Fuel Cell Systems

4AT060 / 5AT010

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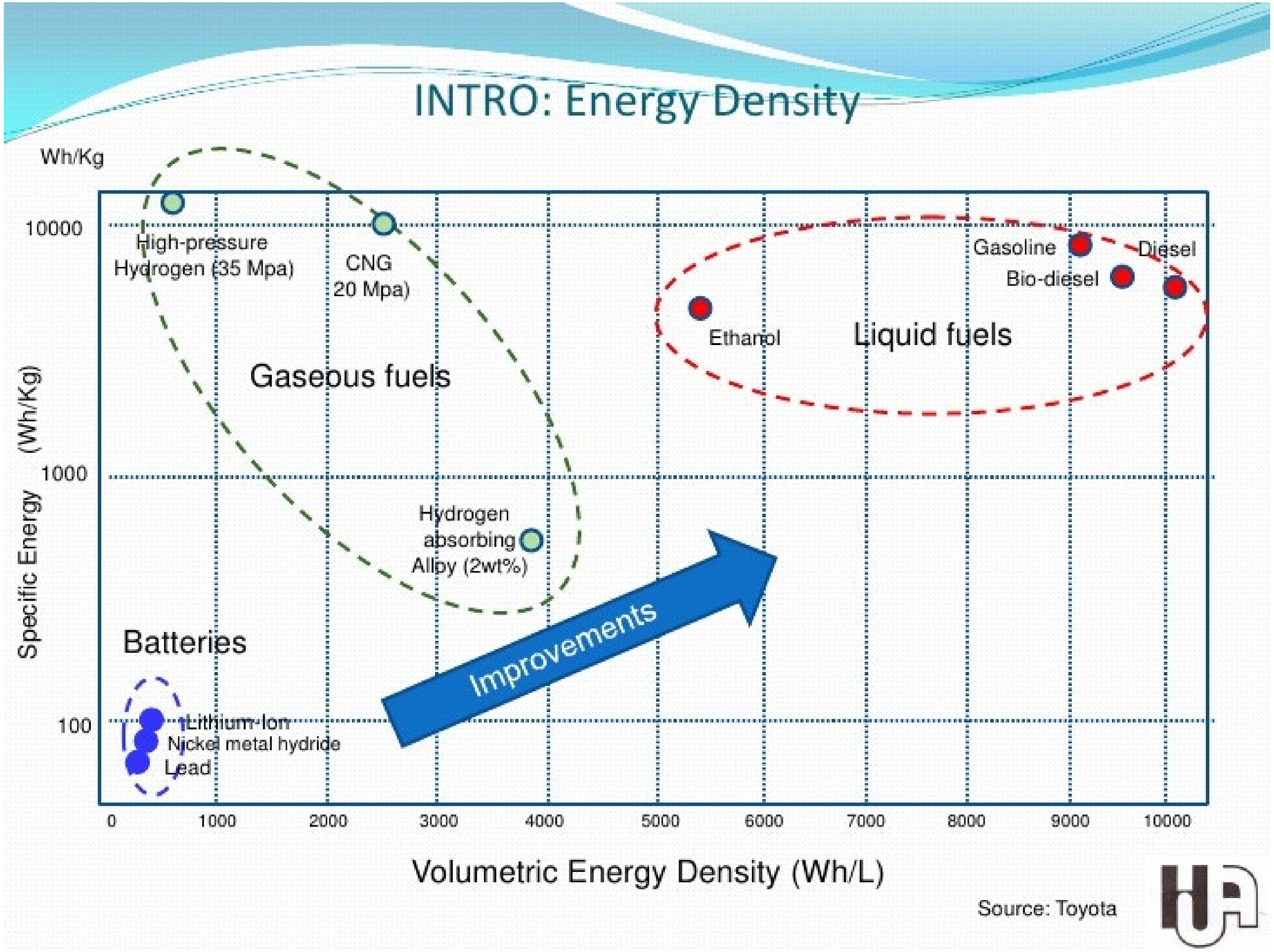
Fuel Cell Context

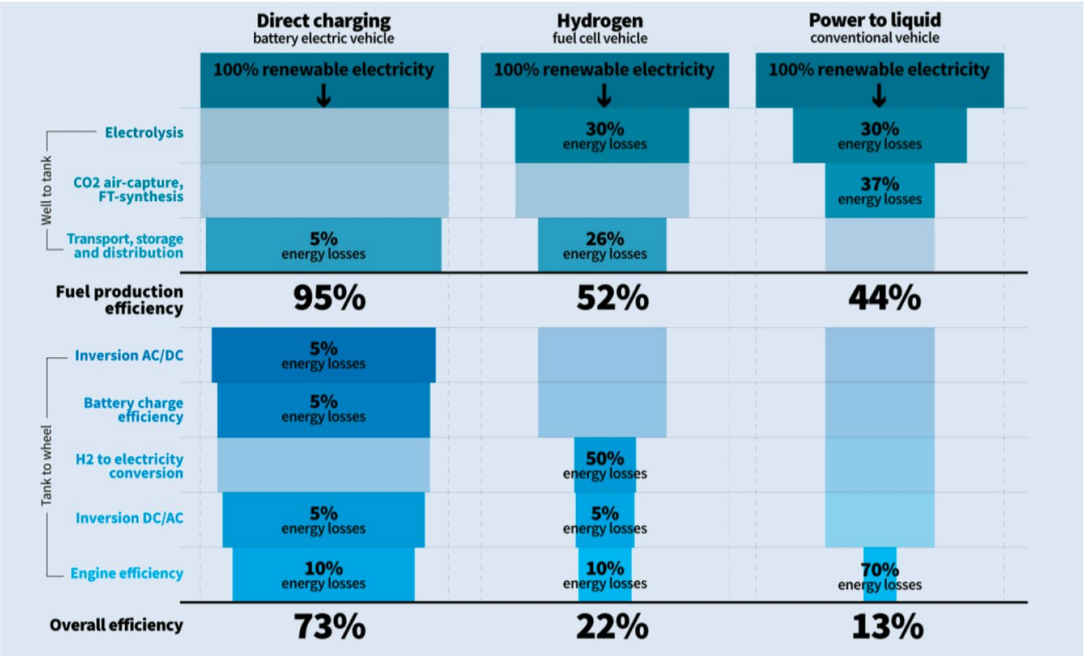
Why is Hydrogen Interesting as a Fuel?

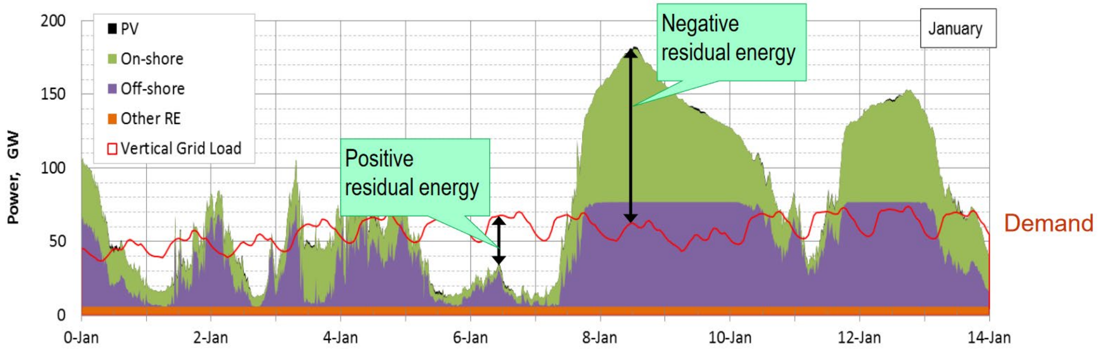
Difficult to obtain in practice due to storage weight (pressurised cylinders)

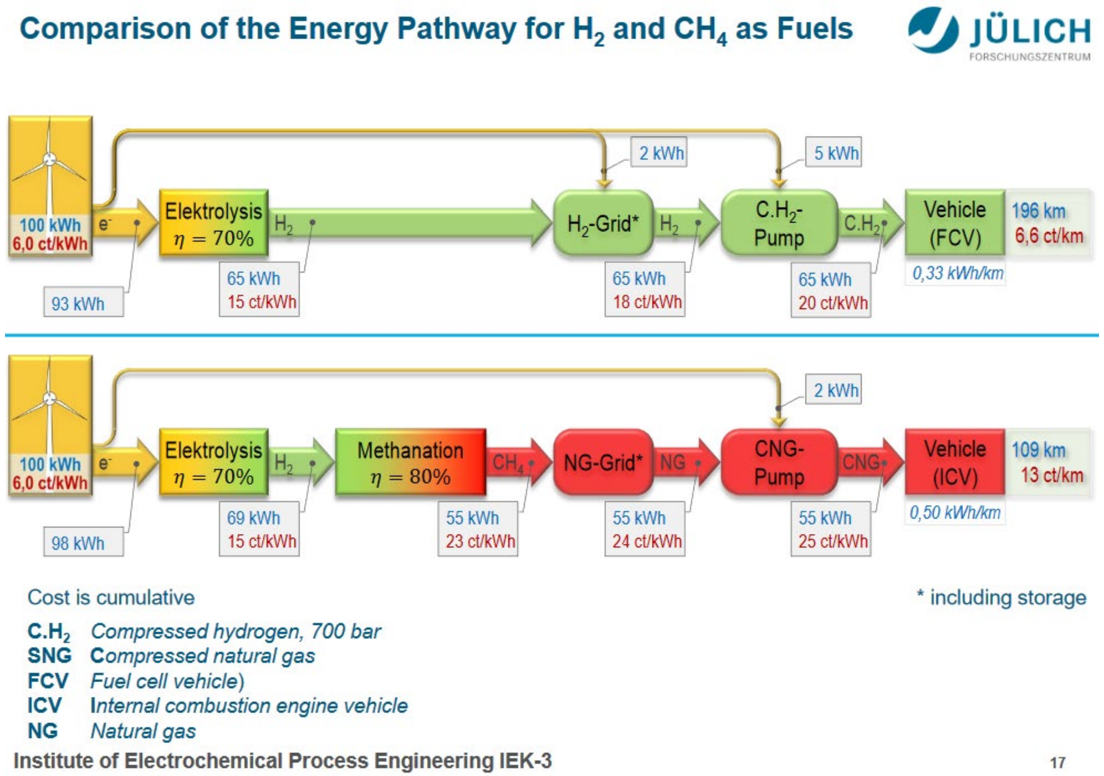
Alternative storage systems (storage in metal hydrides)



Recall Lecture 1, Part 1: 2050 – Options for CO2







Market Examples

Recent Fuel Cell Vehicles

- Honda FCX Clarity 2017
  - 130kW motor
  - 589km range
  - ~67mpg-e (approx. 28.5km/l)

- Toyota Mirai 2016
  - 113kW motor / 335Nm
  - 502km range
  - 66mpg-e (approx. 28km/l)
  - 1.6kWh [NiMH] battery
  - 70MPa 87.5kg (5kg cap)

Toyota’s Fuel Cell Developments

Toyota Motor Corporation
FCV

「MIRAI」

Hino Motors, Ltd.
FC bus

ta Tsusho Corporation
Hydrogen filling station

evel)

2012

Gas, Kyocera,
ofu Seisakusho

Ecoful-town at Toyota city
(HySUT：Iwatani Corporation, TOHO GAS CO., LTD)

Toyota Industries Corporation
FC forklift

Pilot program period:
Dec. 2012-Mar. 2014

Location:
Kita Kyushu Plant, Toyoda Gosei

Aisin Seiki Co., Ltd.
Co-gen. SOFC system for household use

Generation efficiency:
46.5%
(world's highest

Launched April 2

Osaka
and Ch

Toyo

ronics

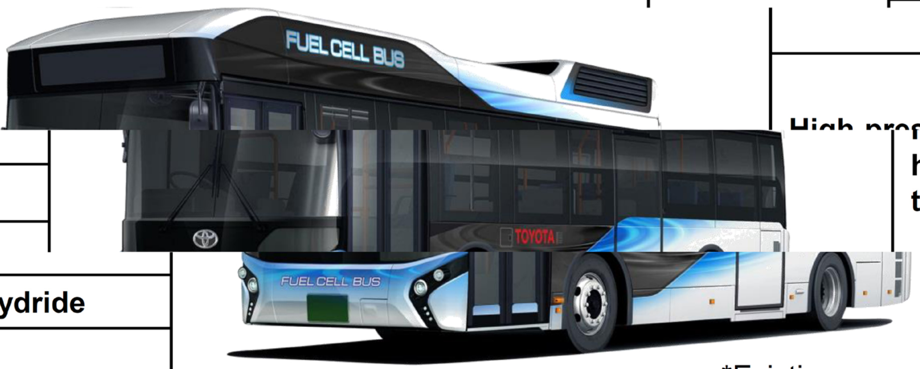
Fuel Cell Buses

Toyota to start sales of FC buses under the Toyota brand from early 2017
The Tokyo Metropolitan Government plans to utilize as fixed-route buses.

- Toyota aims to engage continuously in the diligent development targeted at the expansion of the introduction of the new FC buses from 2018

Vehicle	Length/width/height (mm)		10,525/2,490/3,340
	Capacity (seated+standing+driver)		77(26+50+1)
FC stack* (Fuel Cell)	Name		Toyota FC stack
	Type		Solid polymer electrolyte
	Maximum output		114 kw x 2units
Motor*	Type		AC synchronous
	Maximum output		113kw x 2units
	Maximum torque		335N･m x 2units
High-pressure hydrogen tank*	Type		Compression hydrogen
	Nominal working pressure		70MPa
	Tank internal volume		600L
	Number of tanks		10
Drive battery	Type		Nickel-metal hydride
V2H system	Maximum output/voltage		9kW/DC300V

*Existing component



The FC bus was developed using a unit of MIRAI.
Cruising range is approximately 200km

Toyota's Heavy-Duty Fuel Cell Truck Prototype

200 mile range (322km)
12kWh battery

⇒ Prototype vehicle

⇒ Compare with others

Nikola One Heavy-Duty Fuel Cell Truck

1200 mile range (1900km)
320kWh battery

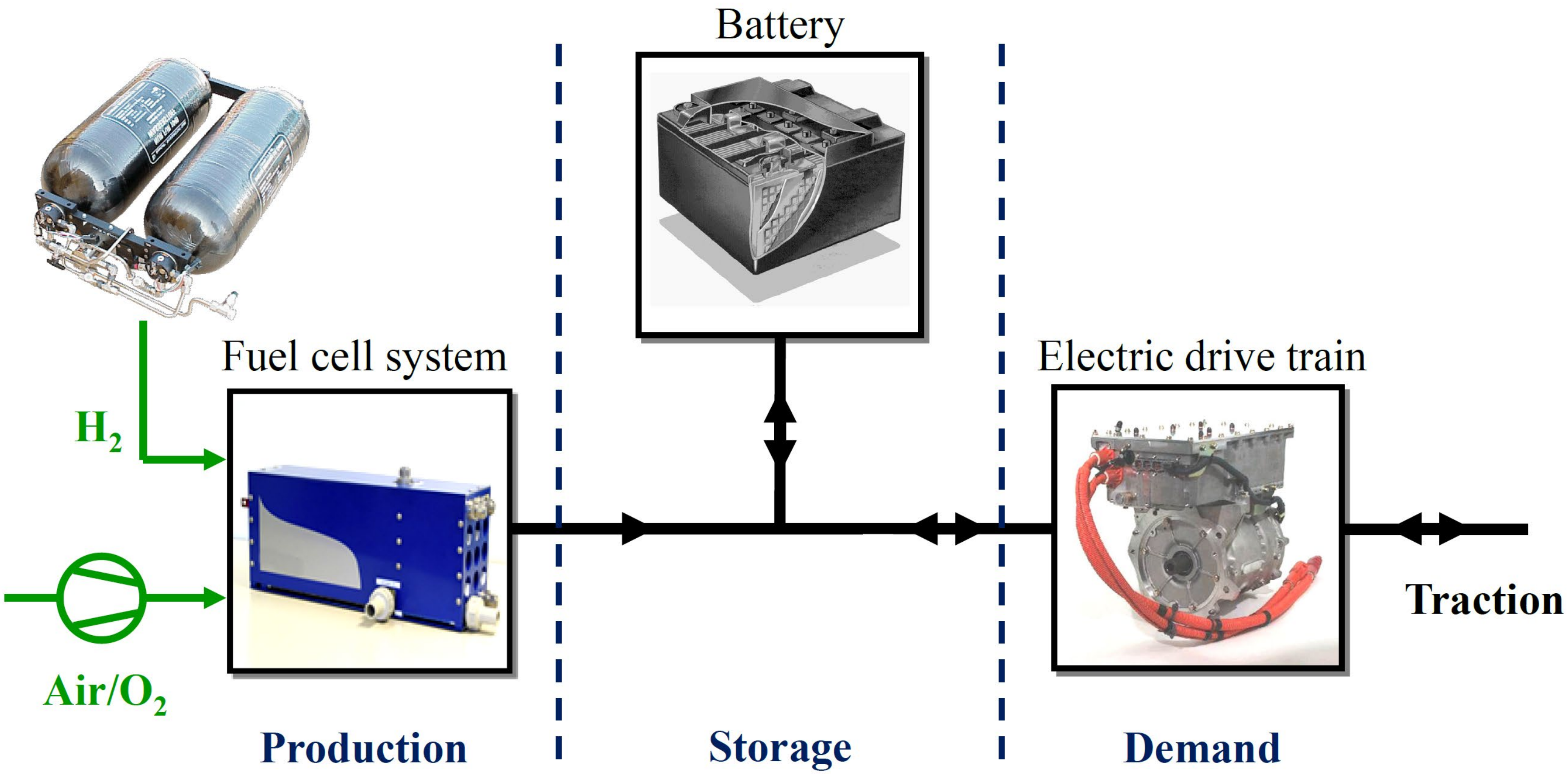
	DIESEL	ELECTRIC
Horsepower	500HP	1,000HP
Torque	1,650 ft-lbs	2,000 ft-lbs
Range	500-750 miles	800 - 1,200 miles
Top Speed Up Hills (6%)	20 - 40 MPH	65 MPH
On Descent	Exhaust & Friction Brakes	Recharging & Saving Brakes
Acceleration 0-60 MPH Under Load	60 seconds	30 seconds
MPG	7.5 MPG	13 - 15 MPG
Weight	19,000 - 23,000 lbs	18,000 - 21,000 lbs

Fuel Cell Requirements (Typical)

	Stationary	Transportation		Portable
		Propulsion	Auxiliary power	
Total life time	> 10 years	Approx. 10 years	Approx. 10 years	1...5 years
Required power production time	40 000...80 000 hrs	5000 hrs	5000 hrs	1000...5000 hrs
Thermal cycles	~ 100	~ 5000	> 10 000	Depending on application
$\eta_{el,system}$	> 50%	> 40%	30...40%	> 20%
Unit size	100...1000 kW Decentralized power 1...50 kW Residential power	50...70 kW automobiles 500...5 000 kW trams...trains 5...500 kW boats 1000...20 000 kW ships	5...10 kW automobiles, trucks, boats 50...200 kW airplanes 100...1000 kW ships	0.1...5 kW
Specific target	Limited through materials' cost	1 kg/kW	10 kg/kW automobiles << 5 kg/kW airplanes	Limited through portability
Specific target cost	1500 US$/kW	30...50 US$/kW automobiles	200...600 US$/kW automobiles	<5000 US$/kW
Acceptable de-gradation rate*	0.13...0.25 %/1000 hrs	~ 2 %/1000 hrs	~ 2 %/1000 hrs	2...10 %/1000 hrs

Fuel Cell Basics

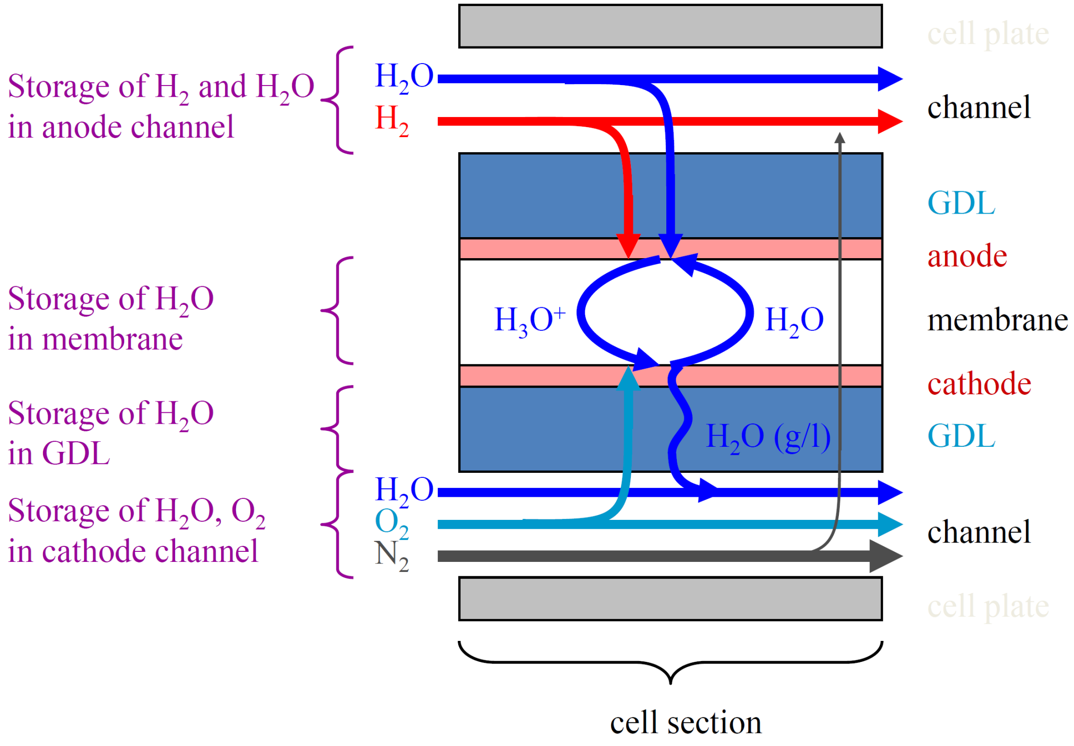
Fuel Cell Electric Vehicle Powertrain

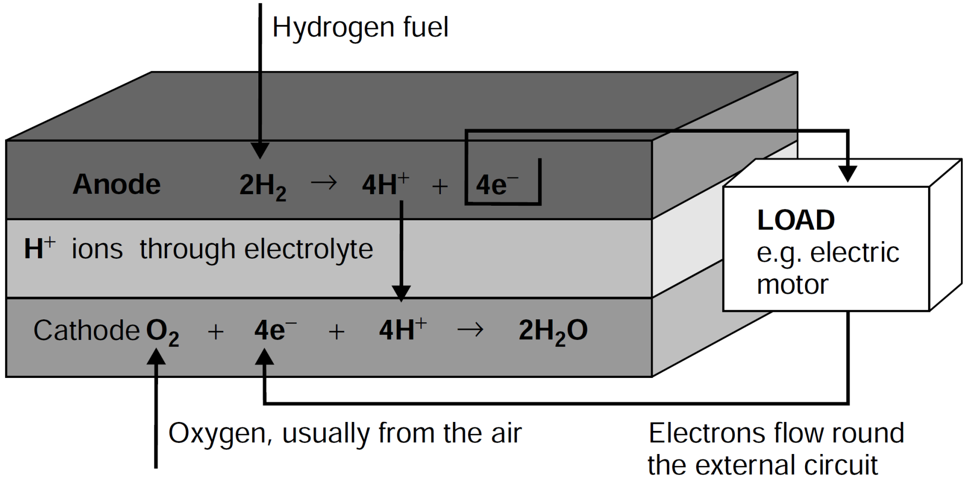


Different Types of Fuel Cell

Fuel cell type	Mobile ion	Operating temp.	Applications and notes
Alkaline (AFC)	OH^-	50–200°C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEMFC)	H^+	30–100°C	Vehicles and mobile applications, and for lower power CHP systems
Direct methanol (DMFC)	H^+	20–90°C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	H^+	~220°C	Large numbers of 200 kW CHP systems in use
Molten carbonate (MCFC)	CO_3^{2-}	~650°C	Suitable for medium to large scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O^{2-}	500–1000°C	Suitable for all sizes of CHP systems, 2 kW to multi MW

Fuel Cell Reactions (Proton Exchange Membrane)



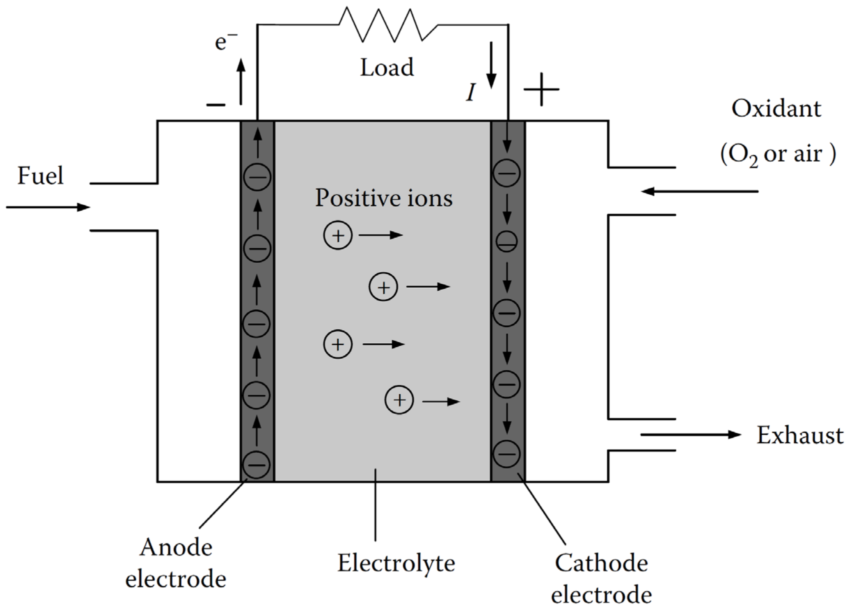


GDL: Gas Diffusion Layer

Fuel Cell Chemical Background

- The energy produced in the reaction of the fuel cell can be written as the change in Gibbs free energy:

$$\Delta G = \sum_{\text{Products}} G_i - \sum_{\text{Reactants}} G_j$$



In a reversible process, the change in Gibbs free energy is converted to electrical energy:

$$\Delta G = -nFV_r$$

Where:

n is the number of electrons transferred in the reaction
F is 96495 coulombs per mole (Faraday constant)
V_r is the reversible voltage of the cell

Fuel Cell Chemical Background

- In standard conditions, we can re-write this as:

$$V_r^0 = -\frac{\Delta G^0}{nF}$$

We can also be reminded that:

$$\Delta G = \Delta H - T\,\Delta S$$

Where

ΔH is the change in enthalpy
ΔS is the change in entropy
T is the absolute temperature
(see right)

We can also define an ideal efficiency:

$$\eta_{id} = \frac{\Delta G}{\Delta H} = 1 - \frac{\Delta S}{\Delta H} T$$

Substance	Formula	ΔH^0_{298} (kJ/mol)	ΔS^0_{298} (kJ/mol K)	ΔG^0_{298} (kJ/mol)
Oxygen	O (g)	0	0	0
Hydrogen	H (g)	0	0	0
Carbon	C (s)	0	0	0
Water	H_2O (l)	−286.2	−0.1641	−237.3
Water	H_2O (g)	−242	−0.045	−228.7
Methane	CH_4 (g)	−74.9	−0.081	−50.8
Methanol	CH_3OH (l)	−238.7	−0.243	−166.3
Ethanol	C_2H_5OH (l)	−277.7	−0.345	−174.8
Carbon monoxide	CO (g)	−111.6	0.087	−137.4
Carbon dioxide	CO_2	−393.8	0.003	−394.6
Ammonia	NH_3 (g)	−46.05	−0.099	−16.7

Fuel Cell Chemical Background

- When ΔS is zero (no change in gas moles), the ηid is 100%; such as:

$$C + O_2 = CO_2$$

- When is positive, the change in enthalpy ΔH, will generate heat TΔS, to convert to electrical energy
- In this situation, the cell voltage depends on the reactants and products:

$$V_r = V_r^0 - \frac{RT}{nF} \ln\left[\frac{\prod(\text{activities of products})}{\prod(\text{activities of reactants})}\right]$$

- Where R is 8.31[J/mol K], T is the temperature [K].

Fuel Cell Chemical Background

- This can be re-written:

$$V_r = V_r^0 - \frac{RT}{nF}\sum_i v_i \ln\left(\frac{p_i}{p_i^0}\right)$$

- Where,

  p_i^0 is the standard pressure (usually 1 atm)

  p_i is the non-standard pressure

  V_r^0 is the standard voltage at standard pressure

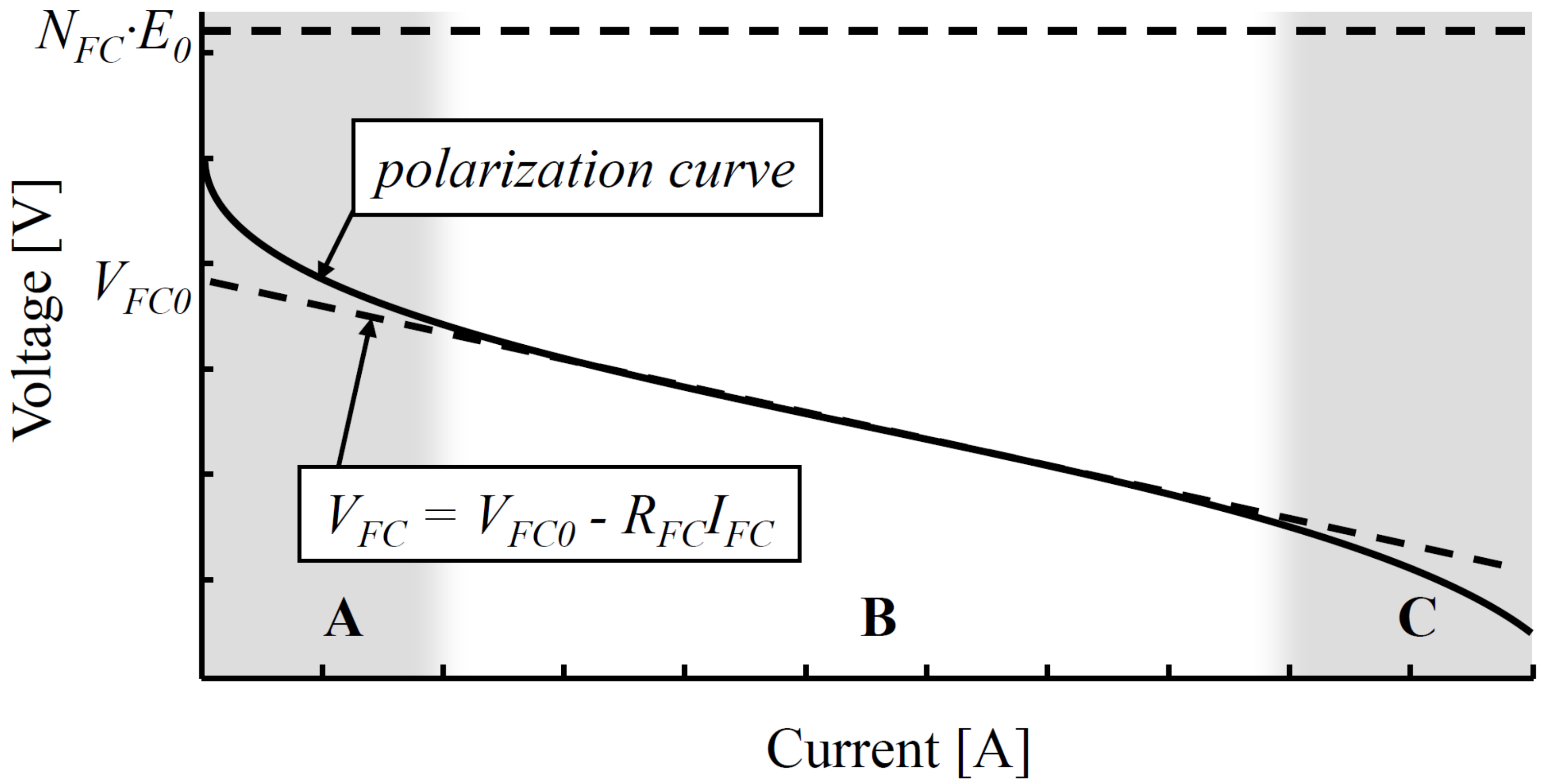
  v_i is the number of moles of species *i* (positive for products, negative for reactants)

	ΔH^0_{298} (kJ/mol)	ΔS^0_{298} (kJ/mol K)	ΔG^0_{298} (kJ/mol)	n	E (V)	η_{id}(%)
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (l)	−286.2	−0.1641	−237.3	2	1.23	83
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (g)	−242	−0.045	−228.7	2	1.19	94
$C + \frac{1}{2}O_2 \rightarrow CO$ (g)	−116.6	0.087	−137.4	2	0.71	124
$C + O_2 \rightarrow CO_2$ (g)	−393.8	0.003	−394.6	4	1.02	100
$CO + \frac{1}{2}O_2 \rightarrow CO_2$ (g)	−279.2	−0.087	−253.3	2	1.33	91

Fuel Cell Modelling

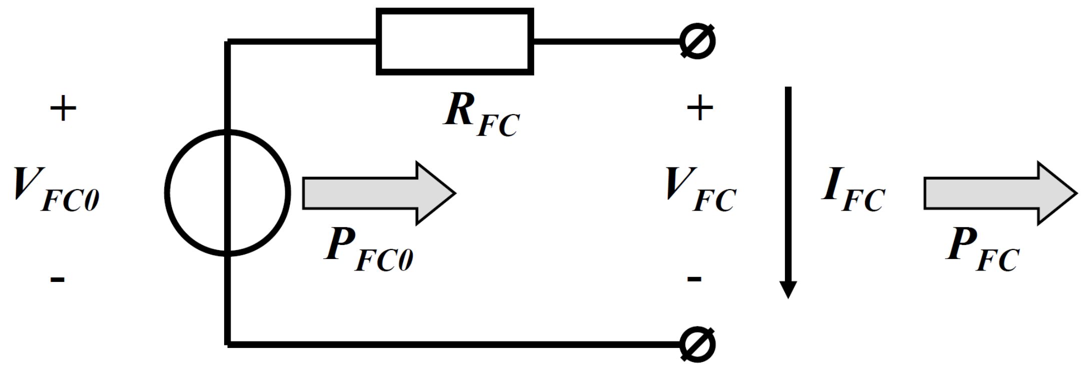
Fuel Cell Polarisation Curve

- Area A:
  - Activation losses dominate at low currents
  - Voltage causes back diffusion of protons (+ageing)
- Area B:
  - ‘Normal operation’
  - Ohmic losses dominate
- Area C:
  - Concentration losses dominate
  - Power decreases



=> Area B is the most important part to model

Fuel Cell Ohmic Losses



The stack voltage can be modelled as an ideal voltage source and ohmic drop:

$$V_{FC} = V_{FC0} - R_{FC} I_{FC}.$$

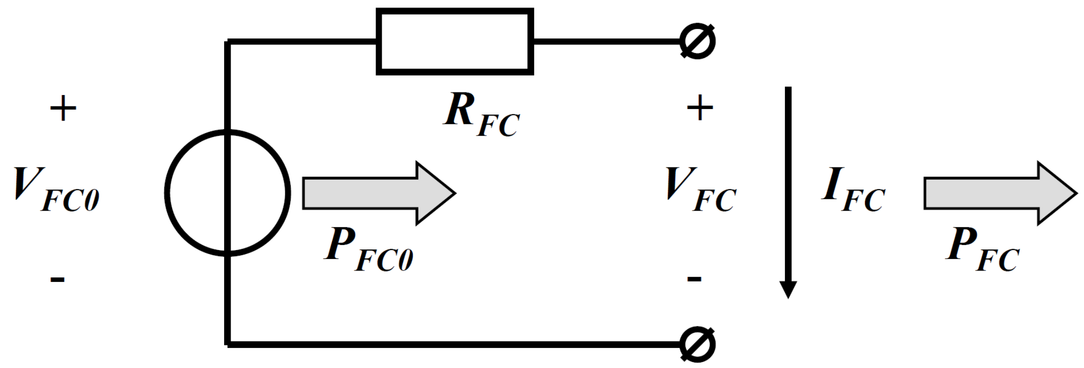
Where, we can likewise define the power:

$$\begin{aligned} P_{FC} &= V_{FC} I_{FC} \\ &= V_{FC0} I_{FC} - R_{FC} I_{FC}^2. \end{aligned}$$

This can therefore have the solution for current:

$$I_{FC} = \frac{V_{FC0}}{2R_{FC}} \left(1 - \sqrt{1 - 4P_{FC} \frac{R_{FC}}{{V_{FC0}}^2}} \right).$$

Fuel Cell Ohmic Losses



Given,

$$I_{FC} = \frac{V_{FC0}}{2R_{FC}}\left(1 - \sqrt{1 - 4P_{FC}\frac{R_{FC}}{{V_{FC0}}^2}}\right).$$

We can define the mass flow of hydrogen:

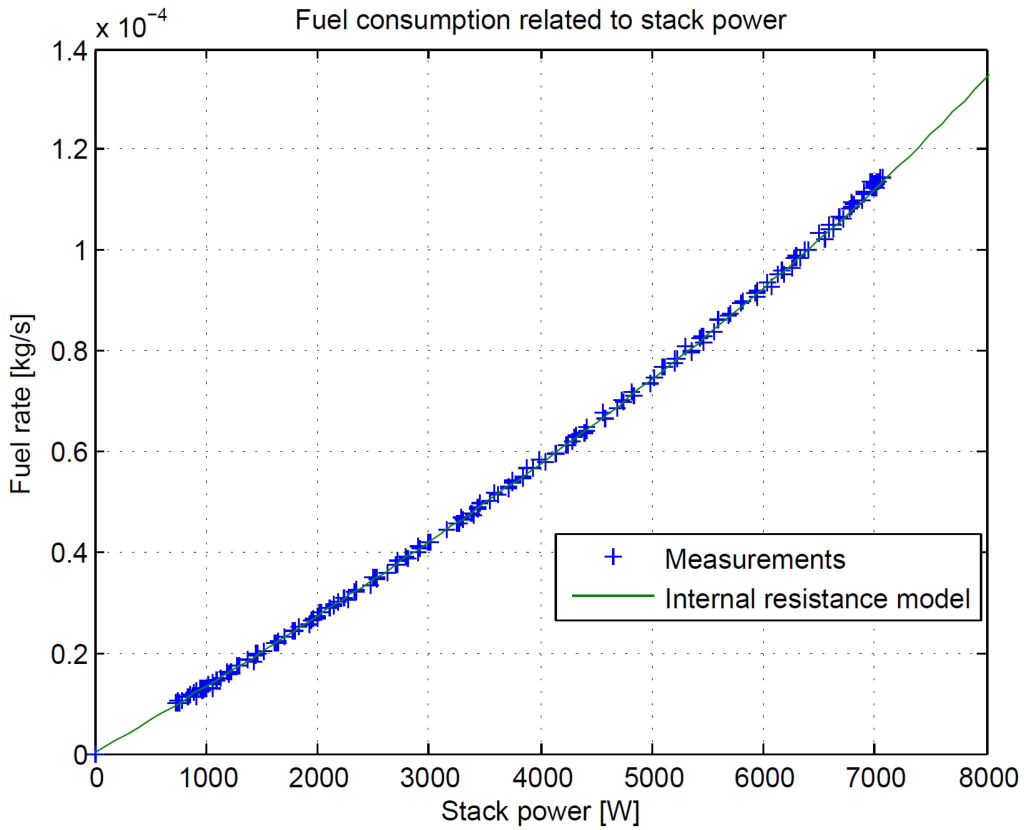
$$\dot{m}_{H_2} = N_{FC}\frac{M_{H_2}}{2F}I_{FC}$$
$$= N_{FC}\frac{M_{H_2}}{2F}\frac{V_{FC0}}{2R_{FC}}\left(1 - \sqrt{1 - 4P_{FC}\frac{R_{FC}}{{V_{FC0}}^2}}\right)$$

Where

M_{H2} is the molar weight of hydrogen
N_{FC} are the number of cells within the stack

Lastly we can limit the power range (typ. 10-100%): $P_{FCmin} \leq P_{FC} \leq P_{FCmax}$

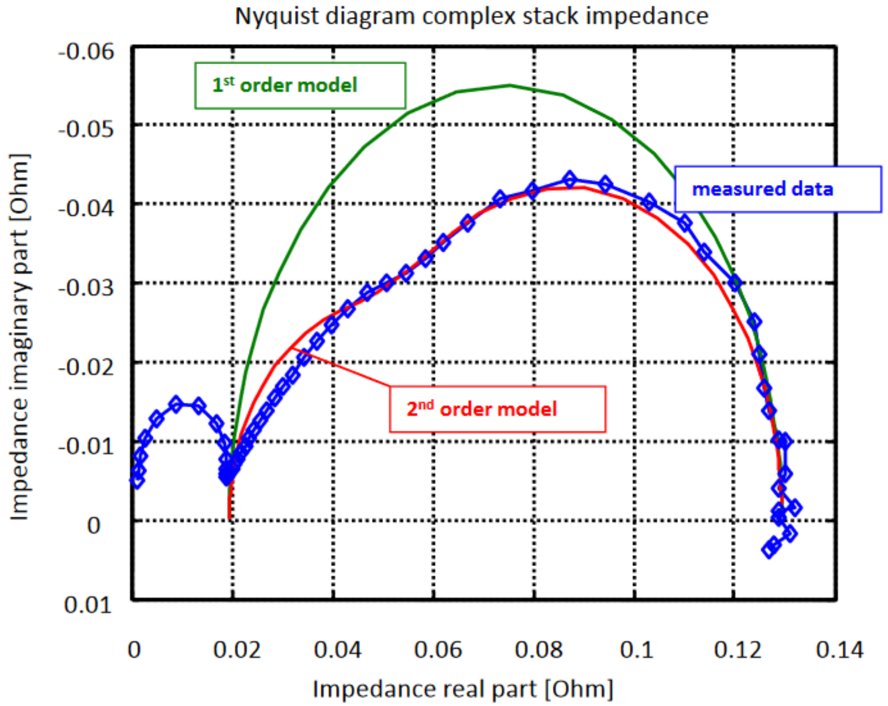
Comparison Against Measured Data

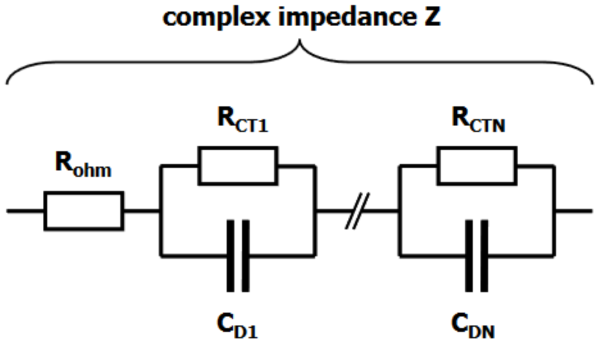


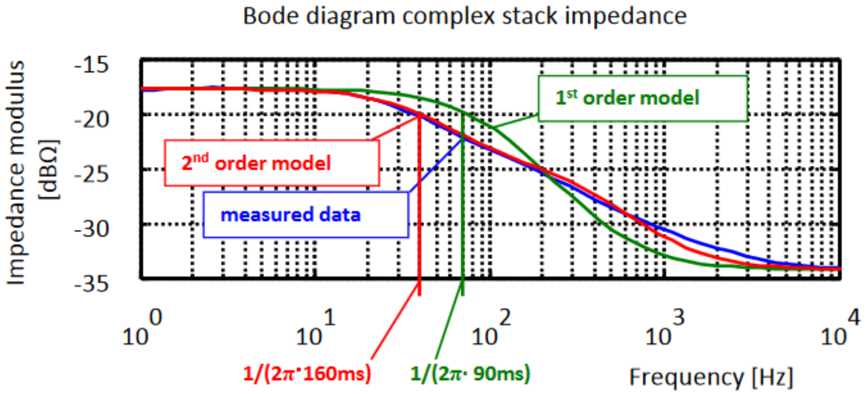
- Comparison between modelled and measured relationship between fuel rate and stack power using simplified model presented

We've Seen This Before?

- Modelling looks similar to batteries… same principles apply

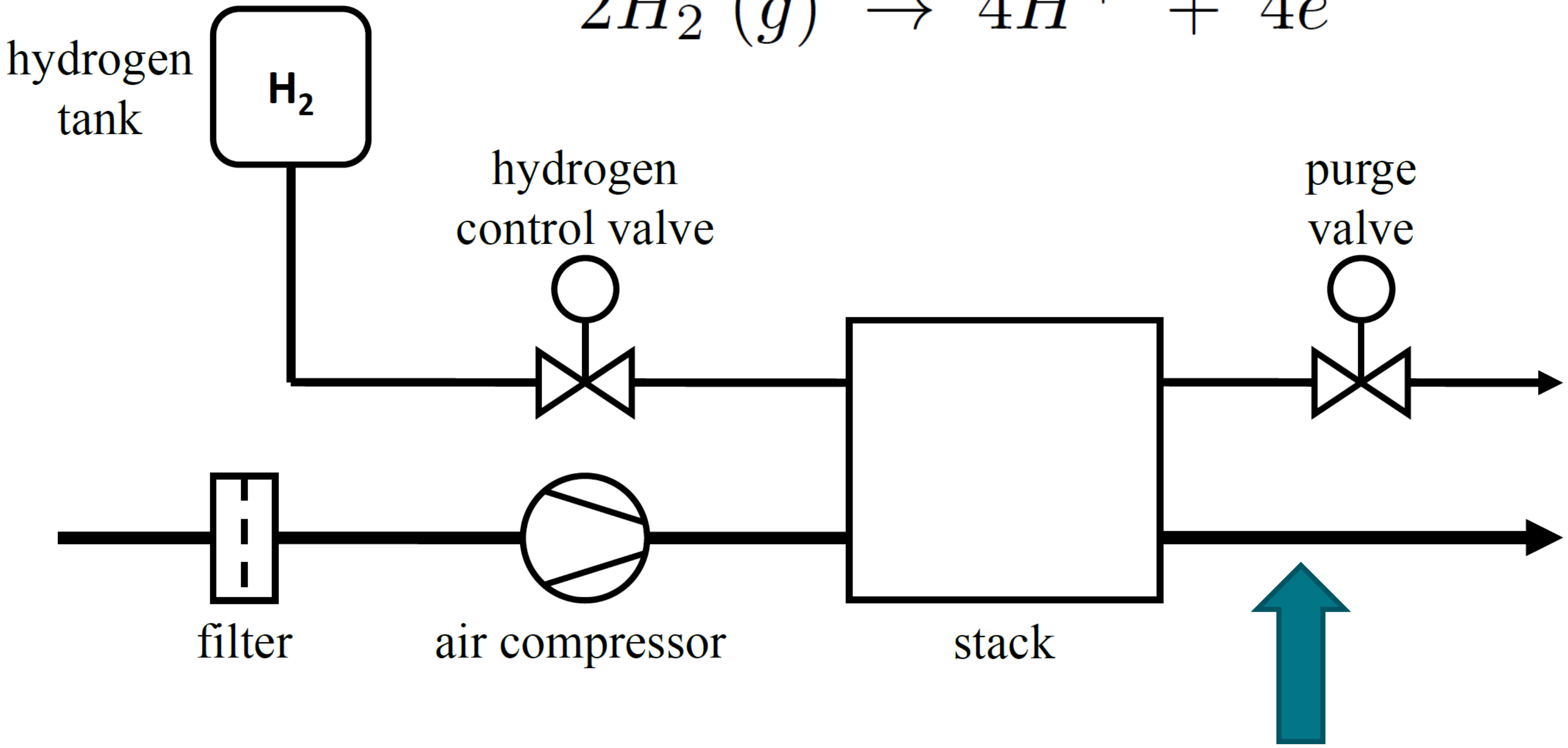






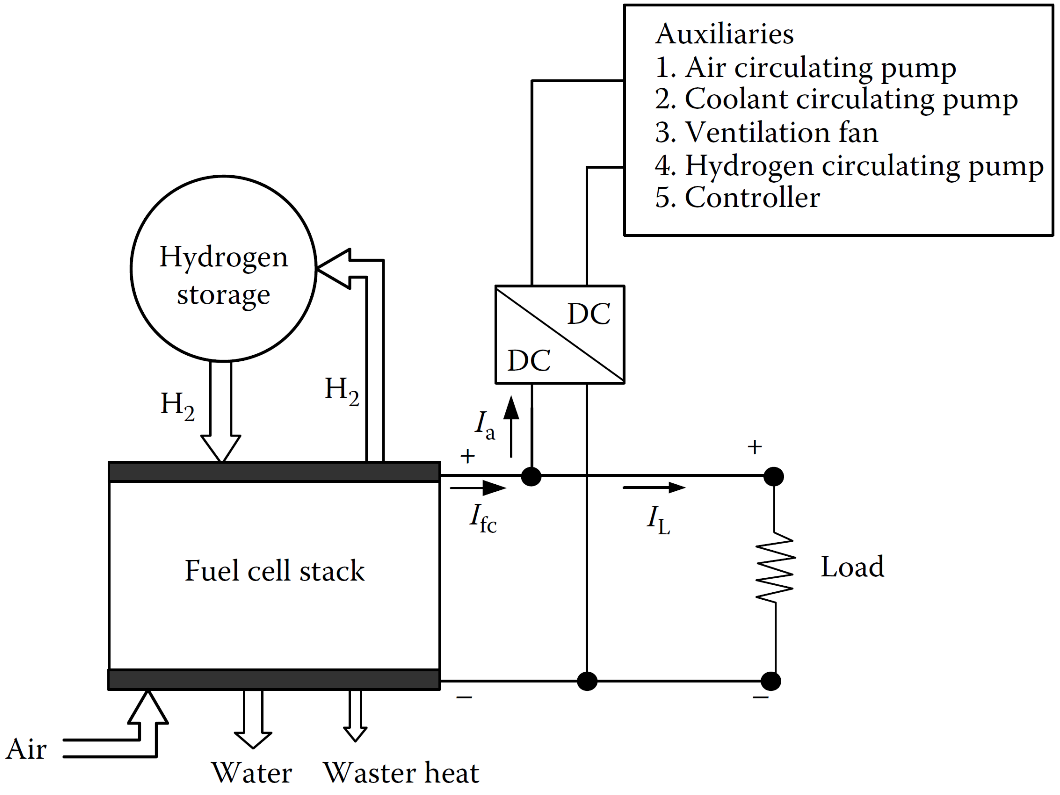
Beyond the Stack

$$2H_2\ (g)\ \rightarrow\ 4H^+\ +\ 4e^-$$



$$O_2\ (g)\ +\ 4H^+\ +\ 4e^-\ \rightarrow\ 2H_2O\ (g/l)$$

Modelling the Air Compression



There are a number of auxiliaries, although the air circulation pump takes up the most power (~10%). We can model the power requirement via:

$$P_{air-comp} = \frac{\gamma}{\gamma - 1}\dot{m}_{air}\, RT\left[\left(\frac{p}{p_0}\right)^{\gamma-1/\gamma} - 1\right](\mathrm{W})$$

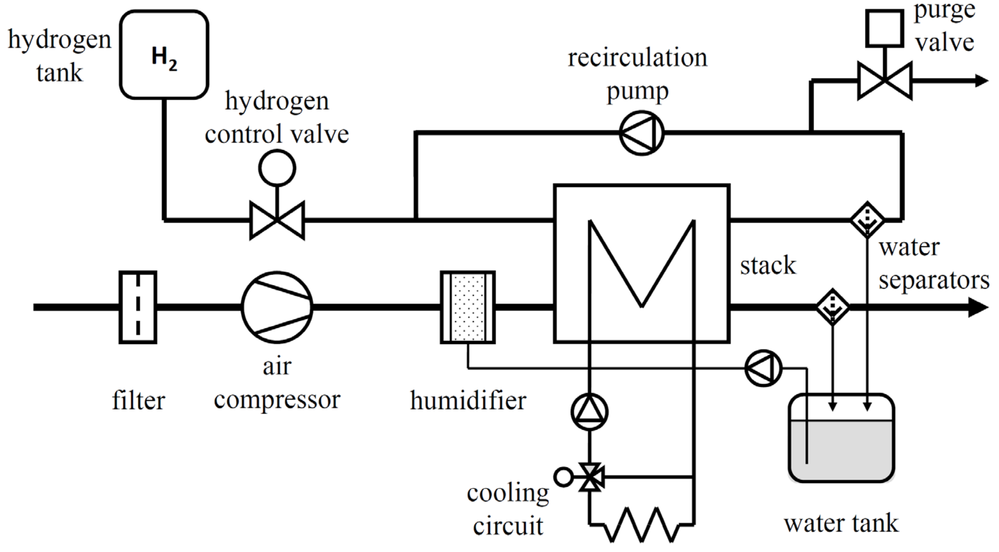
Where gamma is the ratio of specific heats (=1.4)

This is driven by an electric motor, which we can assume to have a fixed efficiency (η_{ap})

$$P_{air-cir} = \frac{P_{air-comp}}{\eta_{ap}}$$

It should also be noted that the acceleration of the speed compressor is often limited.

More Auxiliaries!

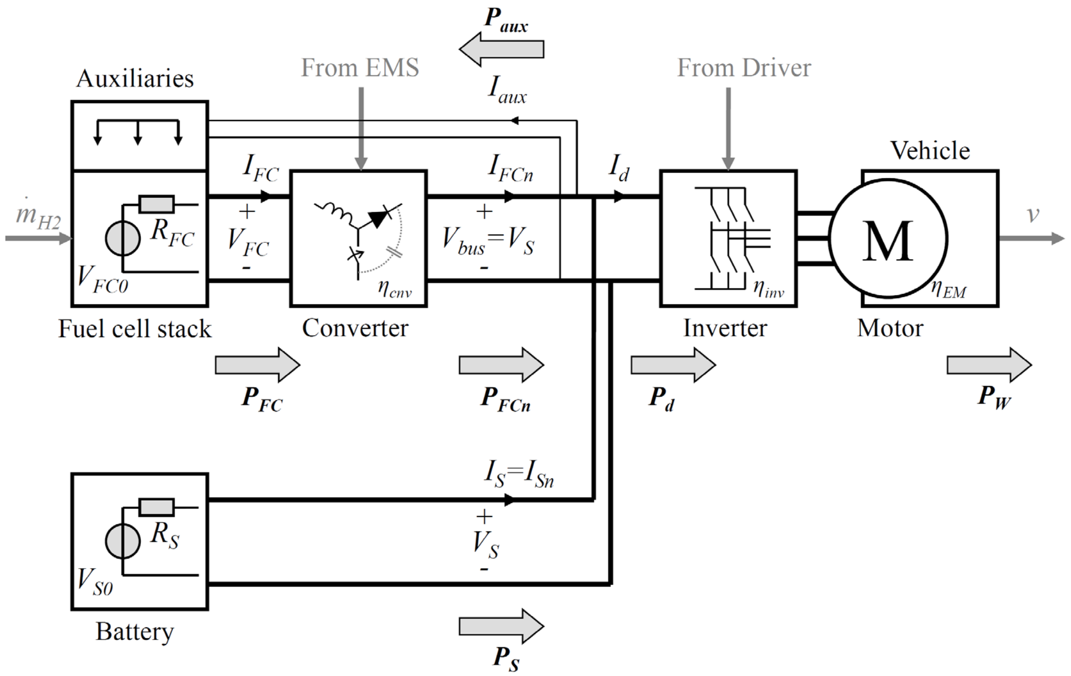


- For PEM fuel cells, water management is an issue:
  - Water helps the proton exchange (must not dry out)
  - Too much water will flood the cell
  - Thermal management is therefore also important
  - In some systems management of CO and Sulphur components is required (to prevent cell poisoning)

Electrically Coupling

- As with batteries, you will note that the power and voltage of the fuel cells are variable
- Additionally, to manage the condition of the cell (particularly during start-up), a battery is normally required
- As such, power electronics once again plays a key role in integrating such systems

- *How much of this can you already model?*



Hydrogen Storage

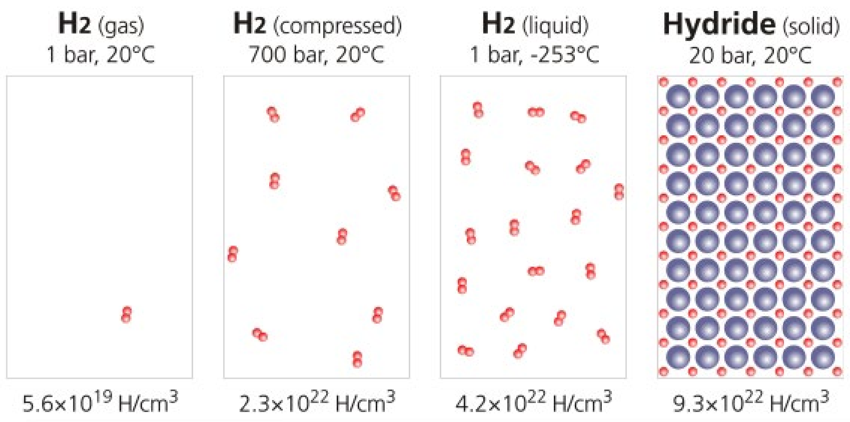
Hydrogen Storage

When compressed, the amount of energy required to (reversibly) compress can be determined by:

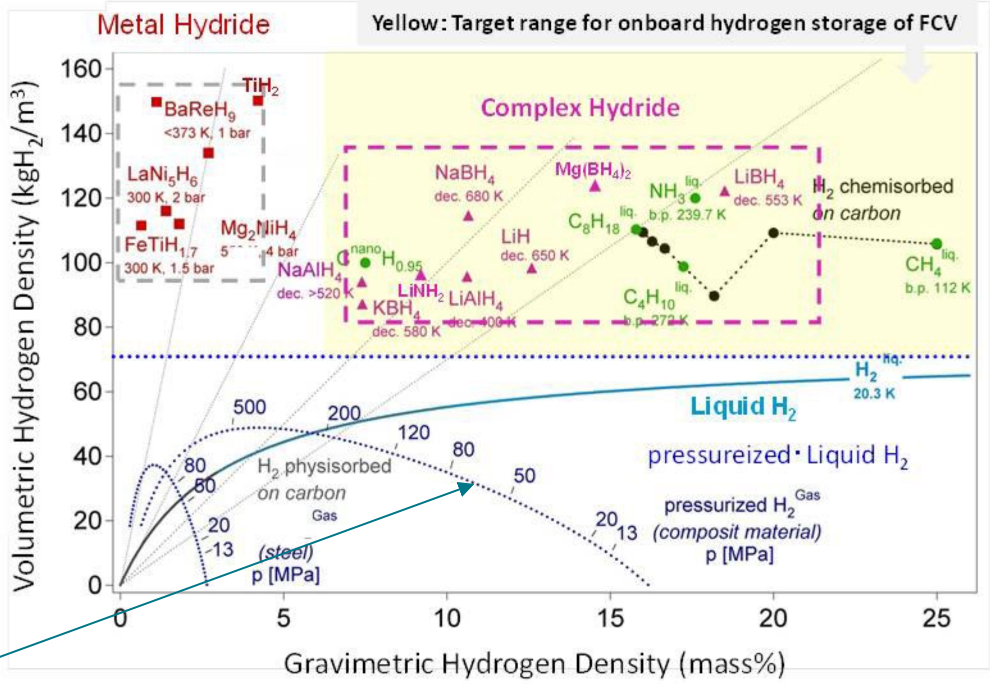
$$E_{\text{comp}} = \frac{\gamma}{\gamma-1}\frac{m}{W_H}RT\left[\left(\frac{p}{p_0}\right)^{\gamma-1/\gamma}-1\right]$$

Where W_H is the molecular weight of hydrogen

Another option is storage in a **metal hydride**



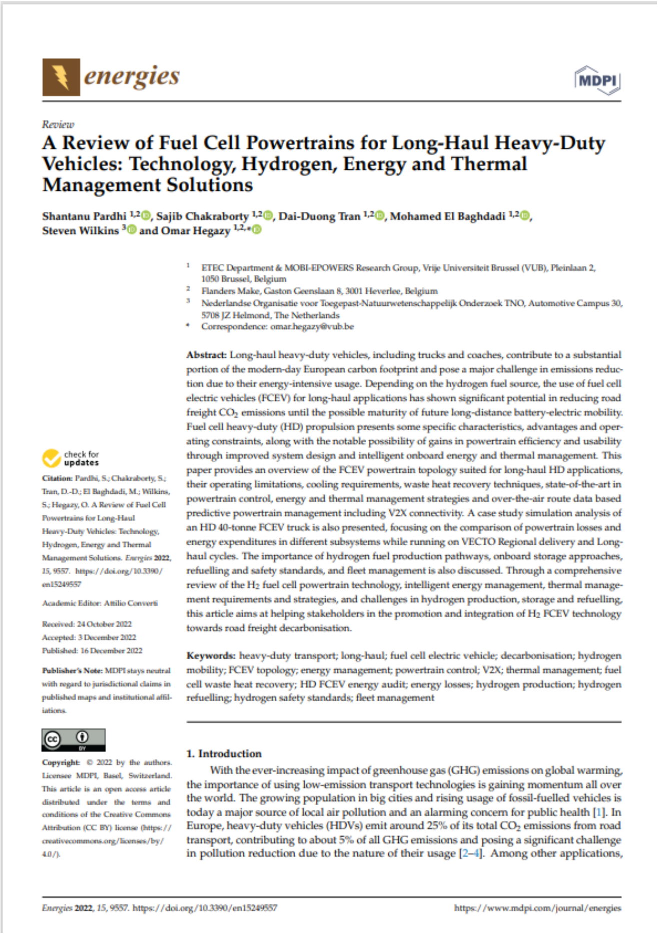
Material	H-Atoms per cm^3 ($\times 10^{22}$)	% of Weight that is Hydrogen
H_2 gas, 200 bar (2900 psi)	0.99	100
H_2 liquid, 20°K (−253°C)	4.2	100
H_2 liquid, 4.2°K (−269°C)	5.3	100
Mg–H_2	6.5	7.6
Mg_2Ni–H_2	5.9	3.6
FeTi–H_2	6.0	1.89
LaNi–H_6	5.5	1.37



Recall Toyota 2016 model @70MPa 87.5kg (5kg cap)

Example Study

Example



energies

MDPI

Review

A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Solutions

Shantanu Pardhi [1,2], Sajib Chakraborty [1,2], Dai-Duong Tran [1,2], Mohamed El Baghdadi [1,2], Steven Wilkins [3] and Omar Hegazy [1,2,*]

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Abstract: Long-haul heavy-duty vehicles, including trucks and coaches, contribute to a substantial portion of the modern-day European carbon footprint and pose a major challenge in emissions reduction due to their energy-intensive usage. Depending on the hydrogen fuel source, the use of fuel cell electric vehicles (FCEV) for long-haul applications has shown significant potential in reducing road freight CO_2 emissions until the possible maturity of future long-distance battery-electric mobility. Fuel cell heavy-duty (HD) propulsion presents some specific characteristics, advantages and operating constraints, along with the notable possibility of gains in powertrain efficiency and usability through improved system design and intelligent onboard energy and thermal management. This paper provides an overview of the FCEV powertrain topology suited for long-haul HD applications, their operating limitations, cooling requirements, waste heat recovery techniques, state-of-the-art in powertrain control, energy and thermal management strategies and over-the-air route data based predictive powertrain management including V2X connectivity. A case study simulation analysis of an HD 40-tonne FCEV truck is also presented, focusing on the comparison of powertrain losses and energy expenditures in different subsystems while running on VECTO Regional delivery and Long-haul cycles. The importance of hydrogen fuel production pathways, onboard storage approaches, refuelling and safety standards, and fleet management is also discussed. Through a comprehensive review of the H_2 fuel cell powertrain technology, intelligent energy management, thermal management requirements and strategies, and challenges in hydrogen production, storage and refuelling, this article aims at helping stakeholders in the promotion and integration of H_2 FCEV technology towards road freight decarbonisation.

Keywords: heavy-duty transport; long-haul; fuel cell electric vehicle; decarbonisation; hydrogen mobility; FCEV topology; energy management; powertrain control; V2X; thermal management; fuel cell waste heat recovery; HD FCEV energy audit; energy losses; hydrogen production; hydrogen refuelling; hydrogen safety standards; fleet management

check for updates

Citation: Pardhi, S.; Chakraborty, S.; Tran, D.-D.; El Baghdadi, M.; Wilkins, S.; Hegazy, O. A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Solutions. *Energies* **2022**, 15, 9557. https://doi.org/10.3390/en15249557

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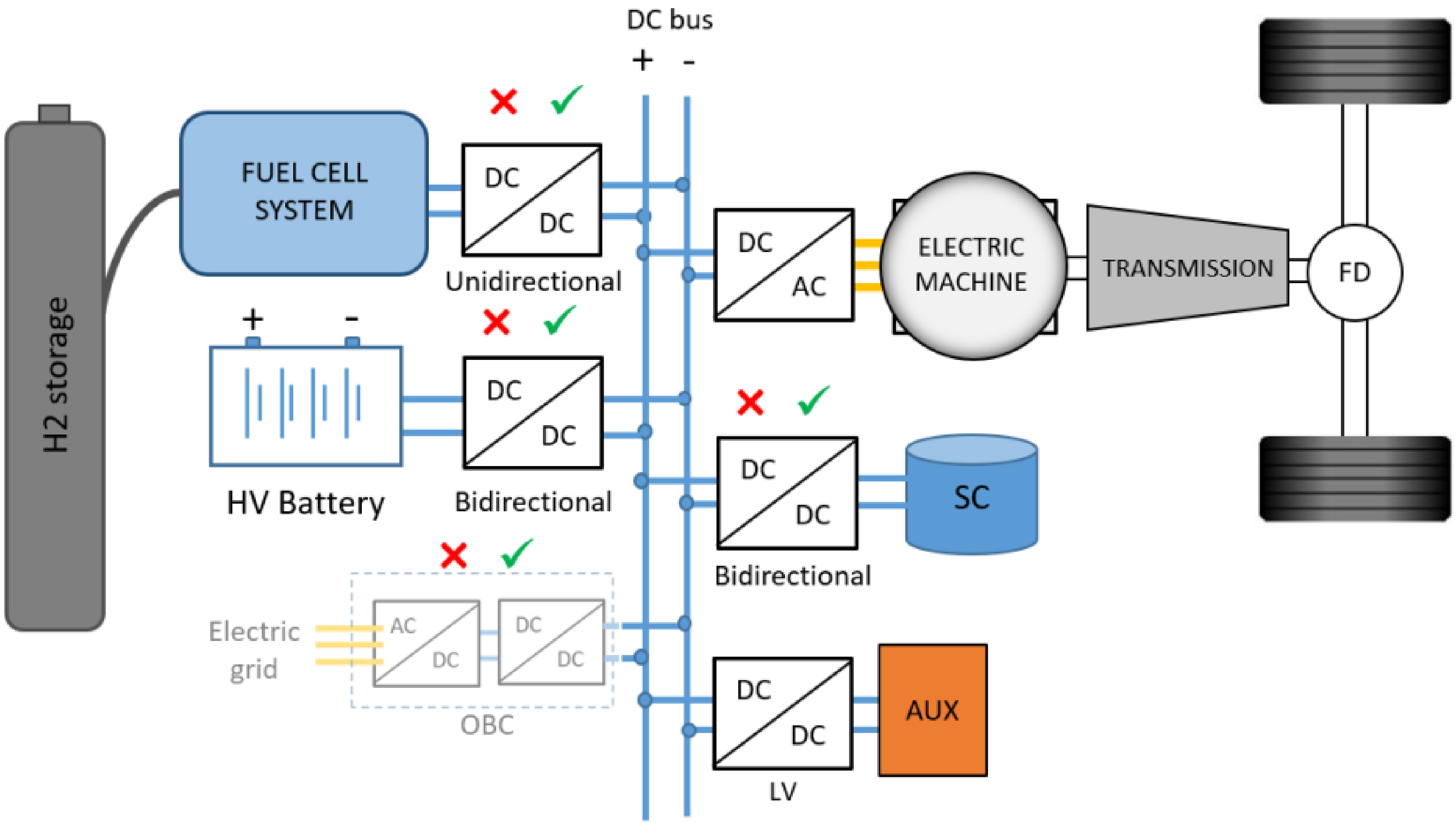
1. Introduction

With the ever-increasing impact of greenhouse gas (GHG) emissions on global warming, the importance of using low-emission transport technologies is gaining momentum all over the world. The growing population in big cities and rising usage of fossil-fuelled vehicles is today a major source of local air pollution and an alarming concern for public health [1]. In Europe, heavy-duty vehicles (HDVs) emit around 25% of its total CO_2 emissions from road transport, contributing to about 5% of all GHG emissions and posing a significant challenge in pollution reduction due to the nature of their usage [2–4]. Among other applications,

[Energies | Free Full-Text | A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Solutions (mdpi.com)](https://www.mdpi.com)

Generic Topology



2022/2023 FCEV HD Overview

Table 1. List of current and upcoming fuel cell electric long-haul heavy-duty vehicle initiatives.

Manufacturer	Initiative	FCS [kW]	eDrive [kW]	Battery Capacity [kWh]	Tank Capacity [kg]	GCW [kg]	Ref.
Hyundai	Xcient	95 × 2	350	73.2	32	36,000	[70]
ESORO (MAN)	Coop logistics	100	250	120	31	34,000	[71–73]
VDL	Medium H2-Share	88	210	84	30	27,000	[56]
VDL	Heavy H2-Share	88	210	72	30	44,000	[57]
IVECO	H2Haul	100 × 2	480	80 × 2	65	42,000	[58]
US Hybrid	Class 8 Drayage	80	320	36	38.56	36,000	[74]
Toyota-Kenworth	Alpha, Beta	226	500	12	40	36,000	[75,76]
Scania-Asko	-	90	290	56	33	27,000	[77]
Cummins	Class 8	90–180	330	100	23.5	36,000	[78]
Nikola motors	Tre	120	480	70	80	40,000	[79]
TransPower BAE	ZECT electric	100	300	100	30	36,000	[62,63]
VDL (DAF)	Waterstofregio 2.0	60	-	-	30	44,000	[2]
AVL	FC4HD	310	540	52	30	42,000	[80,81]
Mercedes-Benz	GenH2	150 × 2	330	70	80-liquid	40,000	[82,83]
VOLVO Trucks	Fuel cell truck	150 × 2	-	-	-	65,000	[84]
CATHYOPE	Camion 44 tonnes	170	390	-	46	44,000	[85]
DAF	REVIVE E-trucks	30–80	210	150	15–38	26,000	[64,65]
Scania	REVIVE Renova	30–80	210	150	15–38	26,000	[64,65]
Mercedes FAUN	HECTOR ENGINIUS	30 × 3	-	85	16.4 at 700 bar	-	[86,87]
Mercedes SEMAT	HECTOR	30 × 2	-	85–112	20 at 700 bar	-	[86,88]
Coachyfied	Bus demonstrator	-	-	-	-	19,500	[89,90]
Renault SYMBIO	Maxity H2	20	47	42	4	4500	[54]
Mitsubishi	150e Canter	75	135	-	10	7500	[91]
UPS Hydrogenics	Class 6	31	-	45	10	12,000	[92]
Caetano Toyota	H2 city gold bus	60	180	44	37.5	-	[59]
Solaris Ballard	Urbino 12 H2 bus	70	125 × 2	30	37.5	-	[60]
VDL	GIANTLEAP city bus	60	160	216	30	18,745	[61]
Rampini	Hydrogen Ale bus	16	-	80-90	35	-	[93]
Safra	HyCity	45	125 × 2	130	35	21,000	[94]
Van Hool	A330 fuel cell bus	120	85 × 2	53	50	16,000	[95]
TATA	Starbus fuel cell	85	186	-	14.5	-	[96]
Mercedes eCitaro	Range extender bus	60	250	243	35	20,000	[97]

Energy Expenditures

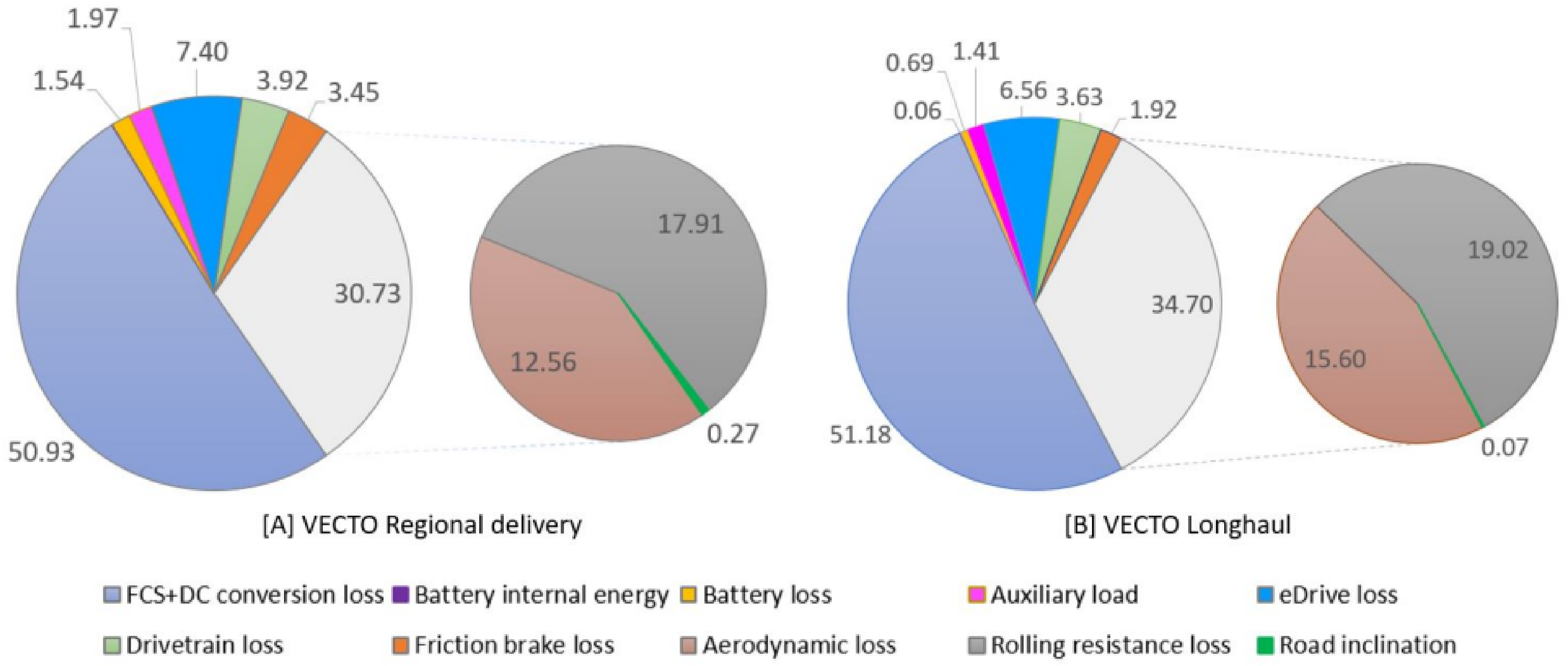


Figure 4. Percentage distribution of H_2 fuel energy expenditures and losses among different powertrain subsystems and driving resistances for 40-tonne fuel cell truck running on (**A**) VECTO Regional Delivery and (**B**) Longhaul drive cycles.

Regional Delivery Cycle

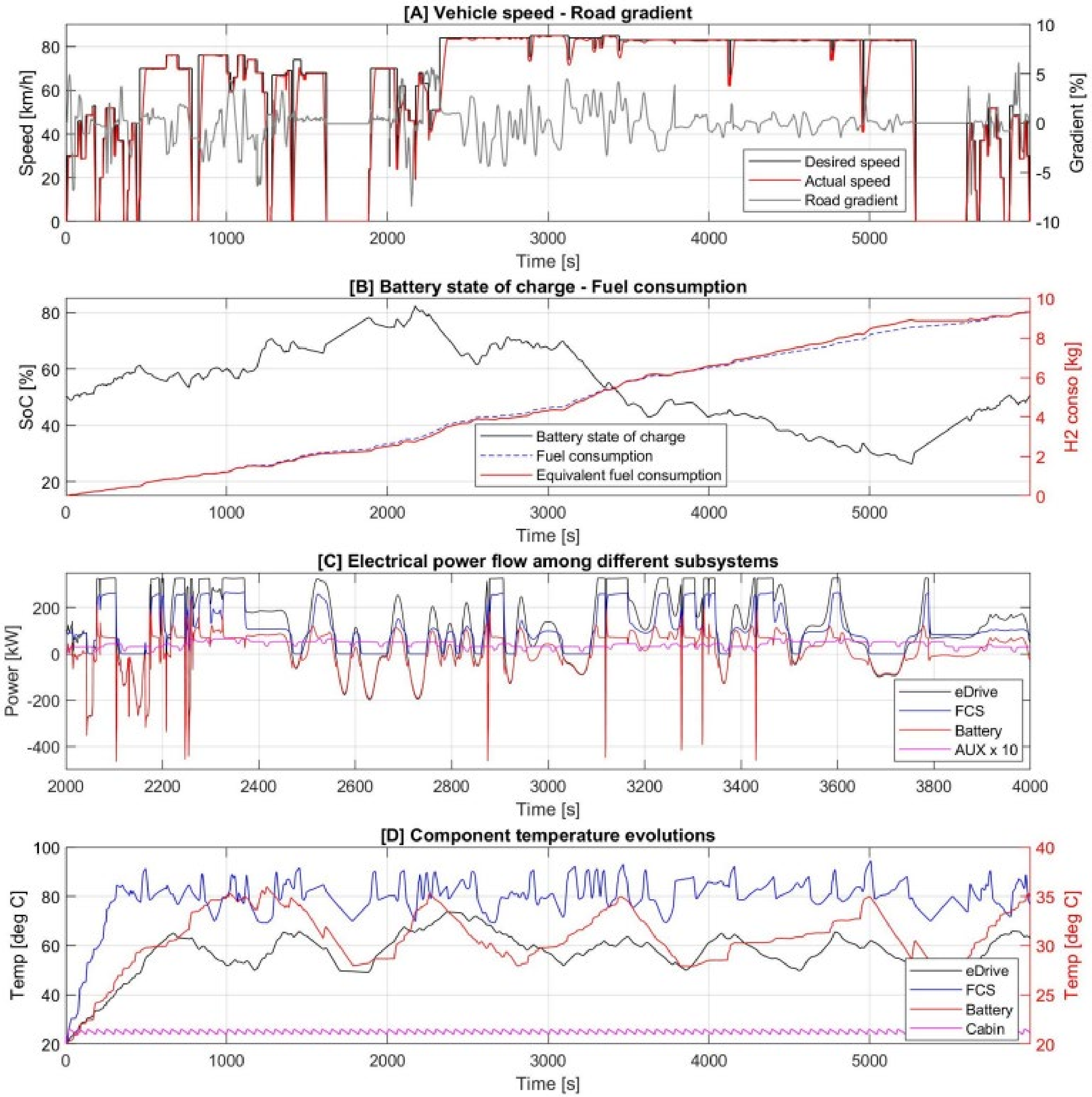


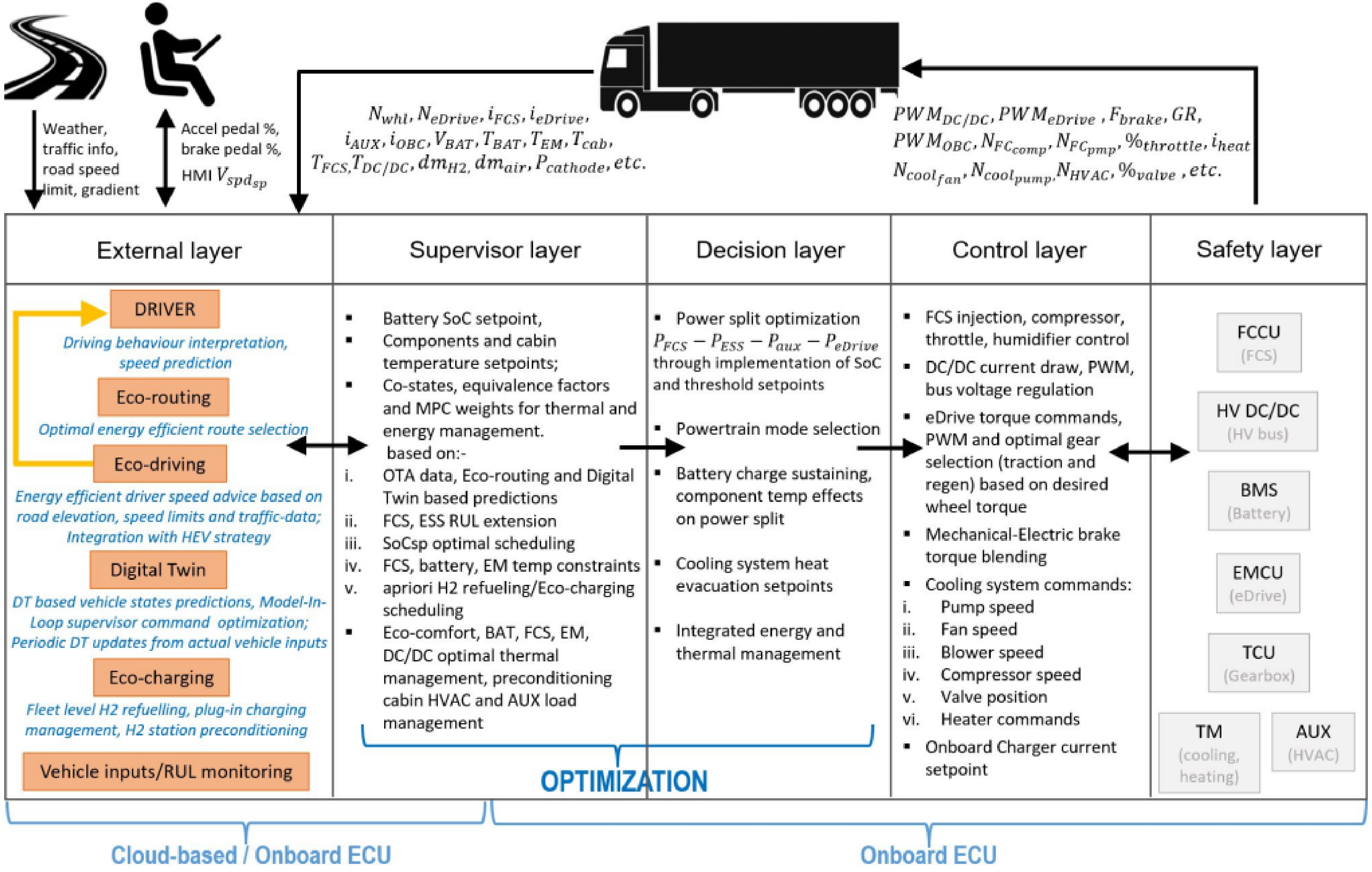
Figure 5. Simulation results for HD FCEV truck running on VECTO Regional delivery cycle: (**A**) distance based desired and actual vehicle speed, road gradient; (**B**) battery state of charge, cumulative and equivalent H_2 fuel consumption; (**C**) electrical power flow among FCS, HV battery, eDrive and auxiliary load governed by the ECMS strategy; and (**D**) component temperature evolution.

Table 4. Average operating efficiencies of various powertrain components from simulation of the 40-tonne fuel cell truck use case running on VECTO Regional delivery and Longhaul cycles.

Subsystem	Average Operating Efficiency: Regional Delivery [%]	Average Operating Efficiency: Longhaul [%]
FCS + DC/DC	49.1	48.8
HV battery	95.2	95.6
eDrive	89.3	88.7
Transmission + Differential	93.9	93.1

Implemented control strategy ECMS –
Equivalent Consumption Minimisation Schedule

Multi-Level Optimisation



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Electromechanics & Power Electronics

Summary

We covered:

- Fuel Cell Context
- Example Applications
- Fuel Cell Basics
- Fuel Cell Modelling
- Fuel Cell Systems
- Hydrogen Storage
- Example

Questions