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Progress, opportunities and challenges in fuel cell propulsion systems

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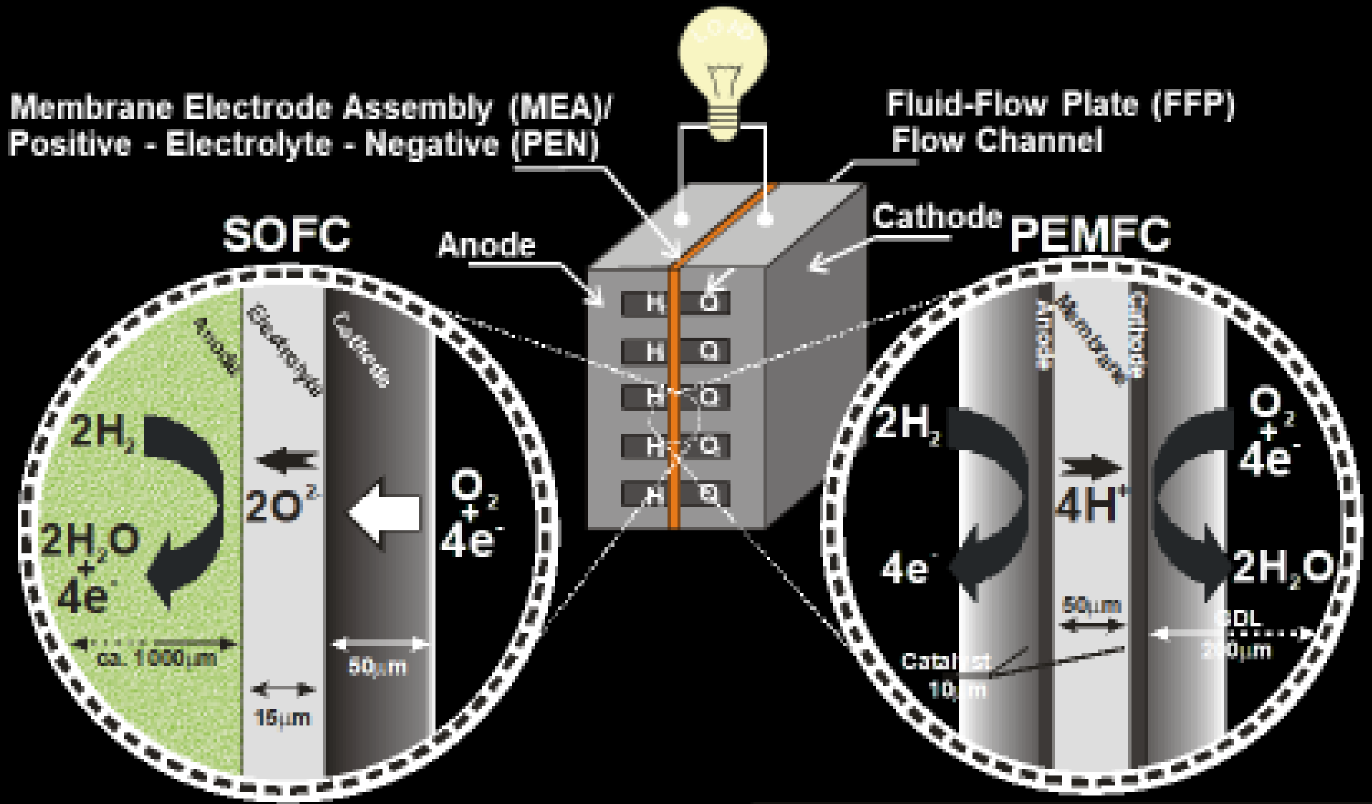
- Fuel cells and their fuels.
- Selected emerging technology options.
- Summary.

Introduction to Fuel Cells



Anode: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$

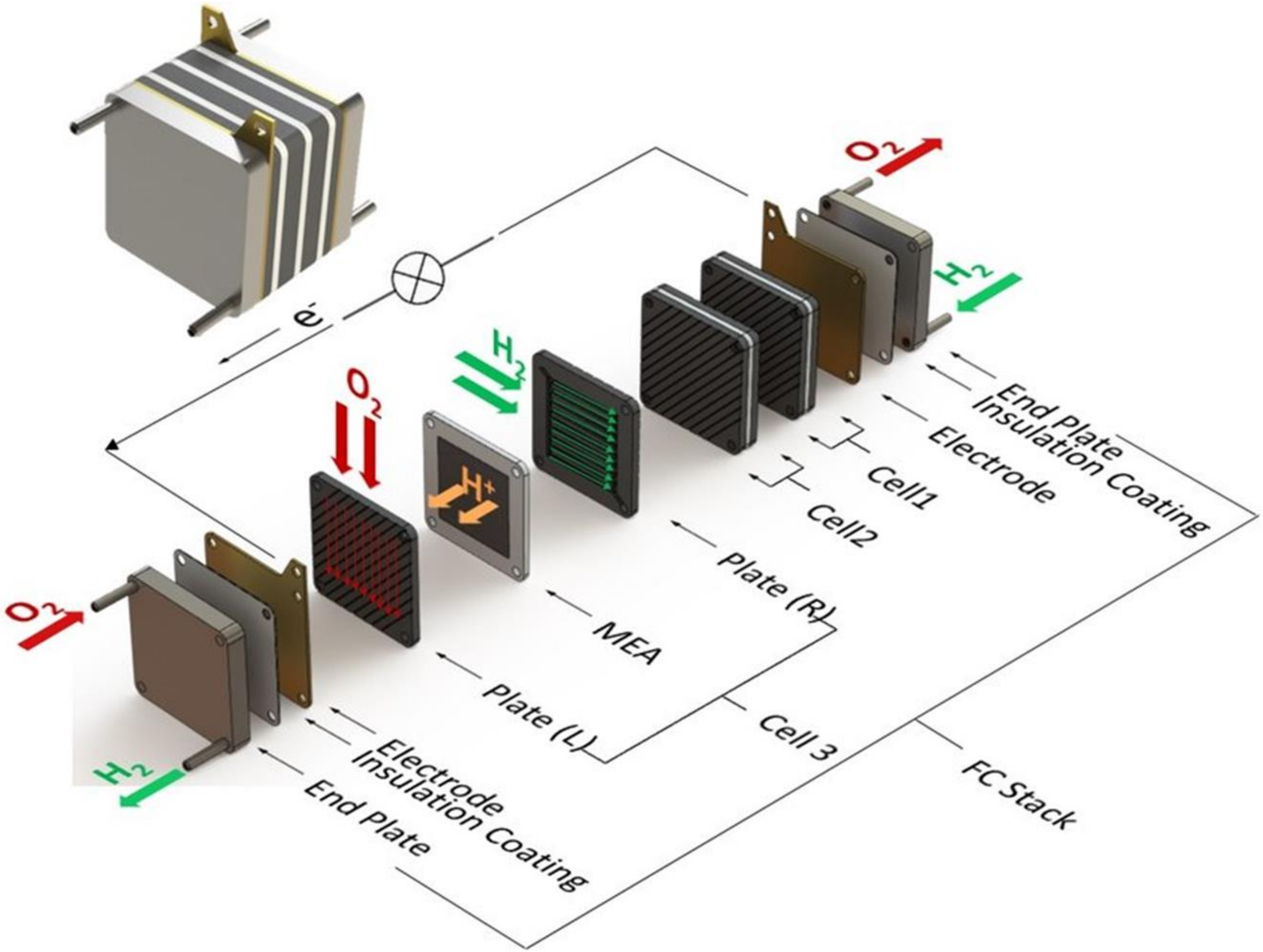
Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $4H^+ + O_2 + 4e^- \rightarrow 2H_2O$

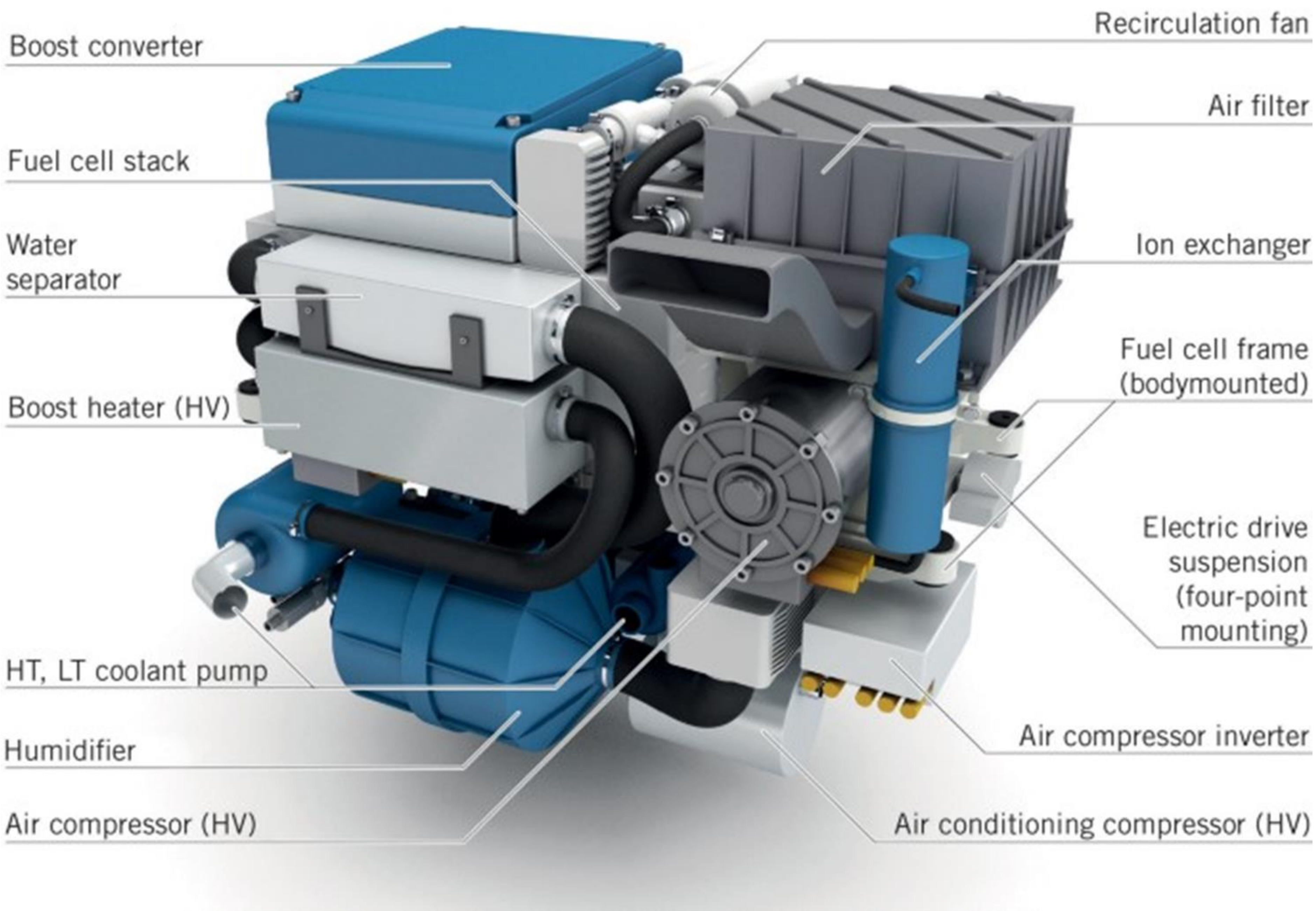
Solid Oxide Fuel Cell

Proton Exchange Membrane Fuel Cell

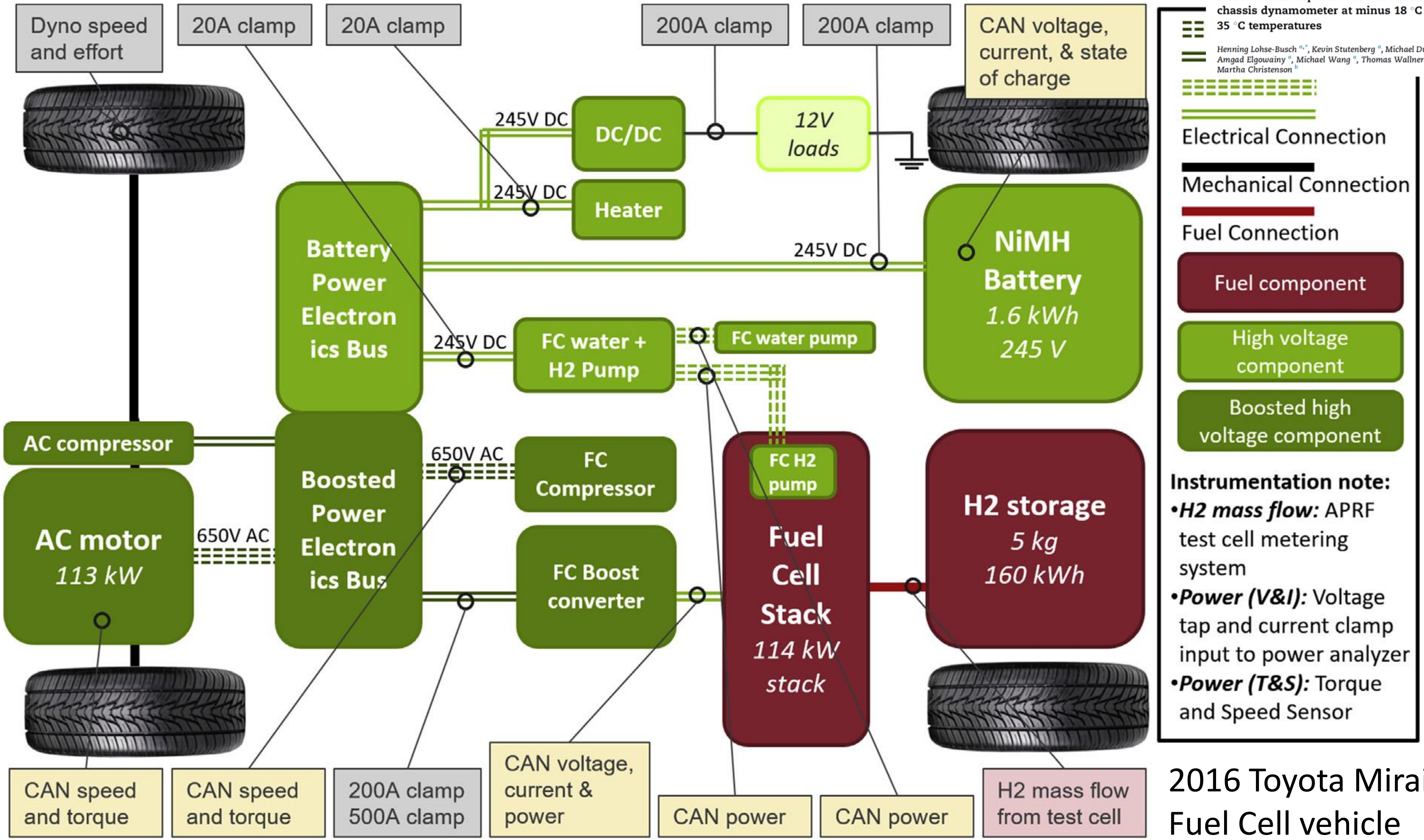
Fuel cell stack engineering

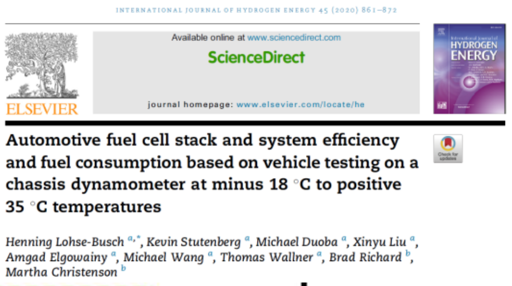


Fuel cell system engineering



Fuel cell system integration




INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 45 (2020) 861–872

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Automotive fuel cell stack and system efficiency and fuel consumption based on vehicle testing on a chassis dynamometer at minus 18 °C to positive 35 °C temperatures

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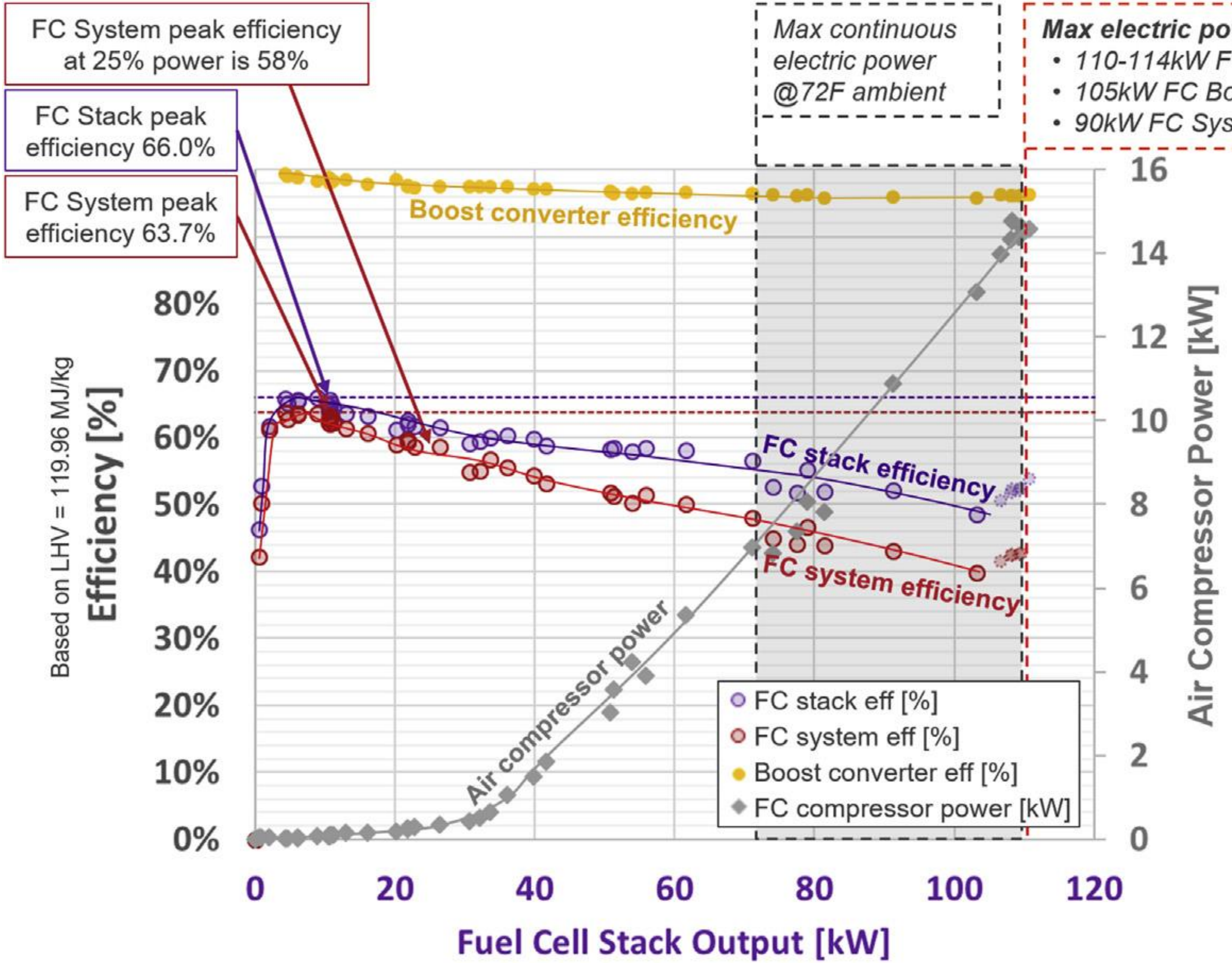
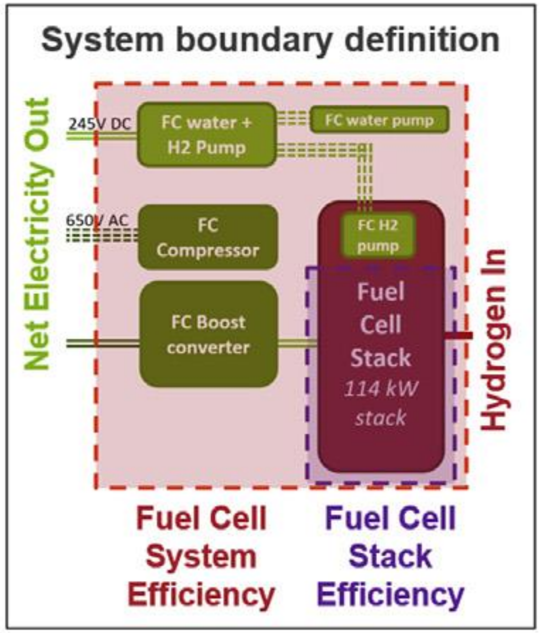
2016 Toyota Mirai Fuel Cell vehicle

Fuel cell stack and system efficiency



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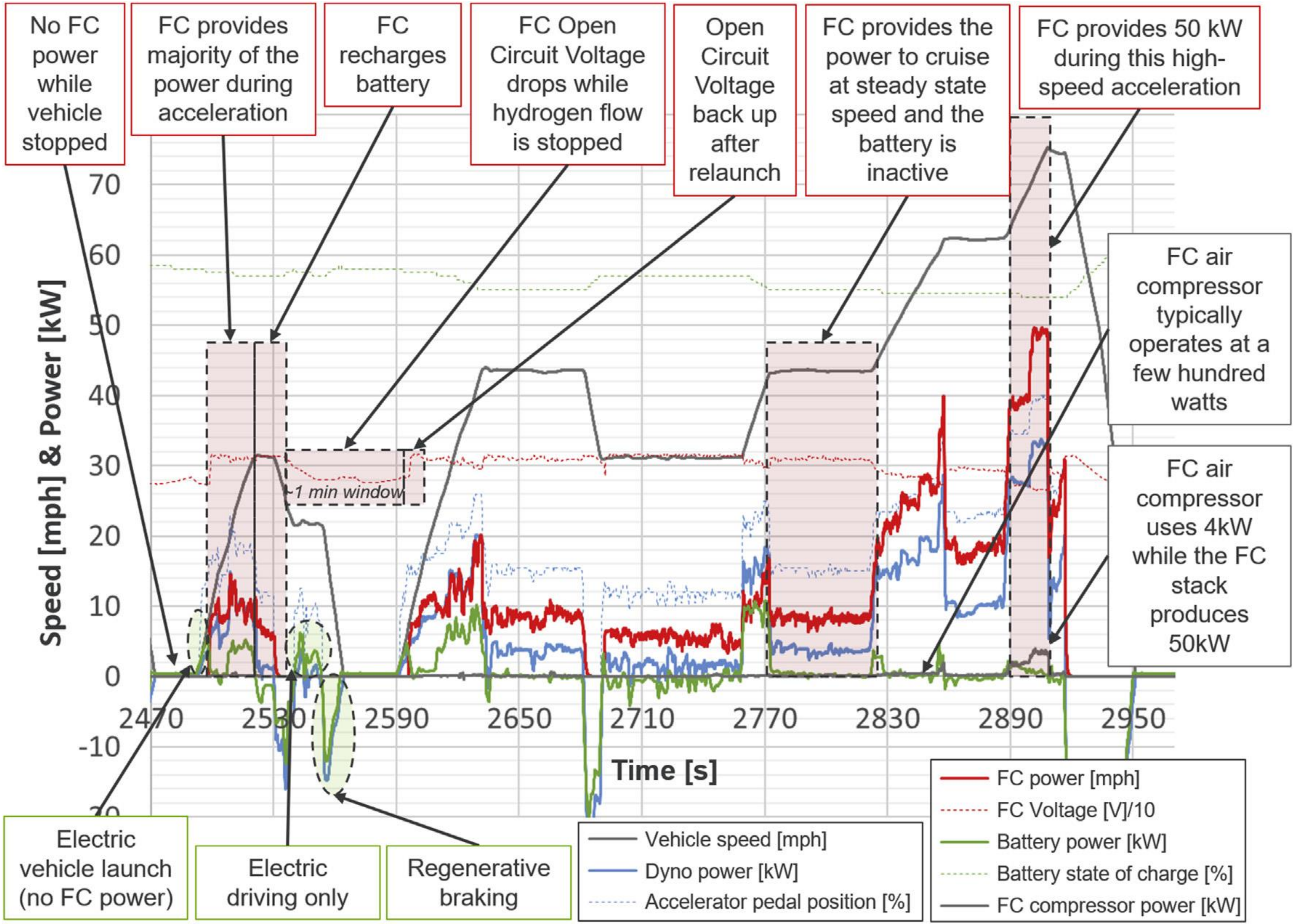

No FC power while vehicle stopped
FC provides majority of the power during acceleration
FC recharges battery
FC Open Circuit Voltage drops while hydrogen flow is stopped
Open Circuit Voltage back up after relaunch
FC provides the power to cruise at steady state speed and the battery is inactive
FC provides 50 kW during this high-speed acceleration
FC air compressor typically operates at a few hundred watts
FC air compressor uses 4kW while the FC stack produces 50kW
~1 min window
Speed [mph] & Power [kW]
Time [s]
70
60
50
40
30
20
10
0
-10
-20
2470
2530
2590
2650
2710
2770
2830
2890
2950
Electric vehicle launch (no FC power)
Electric driving only
Regenerative braking
Vehicle speed [mph]
Dyno power [kW]
Accelerator pedal position [%]
FC power [mph]
FC Voltage [V]/10
Battery power [kW]
Battery state of charge [%]
FC compressor power [kW]

Hydrogen Fuel Cell Electric Buses

At COP26, 13 governments across the world committed to the objective that all new medium-and heavy-duty vehicles from 2040 would be zero emission

USA: California hosts the largest FCEB fleet in the US, accounting for over 50 vehicles in 2021.

South Korea: 108 FCEBs were operating on Korea's roads at the end of 2021. The 2040 target is for 41,000 vehicles.

China: Between 2015-2021, over 5,500 FCEBs shipped in China. China's cities continue to deploy FCEBs at scale.

Japan: At the end of 2021, 110 fuel cell buses were in operation in Japan.

UK: 8 FCEBs in operation since 2011; double-decker FC buses running in Aberdeen

Fuel Cell Transport: Hydrogen FC Electric Trains

- Capable of similar performance to diesel-electric powertrains, fuel cell trains offer an emission free option for nonelectrified lines.
- The world’s first fuel cell passenger train entered revenue service in 2018. Alstom’s Coradia iLint has achieved more than 180,000 km in revenue service in Germany and Austria, with a reliability of 95%.
- France’s SNCF Voyagers placed a €190m order for 12 Alstom units.
- Alstom and Eversholt Rail have developed the Breeze for the UK market- a hydrogen fuel cell/battery hybrid. Range is >600 miles.
- The UK government has set 2040 as the date by which diesel will be phased out.

Hydrogen Fuel Cell Electric Trucks & Off-road

- Hyzon Motors' truck production is underway in Holland, delivering refuse collection, sewer-cleaning and heavy-duty delivery vehicles for the Municipality of Groningen. Daimler, Volvo, Hyundai and Hyzon are vying for European market share through various programmes. H2Accelerate, which includes Volvo, Iveco, and Shell, aims to deploy 100's of trucks in Europe before 2025 and 1000's each year towards 2030.
- JCB has developed the first ever hydrogen powered excavator.
- Hyundai delivered 46 units to Switzerland in 2021.
- China remains top in medium- and heavy-duty deployments, with 1,200 trucks produced in 2021.

Fuel Cell Boats and Ships

- Fuel choices include compressed hydrogen for smaller vessels, liquid hydrogen, green ammonia or e-methanol for large ships; coupled with fuel cells.
- In July 2021, Norled in Norway took delivery of its first LH2 ferry, MF Hydra (with Ballard FCwave fuel cells).
- TECO of Norway have an agreement with Chemgas Shipping to supply up to 200 MW of fuel cell systems for 120 barges and 40-60 tugboats to transport green H2 made in Romania to Germany and Austria.
- Ceres' SOFC technology is being evaluated as a replacement to the diesel generators for 10 MW hotel loads in large cruise ships, with Carnival UK, Southampton University, Shell and Lloyd's Register.

Hydrogen Fuel Cell Aircraft

- Routes shorter than 3,000 km account for 90% of all flights and more than 50% of aviation CO_2 emissions overall. Hydrogen fuel cells are potentially attractive for this application.
- Electric Aviation group, a UK company, are seeking to develop H_2 fuel cell solutions for short haul routes.
- PowerCell, HyPoint and Hyzon Motors have supplied fuel cells to ZeroAvia.
- Airbus has committed to production-ready, zero emission aircraft by 2035, with green H2 a potential enabler.
- ZeroAvia is partnering with British Airways to establish how H_2-powered aircraft can play a leading role in future sustainable flying.

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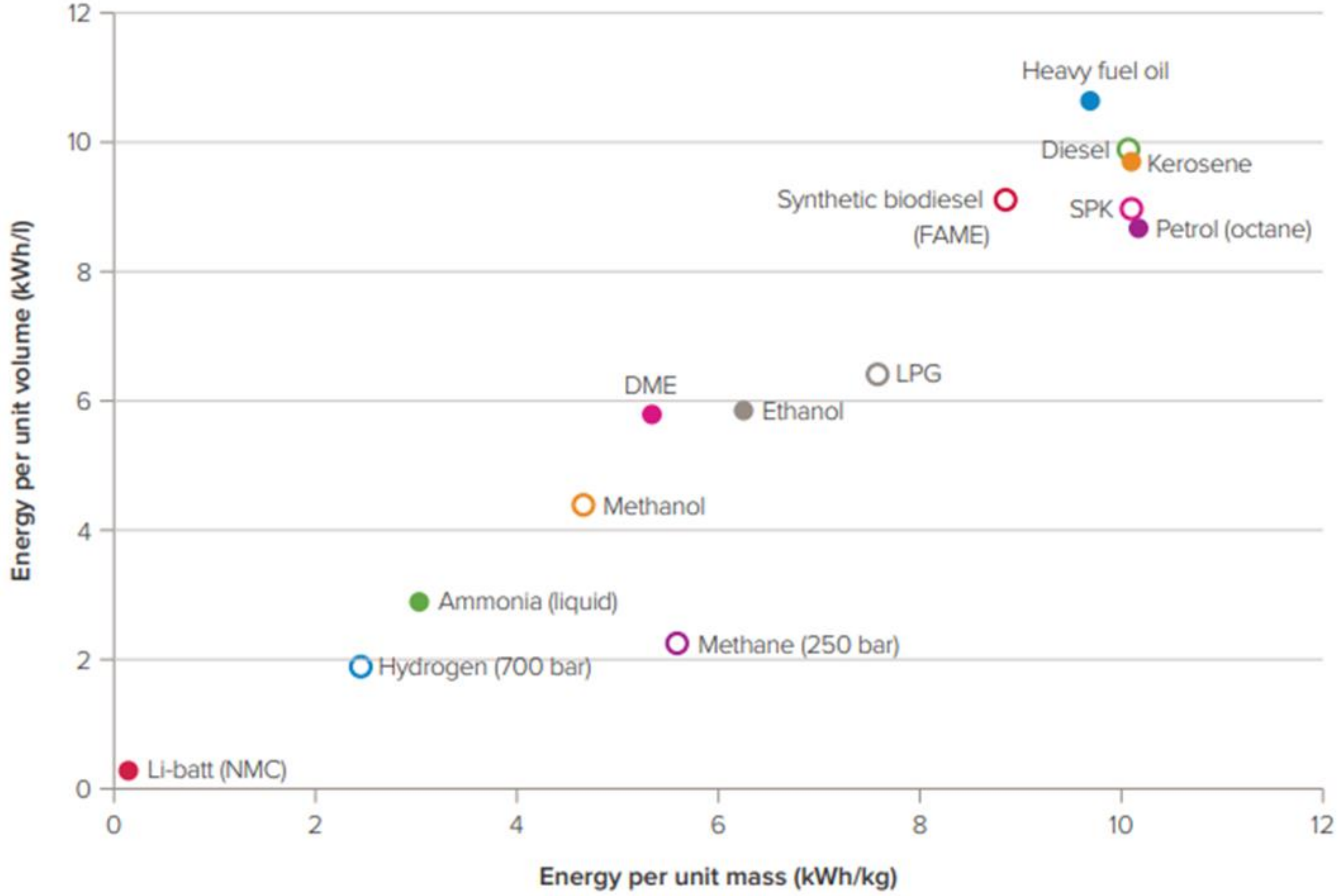
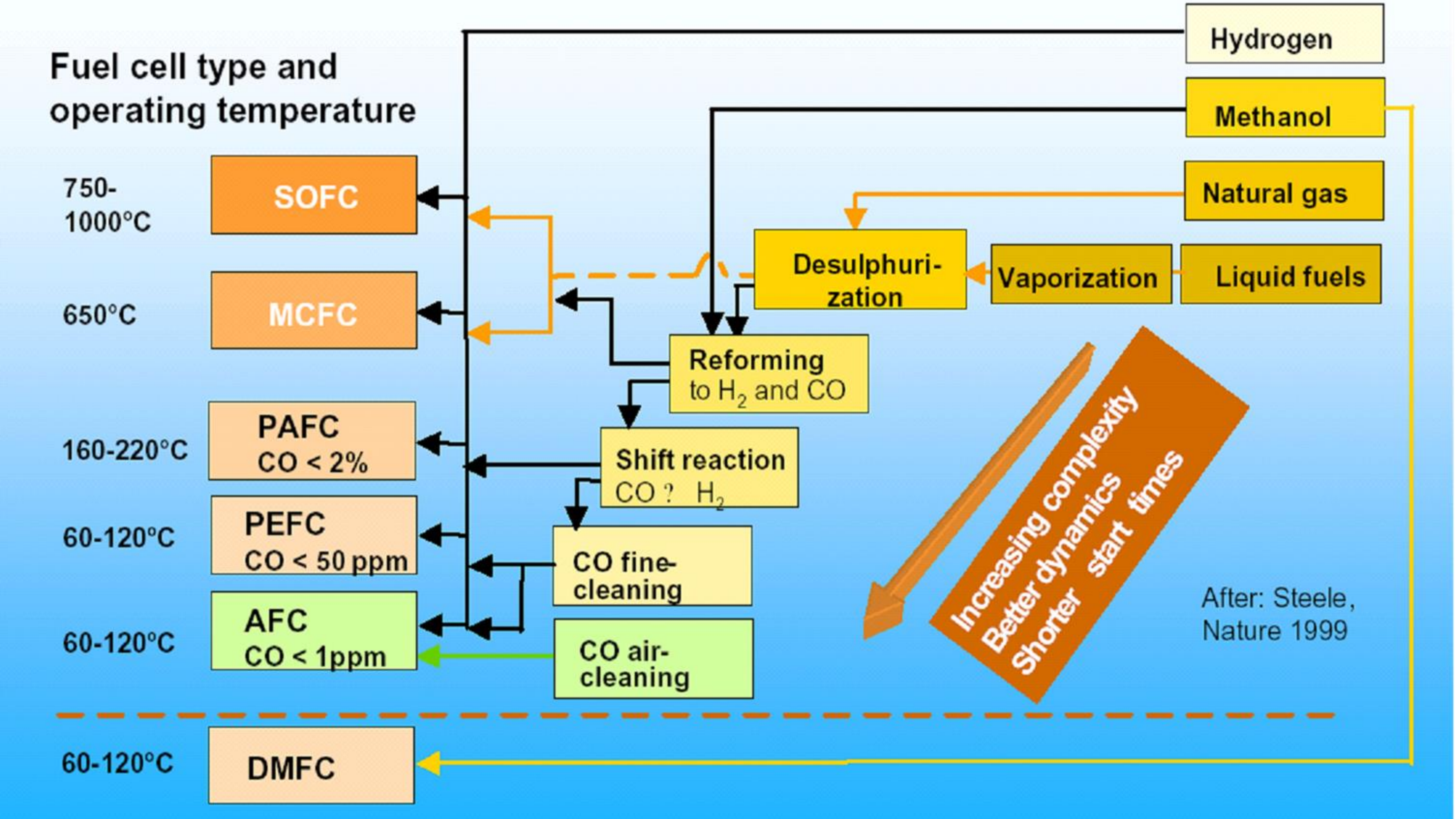
Specific energy and energy density of a range of fuel options, taking into account typical tank weights (lower heating value).



SPK Synthetic Paraffinic Kerosene; **Li-batt(NMC)** Lithium Nickel Manganese Cobalt Oxide Battery; **LPG** Liquid Petroleum Gas; **DME** Dimethyl Ether, **FAME** Fatty Acid Methyl Esters


Fuel cell type and operating temperature
750-1000°C
SOFC
650°C
MCFC
160-220°C
PAFC
CO < 2%
60-120°C
PEFC
CO < 50 ppm
60-120°C
AFC
CO < 1ppm
60-120°C
DMFC
Hydrogen
Methanol
Natural gas
Desulphuri-zation
Vaporization
Liquid fuels
Reforming to H2 and CO
Shift reaction CO ? H2
CO fine-cleaning
CO air-cleaning
Increasing complexity
Better dynamics
Shorter start times
After: Steele, Nature 1999

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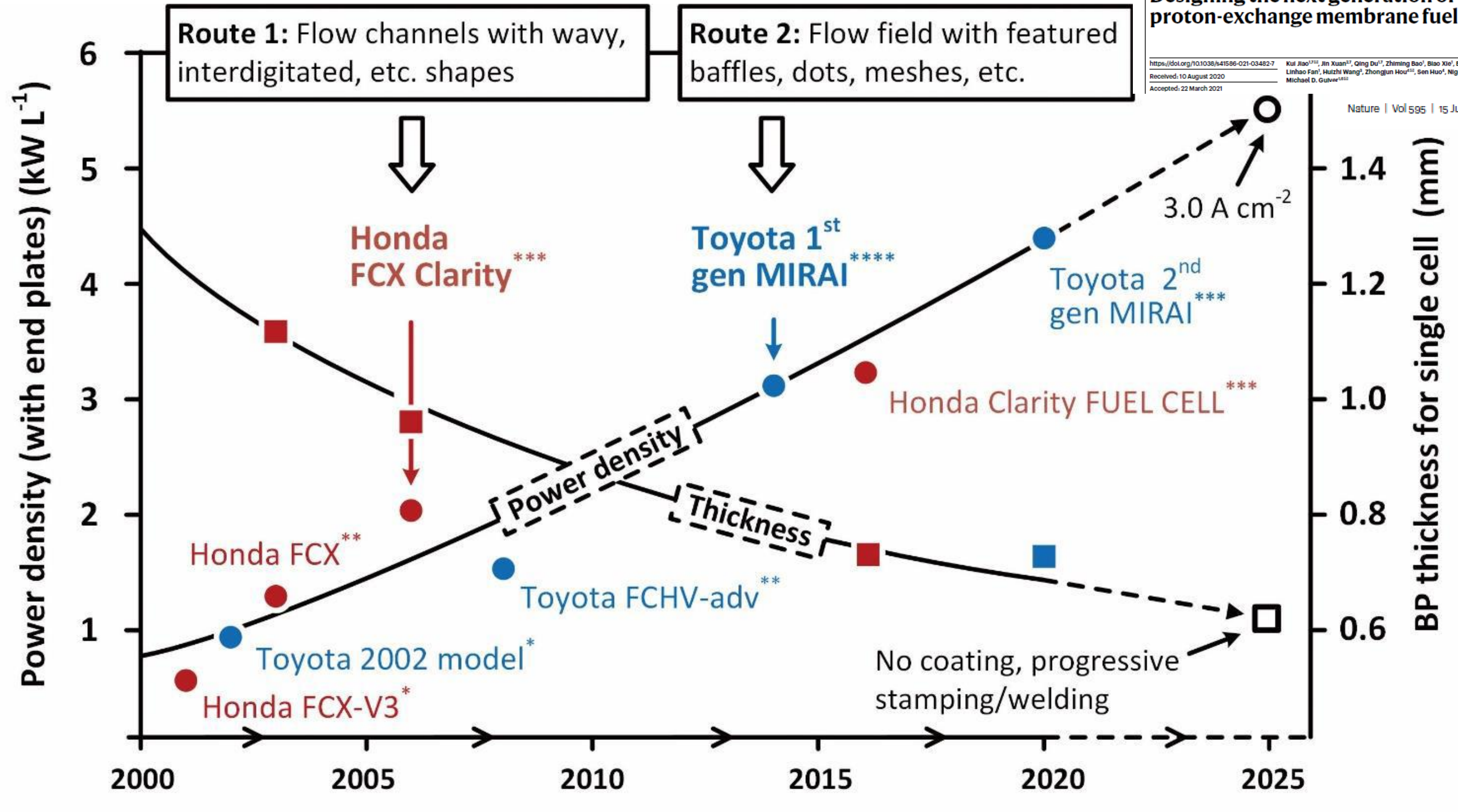


Perspective

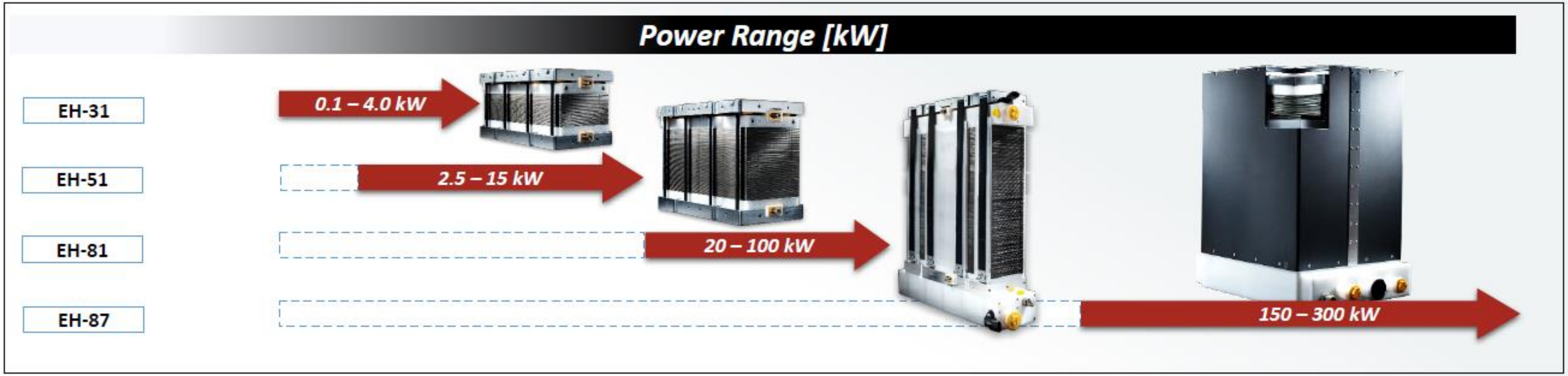
Designing the next generation of proton-exchange membrane fuel cells

https://doi.org/10.1038/s41586-021-03482-7
Received: 10 August 2020
Accepted: 22 March 2021

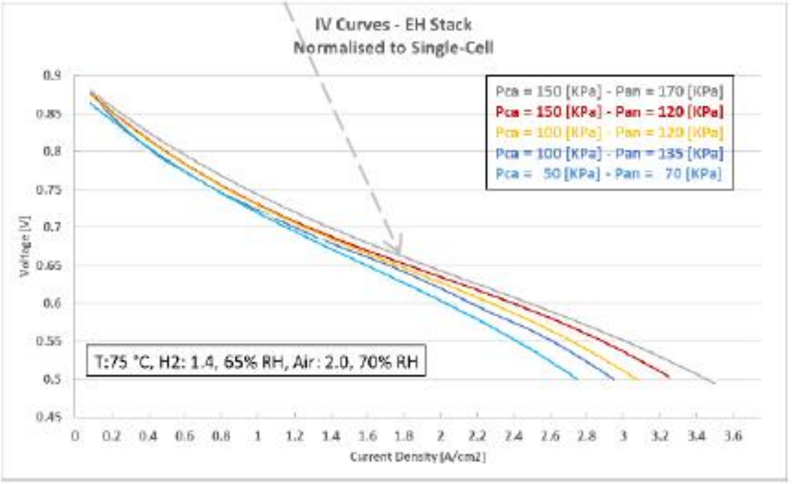
Kui Jiao, Jin Xuan, Qing Du, Zhiming Bao, Biao Xie, Bowen Wang, Yan Zhao, Linhao Fan, Huizhi Wang, Zhongjun Hou, Sen Huo, Nigel P. Brandon, Yan Yin & Michael D. Guiver

Nature | Vol 595 | 15 July 2021 | 361

Fuel Cell Stacks



*High Power Density at **lower** pressure*

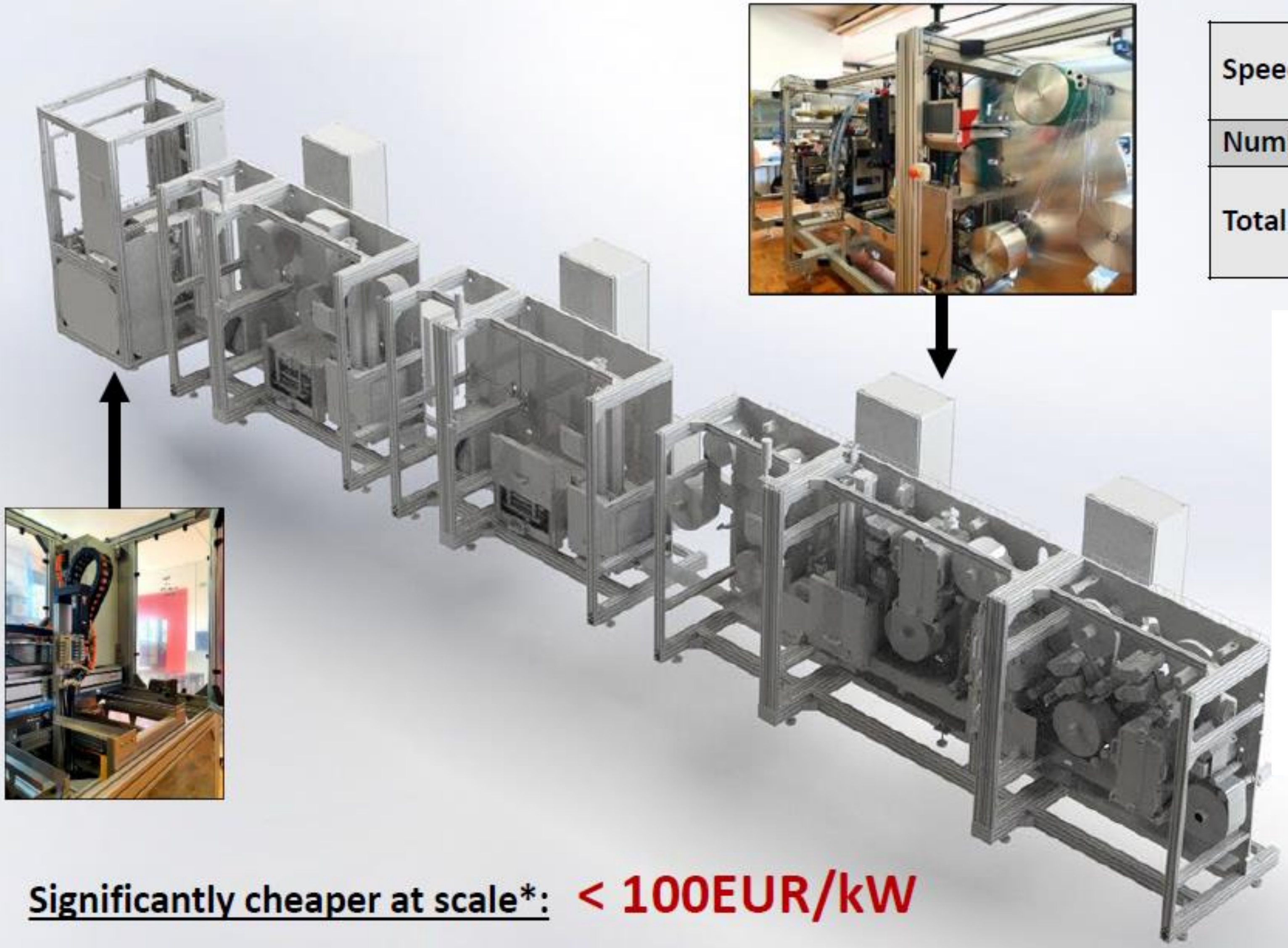


Technology Comparison

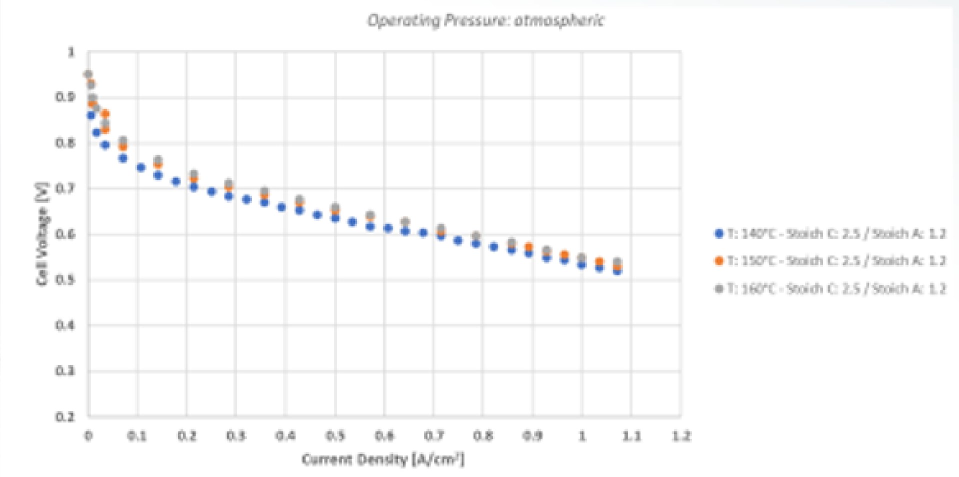
Parameters	Toyota (MIRAI)	Honda	PowerCell	Ballard	EHG FC STACKS
Volume Power Density [kW/L]	5.4	3.1	4.8	4.3	**8.0**
Weight Power Density [kW/kg]	3.0	2.0	2.9	2.7	**4.0**
Cell Pitch [mm]	~1.0	~1	~1.0	N/A	**<0.8**

NOTE: data from other suppliers are collected from the public domain and EHG doesn't guarantee 100% accuracy

FC Automated Production Innovation



Speed of production	100kW → 20min 60kW → 12min
Number of different Stack Platforms	4 (Up to 300kW)
Total capacity	40,000 (100kW stacks) ~4 GW/year

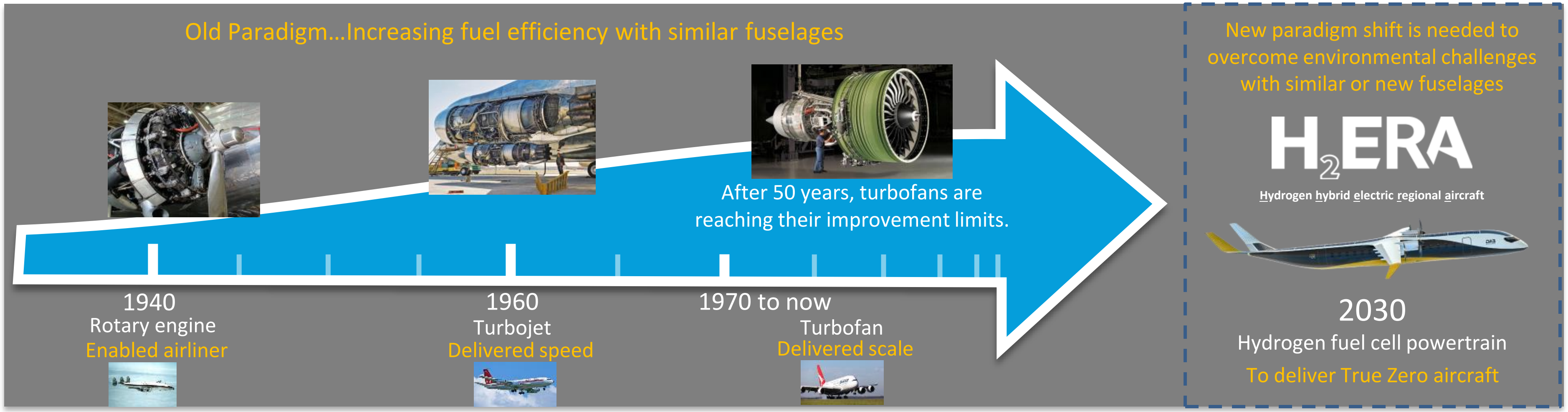


Significantly cheaper at scale*: **< 100EUR/kW**

*100,000 units per year


EAG
ELECTRIC AVIATION GROUP
EAG
EAG HERA 70+
HERA 70+

New Paradigm Shift – EAG’s Hydrogen Electric Solution



How Does EAG’s Solution Work?

Stored Hydrogen

1

Hydrogen is stored cryogenically on the aircraft

Fuel Cells

2

Hydrogen and air used as inputs for fuel cell, which generates power through electrochemical reaction(1)

Electric Motor

3

Power generated is used to run the electric motors

Fan

4

Electric motors rotate propellers on aircraft

Thrust

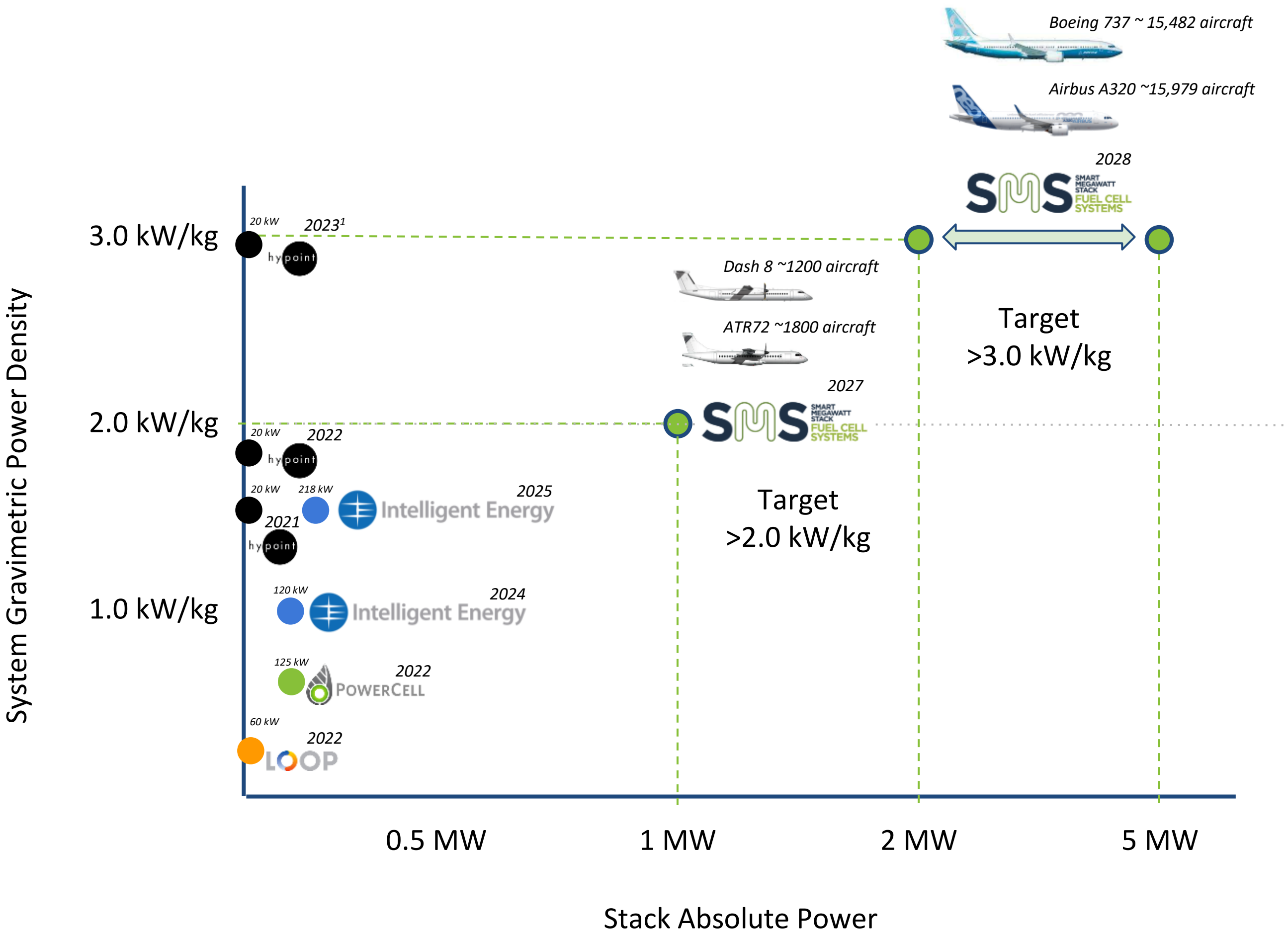
5

Thrust is achieved for aircraft

(1) Only by-product produced is water – no Carbon and NOx emissions

Competitive Landscape

System Gravimetric Power Density vs Stack Absolute Power



Lightweight propulsion units, realistic aircraft MTOW

2.0 kW/kg[2]

Heavy propulsion units, unrealistic aircraft MTOW

Key Point: No fuel cell system exists today with sufficiently high power density for a 90-seater aircraft

[1]HyPoint fuel cell systems achieves high system gravimetric power density at low peak powers (20 kW) with an air cooled system which is not feasible for 90 seater regional aircraft (peak power requirements ~8 MW)

[2]2.0 kW/kg requirement for system level power density (including cooling) of a regional turboprop determined through EAG's in-house aircraft mission analysis and sizing tools, aligning with CleanSky's report (1.5-2.0 kW/kg)

ceres

Clean energy starts with Ceres

January 2024

Sector focus **Maritime**

Collaboration with Alma Clean Power for maritime

Ceres has signed a collaboration with leading developer of marine power systems, Alma Clean Power, which will integrate Ceres' solid oxide fuel cells ("SOFC") into a modularised power system exploiting the inherent fuel flexibility and efficiency of Ceres' SOFC technology.

System development is underway, integrating Ceres' stack technology into development and validation of the power system. The target is to have a complete system ready for testing by the summer of 2024 followed by on-vessel trials.

Ceres' solid oxide fuel cell technology can reduce carbon emissions by up to 47%* on conventional fuels and provide a pathway to zero carbon.

Clean power for heavy duty transport

Ceres and Weichai have developed range extender solution for buses. Successful demonstration achieved on 30kW concept in China, with a five-bus field trial.

These buses are equipped with battery packs, which deliver high-density power to the electric motor. The fuel stacks continually recharge the batteries, so that the range of the bus is extended in a hybrid manner.

The robustness, high-efficiency and fuel flexibility of our technology provides a clear transition pathway to net zero.

Weichai is the largest manufacturer of buses, trucks and combustion engines in China".

Summary

- Fuel cell propulsion systems will have a role to play in selected transport applications, and will be favoured by those with high energy requirements.

- While hydrogen is an important future fuel, fuel cells can also run at high efficiency on other hydrogen carriers such as green ammonia, green methanol, bio-ethanol, etc.

- An important technology direction for PEM fuel cells is to raise the operating temperature towards 160C, and good progress is being made on the membranes needed for this. This improves thermal management and fuel flexibility.

- Solid oxide fuel cells offer the greatest fuel flexibility, and will likely find application in large transport applications such as rail and shipping.

- Countries such as India are moving at pace toward technology based around green hydrogen and its carriers, both fuel cell and ICE, as they want both fuel independence, <u>and</u> supply chain independence.