@HydexMidlands
@EnergyRA

Accelerating the new hydrogen economy in the Midlands

Hydrogen Summer School

Day 3:

University of Birmingham

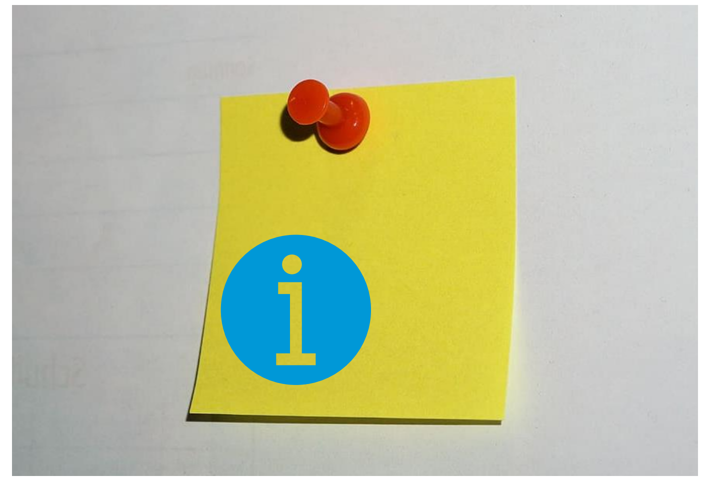
11th September 2024

Funded by UKRI Research England

Lead academic partners ERA Energy Research Accelerator Keele University Midlands Innovation

Housekeeping

- Fire Alarm
- Fire Exits and Assembly Point
- Toilets
- Mobile phones
  Please put on silent, if you need to take or make a call, please leave the room.
- Questions
  You will have the opportunity to ask questions between presentations and throughout the day.



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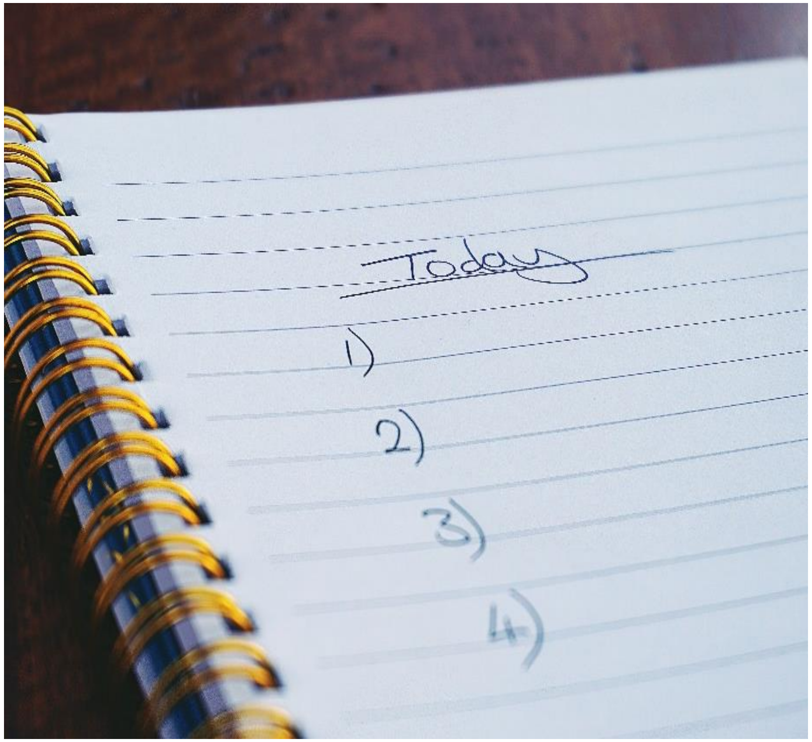
Agenda

Morning:

- Welcome & Fuel cells for transport applications and hydrogen fuel – Dr Yousif Al-Sagheer
- Fuel cell seminars x2 – Dr Hadi Heidary, Dr Bernardo Sarruf, Dr Kun Zhang
- Hydrogen production via biomass conversion, Dr Paula Blanco-Sanchez (Aston University)
- Hydrogen-based fuels – Dr Artur Majewski

Afternoon:

- Tyseley Energy Park visit and tour
- Networking and Q&A



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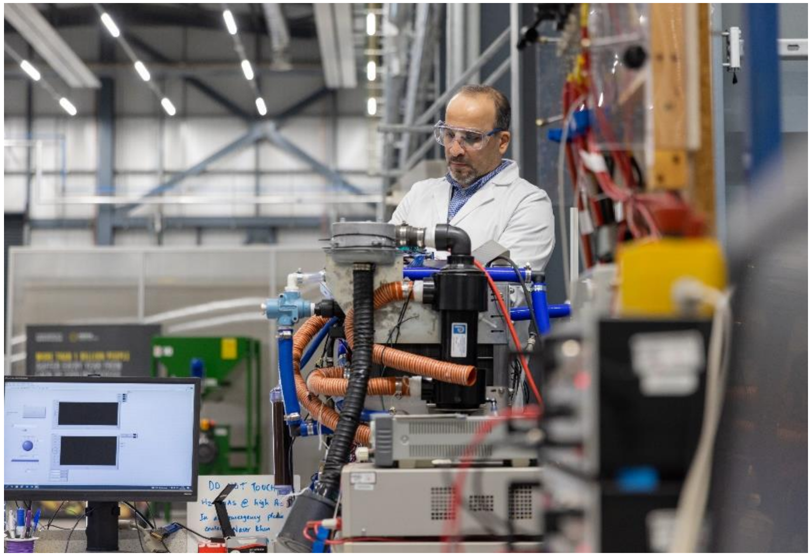
Keele UNIVERSITY

MIDLANDS INNOVATION

Welcome to University of Birmingham

- School of Chemical Engineering
- Fuel Cells and Hydrogen Research Centre
- Birmingham Energy Innovation Centre (BEIC)
- Key partner university in HyDEX Project
- Hydrogen demonstrator facilities at Tyseley Energy Park
- Research and innovation in waste, energy and low carbon vehicle systems



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HyDEX

Dr Yousif Al-Sagheer

Fuel cells for transport applications

Fuel Cells and Hydrogen Research Centre

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Fuel cells for transport applications

- Fuel cell principle
- Fuel cell system
- Hydrogen production shades
- Decarbonising transport
- Fuel cell vehicles
- Fuel cell hybrid EV
- Off-road Vehicle: Fuel cell tractor
- Fuel cell in maritime applications

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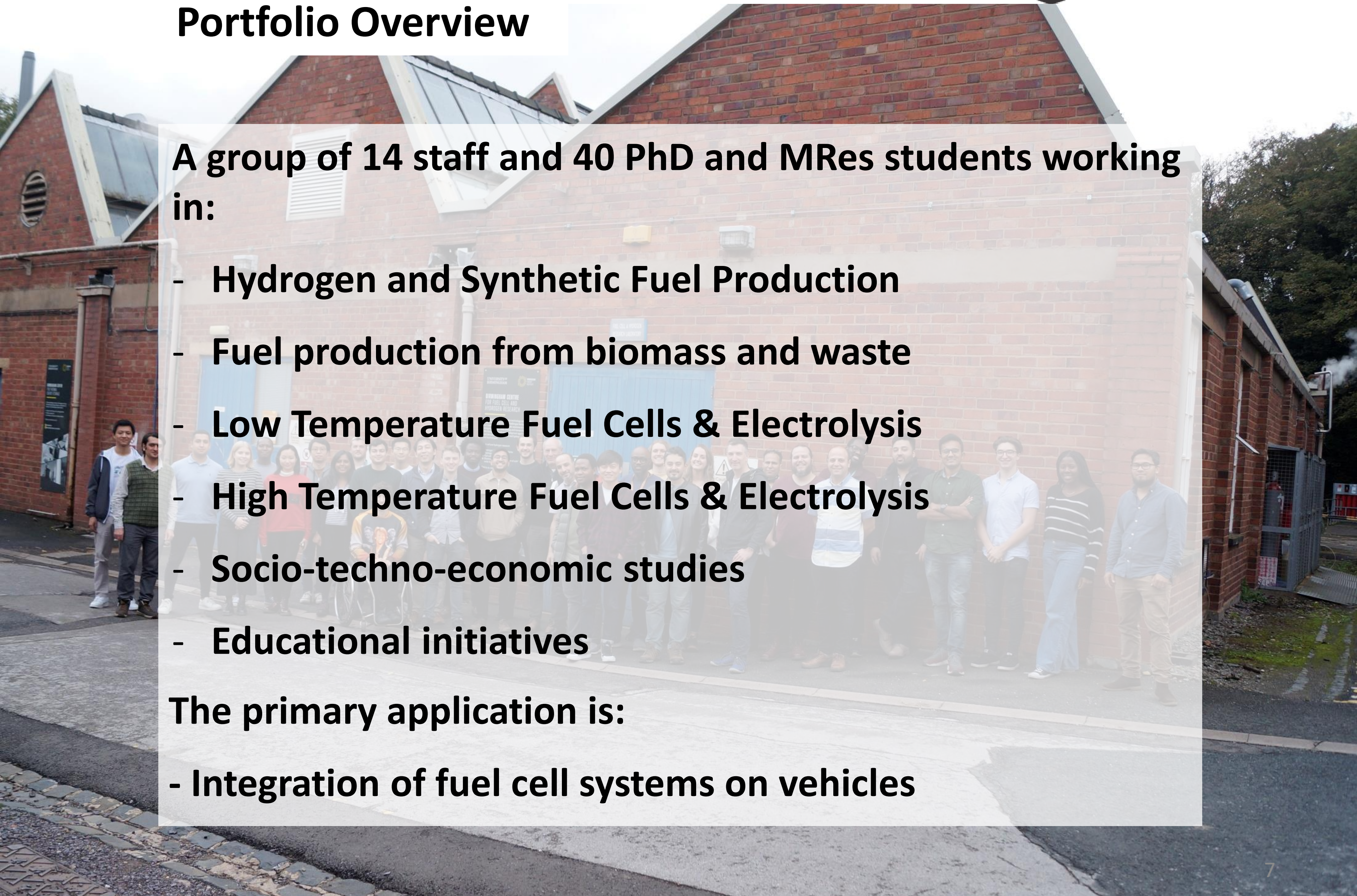
Portfolio Overview



A group of 14 staff and 40 PhD and MRes students working in:

- **Hydrogen and Synthetic Fuel Production**
- **Fuel production from biomass and waste**
- **Low Temperature Fuel Cells & Electrolysis**
- **High Temperature Fuel Cells & Electrolysis**
- **Socio-techno-economic studies**
- **Educational initiatives**

The primary application is:

- Integration of fuel cell systems on vehicles

Research Infrastructure

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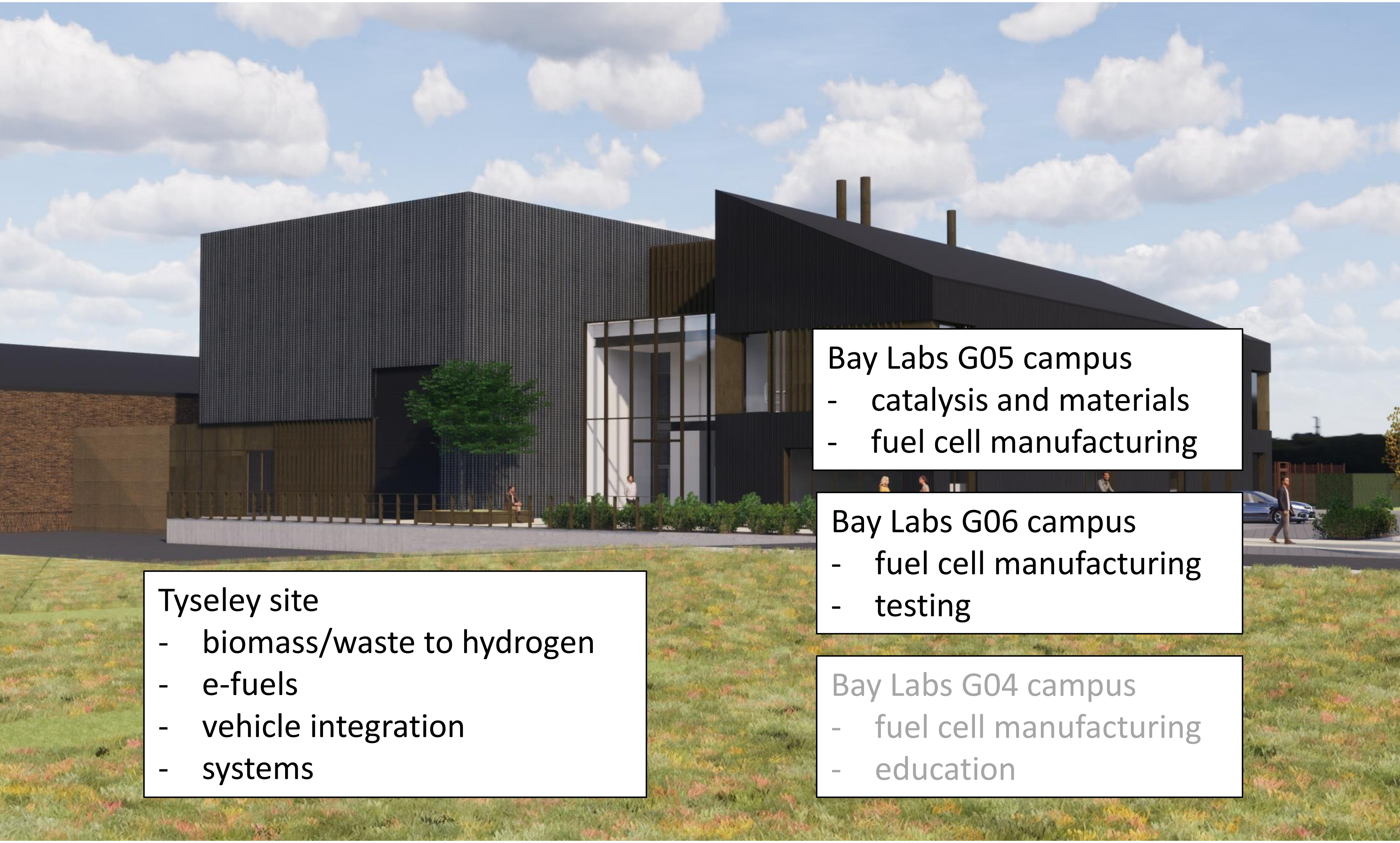


Bay Labs G05 campus
- catalysis and materials
- fuel cell manufacturing

Bay Labs G06 campus
- fuel cell manufacturing
- testing

Tyseley site
- biomass/waste to hydrogen
- e-fuels
- vehicle integration
- systems

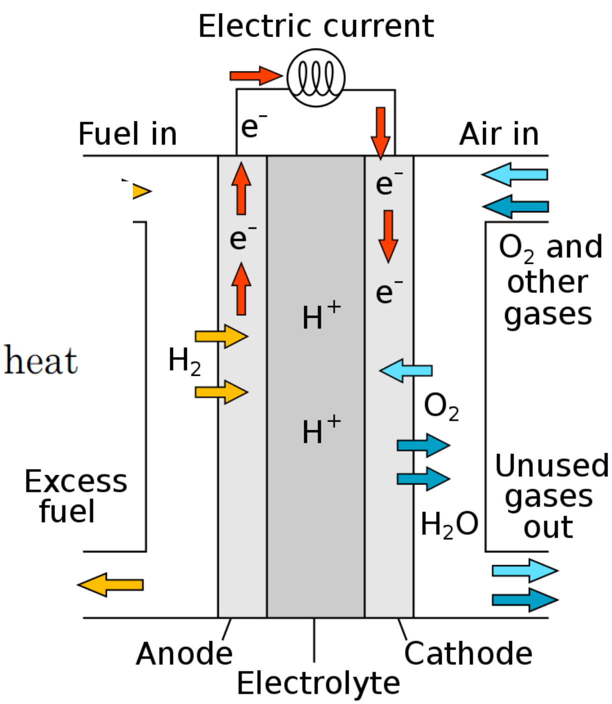
Bay Labs G04 campus
- fuel cell manufacturing
- education

Fuel cell principle / PEM Fuel Cells

Anode: $H_2\,(g) \rightarrow 2H^+\,(aq) + 2e^-$

Cathode: $\tfrac{1}{2}O_2\,(g) + 2H^+\,(aq) + 2e^- \rightarrow H_2O\,(l)$

Overall: $H_2\,(g) + \tfrac{1}{2}O_2\,(g) \rightarrow H_2O\,(l)$ + electric energy + waste heat

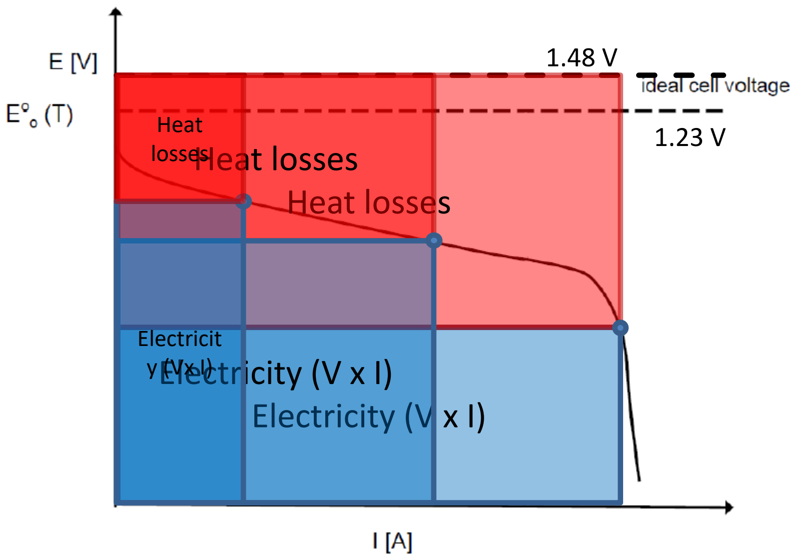


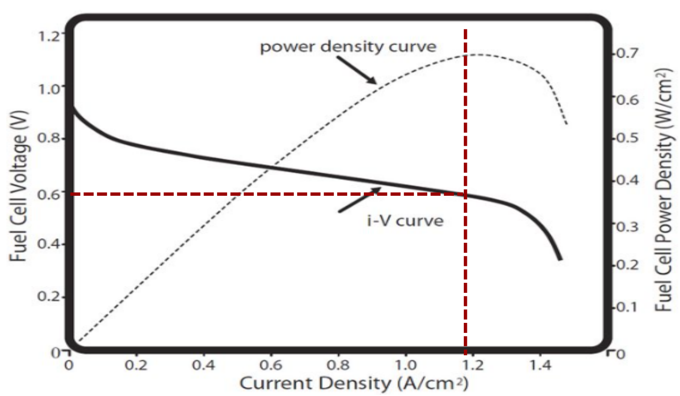
$$H_2 \text{ usage} = \frac{In}{2F} \text{ moles s}^{-1}$$

$$O_2 \text{ usage} = \frac{In}{4F} \text{ moles s}^{-1}$$

$$E = \frac{-\Delta \bar{g}_f}{2F}$$

Fuel cell polarisation / I-V curve





$$E = \frac{-\Delta \bar{g}_f}{2F}$$

$$\text{Efficiency} = \frac{\text{FC electrical power } (V \times I)}{\text{H2 enery input } (E \times I)}$$

$$\text{Efficiency} = \frac{V}{E}$$

$$\text{Efficiency} = \frac{V}{1.23} \qquad \text{w.r.t} \quad \text{LHV}$$

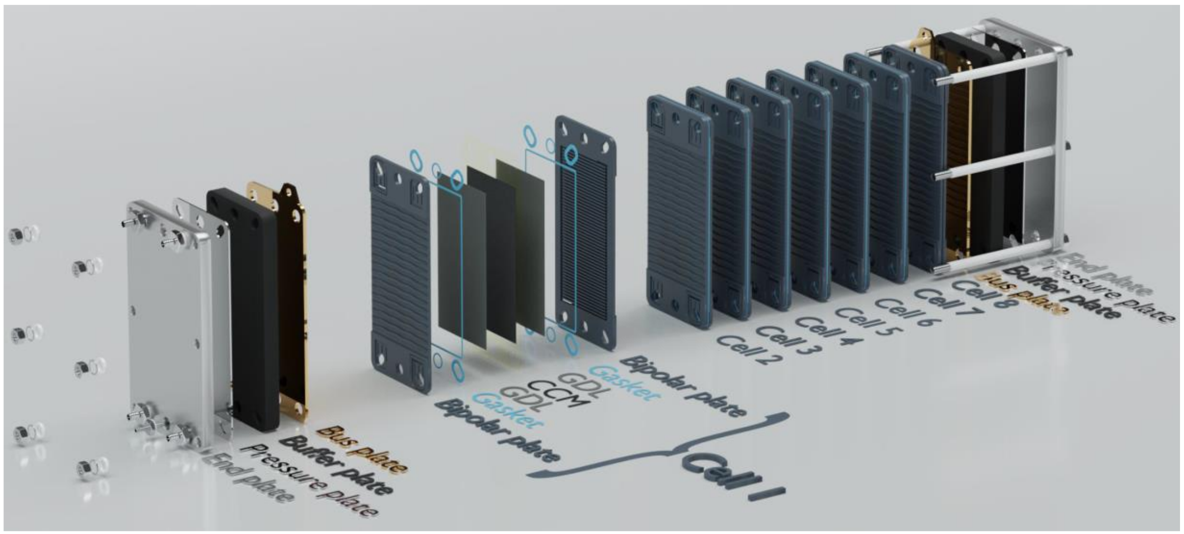
if the water product was in vapour form

$$\text{Efficiency} = \frac{V}{1.48} \qquad \text{w.r.t} \quad \text{HHV}$$

if the water product was in liquid form

$$\text{Efficiency} = \frac{0.6}{1.23} = 49\% \qquad \text{w.r.t} \quad \text{LHV}$$

PEFC Stack Design

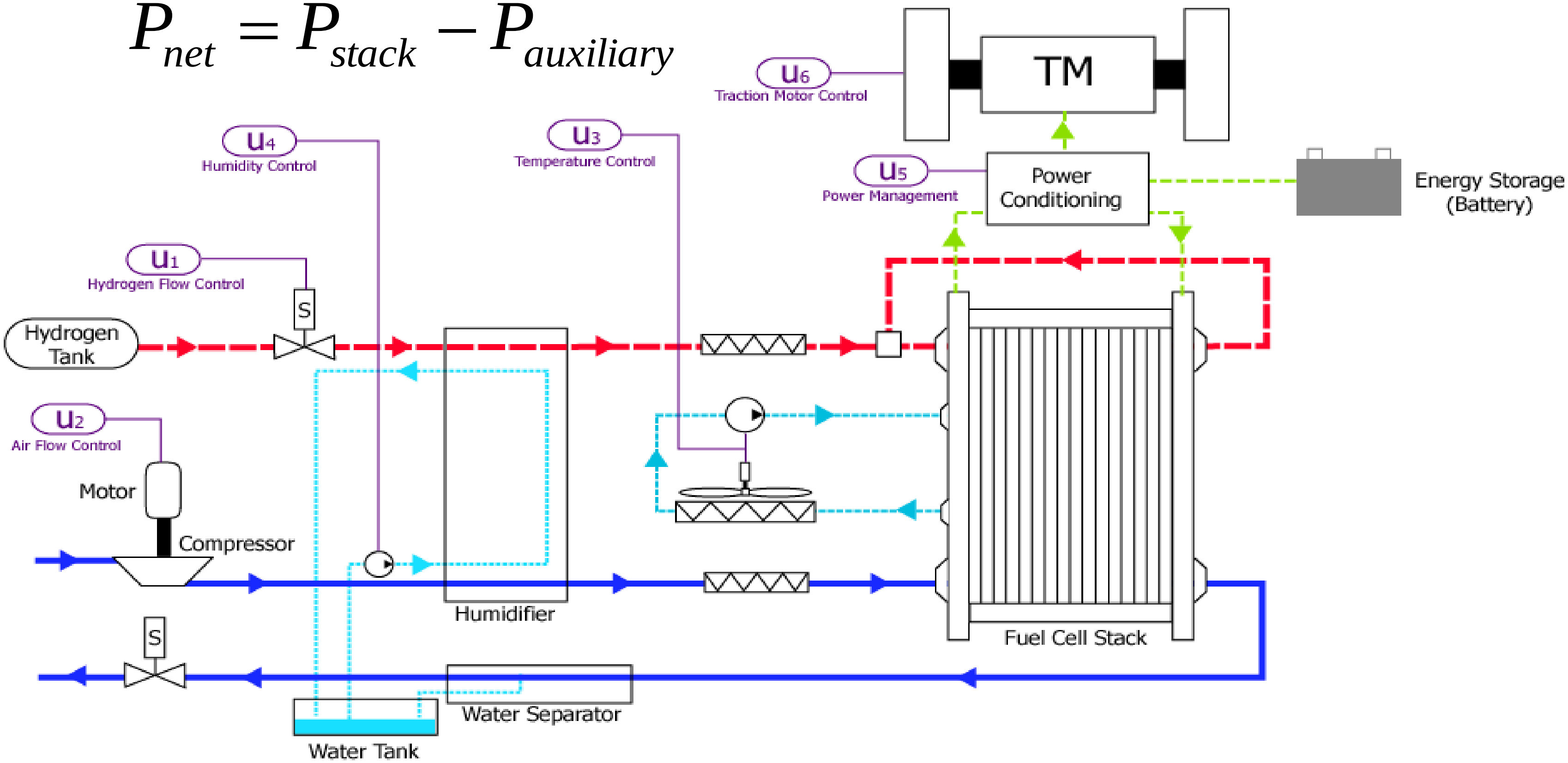


- Number of cells
  - nominal stack voltage
  - OCV voltage (max)
- Cell area
  - Current density
  - Stack current

Fuel Cell System

Power Management Subsystem

$$P_{net} = P_{stack} - P_{auxiliary}$$

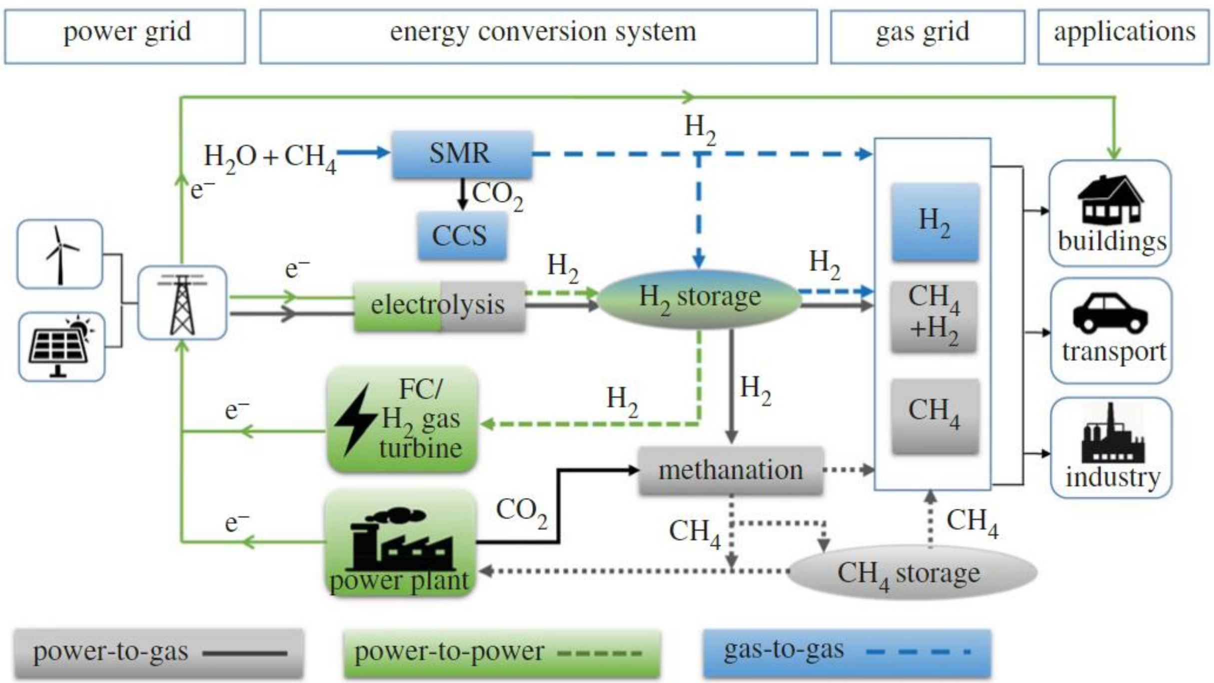


Source: Stephanopoulos

Why Hydrogen?

The role of H2 in clean energy future

- Highest gravimetric energy density 33.6 kWh/kg (LHV)
- No emission at the point of use
- Issue: Low volumetric energy density
- Energy vector
- Interlink multi energy sectors



Clean energy and the hydrogen economy

Different shades of Hydrogen

Colors	Black Hydrogen	Grey Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Yellow Hydrogen	Pink Hydrogen	Green Hydrogen
Process	Gasification	SMR	SMR or gasification with carbon capture (85-95%)	Pyrolisis	Sulfur–iodine cycle Electrolysis	Electrolysis	Electrolysis
Source	Coal	Methane	Methane or coal	Methane	Nuclear power Grid electricity	Nuclear power	Renewable Energy

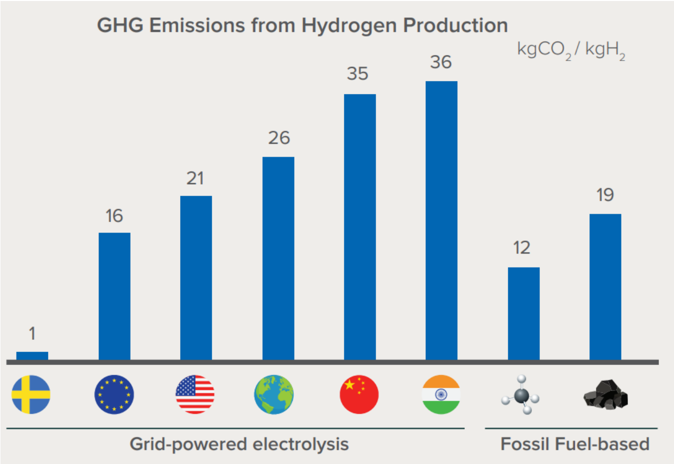
Brown
Gasification

fossil fuel

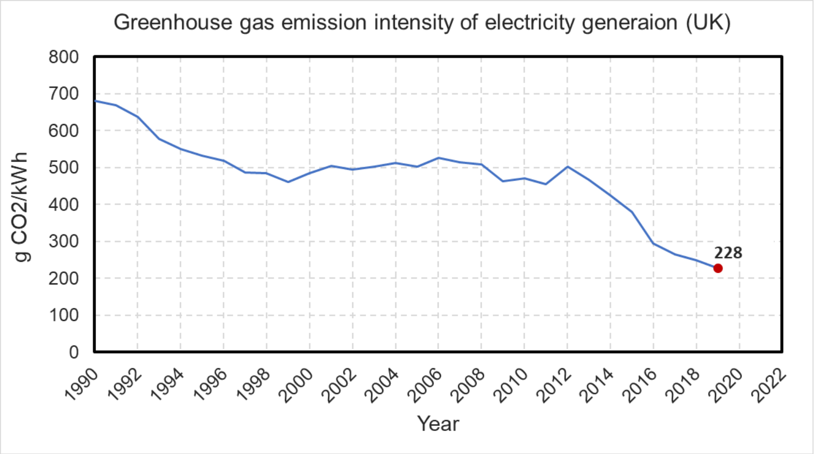
White
H2 as a by-product of industrial processes
OR
H2 naturally occurring underground

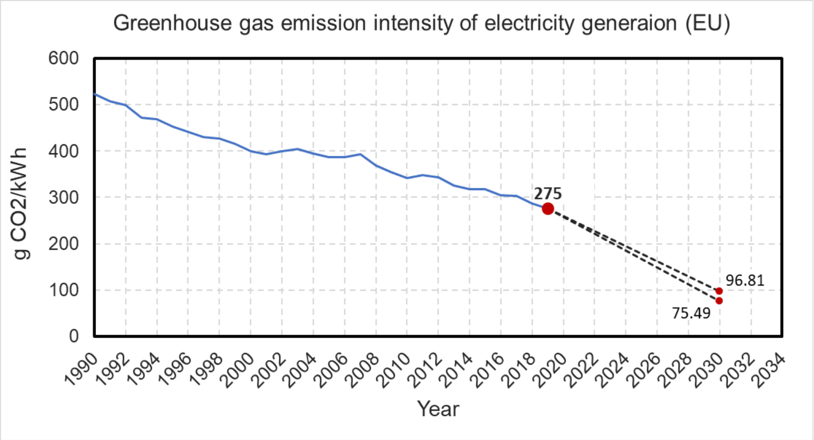
Carbon footprint per kWh (Grid electricity)

- Compare to Steam Methane Reforming (SMR)
  - SMR: 8-12 kg CO_2/ kg of H_2
- Electrolysis: 39.4 kWh/kg HHV with 70% eff.
  - ~ 56 kWh/kg H_2
- EU grid (average): ~15.4 kg CO_2/ kg of H_2
- UK grid: 12.8 kg CO_2/ kg of H_2



Hydrogen's Decarbonization Impact for Industry

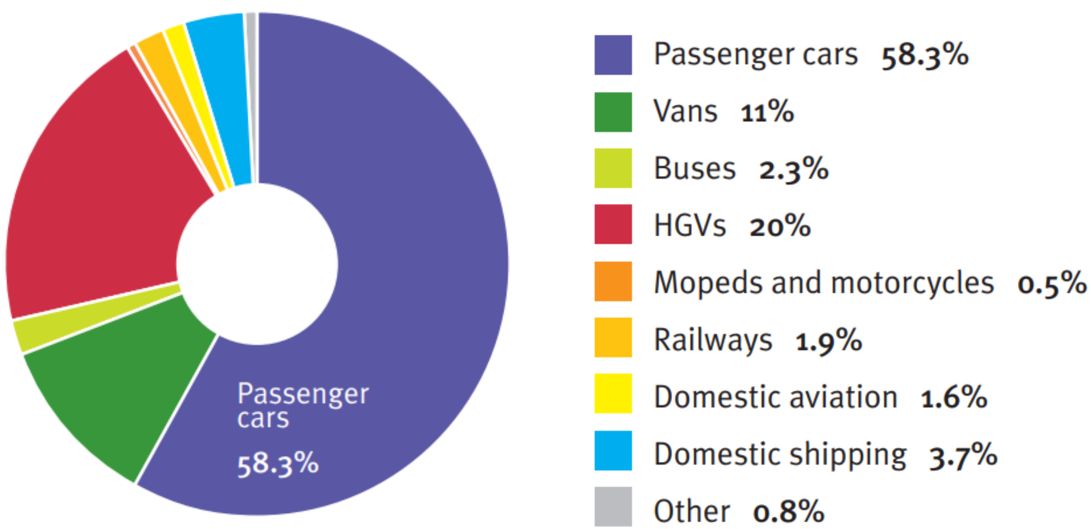




European Environment Agency

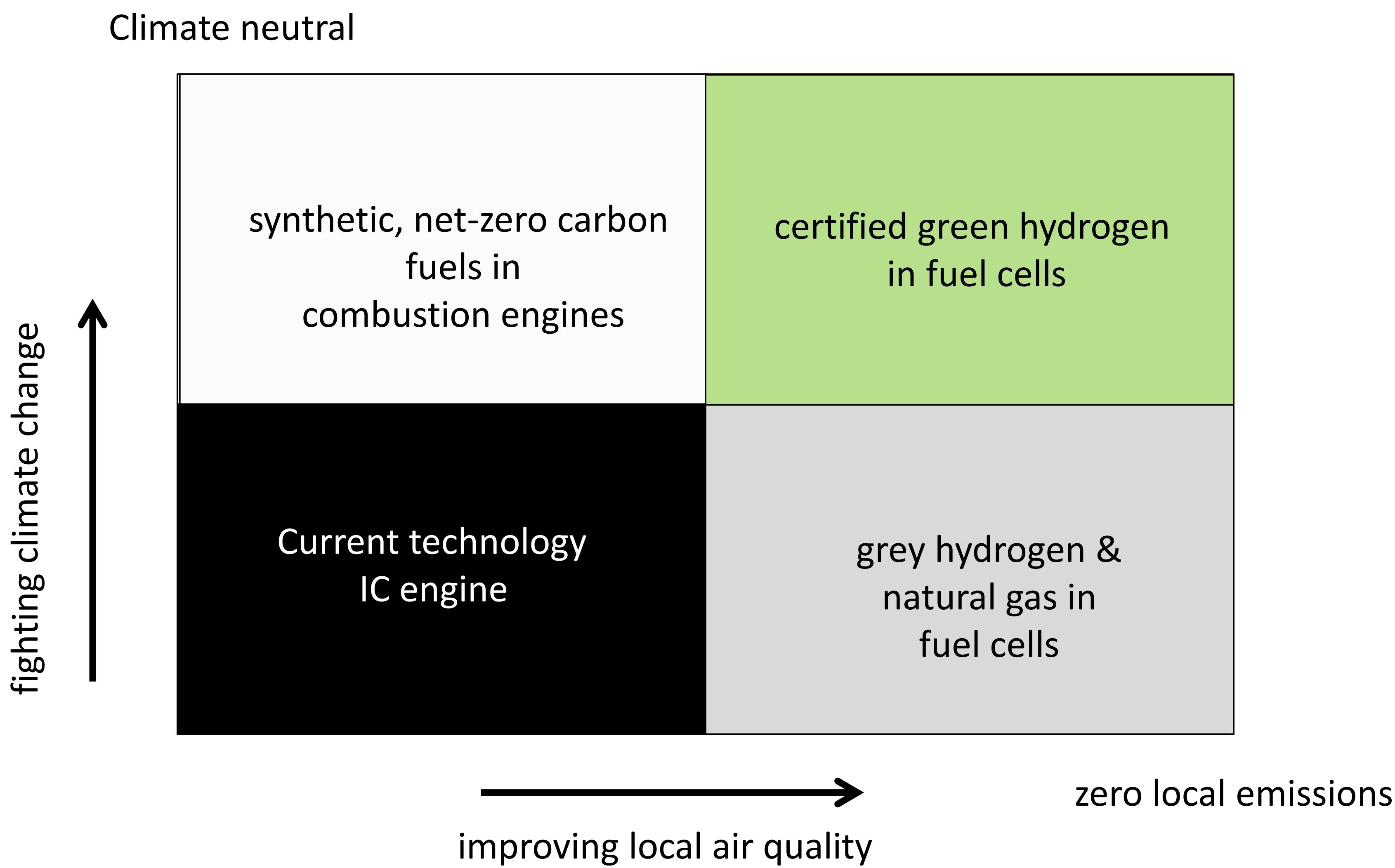
Decarbonising Transport ?

- Greenhouse Gas (GHG) emissions reduction
  - Emissions need to be reduced by 50-60% by 2050.
  - 27% of global CO_2 emissions are from the transport sector
  - For UK, 92% of total transport emissions is from domestic transport.
  - Globally, 73% of transport related CO_2 emissions are from road transport

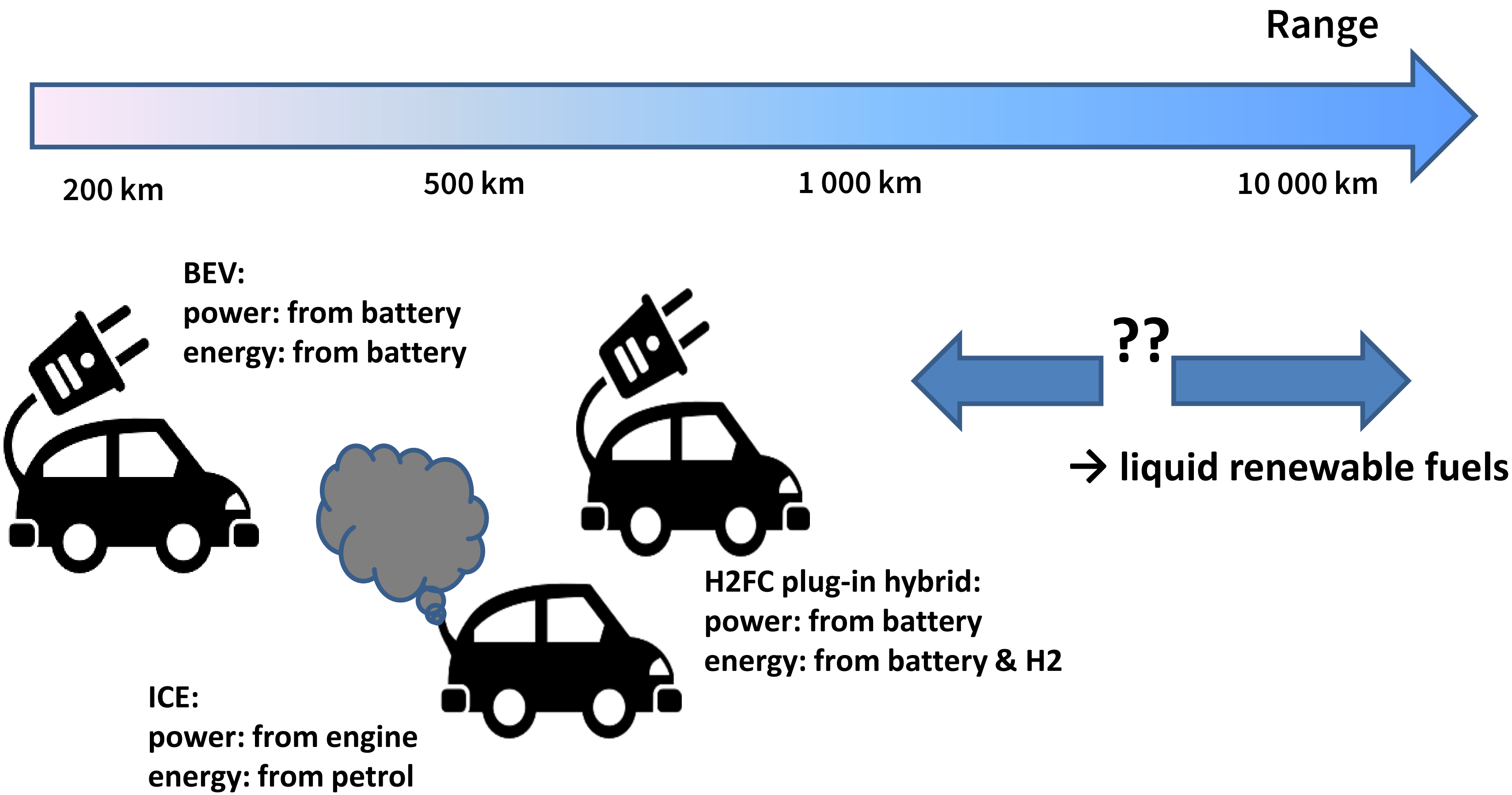


UK domestic transport GHG emissions 2009 excluding travel across borders / Grantham Institute

Global vs. Local Zero Emissions

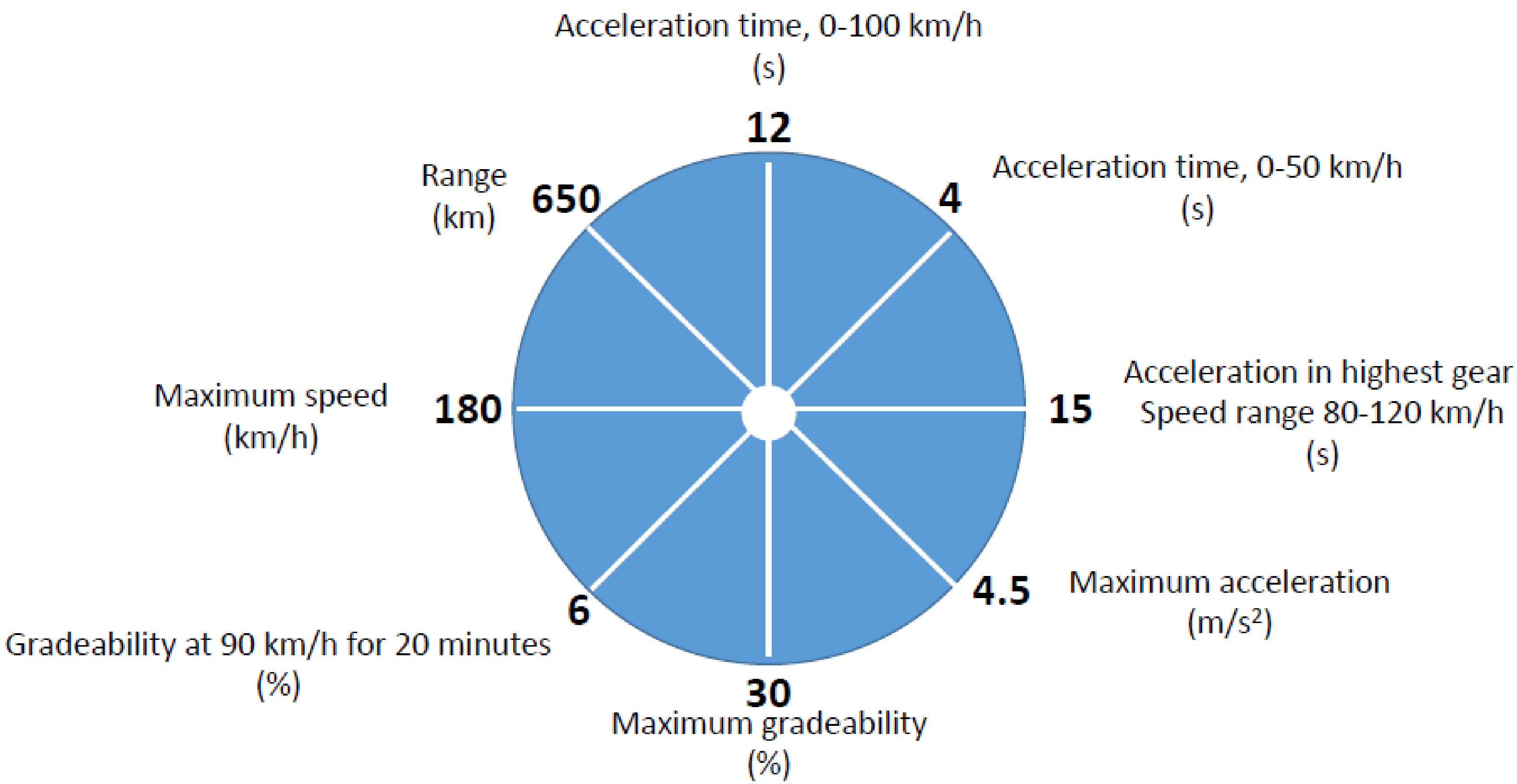


Electric Transport Solutions



Fuel Cell Vehicles

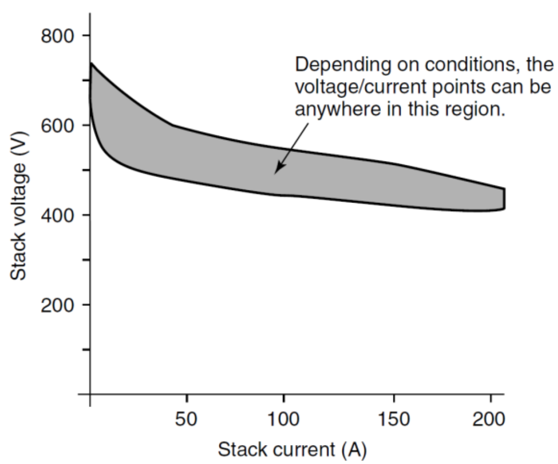
Passenger Vehicle:
Minimal customer performance criteria



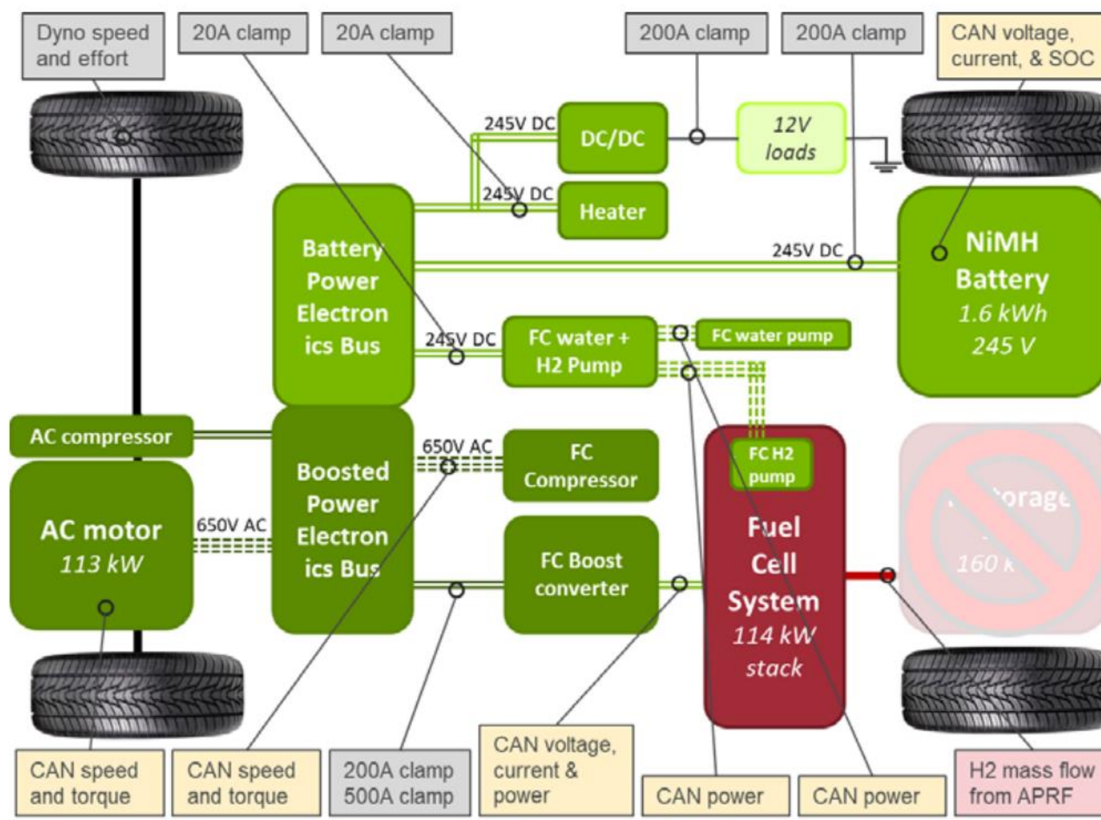
Fuel cell drivetrain

- FC System:
  - Solid polymer electrolyte
  - 370 cells in stack
  - 114 kW, 3.1 kW/L, 2.0 kW/kg

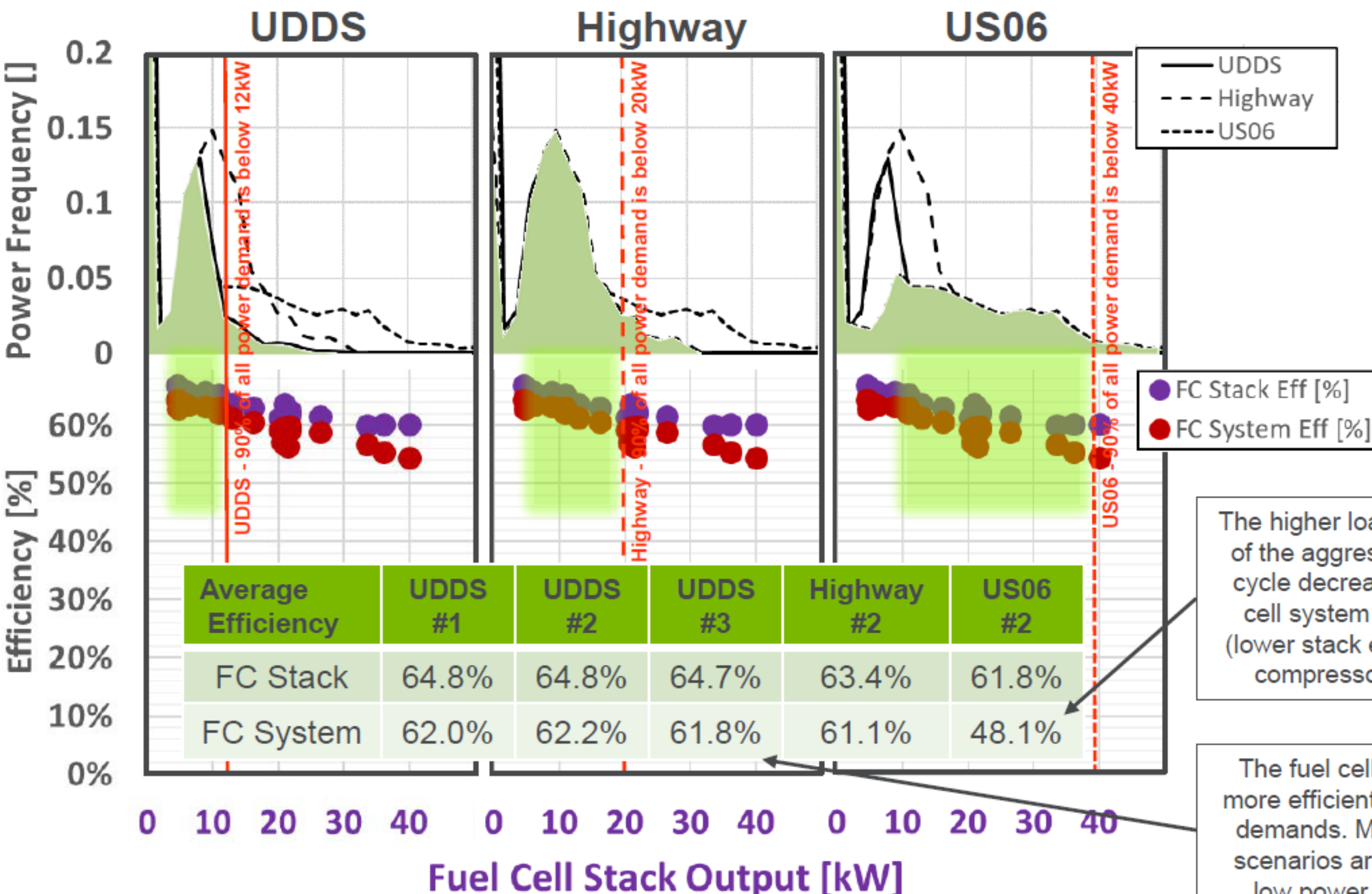
- Battery:
  - Nickel-metal hydride
  - 1.6 kWh, 245 V DC
  - 34 cells
  - Capacity 6.5 Ah



Toyota Mirai FCV electric system (gen. 1)



Energy management - FC vehicles



Average Efficiency	UDDS #1	UDDS #2	UDDS #3	Highway #2	US06 #2
FC Stack	64.8%	64.8%	64.7%	63.4%	61.8%
FC System	62.0%	62.2%	61.8%	61.1%	48.1%

The higher load demands of the aggressive US06 cycle decrease the fuel cell system efficiency (lower stack eff and high compressor power)

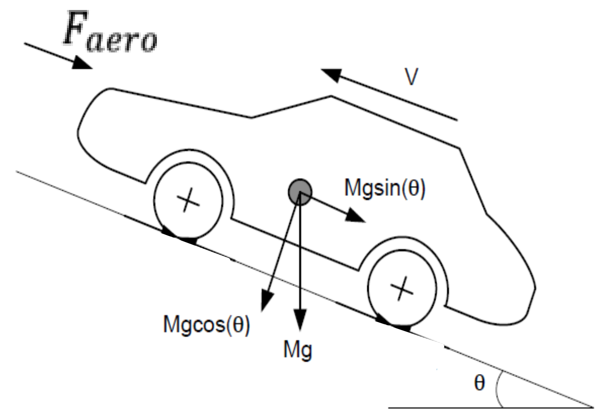
The fuel cell system is more efficient at low load demands. Most driving scenarios are relatively low power demand.

Toyota Mirai Tech. Assess. Report
Argonne National Lab

Vehicle Force Analysis

The motion of the vehicle is opposed by a number of forces (resistances):

$$\boldsymbol{F} = \boldsymbol{F_{aero}} + \boldsymbol{F_{grade}} + \boldsymbol{F_{rr}} + \boldsymbol{F_i}$$



Air drag (aerodynamic) resistance: $F_{aero} = \frac{1}{2}\, \rho\, C_d\, A_f\, v^2$

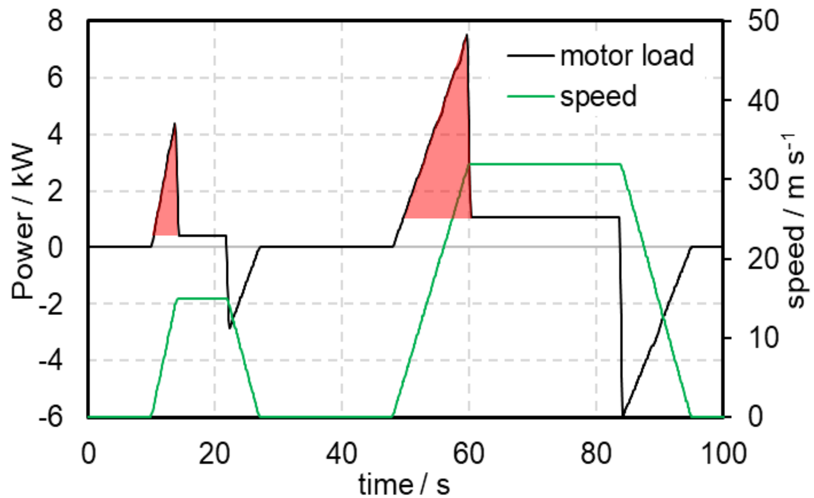
Road gradient resistance: $F_{grade} = m\, g\, sin(\theta)$

Rolling resistance: $F_{rr} = m\, g\, C_{rr}\, cos(\theta)$

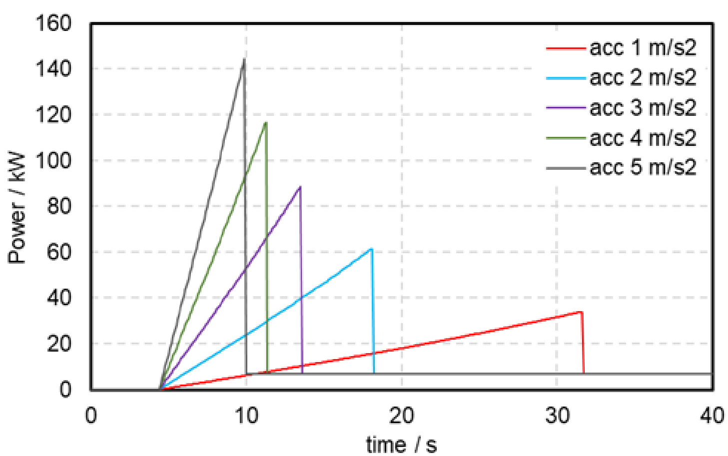
Acceleration force: $F_i = m\, a$

C_d is the drag coefficient
A_f is the cross-section area of the car
ρ is the air density
v is the car speed
g is the gravity acceleration (9.8 m/s^2)
m is the mass of the car
a is the acceleration of the car
C_{rr} is the rolling friction coefficient
θ is the angle between the horizontal plane and the road

Drive Cycle Analysis

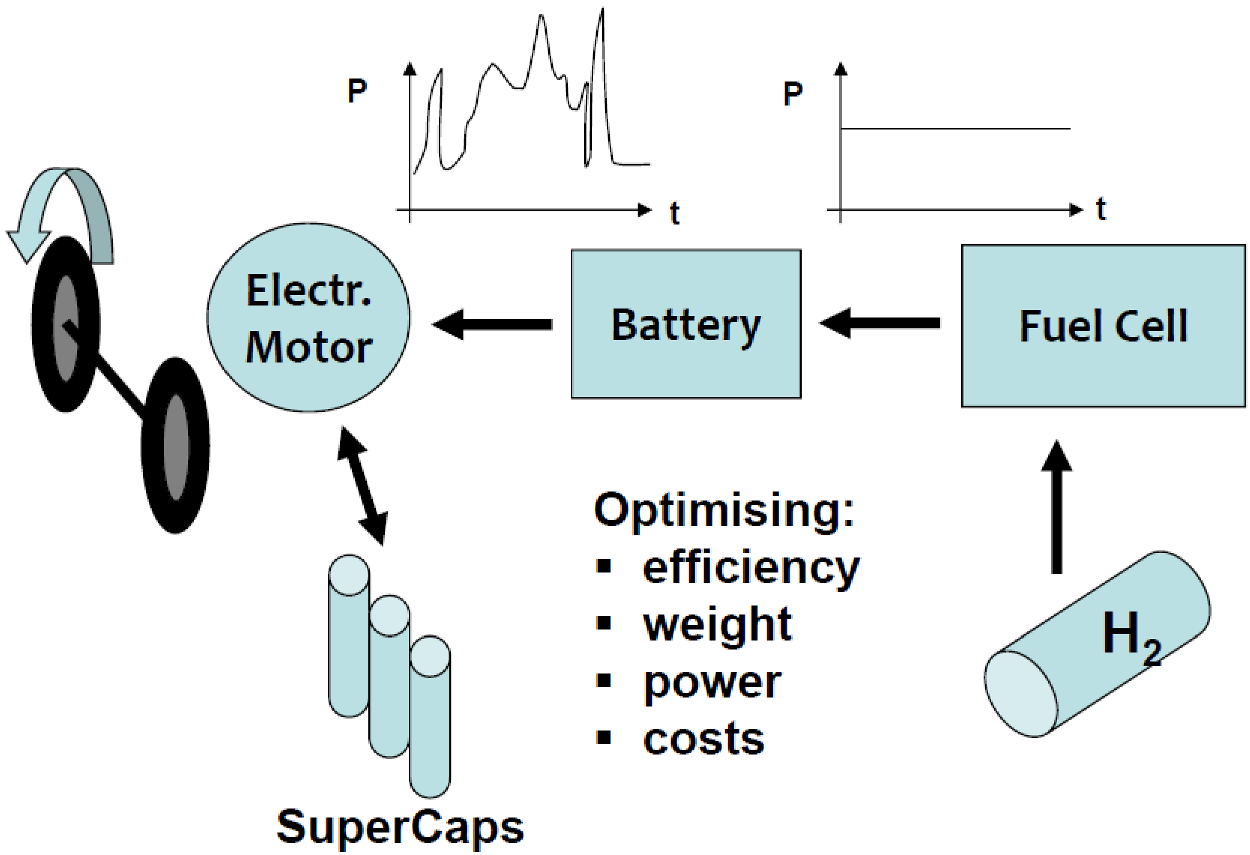


- At constant speed, acceleration is zero ➔ $F_i = 0$
- Acceleration power demand represents a substantial amount of the vehicle's power requirement

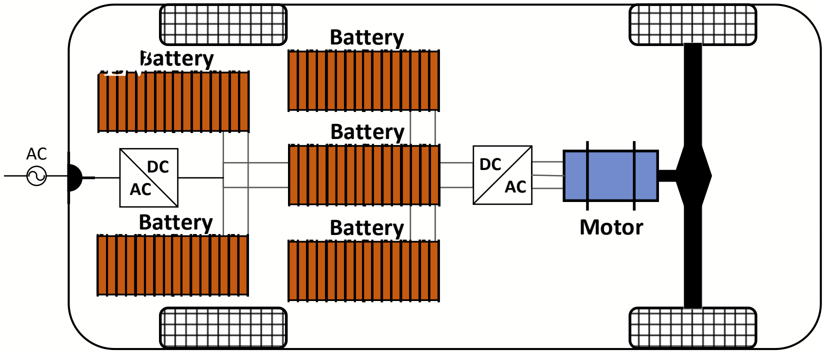


- Driving style has a significant impact on the vehicle's power demand
- **Hybridising** can improve performance and efficiency

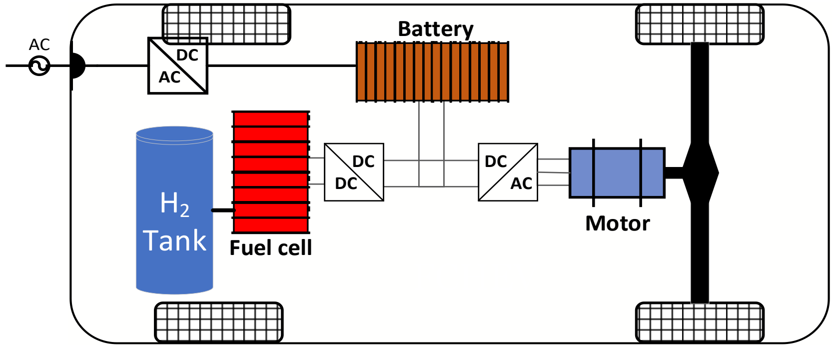
Hybridising



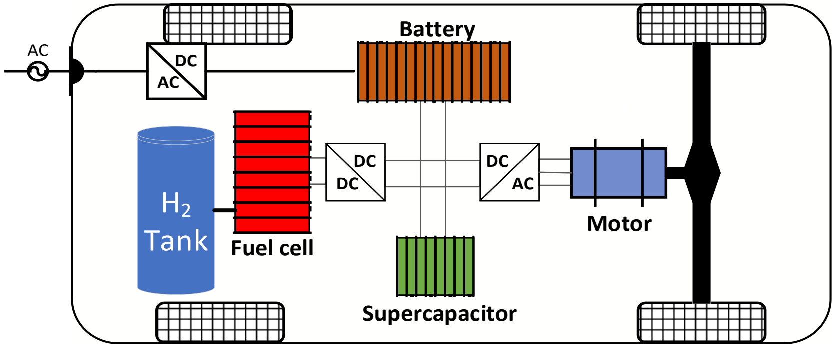
Hybridising



BEV



FCHEV



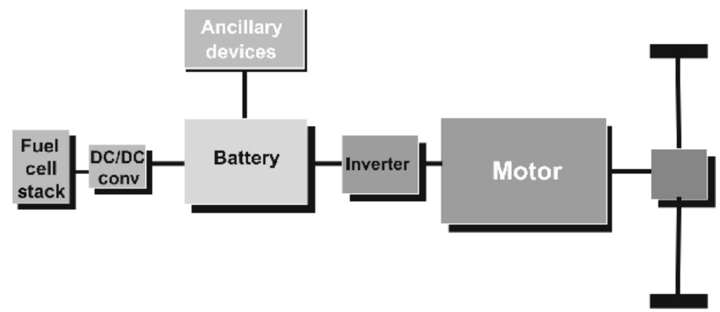
Plug-in option:

- Reduce frequent refuelling.
- Mitigate the need for expanding H2 fuelling infrastructure

Series and Parallel FCHEV

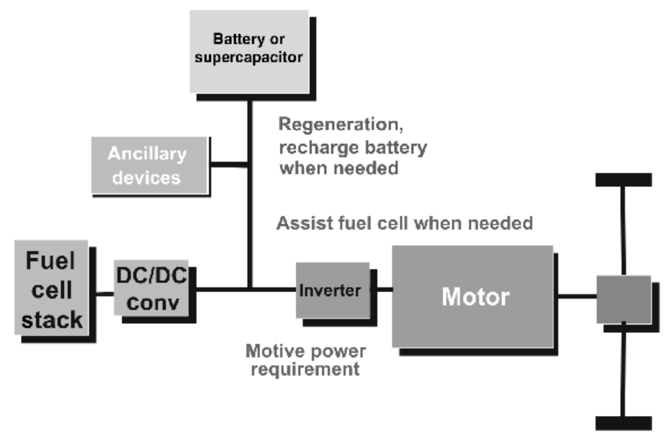
Series Hybrid:

- Small fuel cell, large battery bank
- Battery drives motor at all times
- Fuel cell operates continuously and keeps battery charged
- Fuel cell is not "load-following"



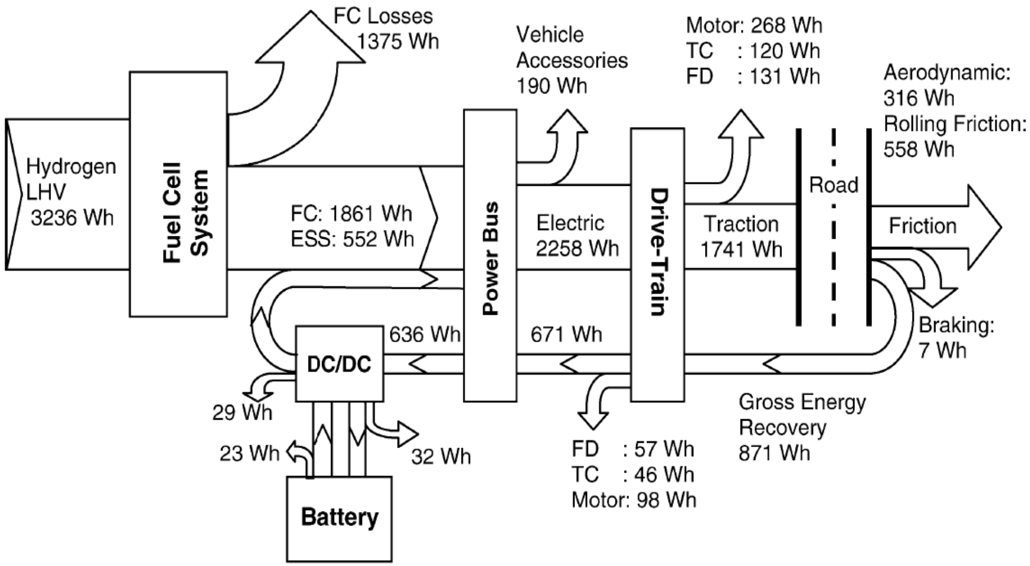
Parallel Hybrid:

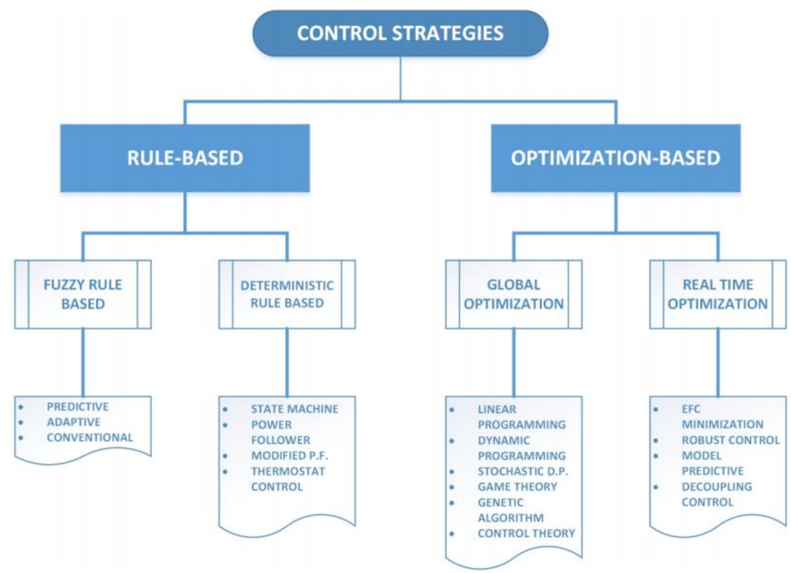
- Large fuel cell, small battery bank
- Fuel cell drives motor most of the time "load-following"
- Battery provides boost power when required



Power Flow Management

Energy Flow within FCHEV drivetrain





Source: R.K. Ahluwalia

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Off-road Vehicles

Agriculture machinery

Allis-Chalmers Fuel Cell Tractor 1959

Amogy's "ammonia to power" zero-emissions tractor.

Harvesters

Off-road Vehicle: Fuel Cell Tractor

Differences between heavy goods and off-road vehicles

	HGV (trucks)	Off road vehicle
Working Speed	60 (miles/hr)	5 (miles/hr)
Cooling	Ram Air	Fan Power
Intake Air	Clean	Variable
Work Surface	Pavement	Dirt
Refill	At Station	At Machine
Usage	Continuous	Seasonal
Transient Demand	Medium	High
Off-Level	Minor	Substantial
Vibration	Mild	Severe
Environment	Clean	Debris

(i) A Utility tractor, small farms, power range 50-100 kW, low energy usage.

(ii) medium size tractor for dairy and livestock, a power range 100-200 kW, medium energy usage.

(iii) A large size tractor for crop farming in big farms, power range 200-450+ kW, high energy usage.

JCB Fastrac 4220 Tractor

- Diesel engine efficiency ~30-35%
- Tank capacity 390 L
- Rated power 217 hp = ~ 161.8 kW
- Maximum power 235 hp = ~ 175.2 kW
- Power Take Off 195 hp = 145.4 kW

JCB Fastrac 4220 Tractor

- The calorific value of diesel fuel 36.9 MJ/L (~10 kWh/L)
- Energy equivalent (diesel) 10 kWh/L x 390 L = 3900 kWh
- Energy equivalent (H2) 3900 x 0.3/ 0.5 = 2340 kWh
- H2 tank capacity = 2340 kW / 39 kWh/kg = 60 kg
- @ 350 bar (~24 kg/m³): 2.22 m³ (5.7x diesel tank)
- @ 700 bar (~42 kg/m³): 1.23 m³ (2.7x diesel tank)

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Hydrogen Storage System

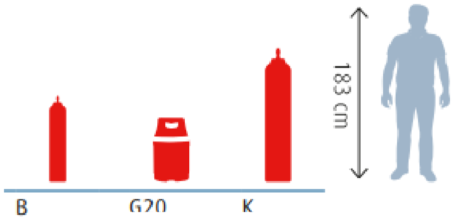
Type 1 Gas Cylinders – All Metal

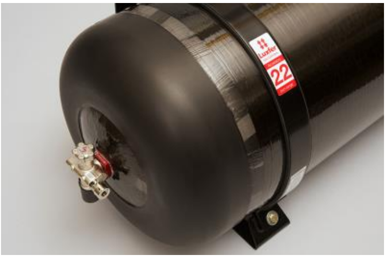
Type 2 Gas Cylinders – hoop-wrapped aluminium

Type 3 Gas Cylinders – Fully-wrapped carbon composite

Type 4 Gas Cylinders – Full composite

Type 5 Gas Cylinders – Linerless Composite





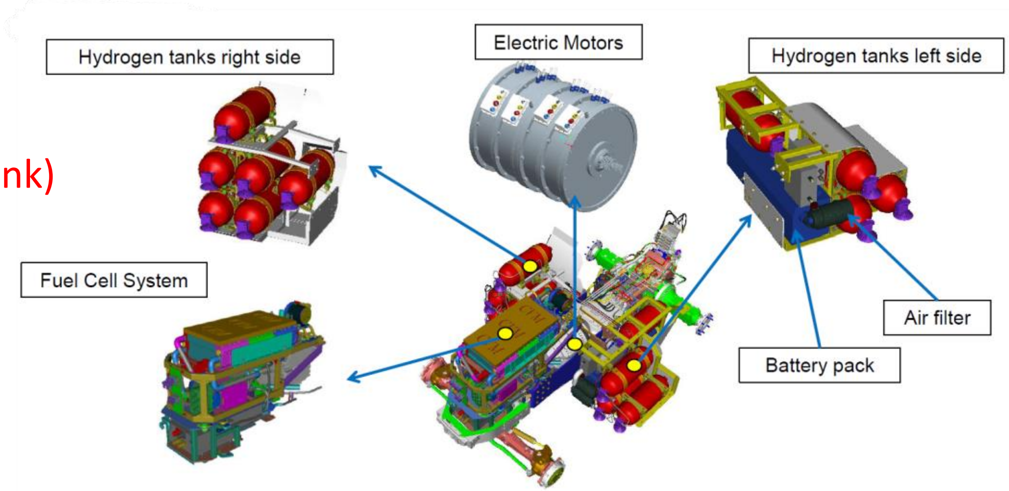
	H2 content kg	Gross weight (kg)	wt%	Bottle pressure bar	H2 density kg/m3	External Volume (L)	Internal volume (L)
K	0.585986	65	0.901516	175	12.70	61	46.123
B	0.120286	19	0.633082	175	12.70	13	9.46769
G20	0.404745	26	1.55671	300	20.07	53	20.15911
Mirai @10-15C	4.9878	92.49306	5.7	700	40.75	165.24	122.4
Luxfer (UK)	7.7	148.7	5.178211	350	24.23	431.5	322

Ratio (External/Internal) ~ 1.35

JCB Fastrac 4220 Tractor

- Tank internal volume
  - @ 350 bar (26.1 kg/m³): 2.3 m³ (5.8X diesel tank)
  - @ 700 bar (42 kg/m³): 1.23 m³ (2.7X diesel tank)

- Tank system volume (+35%)
  - @ 350 bar: 3.1 m³ (8x diesel tank)
  - @ 700 bar: 1.66 m³ (4.5x diesel tank)



CNH Industrial

Challenges (FC Tractor)

- Cost
  - The total cost of fuel cell drivetrain is currently **15X** more expensive than a diesel powertrain
  - The DOE report: the cost fuel cell system and storage can be in parity with diesel if we factor in mass production of fuel cell drivetrain.
- Fuel cell power density:
  - Volumetric power density of fuel cell system includes the electric motor and inverter is ~ 170 kW/m^3, while it is around 280 kW/m^3 for diesel powertrains.

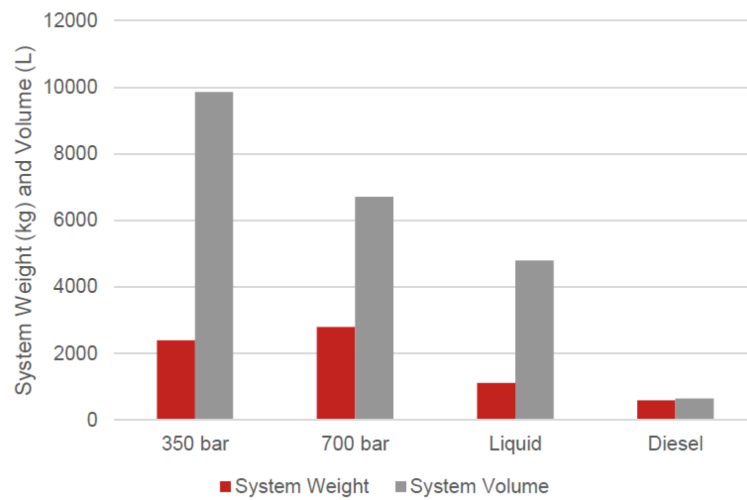
– H2 fuel density:

- A large size tractor of 650 L of diesel

  →→ 2 tones heavier with H2 fuel
- H2 tank volume is an issue

– Stack cooling:

- A huge radiator is required

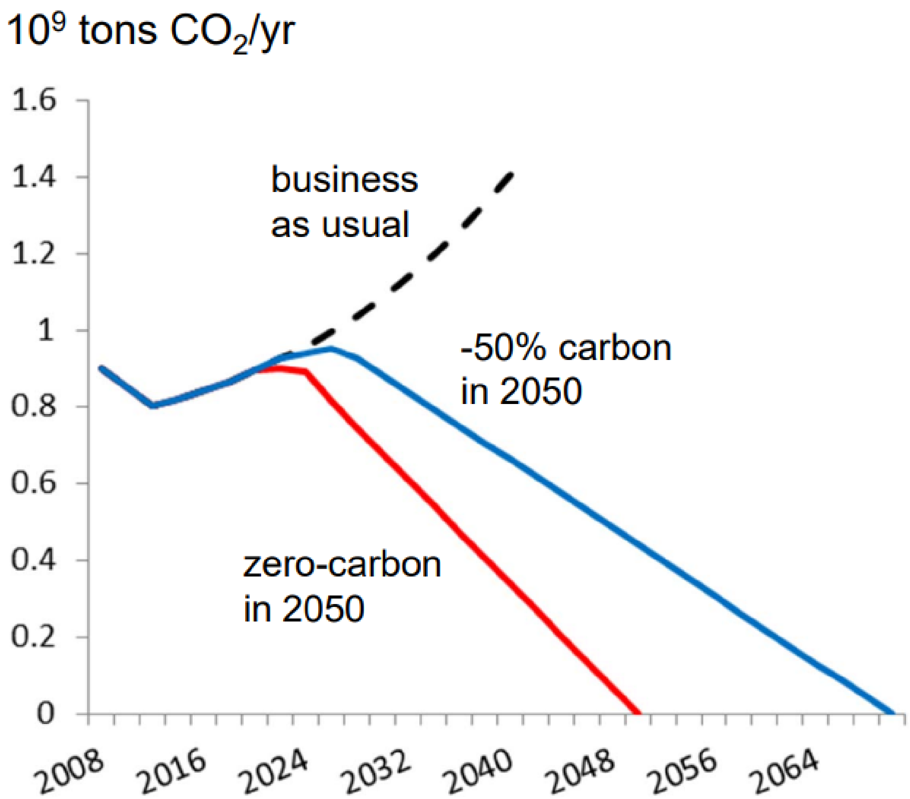


Weight and volume requirements of hydrogen system for a tractor.

CNH Industrial

Fuel Cells in Martitime Applications

Emission Reduction Scenario of the IMO



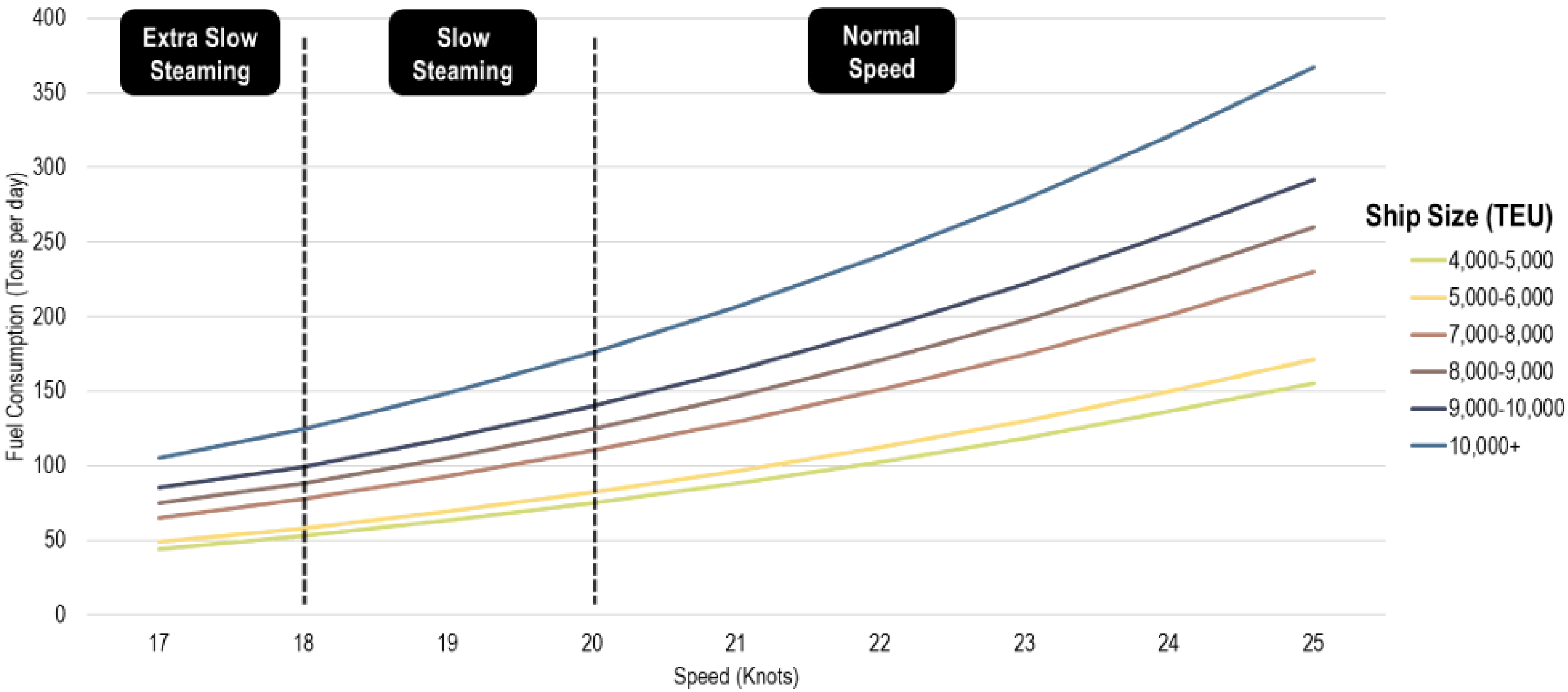
so what now?

- **LNG?**
- **hydrogen?**
- **methanol?**
- **ammonia?**
- **methane?**

What Amounts of Fuel are we talking about?

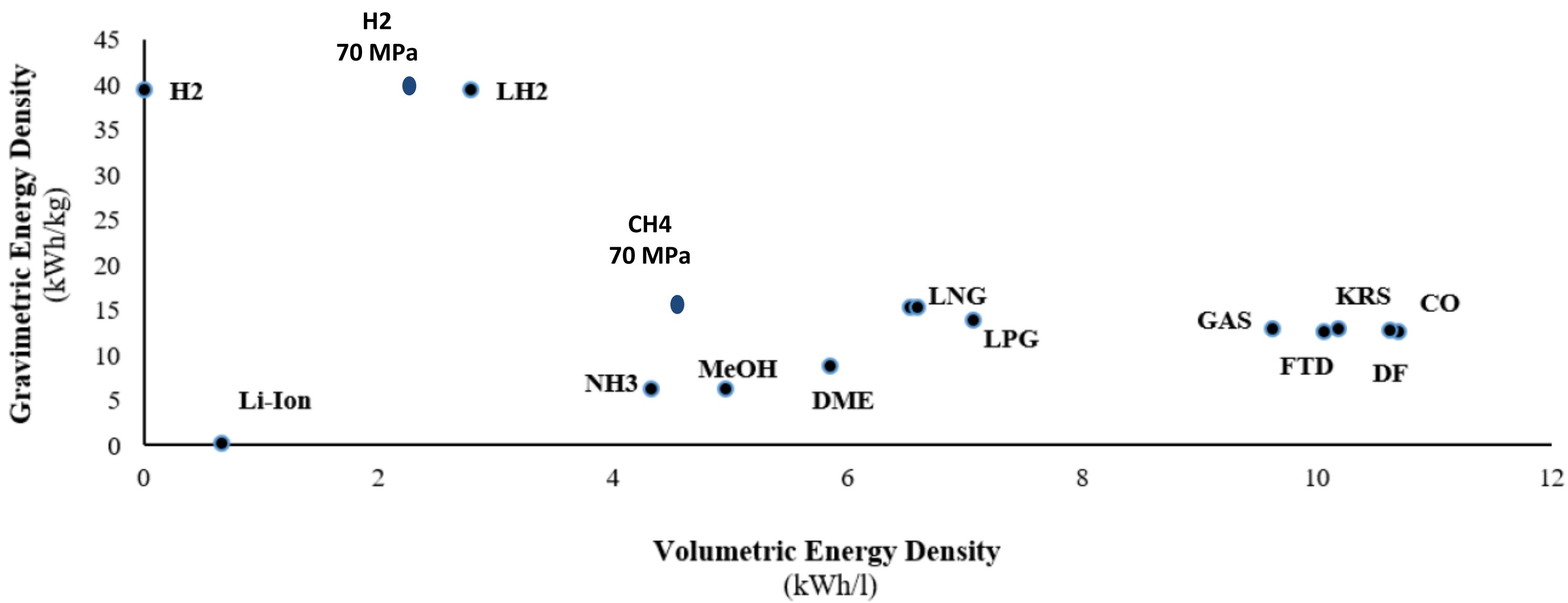
- For shipping

- Steaming distance 10 days, 150 to/dy, 16 500 MWh



source: transportgeography.org

Energy Density Comparisons



Where: GAS is gasoline, KRS is kerosene, DF is diesel fuel and CO is crude oil.

From: Samuel Sogbesan/Robert Steinberger-Wilckens

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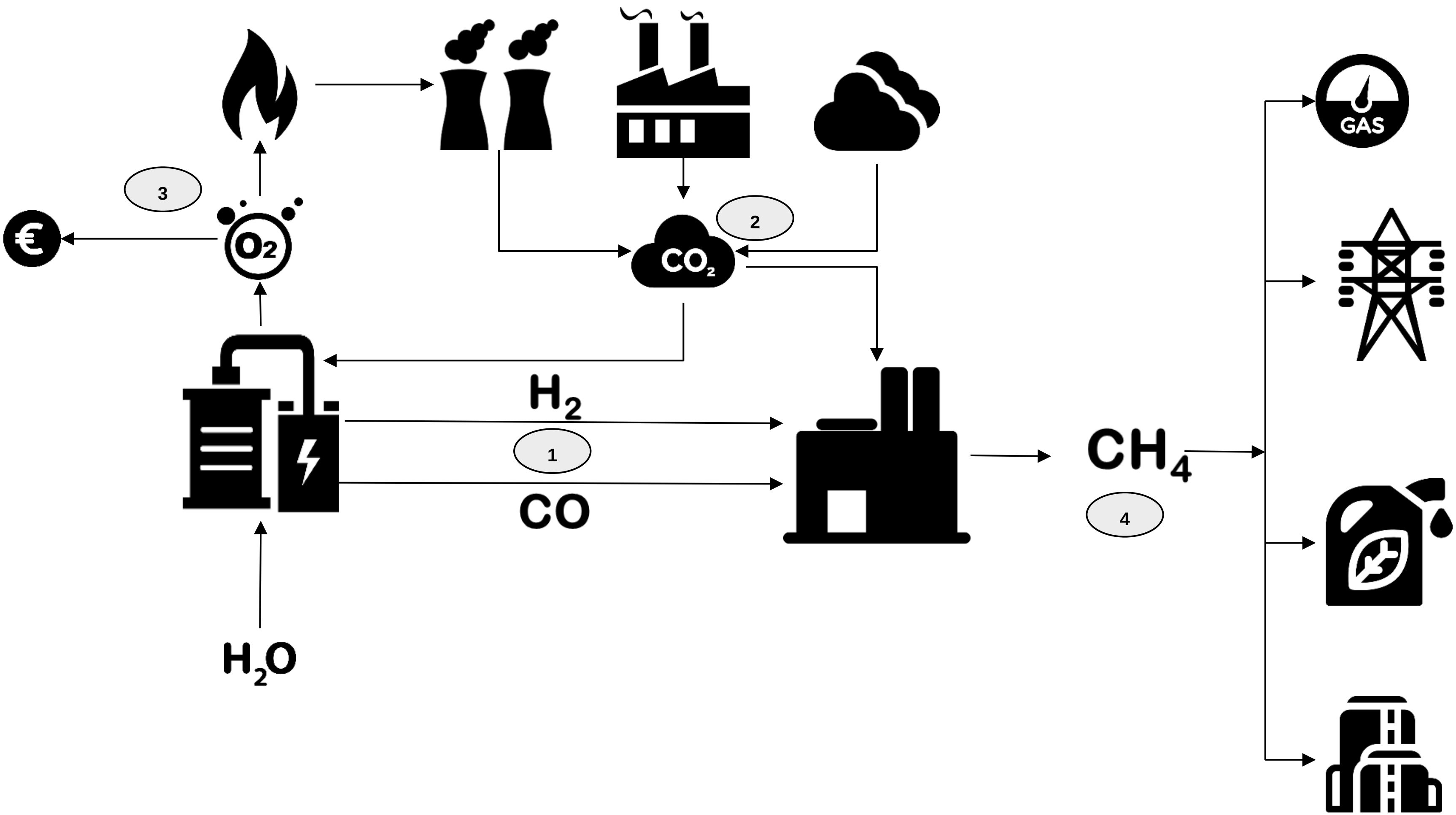
Comparison: Fuel Weight & Volume

- Steaming distance 10 days, 150 to/day, 16 500 MWh

	Boil. Temp. [K]	Heat.Val. [kWh/kg]	Heat.Val. [kWh/L]	Heat.Val. [kWh/ Ncbm]	bunker-volume [cbm]	Fuel weight [to]	
LH2	20	33	2.3	---	7000	500	
LSNG	111	14	6.3	---	3200	1200	
LNG	120	12.5	5.6	---	3500	1300	
H2	---	33	---	3	9900	500	**70 MPa**
CH4	---	14	---	9	8900	1300	**25 MPa**
NH3	240	5.2	3.2	3.9	5200	3350	
CH3OH	---	5.5	4.4	---	3750	3250	
M.Diesel	---	12	10	---	1500	1500	

Power to Gas from CCU



From: Samuel Sogbesan/Robert Steinberger-Wilckens

The Cycle of Zero-Carbon Methane

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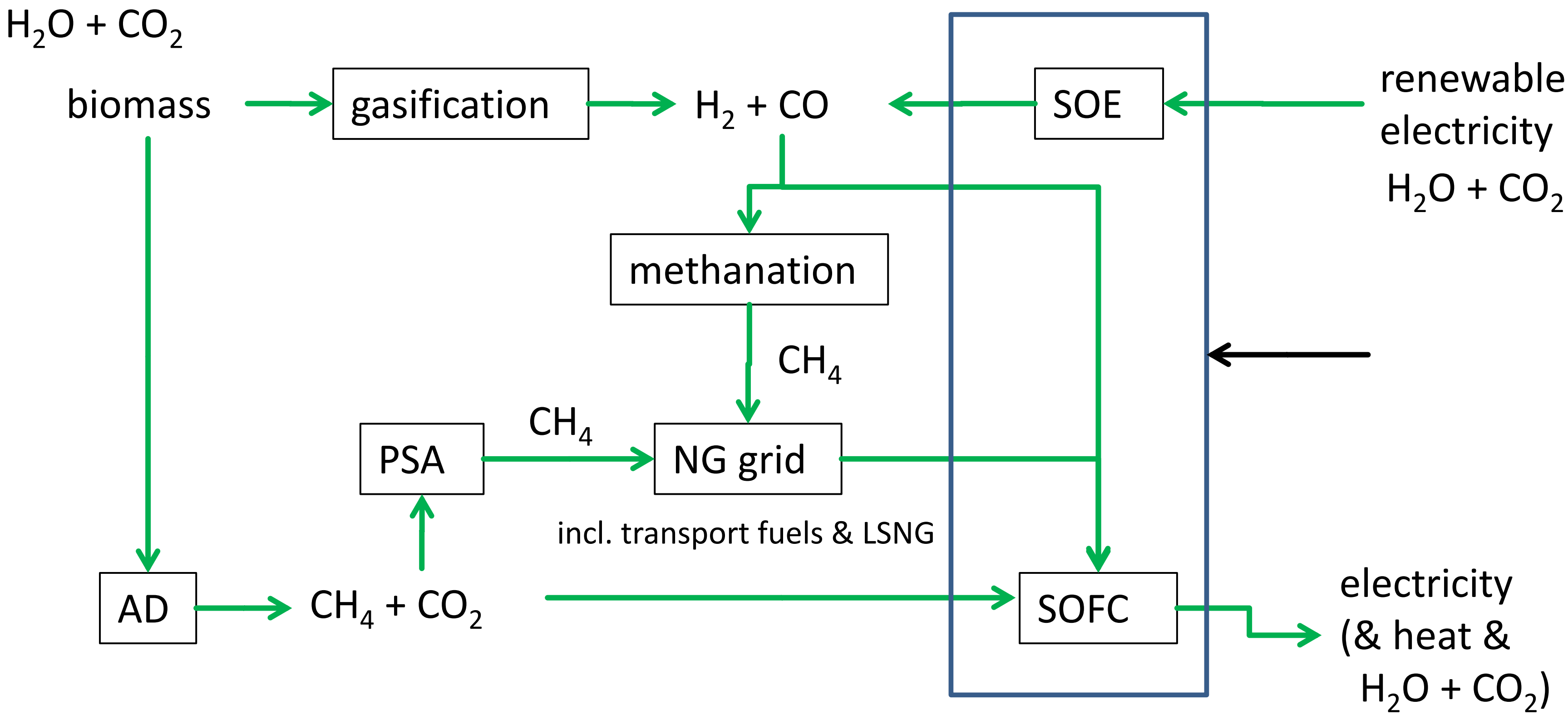

supplies synthetic natural gas for stationary applications and transport fuels without any fossil carbon conversion involved

Zero-Net Carbon Methane (CH_4) for electrifying large vehicles

- fully compatible with natural gas (NG) grid infrastructure
- compatible of biomass-based fuels with NG/LNG trend
- hybridise vehicles with existing NG engine technology and Solid Oxide Fuel Cells (SOFC)
- no fossil carbon emission with massive reductions in CO, particle and noise emissions

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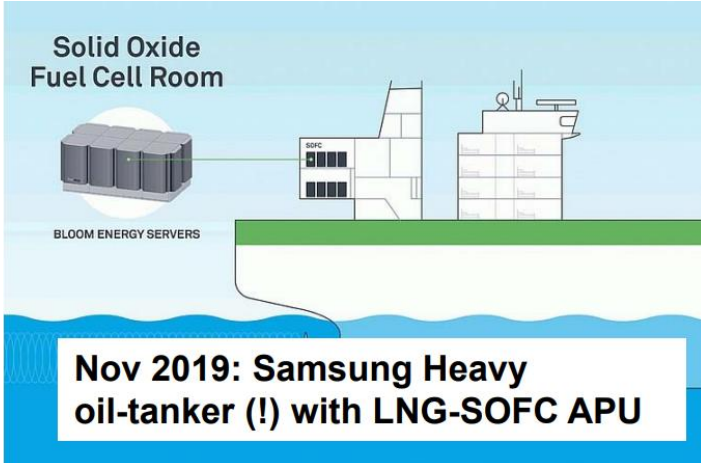
Outlook

- besides the fuels, efficiency and emissions from shipping main engines play a major role in the emissions management in harbours
- electric propulsion based on fuel cells is a key technology to tackle harbour emissions
- today‘s decisions should already prepare for this pathway

- the choice of fuel should be based on the complete picture of emissions and energy use



Educational Activities

- KnowHy – distance / e-learning technician training: , L5 Train-the-Trainer programme.
- TeacHy – European MSc course in FCH technologies – delivered in blended learning (25% face2face and 75% e-learning)
- Centre for Doctoral Training in Fuel Cells and their Fuels.. (mini CDT programme 2022-23)
- Joint European Summer School on Fuel Cell, Electrolyser, and Battery Technologies (JESS) https://www.jess-summerschool.eu/
- we are building a ‚portal‘ as entry point for the above and adding general public suitable material such as MOOC‘s, general information etc.
- HyAcademy.EU Project 2024-2028

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MSc / MRes / CPD modules

Section	No.	Title
Core / Mandatory (for MSc)	C1	Introduction to Electrochemistry
	C2	Fuel Cell Technologies and Applications
	C3	Hydrogen and hydrogen-based fuels
	C4	Fuel cell modelling tools and control
	C5	Characterisation methods
	C6	Fuel Cell and Hydrogen Lab
	C7	(Principles of) Hydrogen Safety
Optional / Elected	O1	Environmental analysis, LCA
	O2/O3	Low/High temperature fuel cells
	O4	Fuel Cell Systems
	O5	Advanced electrochemical applications
	O6	Fuel cell electric vehicles
	O7 / O8	Electrolysers and Hydrogen Infrastructure
	O9	Hydrogen markets, policies, RCS
	O10	Energy systems and Energy storage
	O11	Advanced modelling

MSc: 180 credit
120 taught module
60 research project

MRes: 180 credit
60 taught module
120 research project

www.hydex.ac.uk

Thank you

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