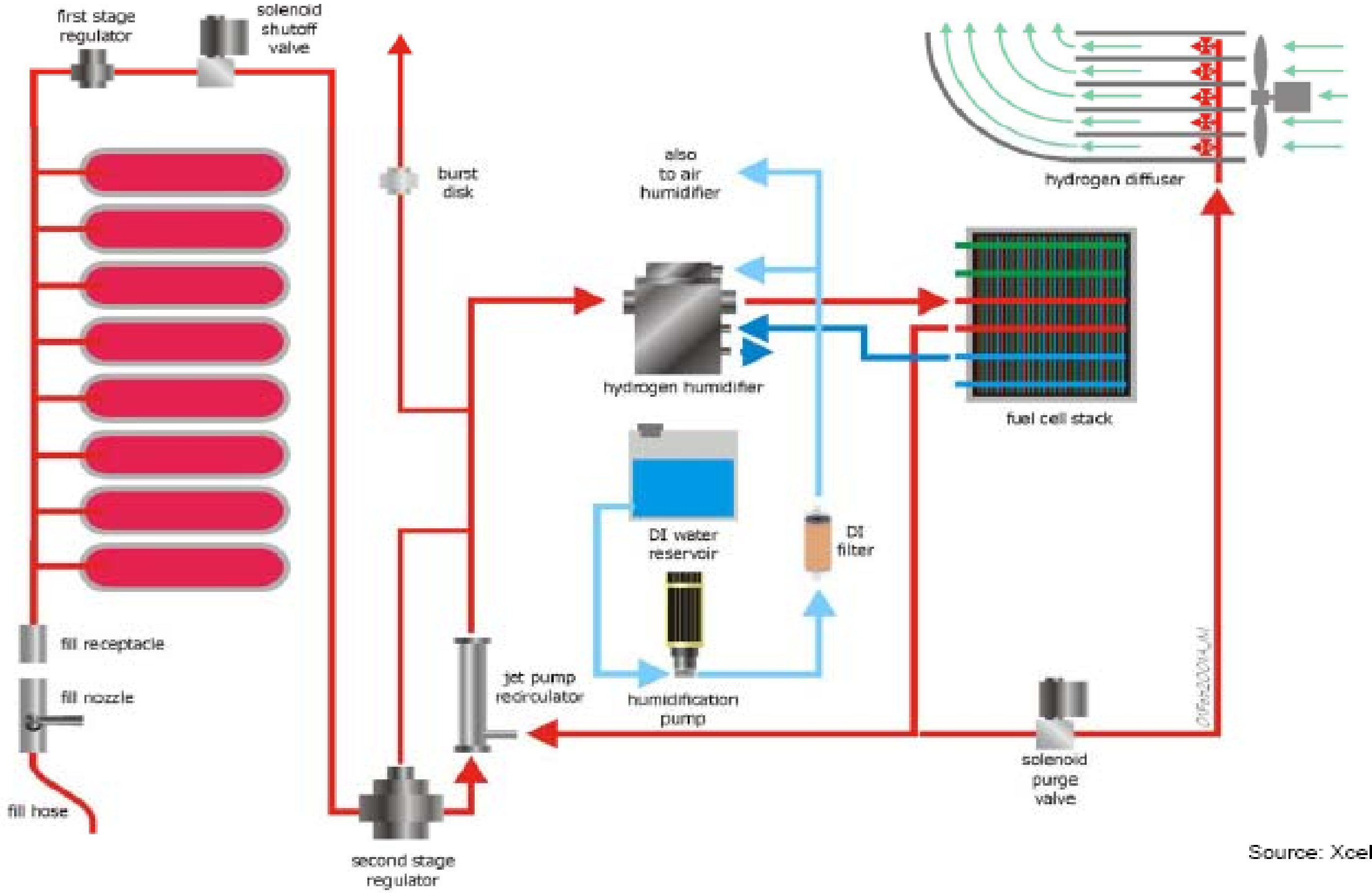
Principal Function of a Hydrogen Fuel Cell System



2. Fuel Cell Vehicle Systems/ Hydrogen Supply

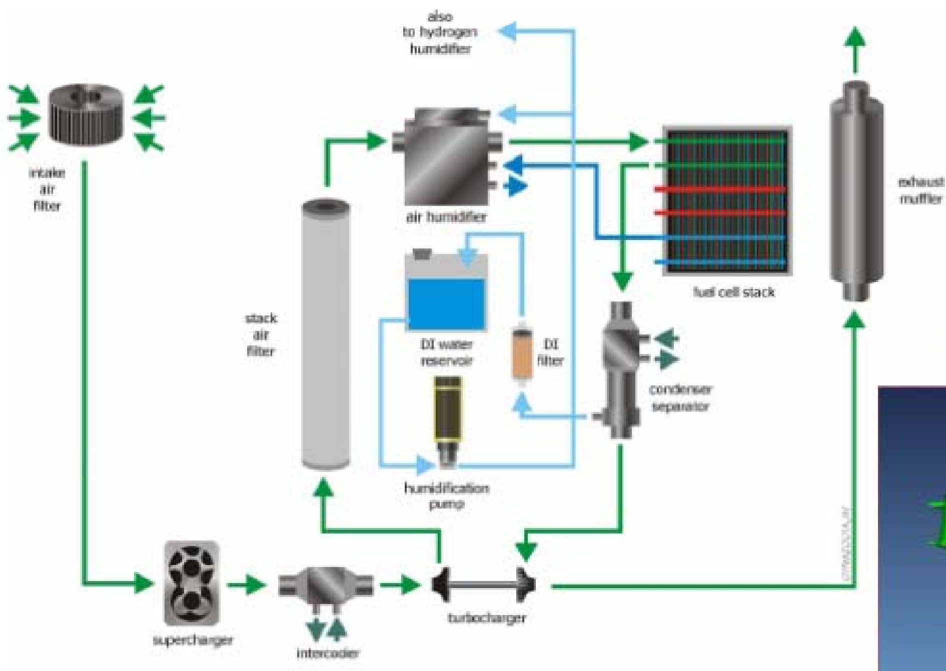
Hydrogen Fuel Cell System - *Hydrogen Subsystem*

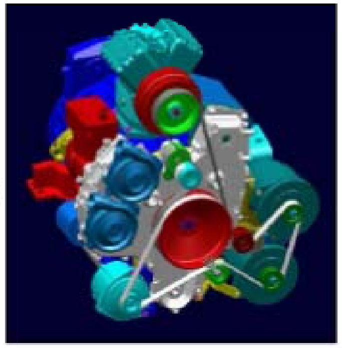


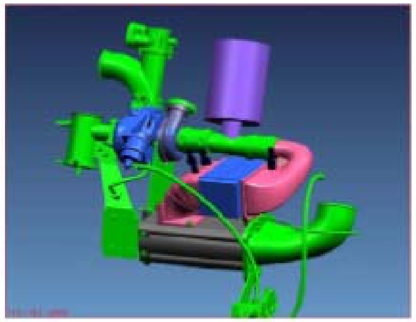
Source: Xcellsis

2. Fuel Cell Vehicle Systems/ Air Supply

Hydrogen Fuel Cell System - *Air Subsystem*





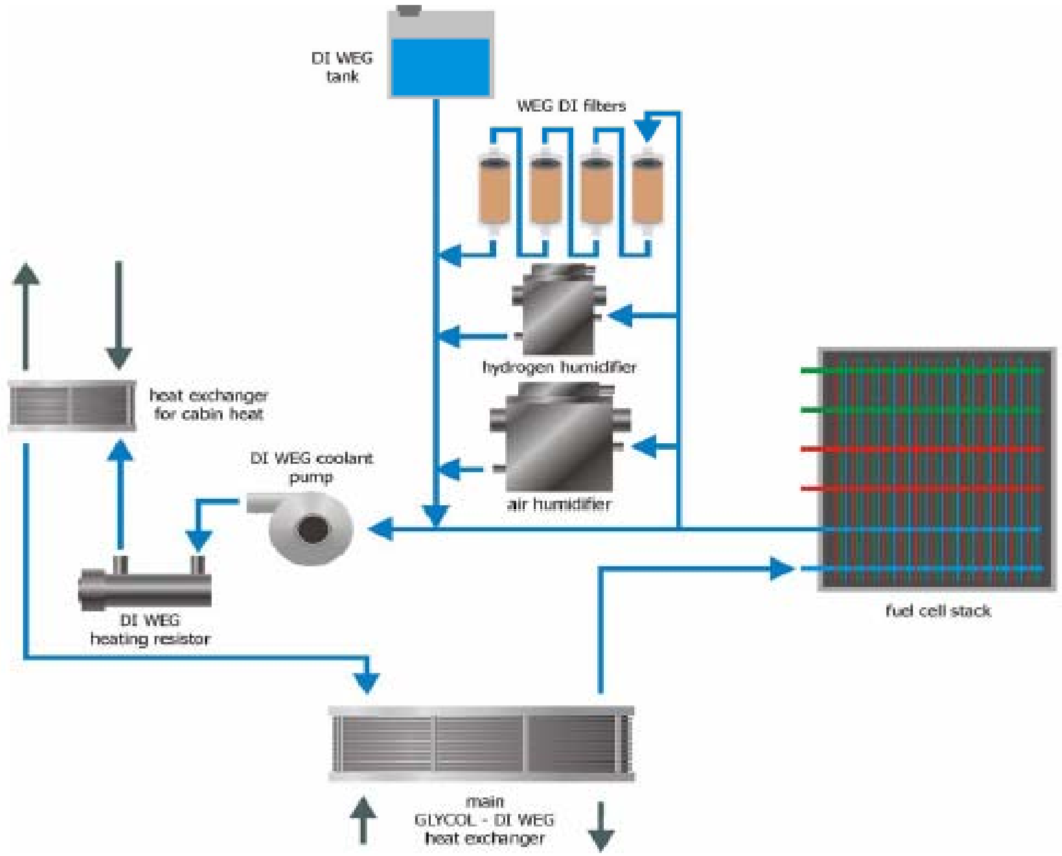


15.12.2004 Wolfram Fleck

2. Fuel Cell Vehicle Systems/ Cooling

Hydrogen Fuel Cell System

Cooling Subsystem primary Cooling (DI-W) Loop



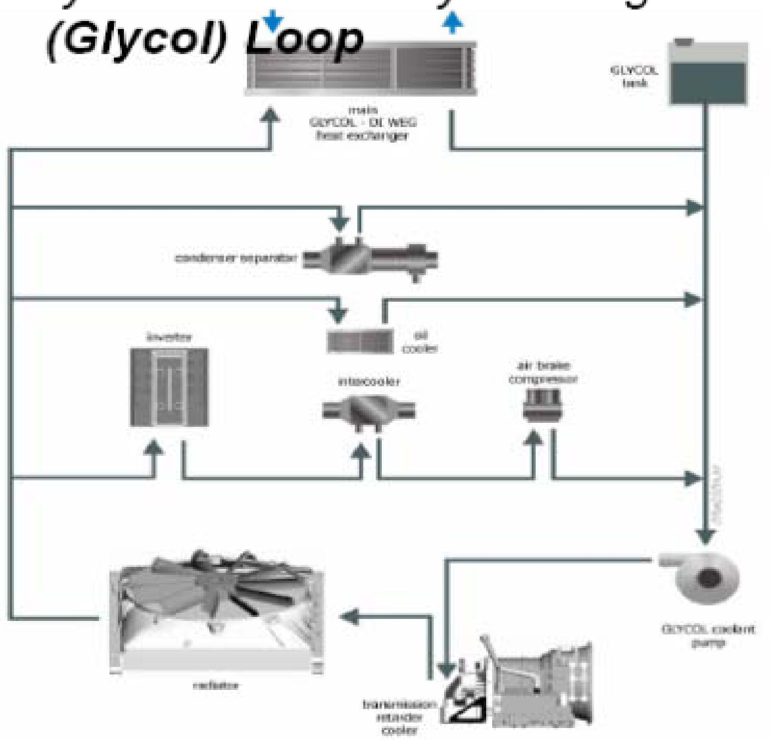
15.12.2004

Source: Xcellsis

2. Fuel Cell Vehicle Systems/ Cooling

Hydrogen Fuel Cell System

Cooling Subsystem Secondary Cooling
(Glycol) Loop

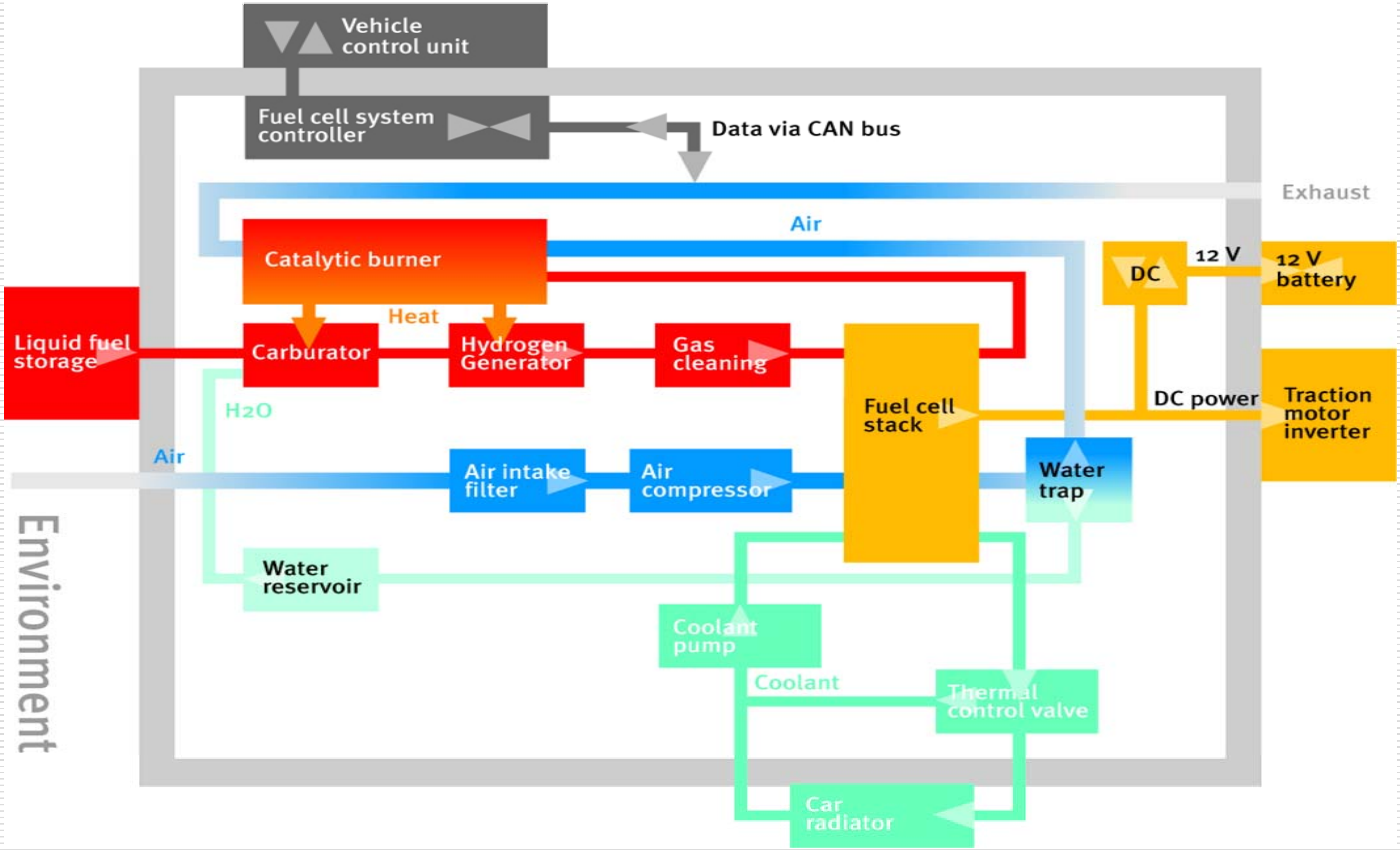


15.12.2004 Wolfram Fleck

Source: Xcellsis

2. Fuel Cell Vehicle Systems/ Reformer

Principal Function of a Methanol Fuel Cell Engine



Methanol Reforming - Chemical Reactions

Reforming (wanted):

$CH_3OH + H_2O => CO_2 + 3H_2$ $\Delta H^0 = +131 kJ/mol$

Partial Oxidation (wanted):

$CH_3OH + 1/2\ O_2 => CO_2 + 2H_2$ $\Delta H^0 = -155 kJ/mol$

Complete Oxidation (not wanted):

$CH_3OH + O_2 => CO_2 + 2H_2O$ $\Delta H^0 = -726\ kJ/mol$

Pyrolyse (not wanted):

$CH_3OH => CO + 2H_2$ $\Delta H^0 = +129 kJ/mol$

Gas Cleaning

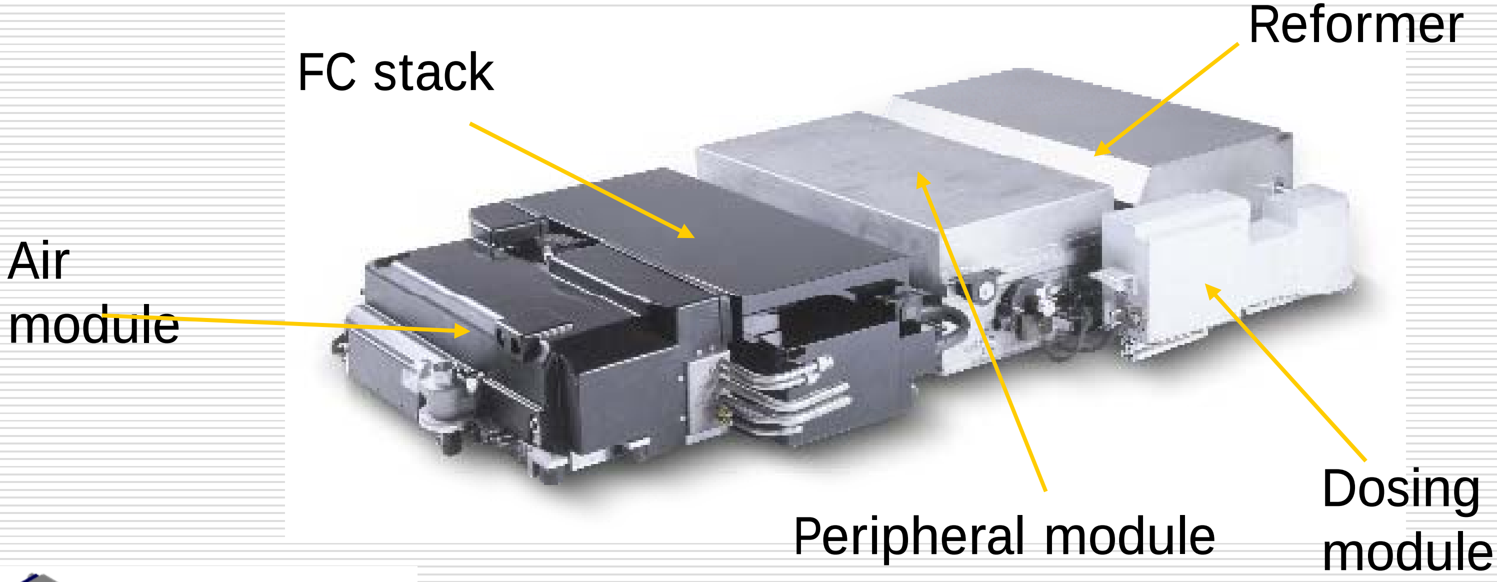
CO-Oxidation (wanted):

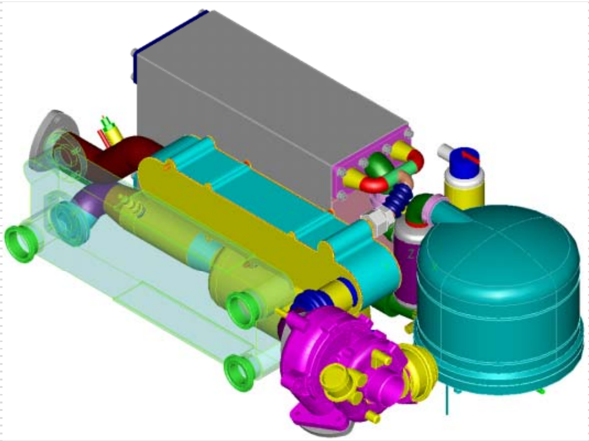
$CO + 1/2\ O_2 => CO_2$ $\Delta H^0 = -286 kJ/mol$

Water-gas-Shift-reaction (wanted):

$CO + H_2O => CO_2 + H_2$ $\Delta H^0 = +3 kJ/mol$

Aufbau eines Methanol Brennstoffzellensystems





Reformer 75 kW/ 64 l

stack gross power:	75 kW
system net power:	57 kW
max. system efficiency:	> 40%
max. power system efficiency:	32%

Mobil Applications, Demos and Practical Work

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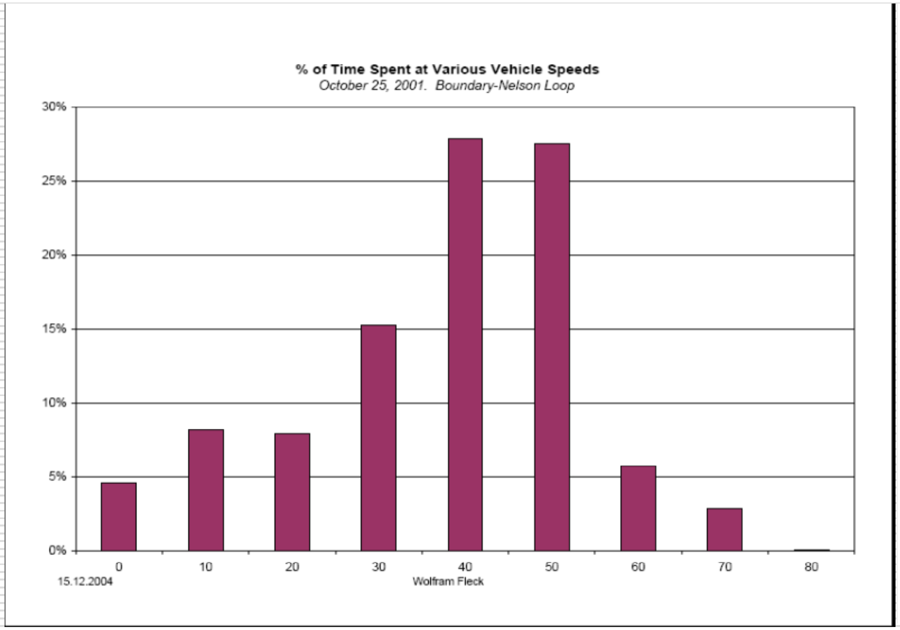
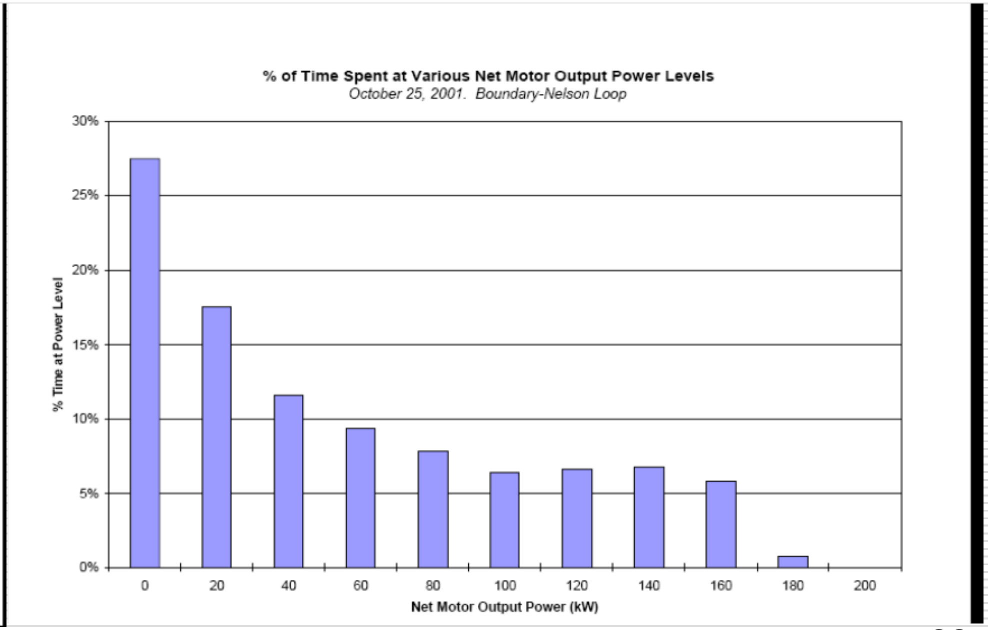
Basic Specifications and Requirements Fuel Cell Bus

Weight empty /loaded	14,2 t / 18 or 19 t*
Vehicle dimensions	12,0 m (l) * 2,55 m (w) * 3,67 m (h)
wall-to-wall turning diameter	21,5 m **
Fuel cell gross power	> 250 kW
Net shaft power	200 kW
Acceleration 0 - 50 km/h	< 12 s***
Range	200 km
Passenger capacity	up to 70
Vmax	up to 80 km/h
H2 storage system pressure	350 Bar
H2 storage system capacity	> 40 kg in 9 pressure cylinders

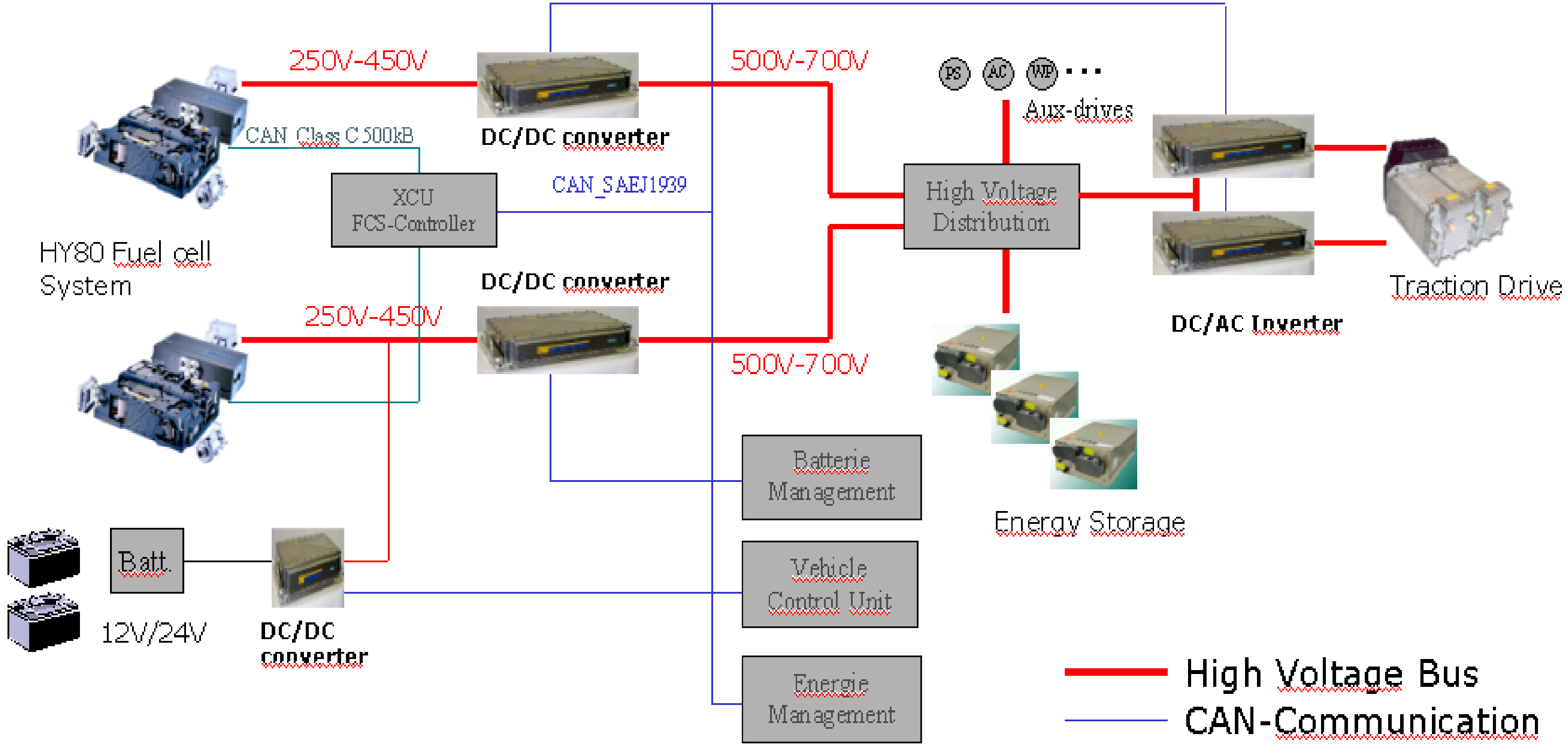




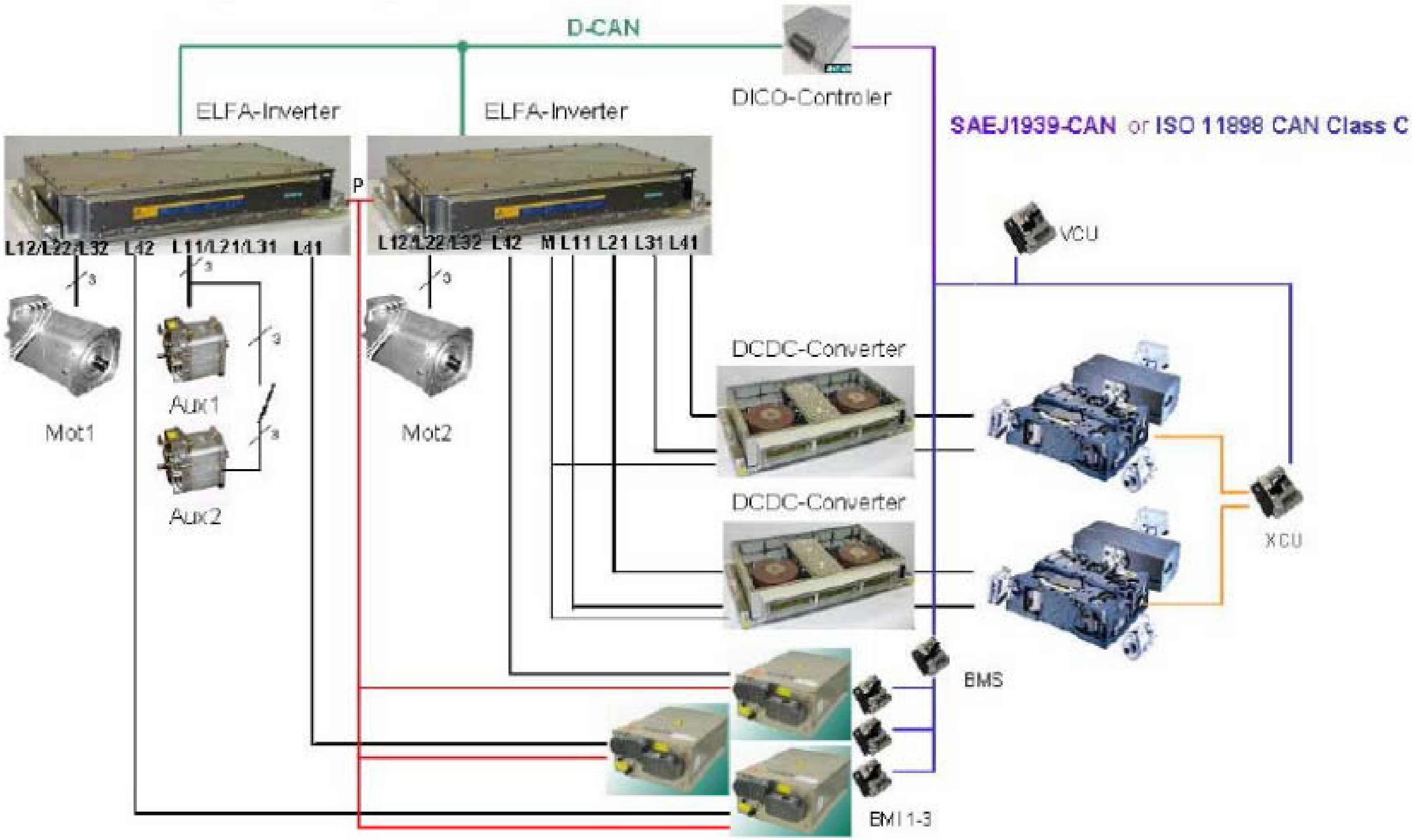
The BUS DRIVE TRAIN Configuration I

Hybrid System of 2 Integrated Nucellsys HY-80kW Fuel Cell Systems +

3 MES-DEA Zebra Batteries of total 105 kW/60 kWh + Siemens ELFA Electric Traction System

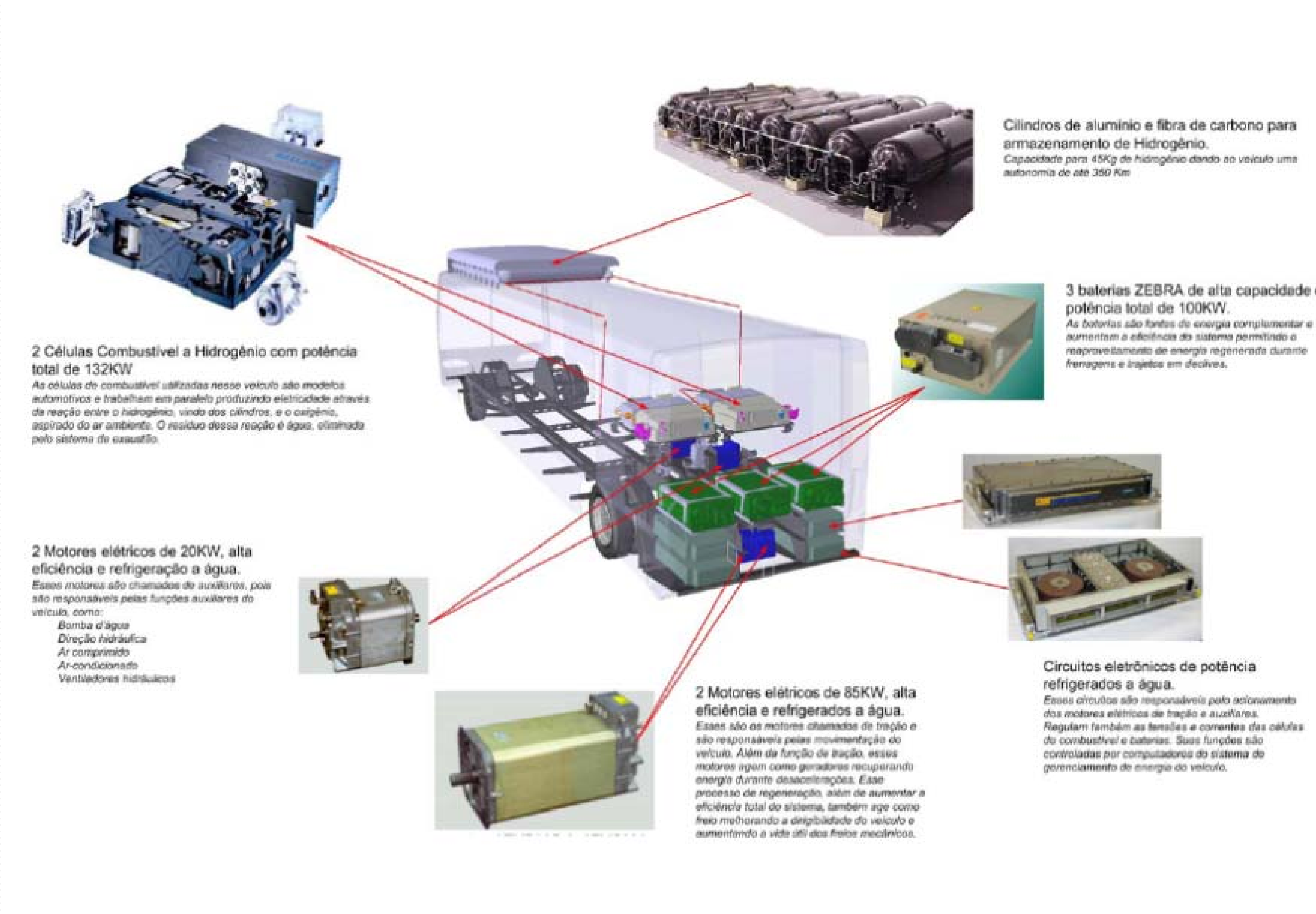


The BUS DRIVE TRAIN Configuration II



3. Fuel Cell Drive Trains/ Packaging

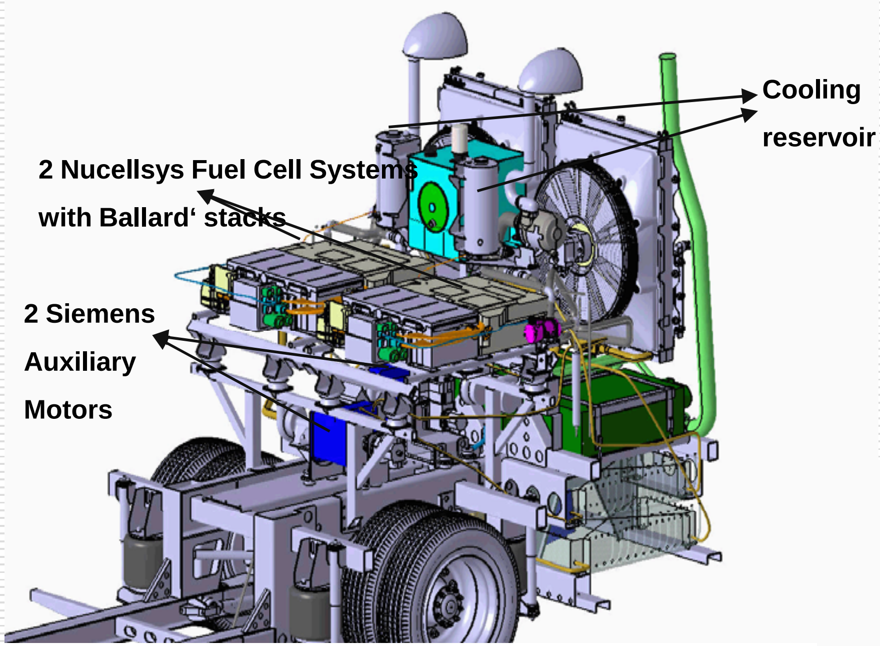
The Packaging Concept I

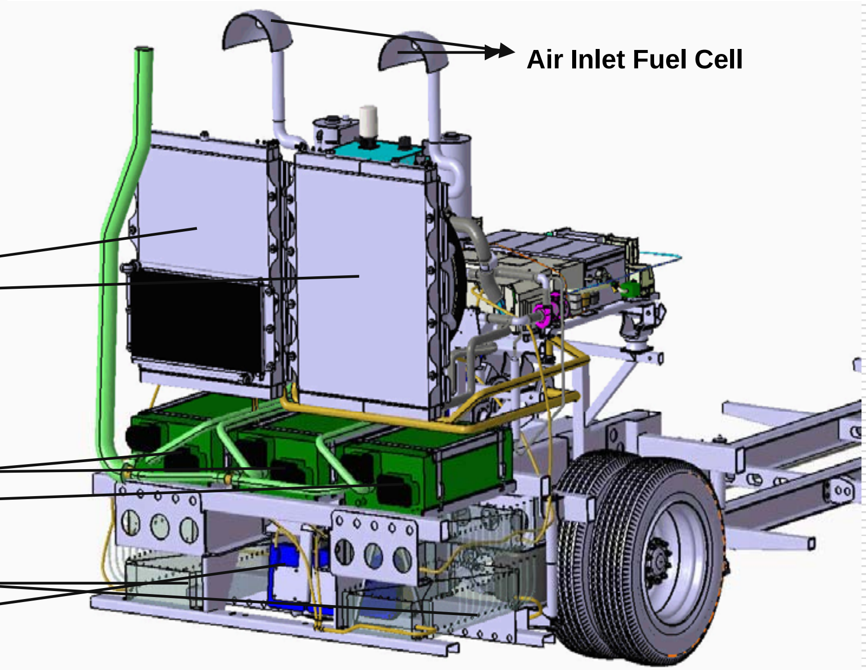


Hochschule Esslingen
University of Applied Sciences

3. Fuel Cell Drive Trains/ Packaging

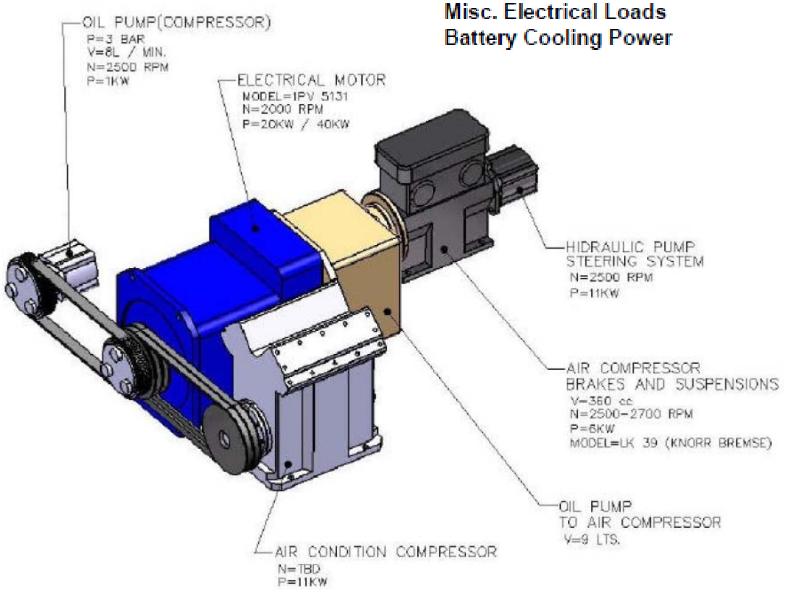
The Packaging Concept II

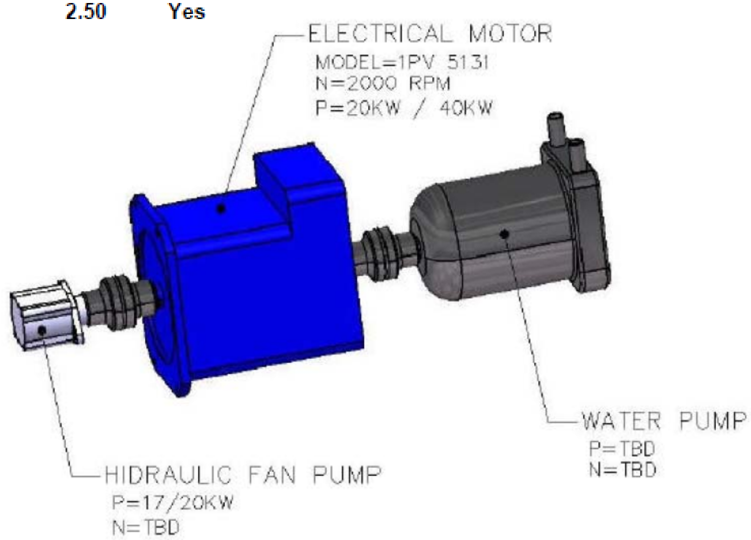




Assumptions of accessory component power

Accessory Component	Peak Power (kW)	Est. Duty Cycle	Average Power (kW)	Load Interruptible?
Accessory Drive Motor 1				
Oil Pump	1	100%	1.00	No
Air Conditioning Compressor	11	100%	11.00	Yes
Oil Pump to Air Compressor	2	100%	2.00	No
Air Compressor, Brakes and Suspension	6	50%	3.00	No
Hydraulic Pump, Steering System	11	25%	2.75	No
Peak ADM1 Power	**31**		**19.75**	
Accessory Drive Motor 2				
Hydraulic Fan Pump	17	75%	12.75	No
Water/Coolant Pump	10	50%	5.00	No
Peak ADM2 Power	**27**		**17.75**	
Total of ADM Loads	**58**		**37.50**	
Misc. Electrical Loads	**3**	**50%**	**1.50**	**No**
Battery Cooling Power	**5**	**50%**	**2.50**	**Yes**





The FUEL CELL STACK

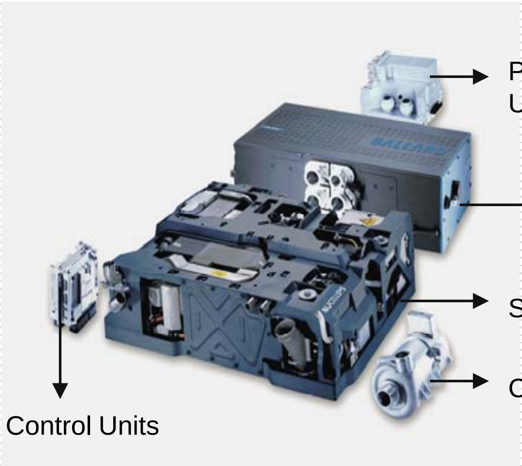
Typical characteristics of a Ballard® PEM Fuel Cell (Mark 902):

Temperature (nominal):	**80 °C (176°F)**
Fuel pressure (nominal):	**1- 2 barg**
Rated net output (continuous):	**85 kW**
Current (max.):	**300 Amps**
DC voltage (min at rated power):	**280 Volts**

3. Fuel Cell Drive Trains/ Components

The FUEL CELL SYSTEM

2 Integrated Nucellsys HY-80 Fuel Cell Systems



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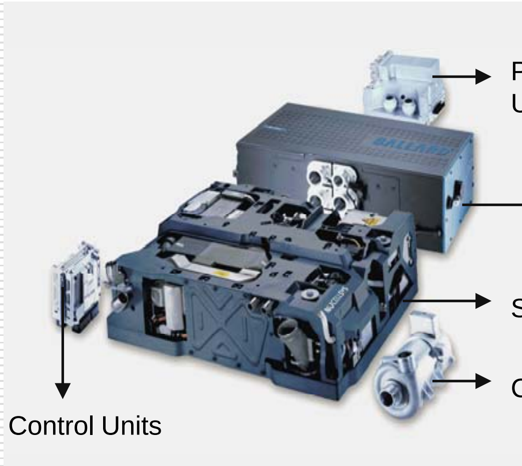
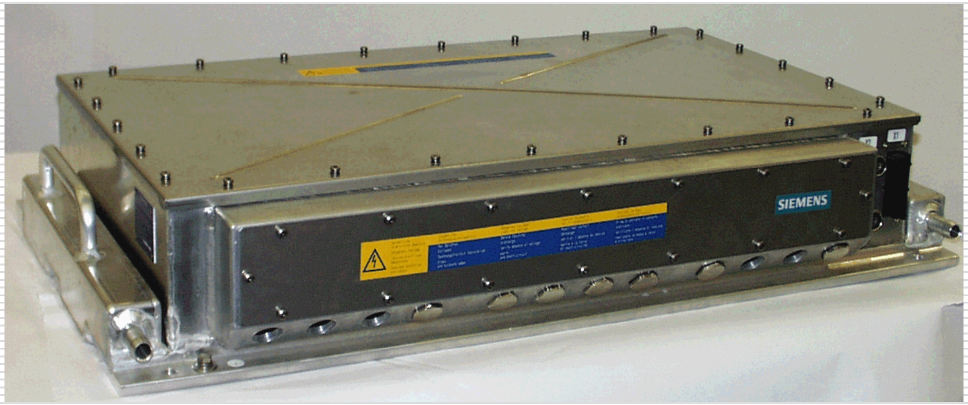


Characteristics of a HY-80 Nucellsys Fuel Cell System:

- **Engine Weight: 220 kg**
- **Engine Volume: 220 l**
- **Max. system net power 68 kW**
- **Idle to 90 % power < 1 sec**
- **Max. efficiency 52 %**

The DUO-inverter (Siemens):

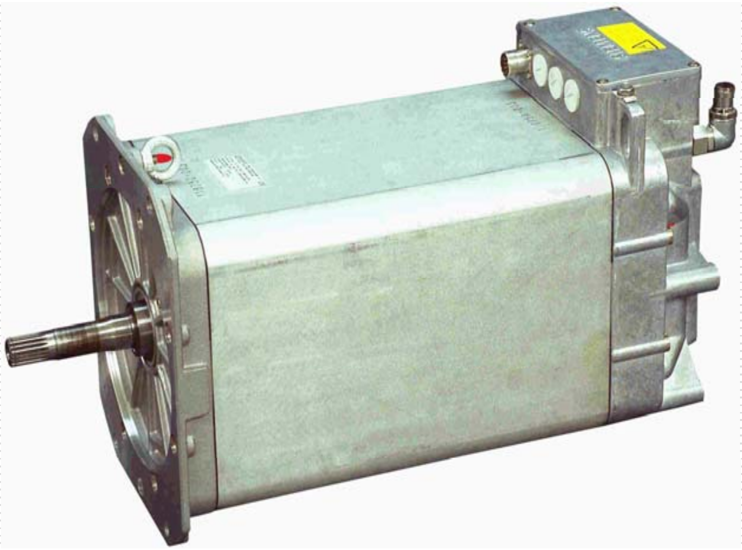
Is the key-component of the ELFA-drive-system and controls the drive motors, the auxiliary motors and the DC/DC-step-up function. Due to it´s integrated software the DUO-inverter operates flexible and modular within the overall drive-system and enables the easy use in different drive-train configurations. Due to the compact water cooled housing the inverter has a high power-density and allows easy assembly into the vehicle. The superposed system-software is integrated in a separate hardware called DICO (Digital Input Control). This software includes the customized interfaces to the vehicle as well as to the subsidiary inverter controllers. In addition the vehicle control, hybrid control and a safety concept is included.



Type	Inverter 8 Phases
Cooling Media	Water-Glycol
Rated Voltage DC	650 V
Operating Voltage DC	110 V - 650 V
Rated Current Inv.	170 A
Rated Power Inv.	2 x 120 KVA
Rated Power Chopper	2 x 60 KW (@ 90 A)
Max. Current	300 A
Max. Power	2 x 210 KVA
Frequency Inv.	6 KHz
Frequency Chopper	2 KHz
Weight	65 kg
Dim. (lxwxh)	1000 x 567 x 180 mm
Degree of Protection	IP 54
Ambient Temperature	- 25 °C to 70 °C

The Traction Motors (Siemens):

The motors are water-cooled, 4-pole asynchronous-motors with squirrel-cage rotors.
They are equipped with a temperature sensor integrated in the stator winding for measuring the temperature response, as well as for regulation and preventing the motor from overheating.
A second, redundant temperature sensor is also provided in the stator winding.
An Encoder system for measuring the motor speed and the direction of rotation is included.



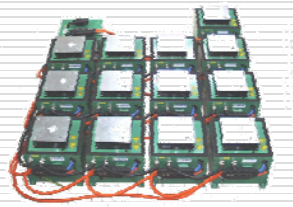
Type	AC Induction Motor
Cooling Media	Water-Glycol
Rated Voltage DC	650 V
Rated Power	85 KW
Rated Torque	220 Nm
Max. Torque	530 Nm @ 300A
Rated Current	142 A
Max. Speed	10,000 rpm
Weight	120 kg
Dim. (LxWxH)	510 x 245 x 245 mm
Ambient Temperature	- 30 °C to 70 °C
Degree of Protection	IP 65 / 9k

Rear axle (Meritor) and twin motor (Siemens)

The two traction motors are mounted on a summation gear box and can be operated by two physically different inverters. In case of any single failure of one inverter or any problem with one of the two energy loops - e.g. battery or generator loop - it is possible to operate the bus with one traction motor on the remaining loop. In this case the bus can either finish its route with less performance or just leave hazardous areas such as railway tracks, tunnels or intersections.

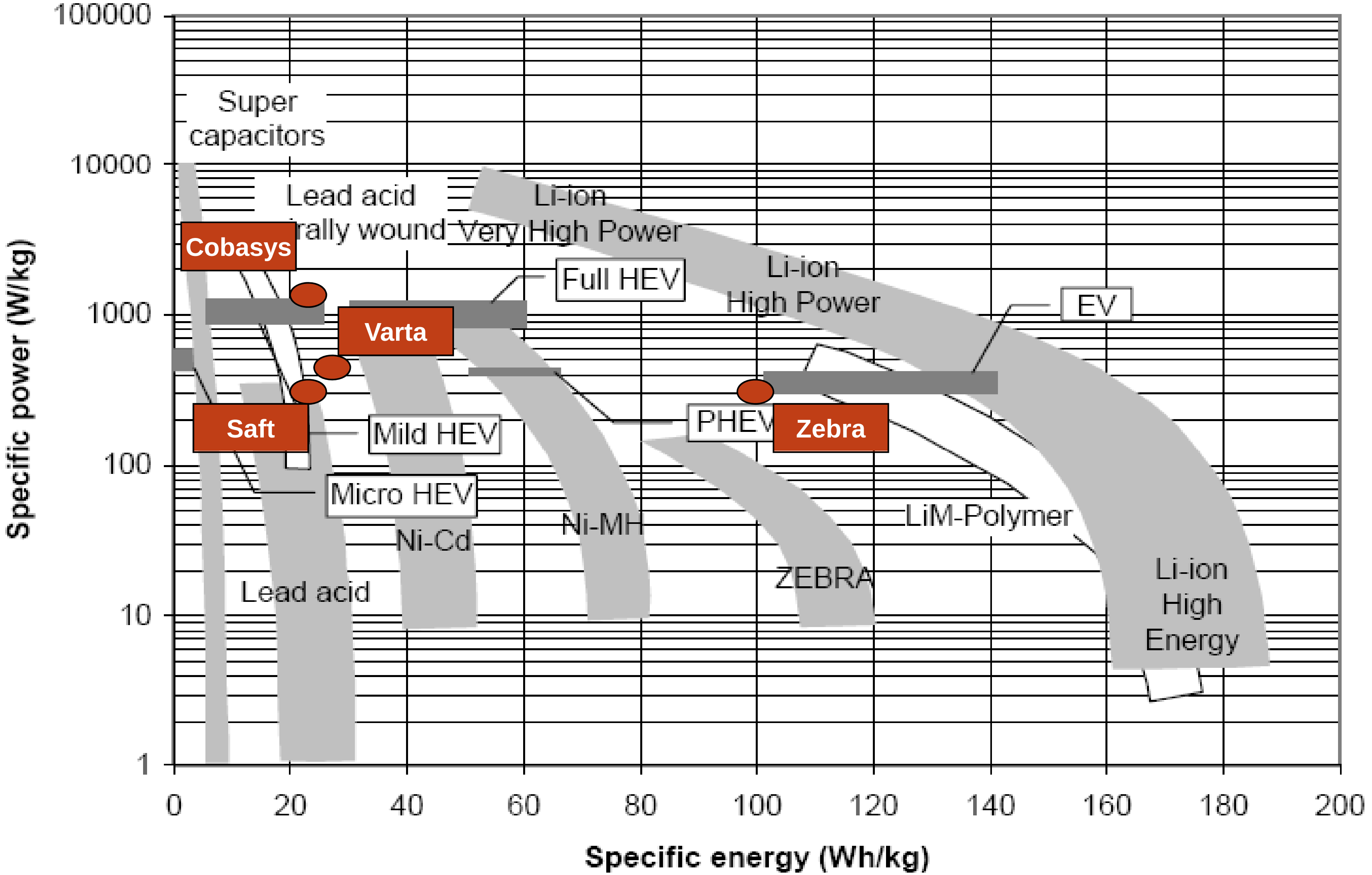
3. Fuel Cell Drive Trains/ Components

Battery Systems: Proposed Candidates




	VARTA	Cobasys	SAFT	ZEBRA
No. Of cells	416		450	3x240
cell Voltage	1,25V		1,2V	2,58V @ 300degC
Nominal Voltage	520V	576V	540V	620V
max dischg Current			200A 5min	112A
Energy content	13 kWh 25Ah	9,6 kWh 17Ah	19 kWh 34Ah	3x 19,8kWh 32Ah
peak Power	230kW @ 340V	240kW	189 kW	3*36kW @ DOD80
Weight	593kg	300kg	392 / 700kg	3x207kg
Dimensions	13x 411x354x290		412 l	3x 900x530x290mm
Cooling	air	air	water	air

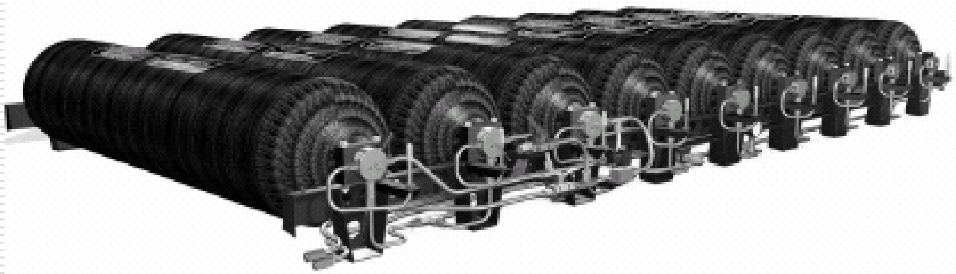
Spezifische Energie- und Leistungsbereiche von Batterietechnologien und - systemen



3. Fuel Cell Drive Trains/ Components

Hydrogen Storage System

Transverse Roof Mount Fuel Storage System (already certified and used in other bus projects)



Service Pressure:	350 barg
Maximum Fill Pressure:	438 barg
Nominal Outlet Pressure:	Up to 17 barg
Nominal Weight	1150 kg
Nominal Capacity @ 15 °C	44.8 kg Hydrogen
Overall Dimensions (Including Roof Cover)	
Length:	4225 mm
Width:	2340 mm
Height:	550 mm
Maximum System Pressure	438 bar
Minimum System Pressure	30 bar
Hydrogen Supply Pressure (Nominal)	12 bar
Electrical Voltage	24 VDC
Certification	Varies depending on location
Operating Temperature Range	-40 °C to +85 °C
Service Life	15 Years

Hydrogen Storage System:
Energy Density 44,8 kg H2 / 1150 kg = 3,9 Weight -% = 1,297 kWh/ kg

Mobil Applications, Demos and Practical Work

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1. Fuel Cell Vehicles
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2. Fuel Cell Vehicle Systems
    2.1 Hydrogen Supply
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    2.4 Reformer Technology

3. Fuel Cell Drive Trains
    3.1 Architecture
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4. Simulation
    4.1 Introduction
    4.2 Control Strategy
    4.3 Results

Background

- Fuel cell hybrid operation enables most efficient use of the inherently high energy density of the fuel cell and high power density of the battery

- Advantages of hybridization
  - Energy efficiency improvement: regenerative braking capture + shift in fuel cell operrating conditions
  - Fuel cell sizing optimization: uses a smaller, lower cost fuel cell
  - Improve vehicle performance: cold start and dynamic response

4. Simulation/ Introduction

Objectives

- Develop a simulation model for a Fuel Cell Hybrid Sprinter
- Develop control strategy for the fuel cell sprinter model which can:
  - Satisfy instantaneous driver power demands
  - Satisfy fuel cell system dynamic responses
  - Improve vehicle fuel economy
- With respect to:
  - Components limits
  - Charge-sustaining constraints

4. Simulation/ Introduction

Vehicle Characteristics

Base vehicle

Curb weight	2050 kg
Pay load	1450 kg
Static/dynamic Tire radius	0.336 / 0.314 m
Rolling resistance	0.014
Front area	3.48 m^2
Air drag coefficient	0.44

Fuel Cell System

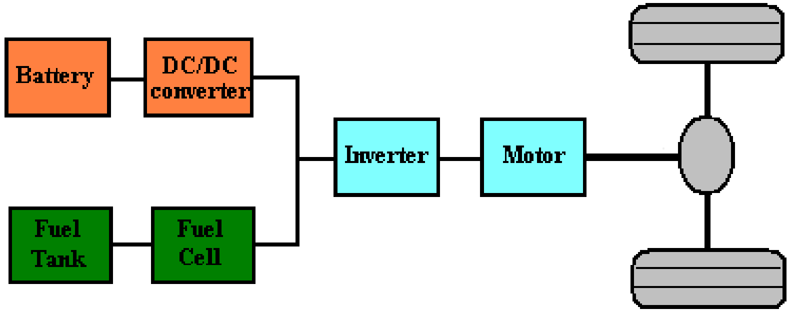
Type	PEM
Nominal power	70 kW

E-Motor

Torque (peak)	180 Nm (230 Nm)
Power (peak)	70 kW (90 kW)

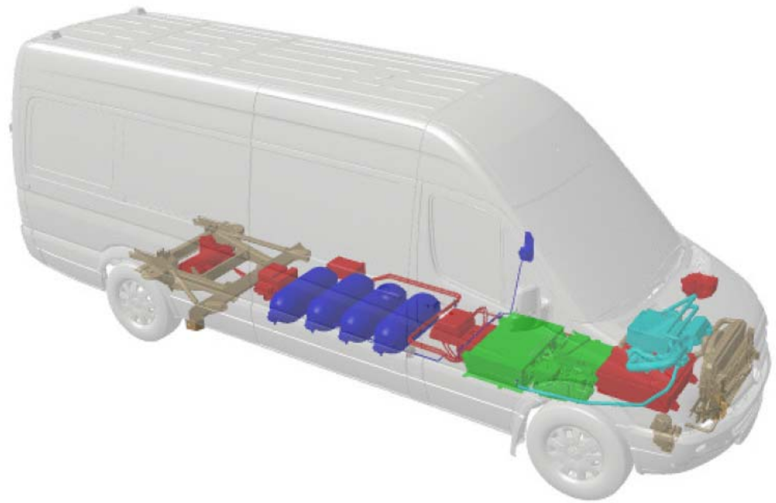
Battery

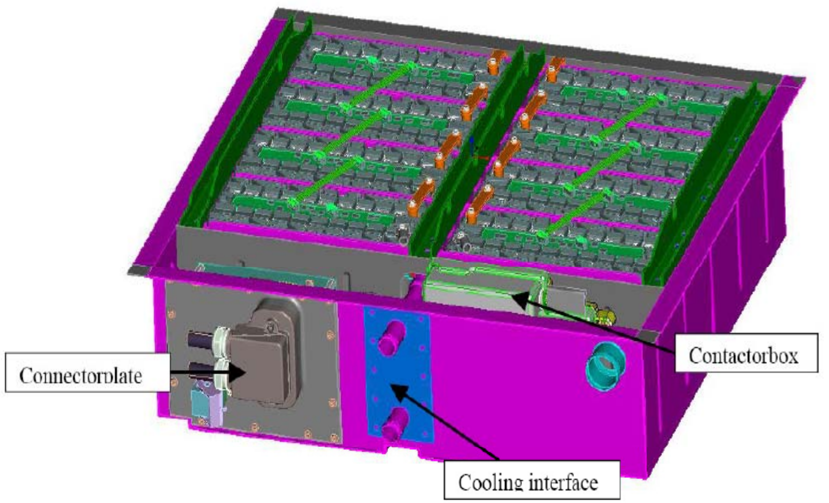
Type	Li-Ion
Capacity	13 Ah

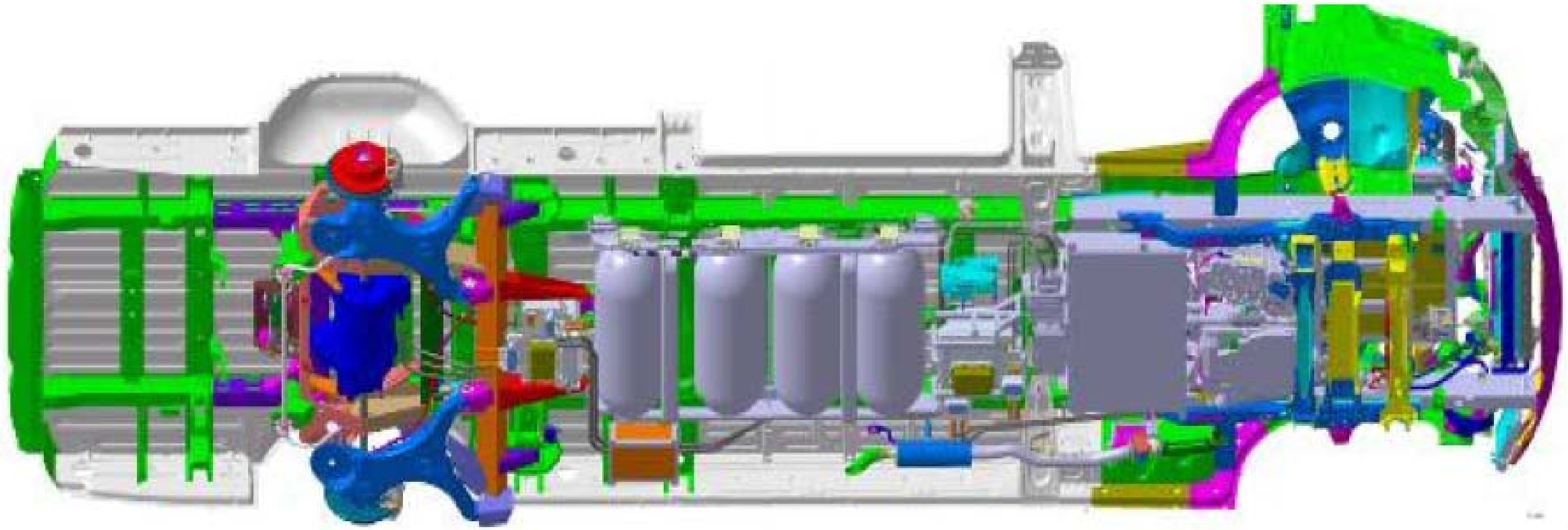


Packaging Daimler - Hysys Sprinter

Packaging and Battery-Module

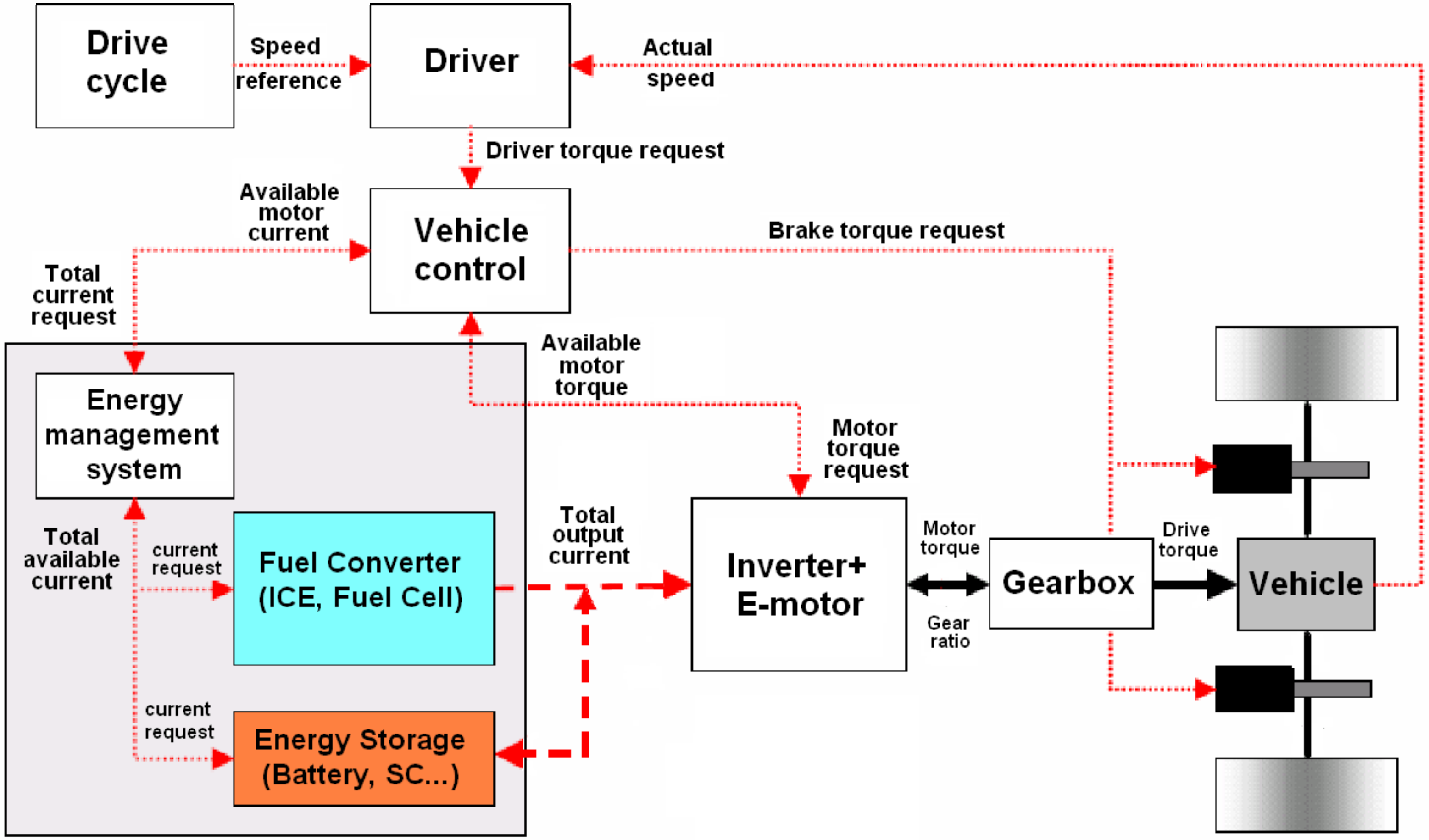






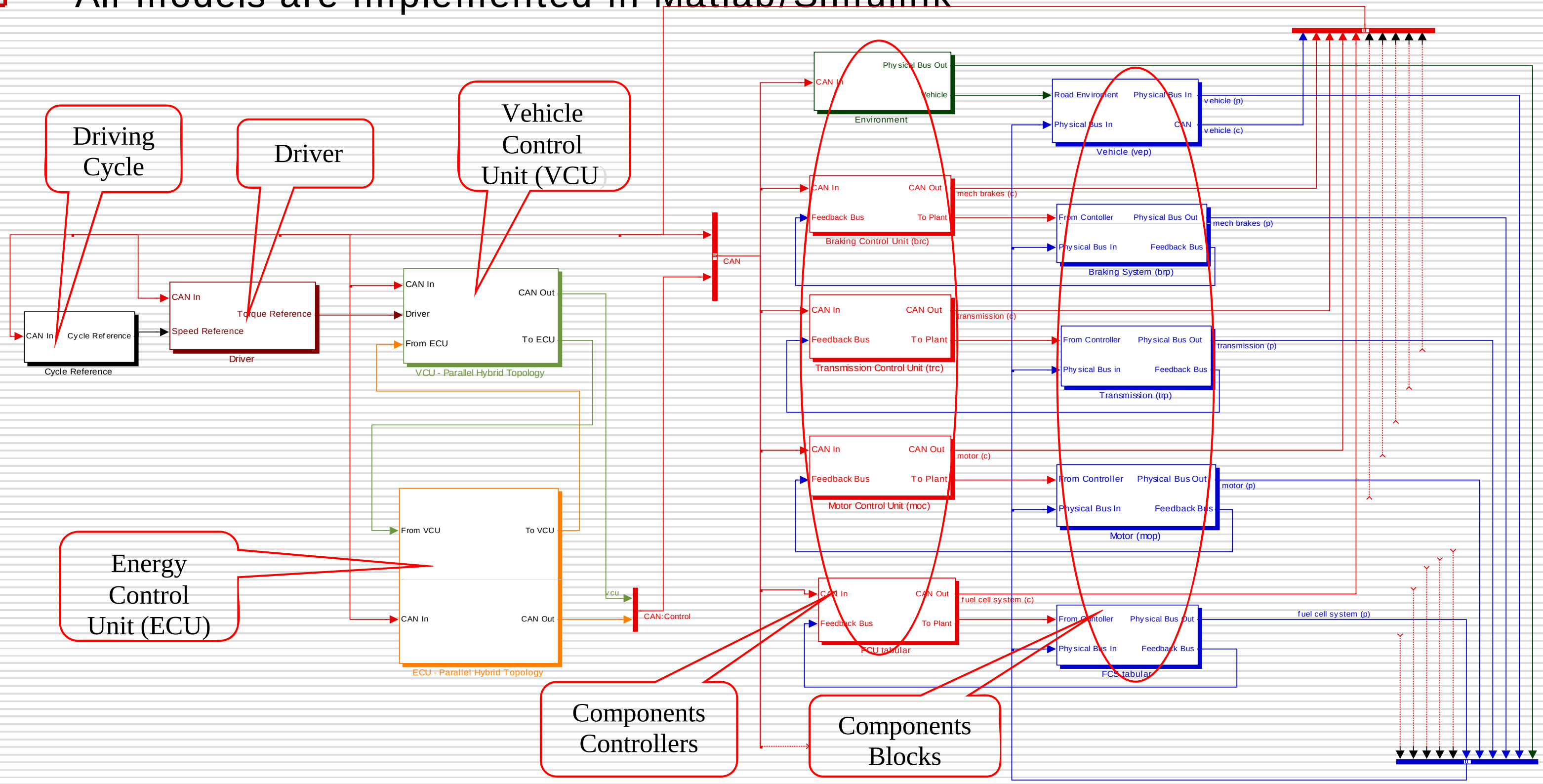
4. Simulation/ Introduction

Schematic of Simulation Model



Introduction of Simulation Model

- Emphasis on complete systems rather than in-depth component analysis, treat the electro-chemistry as a ‘black-box‘
- Suitable for energy analysis at the system level and vehicle level, system optimization and control strategy development
- All models are implemented in Matlab/Simulink



4. Simulation/ Control Strategy

Goals and Principles

- Goals of control strategy:
  - Achieve a driving feel comparable to a traditional vehicle
  - Maintain the battery SOC within a range that is compatible with high fuel economy and long battery life.
  - Increase the overall efficiency of the fuel cell by limiting its use in low efficiency situations and using it extensively when high efficiency is possible.

- Principles:
  - The fuel cell is limited to a certain operating range: (P_{fc_min}, P_{fc_max}). Note: P_{fc_min}, P_{fc_max} is defined based on the fuel cell system efficiency map
  - The fuel cell dynamic response is limited: 5 kW/sec for ramp-up rate and -5 kW/sec for ramp-down rate
  - The battery will be shut down when the SOC is greater than 90% or less than 20%, and (55%, 65%) is defined as the optimum battery SOC operating range.

Control Strategy – Implementation (1)

- Operation modes: three operation modes are determined based on the driver torque request and motor speed
  - Motor opration mode: $T_{drv\_req} > 0$
  - Generator operation mode: $T_{drv\_req} < 0$ and $n_{motor\_actual} > 0$
  - Idling mode: $T_{drv\_req} = 0$ and $n_{motor\_actual} = 0$

- With the driver torque request and motor speed, the driver power request can be calculated: $P_{drv\_req} = T_{drv\_req} * n_{motor\_actual}$

- Then the electric motor power request is determined as below:
  - $P_{motor\_req} = \min(P_{drv\_req}, P_{motor\_avail})$
  - Note: the available electric motor power (P_{motor_avail}) is determined based on the motor constraints and the state of energy supply system

Control Strategy – Implementation (2)

- In motor operation mode:
  - Fuel cell power request $P_{fc\_req} = max\ (P_{fc\_min}, P_{motor\_req} + P_{aux\_total} + P_{soc\_req})$
  - For the fuel cell max power and ramp rate limits, the available fuel cell power would be: $P_{fc\_avail} = min\ (P_{fc\_req}, P_{fc\_max}, P_{fc\_ramp\_rate})$
  - Then $P_{batt\_req} = P_{fc\_avail} – P_{motor\_req} – P_{aux\_total}$
  - Note: P_{soc_req} is a power request for charging or discharging the baterry, based on the current battery SOC. It is used to control the battery SOC (it will be explained in the following section)
- In generator operation mode:
  - Fuel cell power request $P_{fc\_req} = P_{fc\_min}$
  - Then $P_{batt\_req} = P_{fc\_min} – P_{motor\_req} – P_{aux\_total}$
  - Note: in generator operation mode, electric motor acts as generator and has negative power requests
- In idling mode:
  - Fuel cell power request $P_{fc\_req} = max\ (P_{fc\_min,} P_{aux\_total})$
  - Then $P_{batt\_req} = P_{fc\_req} – P_{aux\_total}$
  - Note: If SOC control is required in idling mode, then an extra power request is added and the fuel cell power request is changed into: $P_{fc\_req} = P_{fc\_min} + P_{soc\_req}$

Control Strategy – Implementation (3)

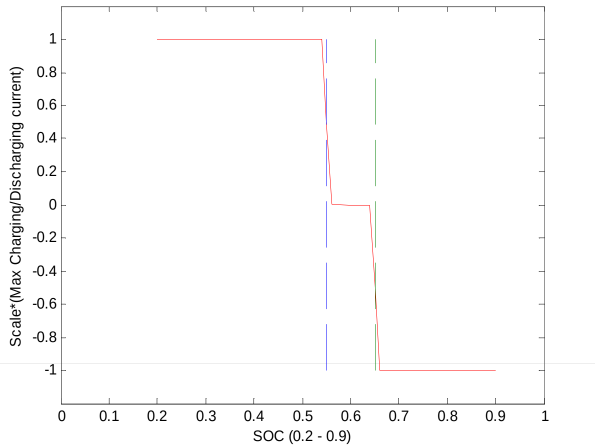
- To keep the battery SOC within the optimum operating range during operation, two types of SOC control methods were developed and integrated into the control strategy separately
- SOC control method 1
  - Take (0.55, 0.65) as the optimum operating range. When battery SOC is within this window, no (or very small) extra current is required
  - As SOC is greater than 0.65, an extra discharge current is required from the battery
  - As SOC is less than 0.55, an extra charging current is required from the fuel cell
  - The extra current request is calculated as below:

- Charging:

$$i_{soc\_req} = i_{hv\_buck\_\max} * \left(\frac{1}{1+e^{(0.65-SOC)*1000}} - \frac{e^{(0.55-SOC)*1000}}{1+e^{(0.55-SOC)*1000}} \right)$$

- Discharging:

$$i_{soc\_req} = i_{hv\_boost\_\max} * \left(\frac{1}{1+e^{(0.65-SOC)*1000}} - \frac{e^{(0.55-SOC)*1000}}{1+e^{(0.55-SOC)*1000}} \right)$$



Note: ihv_buck_max and ihv_boost_max are the max buck and boost current the battery can supply, which are determined based on the DC/DC converter efficiency and battery characteristics

Control Strategy – Implementation (4)

- SOC control method 2
  - Take SOC of 60% as the best operating point, when the actual SOC deviates from that value, an extra current request is added
  - The extra current request is calculated as below:

    Charging

$$i_{soc\_req} = i_{hv\_buck\_\max} * \left(\frac{SOC - (SOC_l + SOC_h)/2}{SOC_h - SOC_l} - k * \int \frac{SOC - (SOC_l + SOC_h)/2}{SOC_h - SOC_l} dt \right)$$

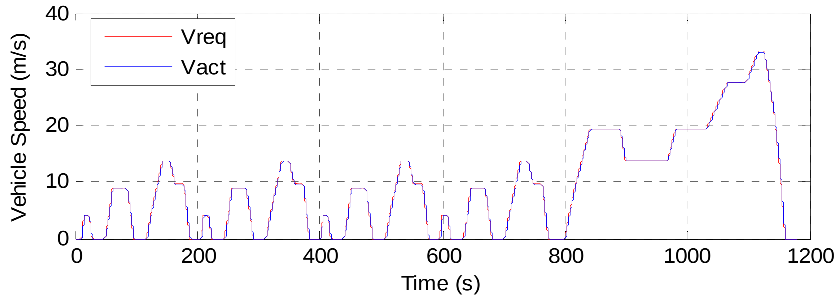
Discharging

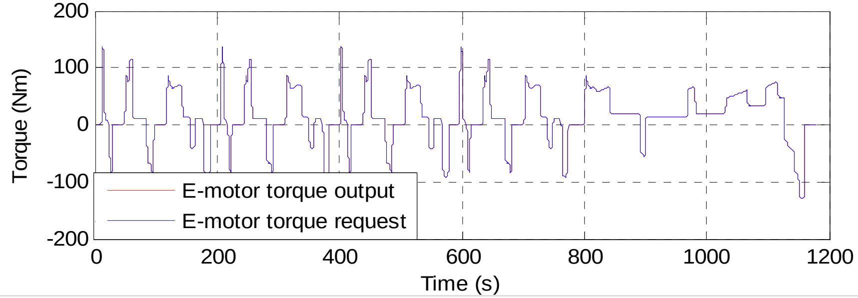
$$i_{soc\_req} = i_{hv\_boost\_\max} * \left(\frac{SOC - (SOC_l + SOC_h)/2}{SOC_h - SOC_l} - k * \int \frac{SOC - (SOC_l + SOC_h)/2}{SOC_h - SOC_l} dt \right)$$

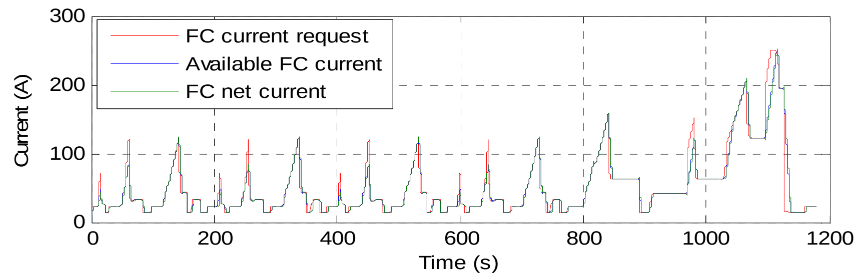
- It is similar to a PI controller. It reflects not only the instantaneous deviation from the target SOC, but also the accumulated deviation. However, the integral term, 'k' must be weak enough (for example, using 0.02) to allow enough 'flexibility', i.e., instantaneous and short-term deviations from target SOC are required to best utilize the hybridization potential.

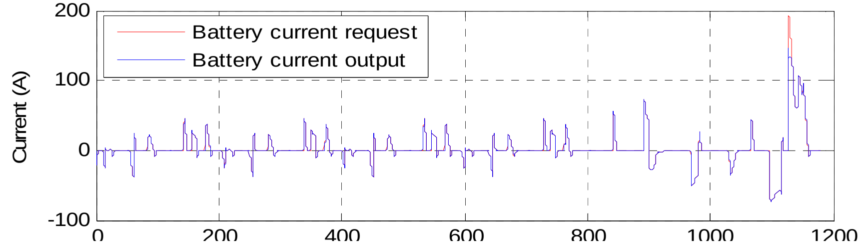
Simulation Results (1)

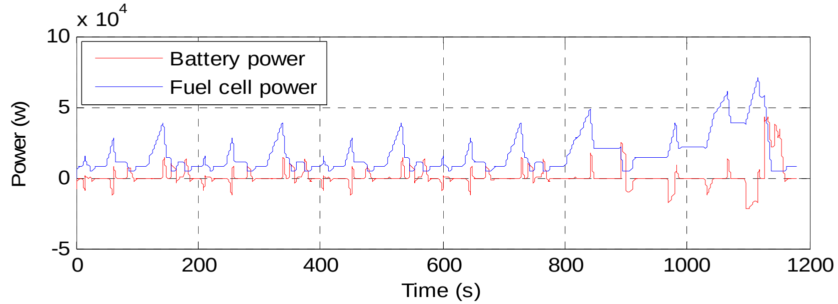
- FC Sprinter (M_v=2900 kg, C_D=0.44
  A_f= 3.52 m2, R_{dyn}=0.314 m)
- Air-conditioning (6 kW) is on
- Initial battery SOC: 60%
- Test cycle: NEDC (hot start)
- SOC control method 1

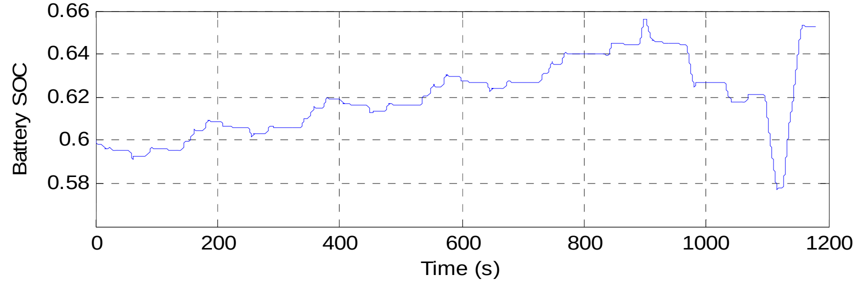




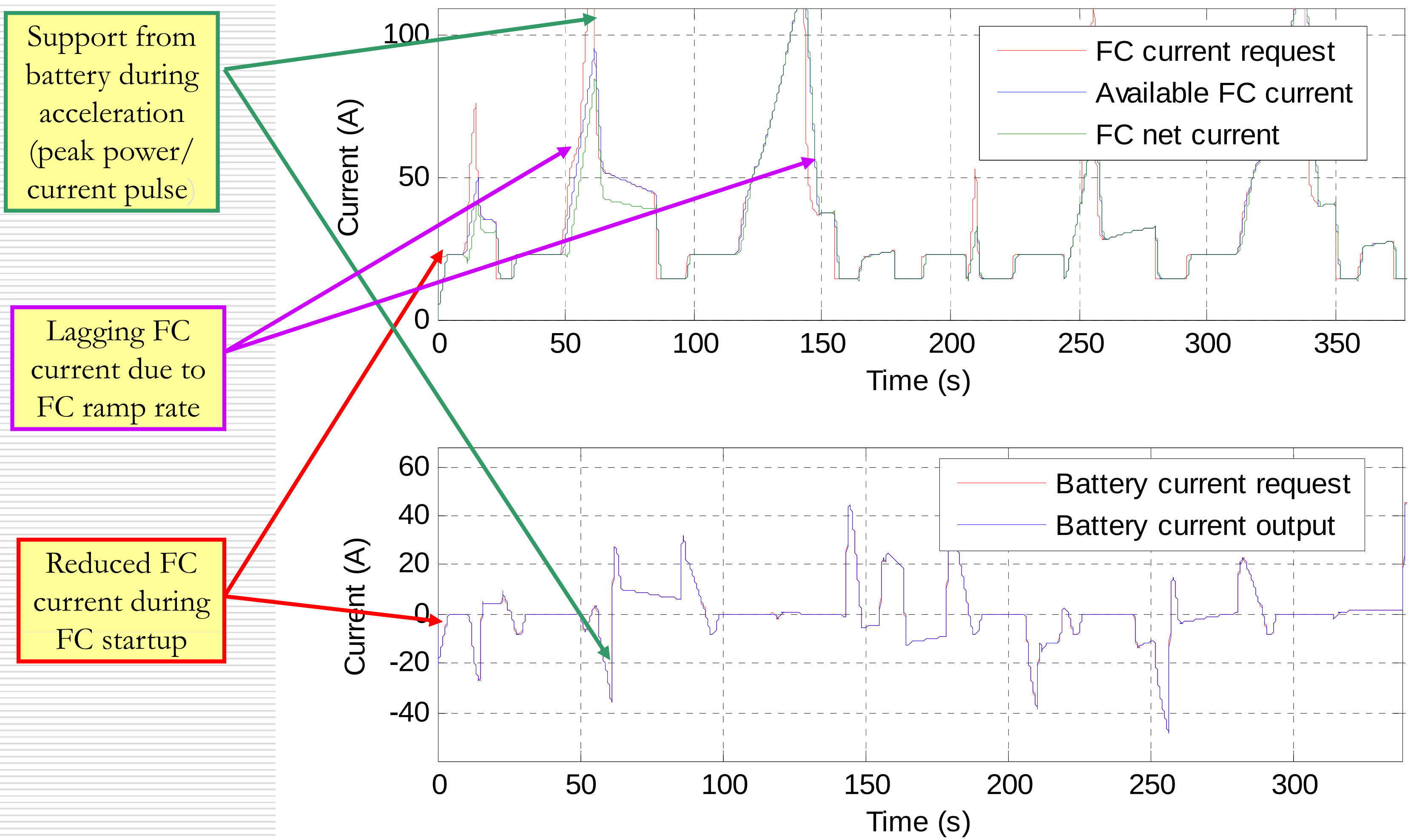








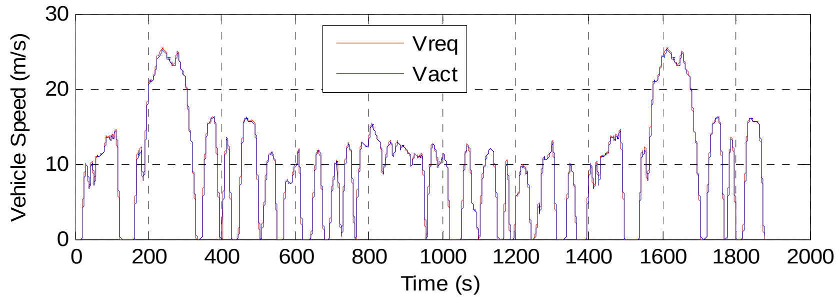
Simulation Results (2)

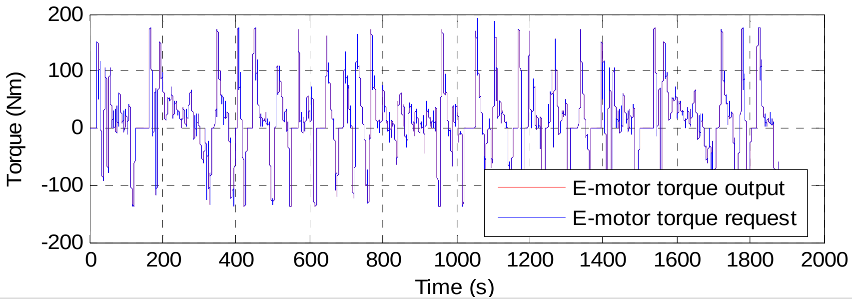


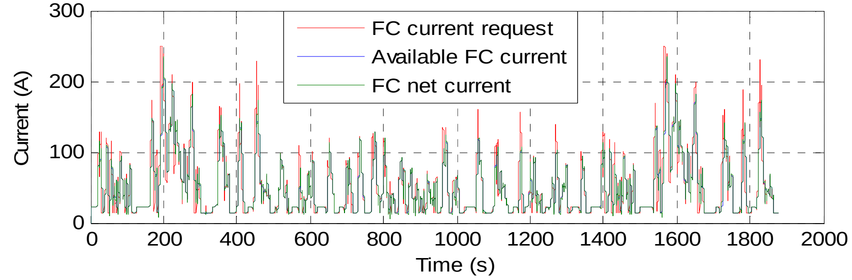
4. Simulation/ Results

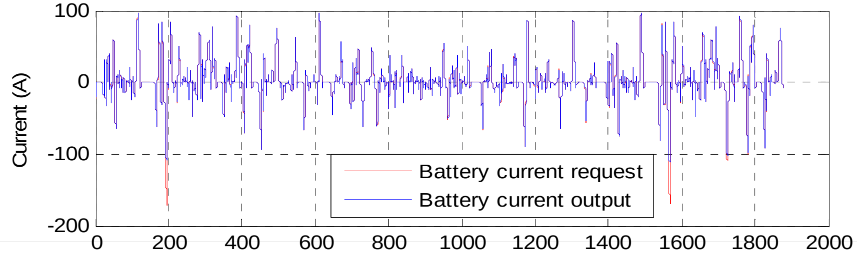
Simulation Results (3)

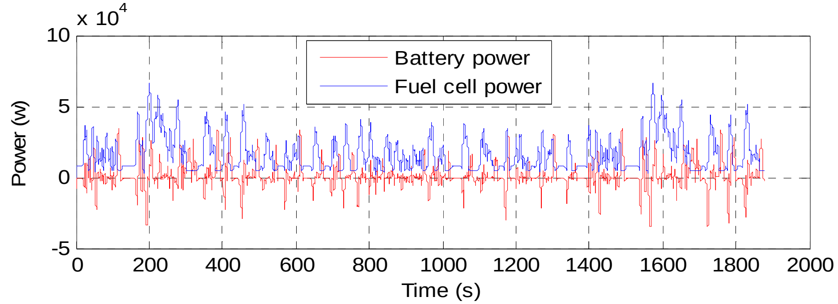
- FC Sprinter (M_v=2900 kg, C_D=0.44 A_f= 3.52 m2, R_{dyn}=0.314 m)
- Air-conditioning (6 kW) is on
- Initial battery SOC: 60%
- Test cycle: FTP-75 (hot start)
- SOC control method 1

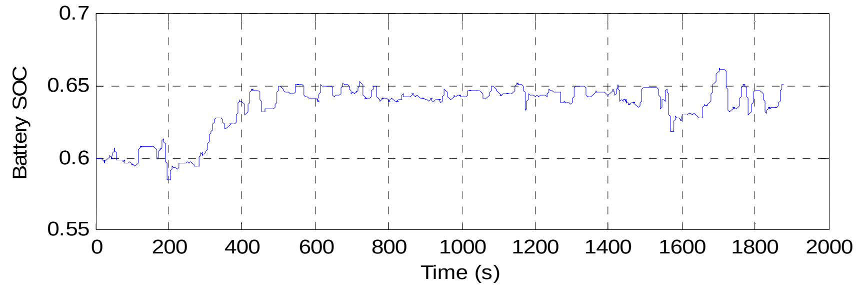






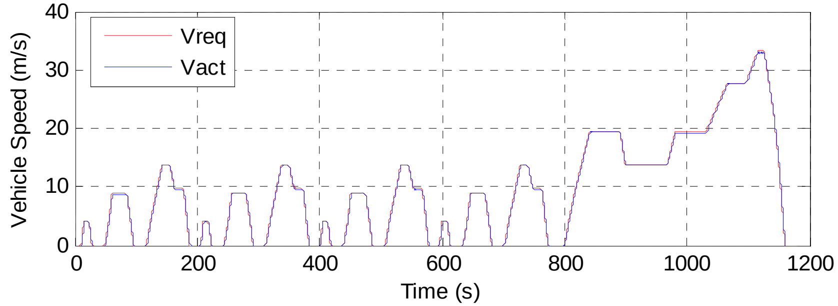


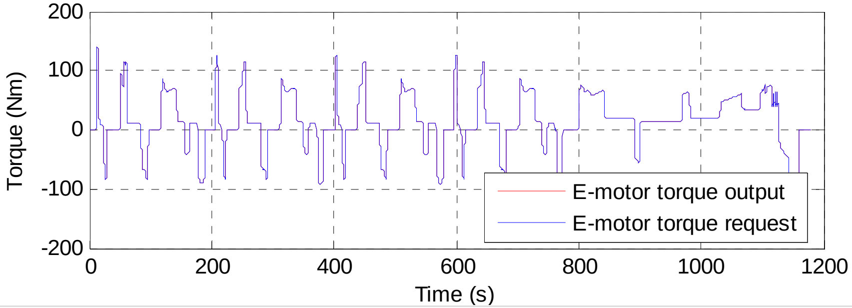


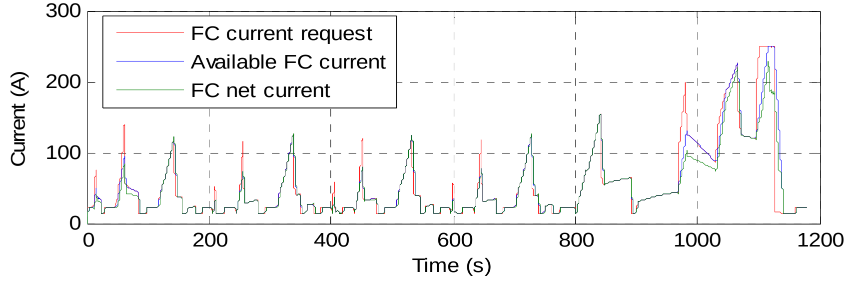


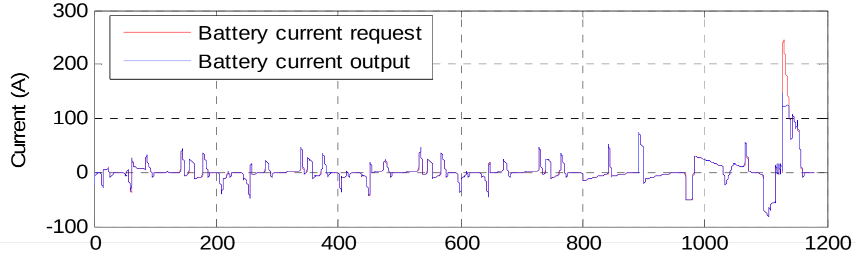
Simulation Results (4)

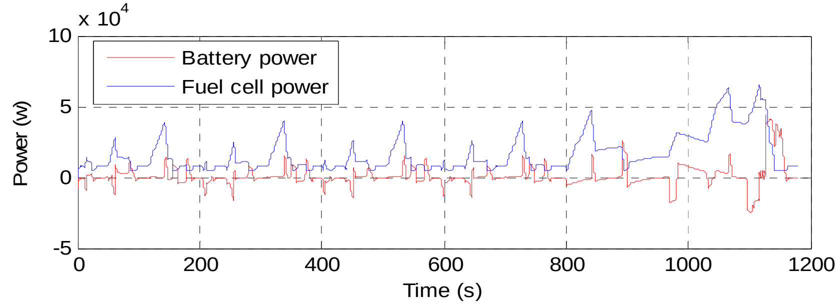
- FC Sprinter (M_v=2900 kg, C_D=0.44
  A_f= 3.52 m2, R_{dyn}=0.314 m)
- Air-conditioning (6 kW) is on
- Initial battery SOC: 60%
- Test cycle: NEDC (hot start)
- SOC control method 2

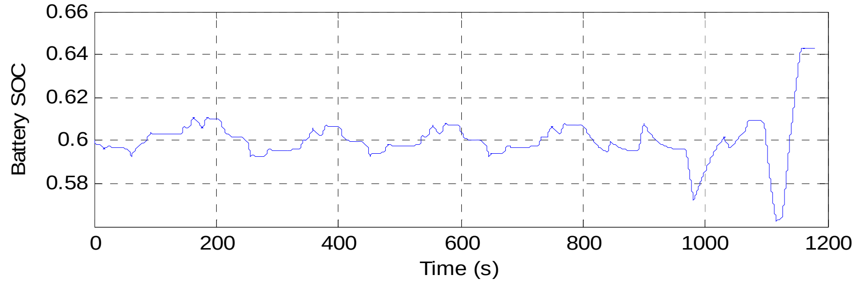






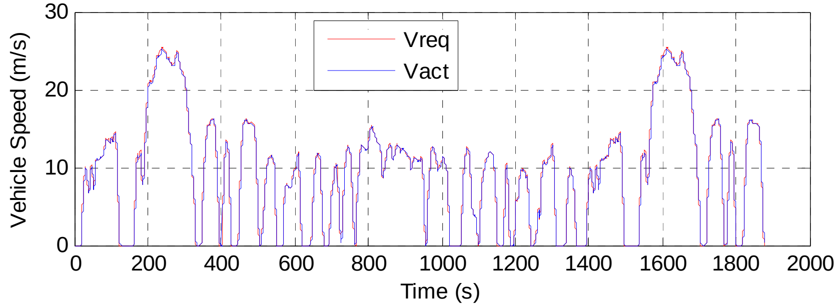


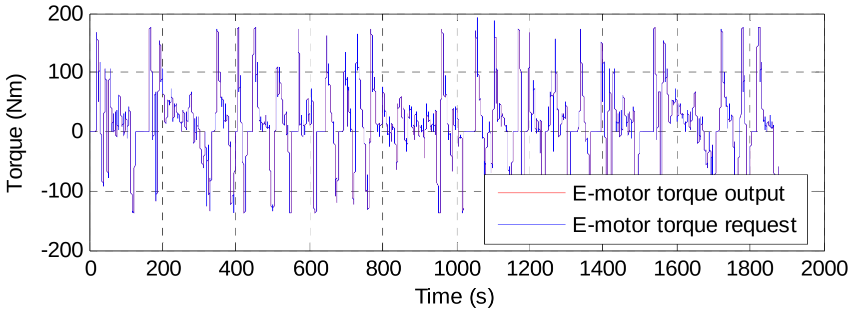


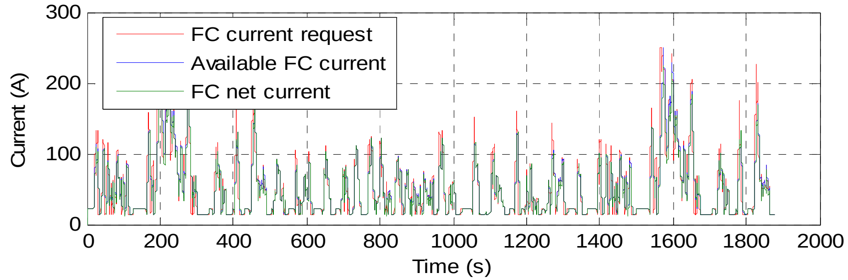


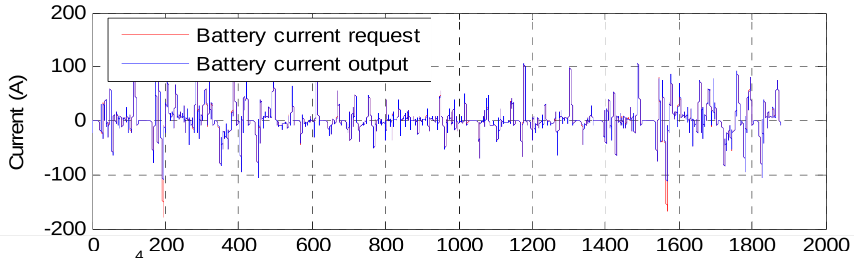
Simulation Results (5)

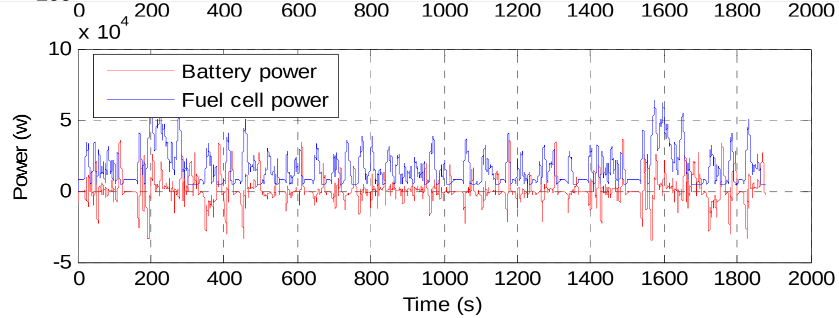
- FC Sprinter (M_v=2900 kg, C_D=0.44 A_f= 3.52 m2, R_{dyn}=0.314 m)
- Air-conditioning (6 kW) is on
- Initial battery SOC: 60%
- Test cycle: FTP-75 (hot start)
- SOC control method 2

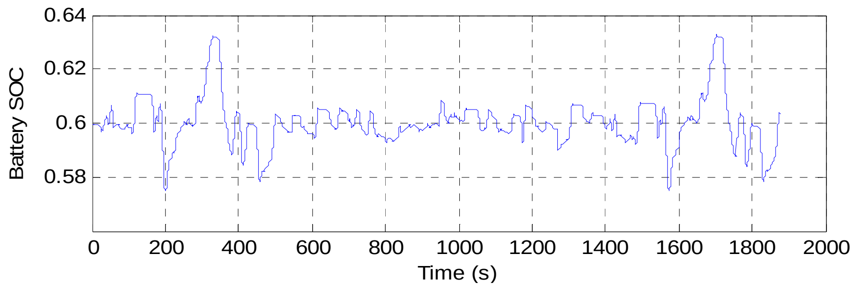












Conclusions

- Hybridization enables downsizing of the fuel cell system, regenerative braking energy capture and faster dynamic response, thus it can improve both the vehicle performance and fuel economy
- Maximizing fuel economy depends on drive cycles and fuel cell system characteristics (efficiency curve)
- Ramp rate is important to the life of the fuel cell system, and it also has a direct influence on the vehicle fuel economy and performance. So it must be taken into consideration when designing the control strategy
- Regen capture is the key contribution of the battery to vehicle efficiecy
- Due to the electrical coversion efficiency, shifting the fuel cell operating points to higher efficiency regions may not lead to higher vehicle efficiency. It depends on the drive cycles (vehicle power distribution) and the fuel cell system characteristics (efficiency curve)

B) Markets,market development

5. Status ans Strategies

5.1 EU- Powertrain Study (Passenger Cars)

5.2 USA- Fuel Cell Powertrains Status

5.3 Asia

5,4 RoW

C) Outlook

6. Batteries and/or Fuel Cells

5.1 EU- Powertrain Study (Passenger Cars)

A global industry group assessed the potential of alternative power-trains for passenger cars in Europe on behalf of the EU Comission based on proprietary company data

Core questions

How do FCEVs, BEVs, and PHEVs compare to ICEs on

- Cost
- Emissions
- Energy efficiency
- Driving performance?

What are viable production and supply pathways?

What are the potential market segments for the different power-train technologies?

1 Report can be downloaded from
www.now-gmbh.de/presse/studie-entkarbonisierung-individualverkehrs.html
www.europeanclimate.org/index.php?option=com_content&task=view&id=92&Itemid=42

5.1 EU- Powertrain Study (Passenger Cars)

EU-Studie “A portfolio of power-trains for Europe” Different Powertrains meet different needs

Excellent | Good | Moderate | Challenged — C/D SEGMENT 2030

	FCEV 	BEV 	PHEV 	ICE 
Perfor-mance	• Driving perfomance in similar range to ICE • ~600 km average driving range • Refueling only takes a couple of minutes • Fewer services needed	• Limited energy storage capacity and driving range (150-250 km) • Refueling time in the order of hours[2] • Ideally suited to smaller cars and urban driving	• Driving range equal to ICE in ICE drive (>600km); 40-60 km in electric drive • Similar top speed, gasoline refueling time & service intervals • Battery recharging takes some hours	• Highest driving range • Best top speed and refueling time • Only service intervals shorter
Environ-ment	• High CO_2 reduction (~80%) compared to today with CCS & water electrolysis • No local vehicle emissions • Lowest carbon solution for medium/larger cars & longer trips	• High CO_2 reduction (~80%) if CCS or renewable energy is used • Depends on electricity footprint • No local vehicle emissions	• Considerable CO_2 reduction (~70%) • Some local emissions in ICE drive • Low CO_2 if 100% biofuels	• Highest CO_2 and local vehicle emissions • Unlikely to meet EU CO_2 reduction goal for 2050 • Low CO_2 if 100% biofuels
Econo-mics[1]	• Purchase price is ~€4,000 higher than ICE • TCO comparable to ICE for larger, but not smaller cars • Infrastructure cost comparable cost to BEVs	• Economic for smaller cars • Purchase price higher than ICE • TCO ~€3,000 higher than ICE TCO • Fuel costs comparable to ICE due to high infrastructure cost	• Higher purchase price and TCO than ICE • Better fuel economy than ICE for larger cars • Low infrastructure cost	• Most economic vehicle • Lowest purchase price • Higher fuel or maintenance costs • Existing infrastructure

1 Consumer economics can be different, dependent on tax region
2 Fast charging for BEVs implies reduced battery lifetime, lower battery load and higher infrastructure costs than included in this study
SOURCE: Study analysis

5.1 EU- Powertrain Study (Passenger Cars)

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Conventional vehicles alone may not achieve EU CO_2 reduction goal for 2050

In September 2009, both the European Union (EU) and G8[1] leaders agreed that CO_2 emissions must be cut by 80% by 2050 if atmospheric CO_2 is to stabilise at 450 parts per million[2] – and global warming stay below the safe level of 2°C. But 80% decarbonisation overall by 2050 may require 95%[3] decarbonisation of the road transport sector.

With the number of passenger cars set to rise to 273 million[4] in Europe – and to 2.5 billion[5] worldwide – by 2050, this may not be achievable through improvements to the traditional internal combustion engine or alternative fuels: the traditional combustion engine is expected to improve by 30%, so achieving full decarbonisation is not possible through efficiency alone. There is also uncertainty as to whether large amounts of (sustainably produced) biofuels - i.e. more than 50% of demand - will be available for passenger cars, given the potential demand for biofuels[6] from other sectors, such as goods vehicles, aviation, marine, power and heavy industry.

Combined with the increasing scarcity and cost of energy resources, it is therefore vital to develop a range of technologies that will ensure the long-term sustainability of mobility in Europe.

5.1 EU- Powertrain Study (Passenger Cars)

A balanced scenario for the electrification of passenger cars in the EU by 2050:

- In order to test the sensitivity of the economics to a broad range of market outcomes, the study envisioned three “worlds” with varying degrees of BEV, FCEV and PHEV penetration
- These cover:
  - a. The full spectrum of expected futures for hydrogen, electricity and primary energy sources
  - b. Market shares and segment penetration rates for the different power-trains
  - c. Coverage area and availability of hydrogen.

All “worlds” assume 273 million passenger cars in the EU in 2050, with a hydrogen retail network infrastructure starting in the most densely populated areas (i.e. large cities) and growing to meet the needs of expanding vehicle clusters, leading to mass market roll-out.

The car fleet is built up by introducing BEVs, FCEVs and PHEVs where they are most competitive with ICEs

5.1 EU- Powertrain Study (Passenger Cars)

EU-Studie “A portfolio of power-trains for Europe” – Market Shares in three Scenarios for 2050

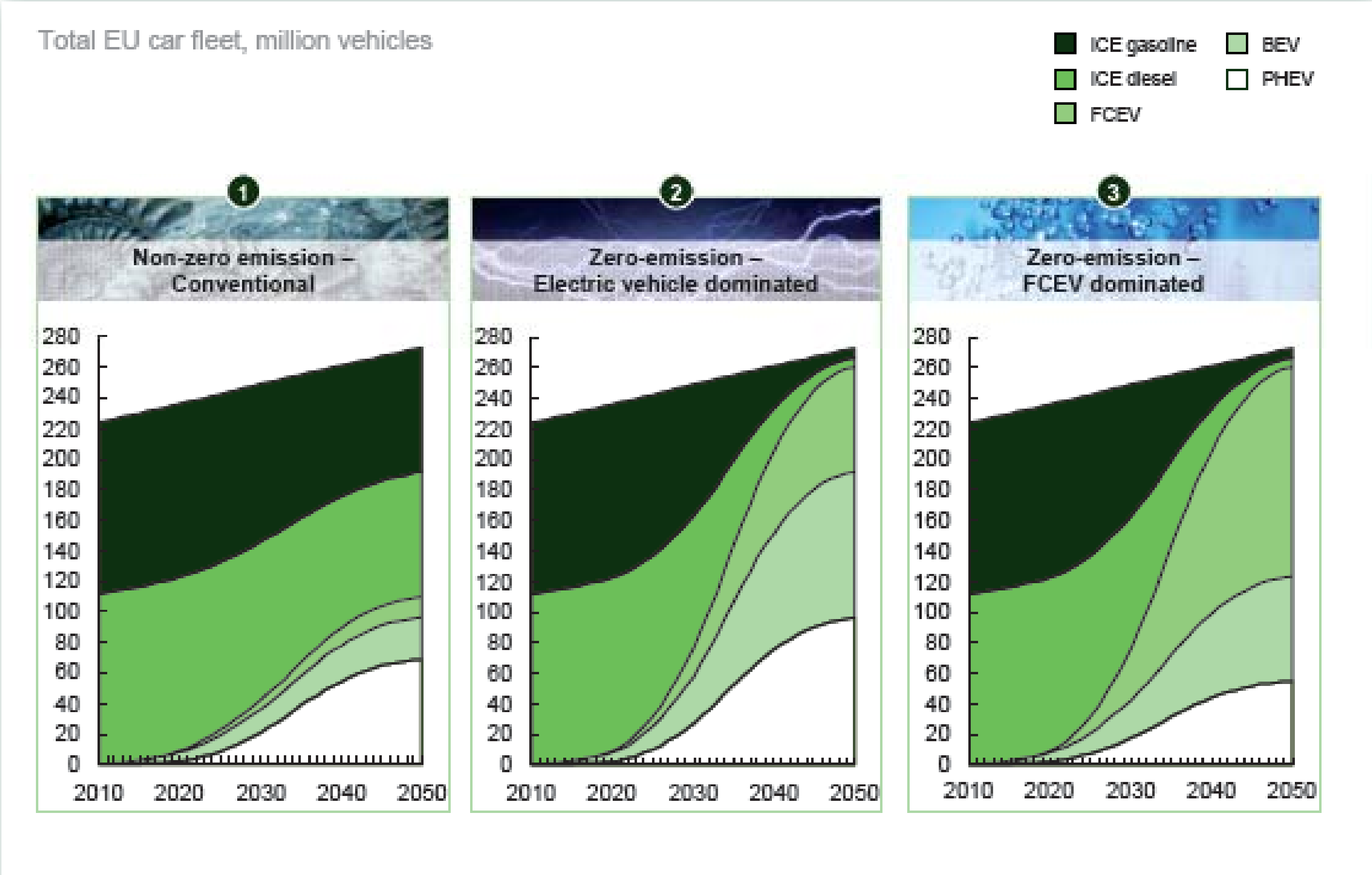
	1 Non-zero emission – Conventional	2 Zero-emission – Electric vehicle dominated	3 Zero-emission – FCEV dominated
2010-2020	▪ For all worlds, coverage grows to include 10% of Europe’s most metropolitan area and 20% of European motorways (>50% of cars)		
FCEV penetration 2050 Percent	FCEV 5%, BEV 10%, PHEV 25%, ICE 60% ▪ FCEV with moderate adoption after 2020 ▪ FCEVs sold in C+ segments, but with limited market shares	FCEV 25%, BEV 35%, PHEV 35%, ICE 5% ▪ BEVs achieve a higher penetration than FCEVs ▪ FCEVs mainly sold in C+ segments with high share in J, M, D	FCEV 50%, BEV 25%, PHEV 20%, ICE 5% ▪ FC is the dominant power-train technology by 2050 so network coverage develops fast ▪ FCEVs sold in all segments with major shares in large segments
Coverage end state 2050	▪ FCEV coverage area increases only to ~1/4 of the EU29 area[1], (75 % cars)	▪ FCEVs are used in all countries with some rural exceptions ▪ Coverage is ~3/4 of the EU29 area[1], (97% cars)	▪ All over Europe, FCEVs are sold and driven. Coverage is equal to the entire EU29 area[1] (9 km average distance between stations)
Size of coverage area million km²	▪ 2020: 0.36 ▪ 2030: 0.60 ▪ 2040: 0.84 ▪ 2050: 1.08	▪ 2020: 0.36 ▪ 2030: 1.3 ▪ 2040: 2.3 ▪ 2050: 3.3	▪ 2020: 0.36 ▪ 2030: 1.7 ▪ 2040: 3.0 ▪ 2050: 4.3

1 EU29 defined to include EU27 + Norway and Switzerland

SOURCE: Study analysis

5.1 EU- Powertrain Study (Passenger Cars)

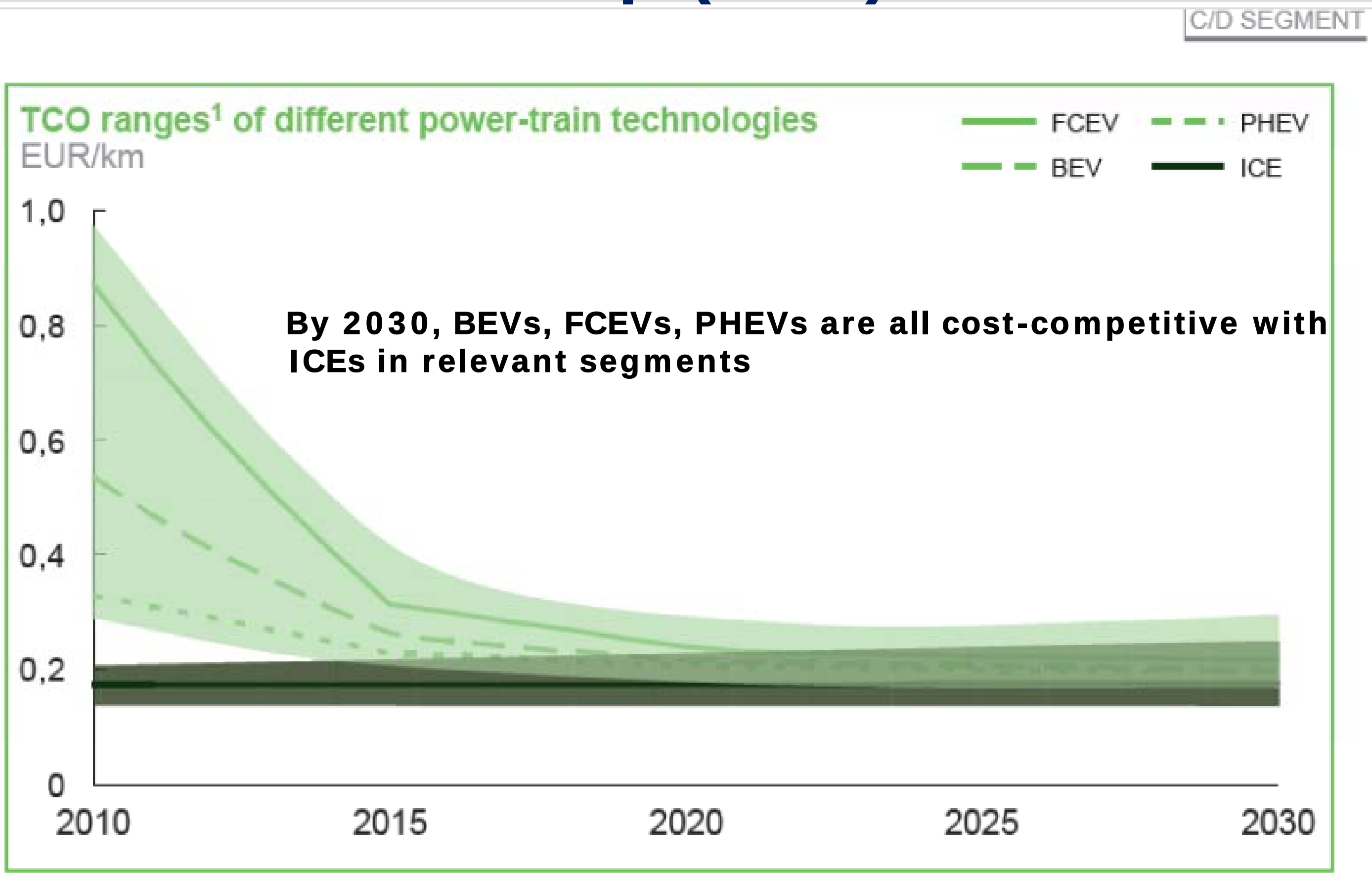
EU-Studie “A portfolio of power-trains for Europe” – Scenarios and Market Shares



SOURCE: Study analysis

5.1 EU- Powertrain Study (Passenger Cars)

Total Cost of Ownership (TCO) 2010 - 2030



1 Ranges based on data variance and sensitivities (fossil fuel prices varied by +/- 50%; learning rates varied by +/- 50%)

SOURCE: Study analysis

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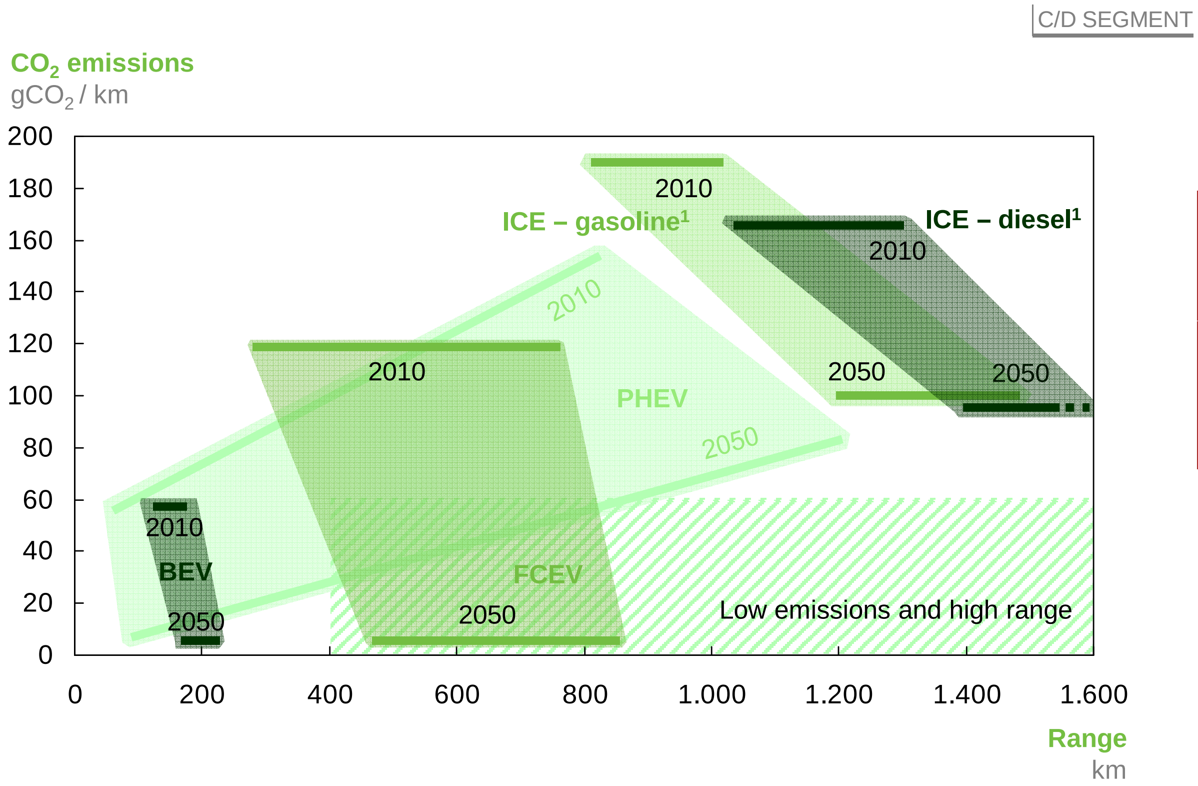
5.1 EU- Powertrain Study (Passenger Cars)

The Potentials of CO2 reduction and range



➔BEVs and FCEVs can achieve significantly lower CO_2 emissions, while BEVs show limitations in range.

1 ICE range for 2050 based on fuel economy improvement and assuming tank size stays constant. Assuming 6% CO2 reduction due to biofuels by 2020; 24% by 2050

SOURCE: Study analysis

5.2 USA- Fuel Cell Powertrains Status

State OF THE States

Fuel Cells in America 2012

FUEL CELLS 2000
www.fuelcells.org

September 2012

5.2 USA- Fuel Cell Powertrains Status

Fuel Cell Vehicles (Deployed)

1st	**CALIFORNIA**	200+ mix of vehicles on road; includes Honda FCX Clarity and Daimler F-CELL leases (20 and 44 respectively)
2nd	**HAWAII**	16 General Motors Equinox fuel cell vehicles
3rd	**NEW YORK**	15 Toyota FCHV-adv vehicles
4th	**CONNECTICUT**	10 Toyota FCHV-adv vehicles
5th	**MICHIGAN**	3 Ford Focus fuel cell vehicles

5.2 USA- Fuel Cell Powertrains Status

Fuel Cell Buses

1st	**CALIFORNIA**	15 active, including 12 at AC Transit; 2 at SunLine Transit, 1 at BurbankBus, 7 planned
2nd	**CONNECTICUT**	6 active at CTTransit
3rd	**DELAWARE**	2 active at the University of Delaware, 3 planned
4th	**TEXAS**	1 active at Capital Metro (Austin) , 1 planned
5th	**HAWAII** and **WASHINGTON**	Hawaii – 1 active (Hickam Air Force Base) Washington – 1 active (Joint Base Lewis-McChord)

5.2 USA- Fuel Cell Powertrains Status

Fuel Cell Forklifts (Deployed or Ordered)

1st	**CALIFORNIA**	762+ by Unified Grocers, Proctor & Gamble, Sysco Riverside, WinCo Foods, Coca-Cola, Martin-Brower, Kroger
2nd	**PENNSYLVANIA**	296 by Sysco Philadelphia, DLA, East Penn, Wegmans
3rd	**ILLINOIS**	274 by Central Grocers, Golden State Foods, Testa Produce
4th	**TEXAS**	257 by Nestle Waters, Coca-Cola, Sysco Houston, Sysco San Antonio, H-E-B
5th	**SOUTH CAROLINA**	255 by BMW, Kimberly-Clark

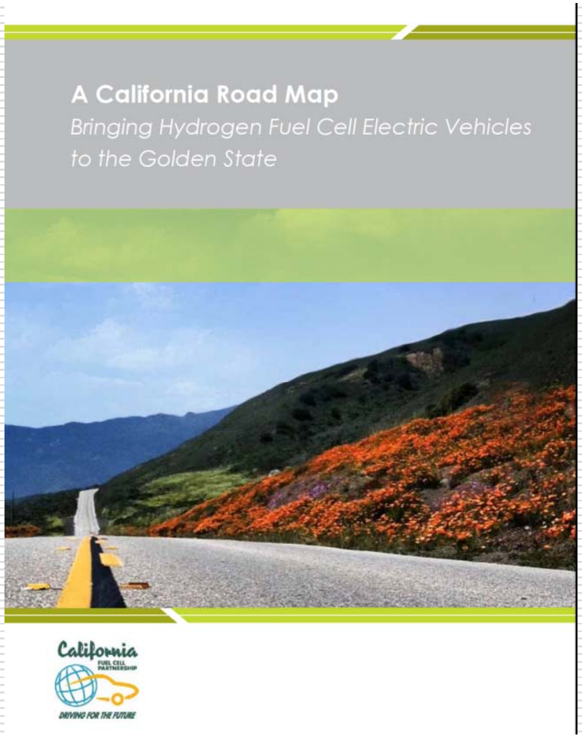
5.2 USA- Fuel Cell Powertrains Status

Hydrogen Fueling Stations

Only for passcars & busses
Fork lift stations not included

1st	CALIFORNIA	8 public stations; 14 new or upgraded stations in development; 15 private stations
2nd	MICHIGAN	9 private stations
3rd	NEW YORK	8 private stations, including a wind-to-hydrogen station in Hempstead
4th	NEVADA	2 private stations, 1 planned
5th	SOUTH CAROLINA	2 private stations, including the first multi-use station at an industrial park

5.2 USA- Fuel Cell Powertrains Status



Year	Start of Year (Station Total)[10]	Added Stations[11]	Number of FCEVs in CA[12]
2012	4	*4*	312
2013	8	*9*	430
2014	17	*20*	1,389
2015	37	*31*	*5,000-15,000*
2016	68	*Market Needs*	*10,000-30,000*
2017	>84	*Market Needs*	53,000
2018	>100	*Market Needs*	>53,000

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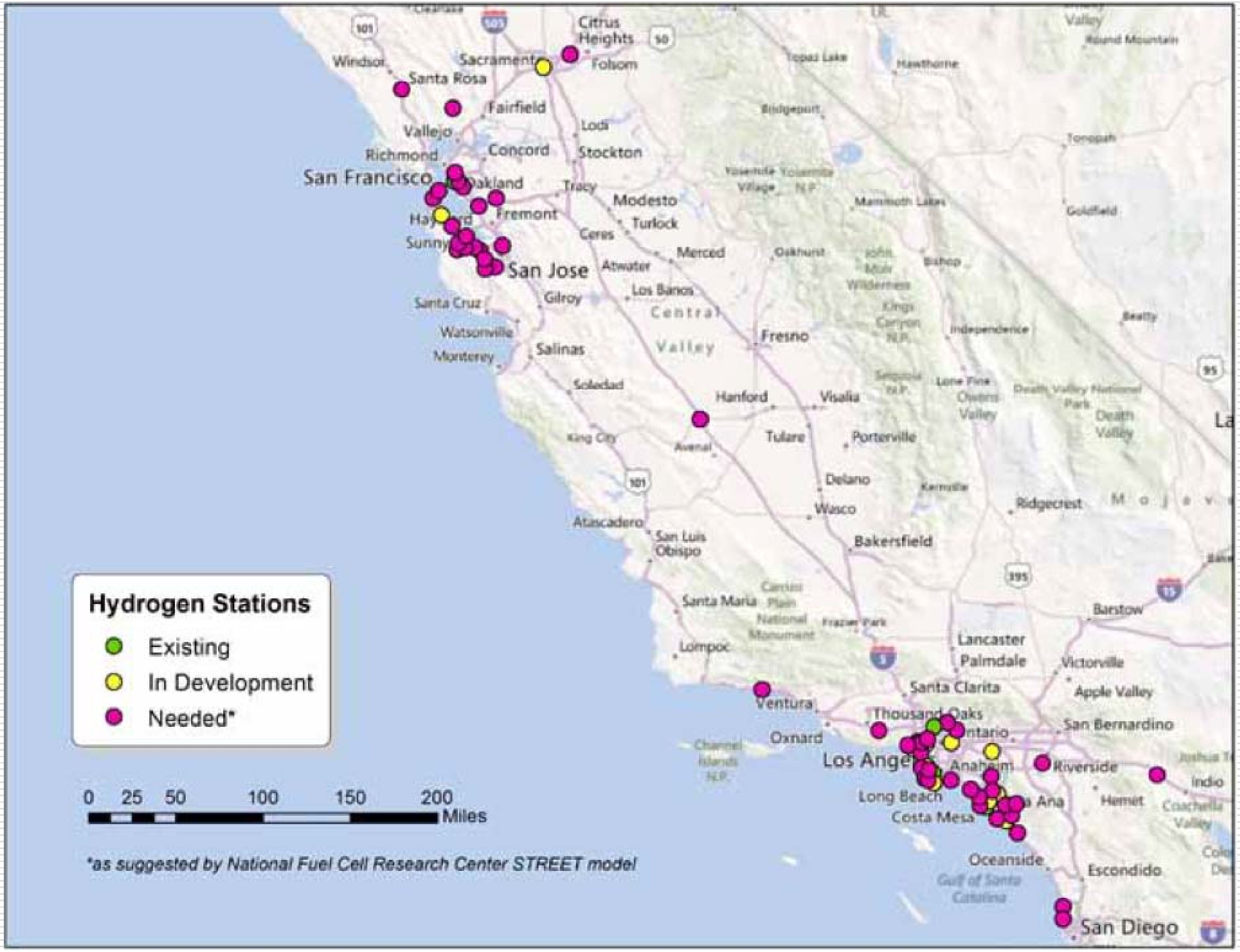
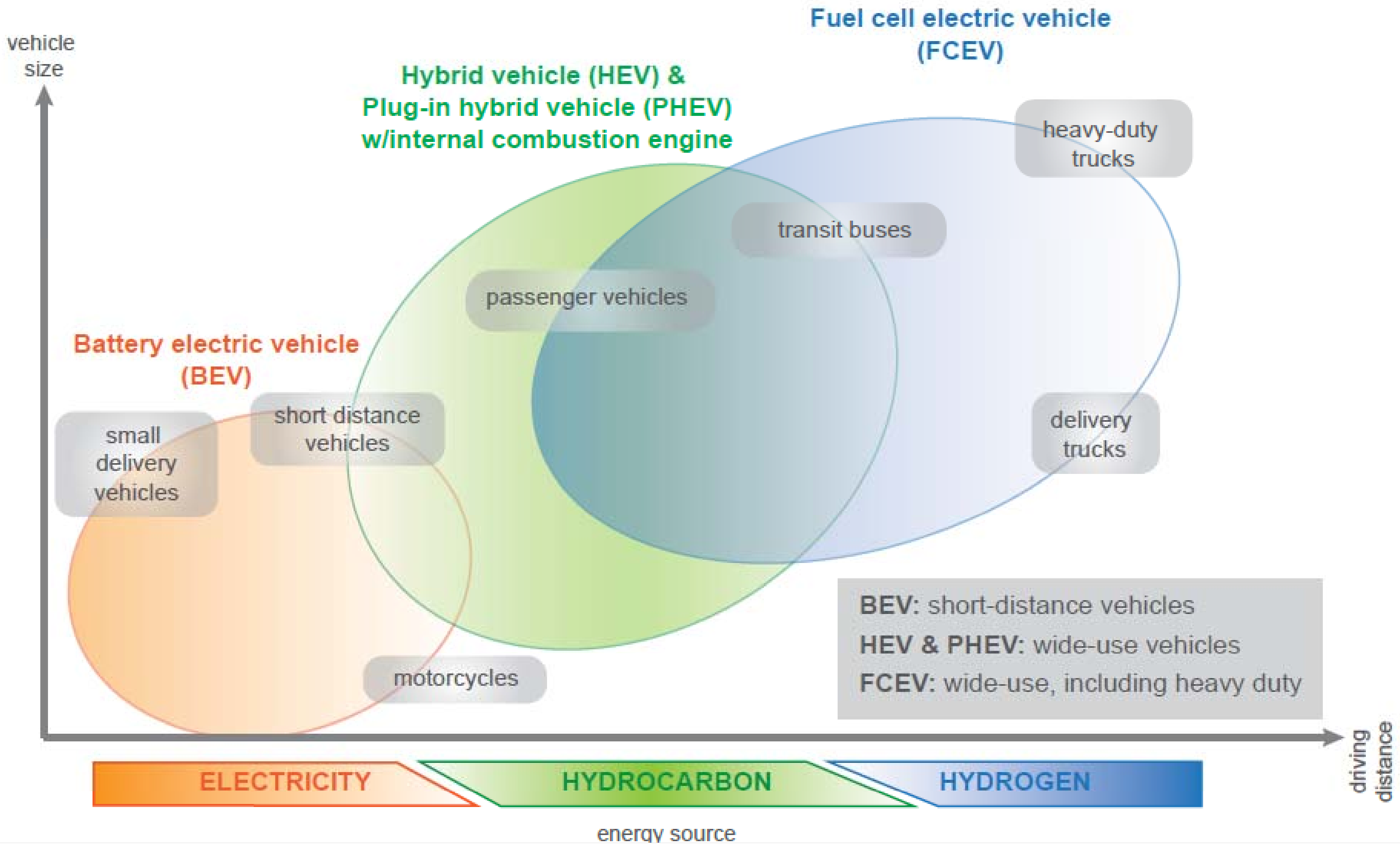
5.2 USA- Fuel Cell Powertrains Status

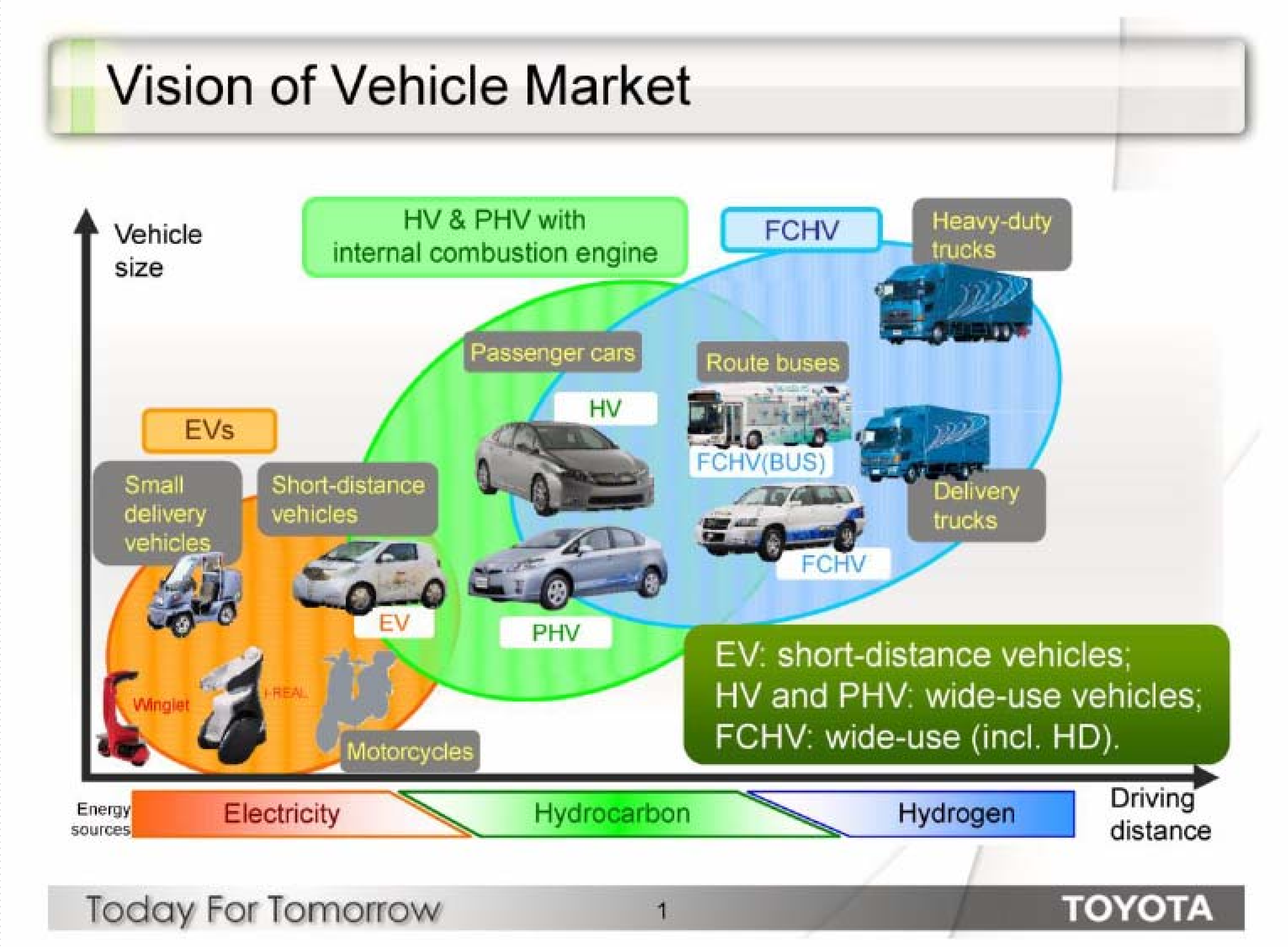
California Map of 68 Hydrogen Fuelling Stations: Existing, in Development and Needed



5.2 USA- Fuel Cell Powertrains Status

Figure 1 – Vision of Vehicle Market




Vision of Vehicle Market
Vehicle size
HV & PHV with internal combustion engine
FCHV
Heavy-duty trucks
Passenger cars
Route buses
HV
EVs
FCHV(BUS)
Delivery trucks
Small delivery vehicles
Short-distance vehicles
FCHV
EV
PHV
Winglet
i-REAL
Motorcycles
EV: short-distance vehicles;
HV and PHV: wide-use vehicles;
FCHV: wide-use (incl. HD).
Energy sources
Electricity
Hydrocarbon
Hydrogen
Driving distance
Today For Tomorrow
1
TOYOTA

5.2 California: The Roadmap of the leading state

California

Region: Pacific

A Top State for:
- Fuel Cell Vehicles
- Fuel Cell Buses
- Fuel Cell Forklifts
- H2 Fueling Stations
- Telecom Backup
- Stationary Systems (Installed & Planned)
- Fuel Cell Patents
- Fuel Cell Policies

Fuel Cell Roadmap

The California Fuel Cell Partnership has published a Roadmap detailing necessary hydrogen station deployments to support the emerging fuel cell vehicle market. Executive Order 6 (2012) also directs state agencies to support and facilitate the rapid commercialization of zero-emission vehicles with three specific milestones:

- 2015: Communities will be ready for plug-in and hydrogen vehicles and infrastructure
- 2020: California will have established adequate infrastructure to support one million zero-emission vehicles
- 2025: More than 1.5 million zero-emission vehicles will be on the road and the market continues to expand.

Transportation

Earlier this year, the Federal Transit Administration awarded $6.6 million to CALSTART, an alternative transportation consortium, for five projects to further the development of fuel cell buses.

Hydrogen Fueling

As of July 2012, there are eight public hydrogen fueling stations, and two more are slated to open soon. The state has committed $29 million to build more stations in advance of 2015 – the target date set by major automakers for the commercial launch of fuel cell electric vehicles.

5.3 RoW: Canada

Canada is a pioneer in the development of automotive fuel cell technologies, including an expertise in the supply of parts and components for FCEVs. Automotive Fuel Cell Cooperation Corp. (a joint venture between Daimler, Ford and Ballard Power Systems), based in Burnaby, BC, continues to develop automotive fuel cell technology and is one of the few next-generation automotive research and development centers in
Canada.
Canada is a leader in the development and deployment of fuel cell bus technology. BC Transit's fleet of 20 fuel cell buses is the largest fleet of its kind in the world, providing regular revenue transit service to residents in the community of Whistler, British Columbia.

5.3 RoW: Asia

In **Japan**, interest in fuel cells goes beyond the Japanese automakers that build fuel cell electric vehicles. JHFC operates demonstration hydrogen stations in Japan that use different feedstocks to make the fuel, and fuel cell buses are on the road in Osaka and Tokyo. In addition, residential fuel cells called ENE-FARM have been highly successful in Japan. Japan's 2012 budget for hydrogen and fuel cell activity is about US$240 million.

South Korea represents one of the world's most promising markets for fuel cell adoption and is one of the foremost countries for fuel cell manufacturing. Since 2003, the South Korean government has been investing the development of FCEVs through its association with Hyundai-Kia. More recently, a firm commitment to the idea of low carbon economic growth and stimulus for new technology has created some of the most supportive policies for stationary fuel cells, including government subsidies of up to 90% for small stationary fuel cell installations. South Korea commits about US$100 million to fuel cell activities every year.

Chinese universities continue their activity FCEVs and hydrogen stations, however, Chinese government activities are more focused on meeting their goals for renewable energy. In 2011 China allocated approximately US$16 million for hydrogen and fuel cell projects, mostly R&D for stationary power projects. FuelCellToday has an excellent report about activities in China.

5.3 RoW: IPHE and IEA-HIA

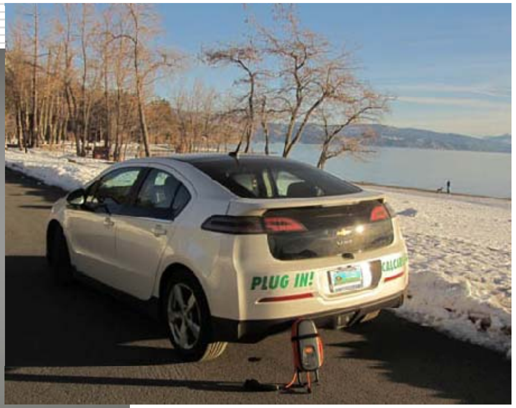
Countries around the world are committed to hydrogen and fuel-cell technologies to improve the security of their energy supply, environment and economy.

In total, 25 countries participate in two international hydrogen and fuel-cell coordinating organizations: IPHE (www.iphe.net) and IEA-HIA (www.ieaHIA.org). Through these organizations, as well as less formal collaboration, CAFCP coordinates with other programs and projects to share information, experience and learnings.

Every country has its own reasons for looking at renewable energy, including hydrogen, and diversifying its energy portfolio. Noted economist and author, Jeremy Rifkin, summarizes it in his book The Third Industrial Revolution, “hydrogen is the universal medium that stores all forms of renewable energy to assure that a stable and reliable supply is available for power generation and, equally important, for transport.”

Back - up Material

GM - Chevrolet Volt Plug-In Hybrid seems to be on the right track



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5. Outlook / Comments

BEVs – It might be difficult to introduce a high cost technology in a low cost product segment


Nissan Leaf Europa- Auto des Jahres 2011

Mitsubishi MiEV


Ford Focus Electric:

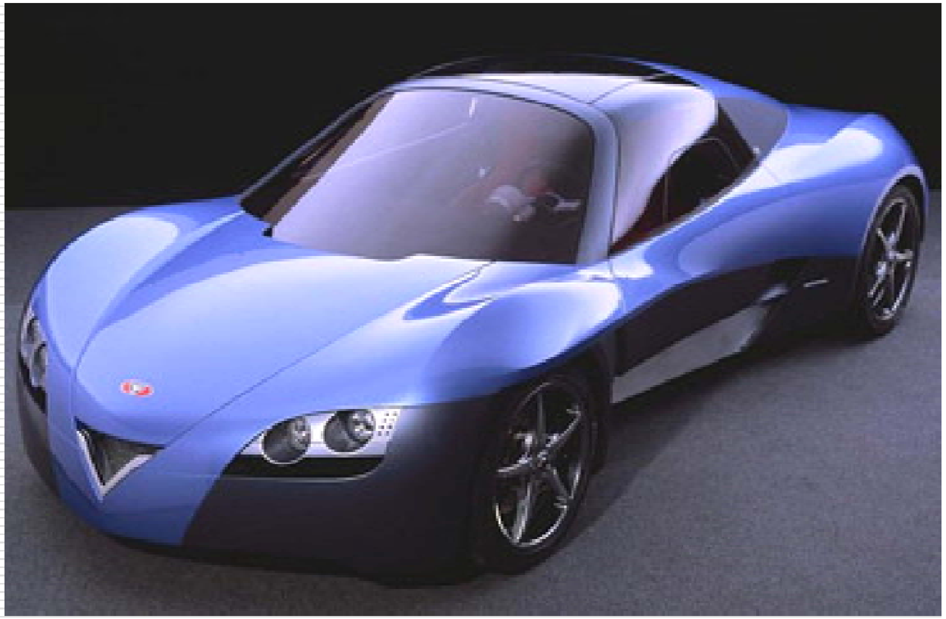
Smart Family

5. Outlook / Comments

The smart approach: In a high prize segment with positive marketing aspects like innovation, high performance, fun-to-drive EVs may become successful by providing in addition a green label and a good hygienic feeling to the market.

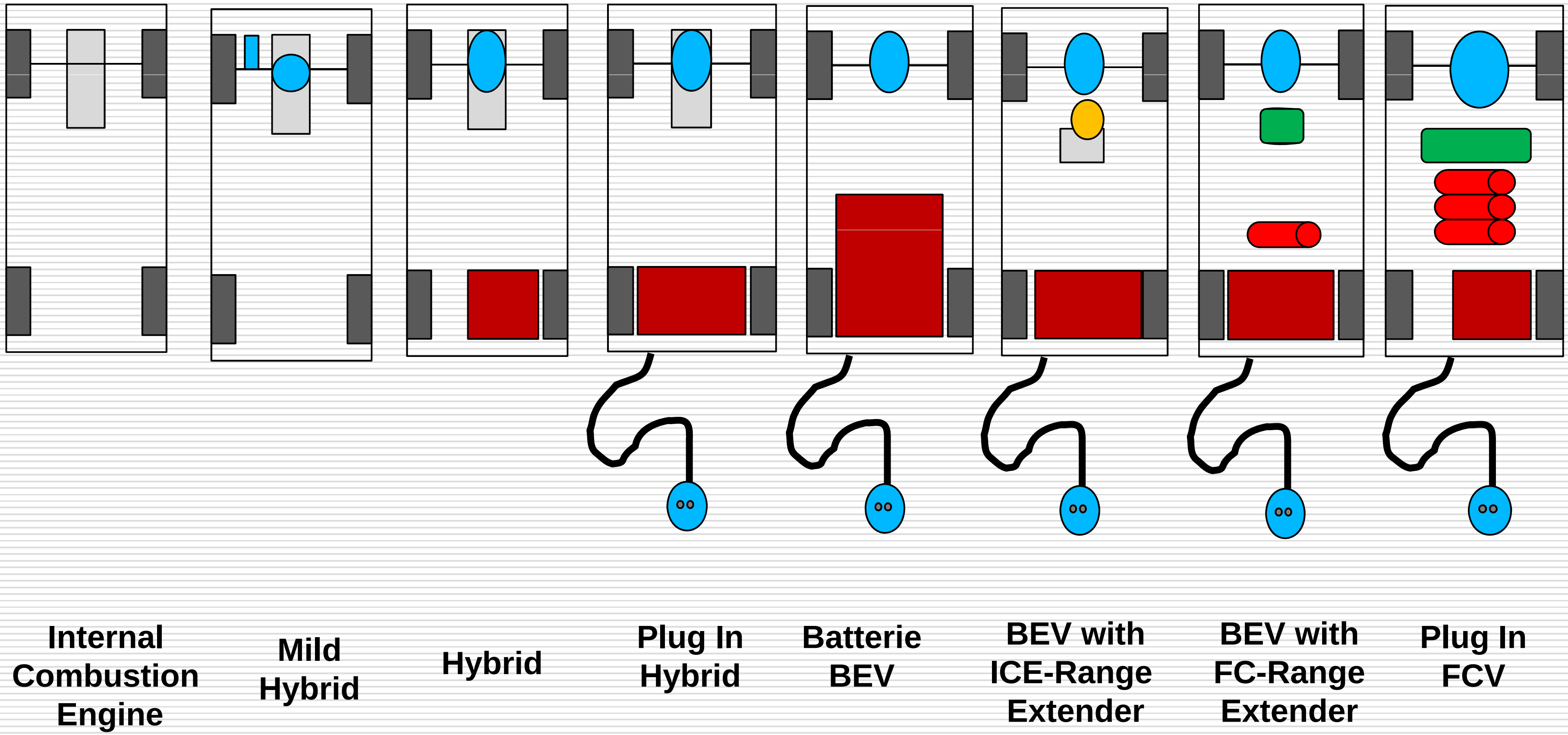
Tesla Roadster

Venturi Fetish

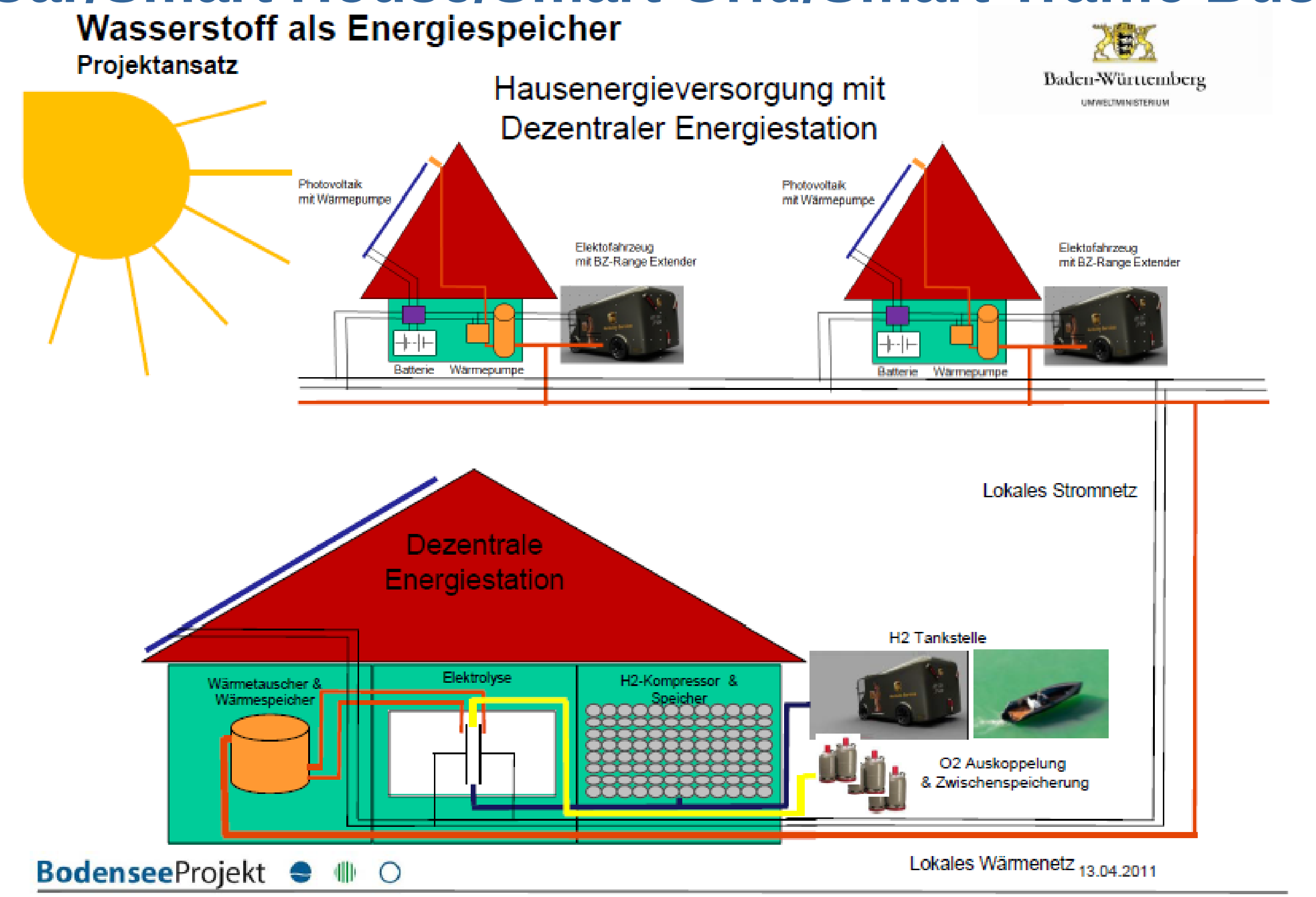


5. Outlook / Comments

At the end the introduction of Electromobility will be more an evolutionary than a revolutionary process driven by the prizes of Batteries and Fuel Cells



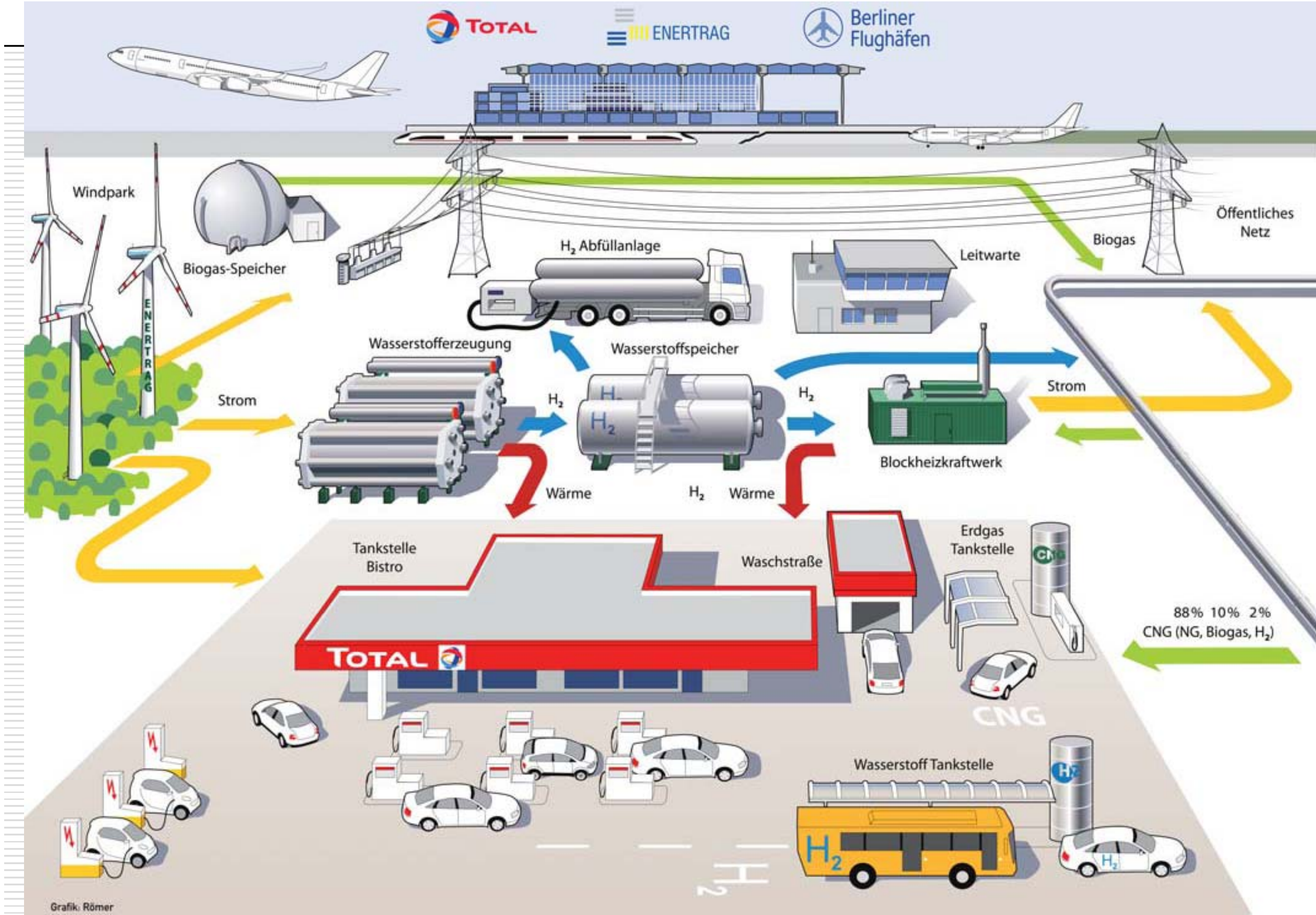
Electromobility will trigger a much broader approach of „Decentralized Energy Systems“ creating an integrated Smart Car/Smart House/Smart Grid/Smart Traffic Business



5. Outlook / Vision

Integrated Decentralized Energy approach: Berlin Airport – (Blueprint)

- Windparc
- Biogas
- Electrolyser
- Storage
- H2-Distribution
- integrated CHP
- feed into natural gas network
- GH2 dispenser
- EV+FCV Fleets



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Thank You very much for your attention