Is Hydrogen the Answer?

David Shirres, Editor RailEngineer

Responding to the environmental agenda

"Public concern about issues such as climate change and the impact of business on society has never been more intense than it is today. Accordingly, sustainability has now risen to the very top of the corporate agenda."

Arthur D Little Global

Greenhouse Gas Emissions

Climate Change Act 2008

CHAPTER 27

CONTENTS

PART 1

CARBON TARGET AND BUDGETING

The target for 2050

1 The target for 2050
2 Amendment of 2050 target or baseline year
3 Consultation on order amending 2050 target or baseline year

Policy paper

Greenhouse Gas Emissions

We're moving the UK to a more efficient, low-carbon economy to meet our legally binding climate change targets.

Published 1 April 2016
From: Department of Energy & Climate Change

Policy paper

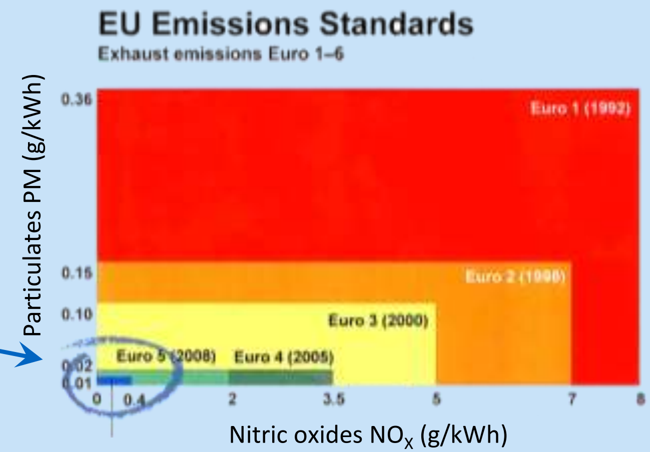
25 Year Environment Plan

'A Green Future: Our 25 Year Plan to Improve the Environment', sets out what we will do to improve the environment, within a generation.

Published 11 January 2018
Last updated 1 February 2018 — see all updates
From: Department for Environment, Food & Rural Affairs and The Rt Hon Michael Gove MP

Responding to the environmental agenda

Diesel engine emissions



Dramatic reduction of diesel road vehicle emissions since 1992, now Euro 6

Emission Component	Unit	HD Truck & Bus EURO 6	Rail 2004 (Current) DMU	Rail 2004 (Current) Locomotive	Rail 2016 (Starting 2020) DMU (RLR)	Rail 2016 (Starting 2020) Locomotive (RLL)
CO	g/kWh	4,000	3,500	3,500	3,500	3,500
HC	g/kWh		0,190		0,190	
THC	g/kWh	0,160		4,000		4,000
NOx	g/kWh	0,460	2,000		2,000	
Particle Mass	g/kWh	0,010	0,025	0,025	0,015	0,025
Particle Count	#/kWh	$6x10^{11}$	N/A	N/A	$1x10^{12}$	N/A

Lower emission standard for rail vehicles – but for now long?

Diesel trains may expose passengers to exhaust

Levels of certain airborne pollutants are up to nine times higher in train cars directly behind diesel locomotives than on a busy city street

Bi-mode concerns at the diesel end of the line

'Hull is being taken for a ride when it comes to cleaner train travel'

This is why Bristol commuters will be breathing in dirty air long after diesel trains are banned

All diesel trains should be scrapped by 2040, Jo Johnson tells rail bosses

Speech

Let's raise our ambitions for a cleaner, greener railway

12th February 2018

Minister calls for diesel-only trains to be phased out as part of new vision to decarbonise the railway.

"I would like to see us take all diesel-only trains off the track by 2040. If that seems an ambitious goal, it should be and I make no apology for that. After all, we're committed to ending sales of petrol and diesel cars by 2040. If we can achieve that, then why can't the railway aspire to a similar objective?"

"As battery technologies improve we expect to see the diesel engines in bi-modes replaced altogether with batteries powering the train between the electrified sections of the network.

Or maybe in the future we could see those batteries and diesel engines replaced with hydrogen unit?

Alternative-fuel trains powered entirely by hydrogen are a prize on the horizon."

Can diesel engines by replaced by Hydrogen?

Answering this question needs an understanding of

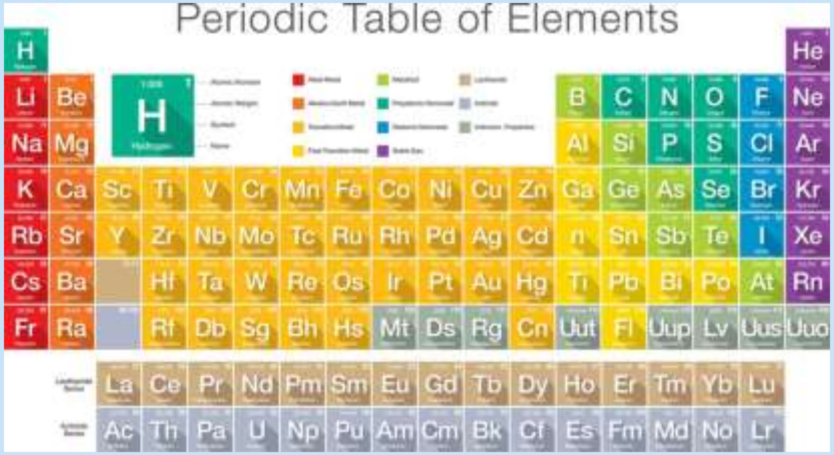
- Hydrogen
- Its production
- Its supply
- How it can power a train
- How hydrogen and its traction equipment can be fitted to a train
- The range and performance of hydrogen powered trains

Understanding Hydrogen – what do we know?

Is it safe?

- Not in an airship with 7 million cubic feet stored in cotton gas bags
- In vehicles, likely to be safer than liquid fuel

Understanding Hydrogen



- Lightest element of the periodic table
- Highly inflammable
- Discovered by Henry Cavendish in 1766 who called it “inflammable air”. He discovered that it formed water on combustion
- French chemist Antoine-Laurent de Lavoisier named the gas as hydrogen which is Greek for “water-former”
- So chemically active that it does not naturally exist
- Available from water (H_2O) or organic compounds
- Most abundant chemical substance in the Universe

Understanding Hydrogen

Low volumetric energy density compared with diesel

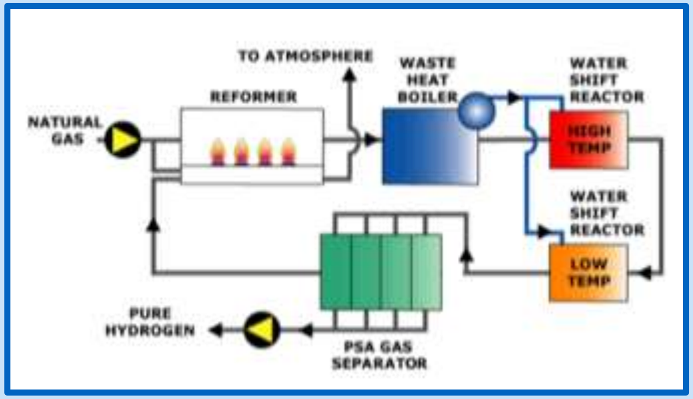
Substance	By volume (MJ/L)	By weight (MJ/kg)
Uranium	1,500,000	80,620,000
Diesel	35.8	48.0
Petrol	34.2	46.4
LPG	26	46.4
Hydrogen (at 350 bar)	**4.6**	**71**
Lithium-ion battery	2.6	0.9
Lead-acid battery	0.6	0.2

The space available to carry fuel on self powered trains is a significant constraint, especially within the UK loading gauge

Producing Hydrogen

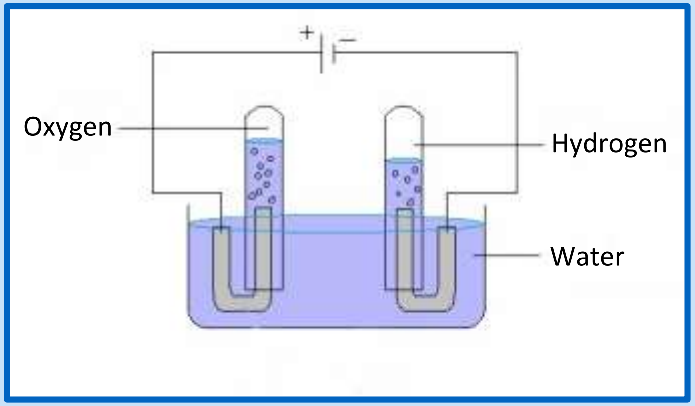
Currently about 50 millions tonnes of hydrogen produced annually mainly for ammonia production or petroleum refining by two main methods:

Steam reforming - extracts hydrogen from organic feedstock, usually Methane



$$CH_4+2H_2O=CO_2+4H_2$$

Electrolysis -DC current splits water molecules into Hydrogen and Oxygen



$$2H_2O=O_2+2H_2$$

Producing Hydrogen

Method	Percentage Production	Cost (£ per kg H_2)
Steam reforming	96%	2.6
Electrolysis (1)	4%	3.8 (2)

1) For small scale production, electrolysis is a more practical option
2) Based on typical electricity cost, less if off-peak energy used

Emissions	C02 (grams per MJ)	Pollutants
Hydrogen - reforming	57	None – exhaust is water
Hydrogen - electrolysis	0 (3)	
Diesel	74	$N0_X$, particulates etc

3) If electrolysis powered by renewable energy

Producing Hydrogen – Wind power developments

- Huge investment in off-shore turbines and specialist ships for maintenance and installation
- 154-metre turbines 7MW now being installed up to 100 km from the shore
- One control room for 7,500 Siemens turbines worldwide.
- With remote condition monitoring, very few visits to turbines, are required

- Wind is now the cheapest form of utility-scale power generation
- In past six years, costs reduced from £200 to £52 MW/hr
- A trend that is likely to continue

Supplying Hydrogen

- An Austrian study considers that by 2030 use of hydrogen for transportation will be double that required for normal industrial use.
- Transportation demand assessed as Rail – 70%; Bus – 20% and Private Vehicles – 10%
- Most hydrogen needed for industrial use is transported by pipeline. Hence its increasing use as transport fuel requires a disproportionate increase in land transportation
- Study is considering most economic and practicable methods of transporting hydrogen by rail including Liquid Organic Hydrogen Carrier (LOHC) in which hydrogen is bonded to a liquid carrier and transported at 50 bar pressure

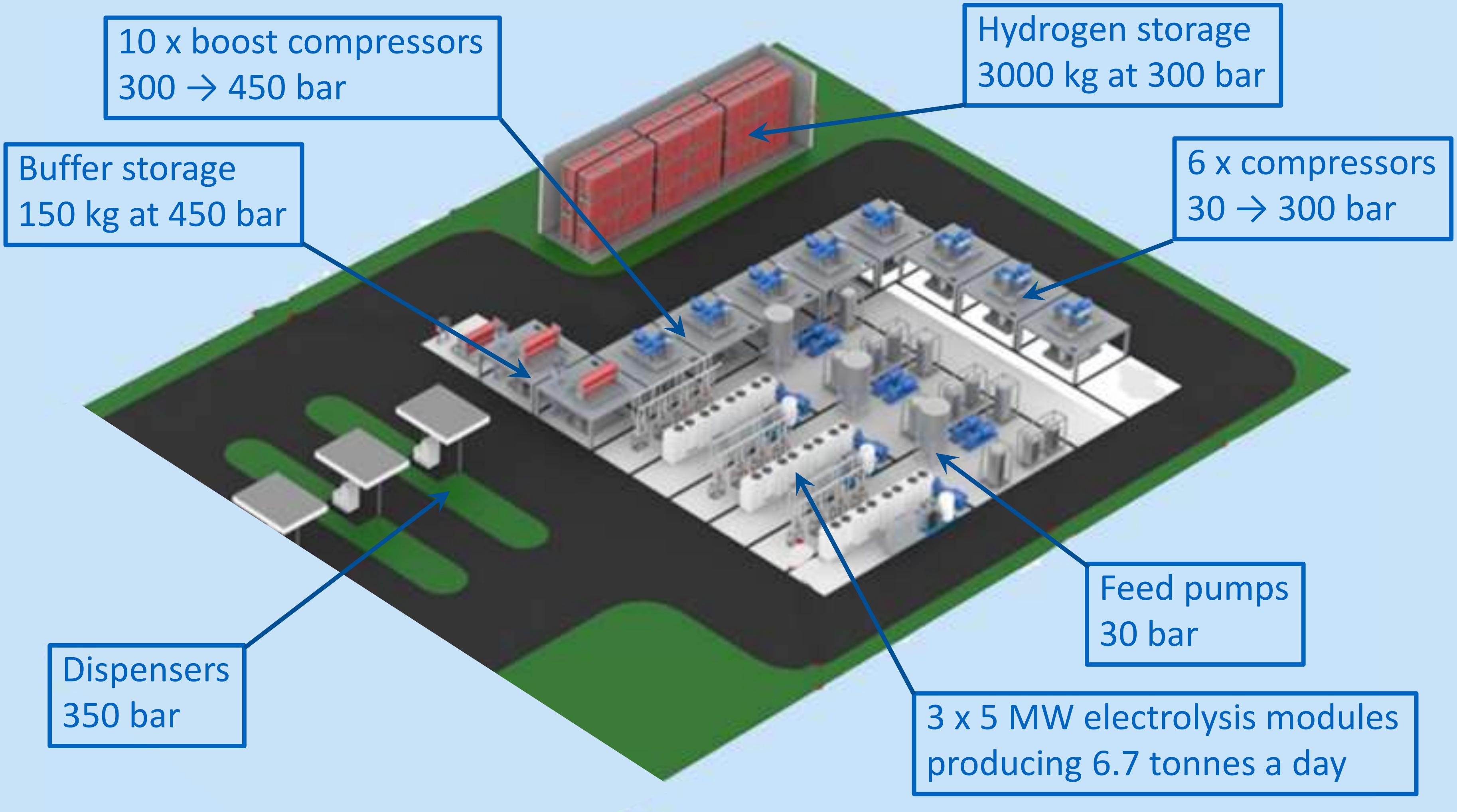
Large scale use of hydrogen for road and rail vehicles requires significant investment in appropriate facilities for its transportation

Small scale use requires resilient supply arrangements

Supplying Hydrogen – on site production

Or produce on site

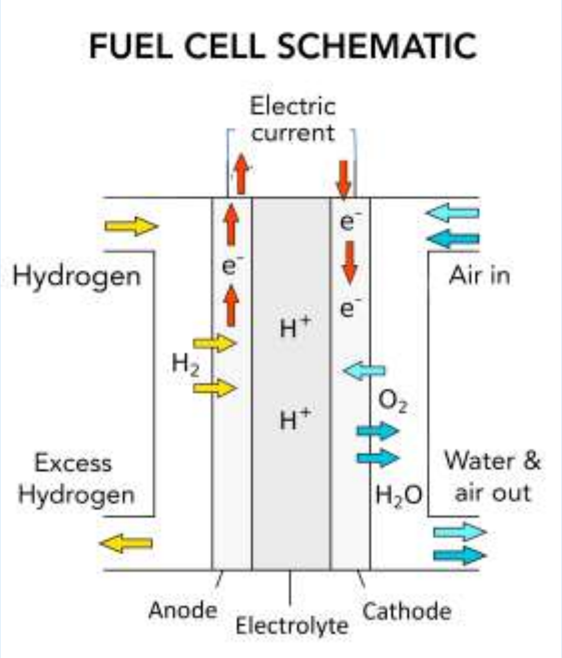
15 MW plant supplying 30 trains or 300 buses



Using Hydrogen – Fuel Cells

- Fuel cells are the reverse of electrolysis
- Invented in 1838
- First commercial use by NASA
- Typically 52% efficient, compared with 35% for a diesel engine
- Significant advances in recent years, fourfold increase in volumetric power density in ten years up to 2011

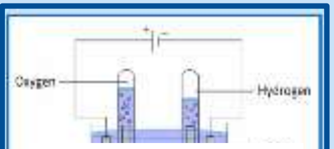
	2001	2003	2009	2011
Power (kW)	25	20	16.5	33
Mass (kg) Power density (W/kg)	290 86	170 117	92 180	75 440
Volume (L) Power density (L/kg)	365 68	180 111	133 124	125 264
Efficiency %	38 - 45	40 – 54	48 - 54	48 – 55
Components	25	8	6	6

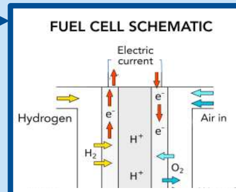


Using Hydrogen – well-to-wheel efficiency comparisons

Hydrogen - on site production from renewable energy

Electricity from grid 3.4 kW	Electrolysis	Compress to 350 bar	Fuel Cell	Converter and Drive	Wheel 1.0 kW
Efficiency	68%	94%	52%	89%	Overall 29%





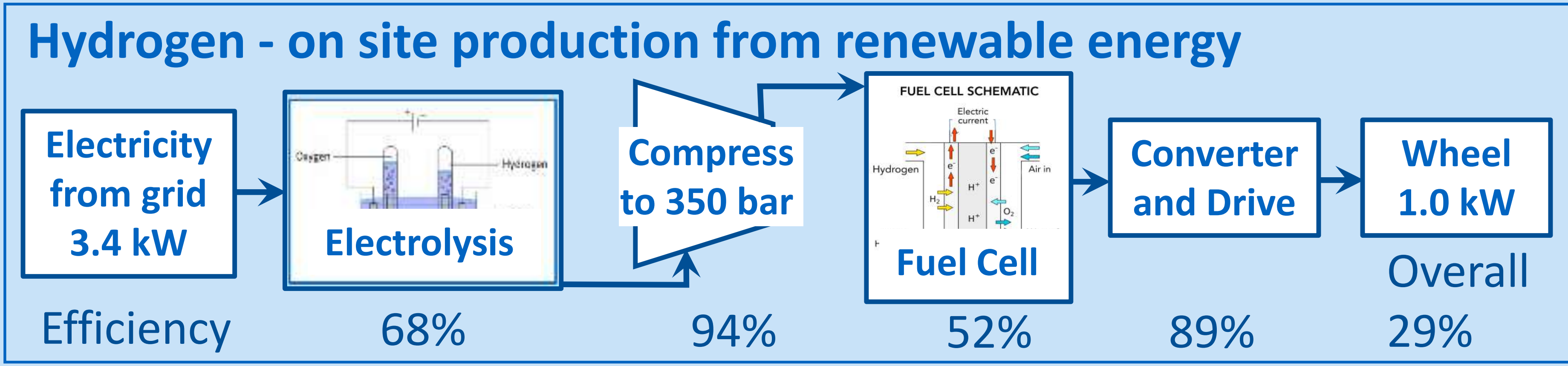
Diesel

Diesel 3.7 kW	Engine	Transmission	Final Drive	Wheel 1.0 kW
Efficiency	38%	78%	94%	Overall 27%

Electrification from renewable energy

Electricity from grid 1.2 kW	OLE Transmission	Transformer	Converter and Drive	Wheel 1.0 kW
Efficiency	98%	95%	89%	Overall 83%

Using Hydrogen - efficiency



Hydrogen offers an "electrified" railway that is only 35% as efficient than one with wires with some time between consuming electricity and using it. It:

- is an energy vector i.e. can be produced from an energy source, stored, transported and converted to another form of energy
- has a predictable cost which is the capital, operational and maintenance cost of the kit required
- offers fuel self-sufficiency
- provides the large scale energy storage which is essential for efficient use of renewable energy
- can be produced from otherwise surplus overnight wind power which is likely to become even cheaper

Using Hydrogen

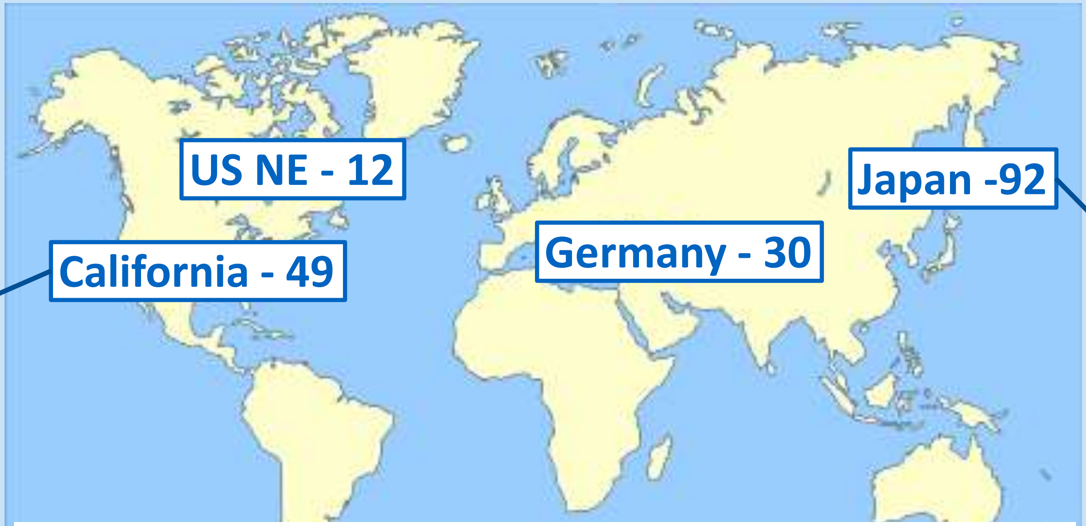
Example Energy Vector

Wind turbine and tidal turbines on Eday provide overnight shore supply for ferries at Kirkwall via

- 0.5MW electrolysis plant and hydrogen storage on Eday
- Hydrogen shipped to Kirkwall
- Hydrogen storage and 75 kW fuel cell at Kirkwall

Hydrogen – on the roads

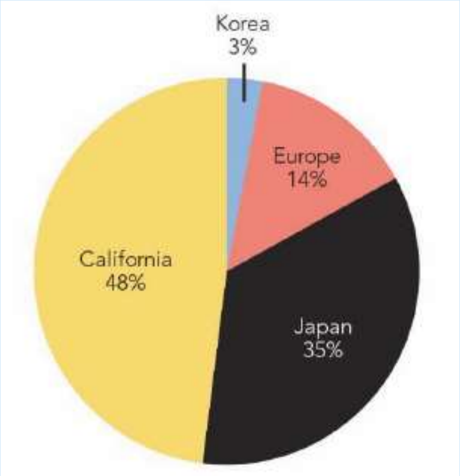
5,000 hydrogen cars in 2017, 18,000 by 2020



Main centres with Hydrogen refuelling stations - 2017

3,000 hydrogen cars in 2017, 40,000 by 2020

European Hydrogen Bus Fleets			
Belgium	8	Netherlands	18
France	5	Norway	5
Germany	17	Switzerland	5
Italy	18	UK	20
		Total	91



Hydrogen vehicles sold in last six years

Hydrogen – on the roads

Europe's joint largest bus fleet in Aberdeen

Hydrogen – on the roads

Mirai helps Met Police clean up London

MARCH 13, 2018

The Metropolitan Police Service is set to team up with the Toyota Mirai to help create the world's largest fleet of zero-emission hydrogen fuel cell electric police vehicles.

The first of 11 cars have been delivered to the Met with support from the FCHJU* grants programme and are equipped to work as both marked and unmarked vehicles for overt and covert response, as well as general purpose use.

The only tailpipe emission they produce is water – a by-product of the fuel cell process, turning hydrogen into electricity to power the vehicle. Their zero-emission performance will help the Met in its efforts to support the Mayor of London's clean air strategy.

Hydrogen with blue lights and sirens

Hydrogen Council

- Launched at Davos in January 2017,
- Initially 13 transport and energy companies who plan to invest 10 billion euros in hydrogen technologies over next five years.
- Membership is now 40 companies

3M | Air Liquide | ALSTOM | AngloAmerican | Audi | BMW GROUP | BOSCH Invented for life | CHN ENERGY 国家能源集团

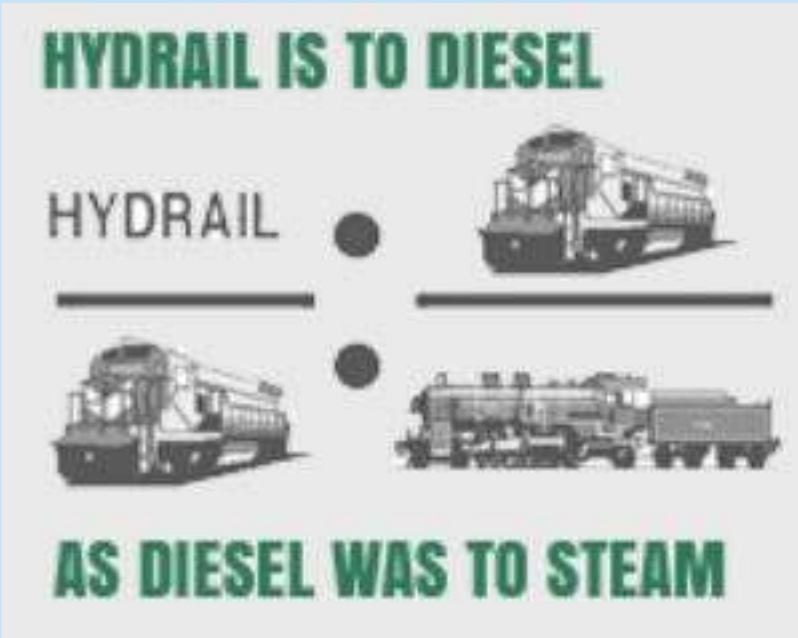
DAIMLER | ENGIE | GM | Great Wall | HONDA | HYUNDAI | Iwatani | JXTG Nippon Oil & Energy

Kawasaki | Plastic Omnium | Shell | Statoil | THE LINDE GROUP | TOTAL | TOYOTA | WEICHAI

BALLARD | Faber Cylinders | faurecia | GORE | HEXAGON | HYDROGENICS | Marubeni | McPhy | Mitsubishi Corporation | MITSUI & CO. | nel | PLUG POWER | TRUE ZERO | TOYOTA TSUSHO | Vopak

Hydrogen Council

Hydrogen – on the rails



2005 First annual international Hydrail conference held in North Carolina, largely an academic affair

2017 Hydrail conference in Graz, most speakers from hydrogen businesses

2006, Japan
World's first Hydrogen train
2 x 95 kW fuel cells

2010, Los Angeles, USA
130-ton diesel shunter
240 kW fuel cell

Hydrogen – on the rails

2011, Spain
Metre-gauge tram
2 x 12 kW fuel cells

2013, China
45 tonne locomotive
150 kW fuel cell

2012, South Africa
Mine locomotive
17 kW fuel cell

2015, China
Tram
200 kW fuel cell

Hydrogen – on the rails

University of Birmingham’s Hydrogen locomotive powered by a 1kW fuel cell at the IMechE’s Railway Challenge on the Stapleford 10 ¼ inch miniature railway 1st July 2012

Hydrogen – on the rails

First prototype of Coradia iLint was unveiled to the public at InnoTrans in Berlin in September 2016

ALSTOM

Hydrogen – Alstom's iLint

2014 Alstom signs Letter of Intent with Germany's Lower Saxony, North Rhine-Westphalia, Baden-Württemberg states to develop a hydrogen fuel cell train

2015 Alstom signs €50 million contract with Canadian fuel cell manufacturer Hydrogenics for supply of 200 fuel cells over 10 years

2016 Production of two prototypes

2017 March - First 80 km/hr test run, approval to carry passengers

2017 November - €81 million contract signed to supply 14 iLints to Lower Saxony by 2021. Letters of Intent with 3 more northern German states for 44 trains

2018 Two prototype iLint trains to enter service in Lower Saxony

Lower Saxony generates a quarter of Germany's wind power and has an installed wind power capacity of 7,800 MW. It plans to increase this to 20,000 MW by 2050

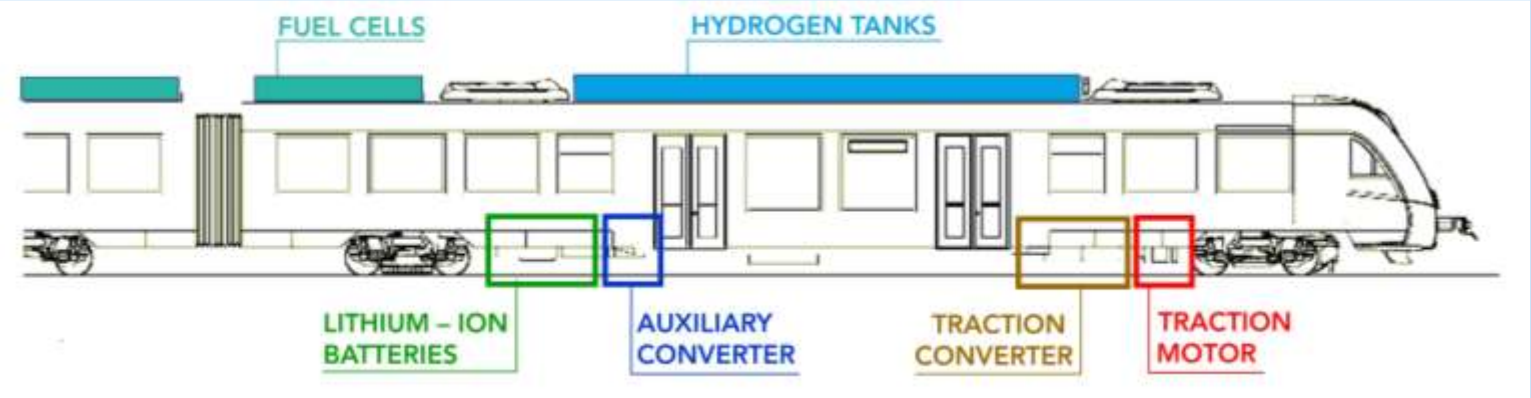
Hydrogen – Alstom's iLint

- First Lower Saxony service to be Buxtehude- Bremerhaven- Cuxhaven
- 240 km with 44 stations and many gradients
- Hydrogen consumption calculated to be 0.23 kg/km or 7.7 kWh/km
- This compares with a DMU's estimated 10.8 kWh/km
- A 29% saving due to regenerative braking
- Each unit covers 600 km/day consuming 138 kg hydrogen
- 2,000 kg /day for 14 units

German states committed to the iLint

Linde Group will provide the world's first train hydrogen filling station at Bremervörde depot at a cost of €10 million to be operated by Alstom who will provide a tanked and maintained train.

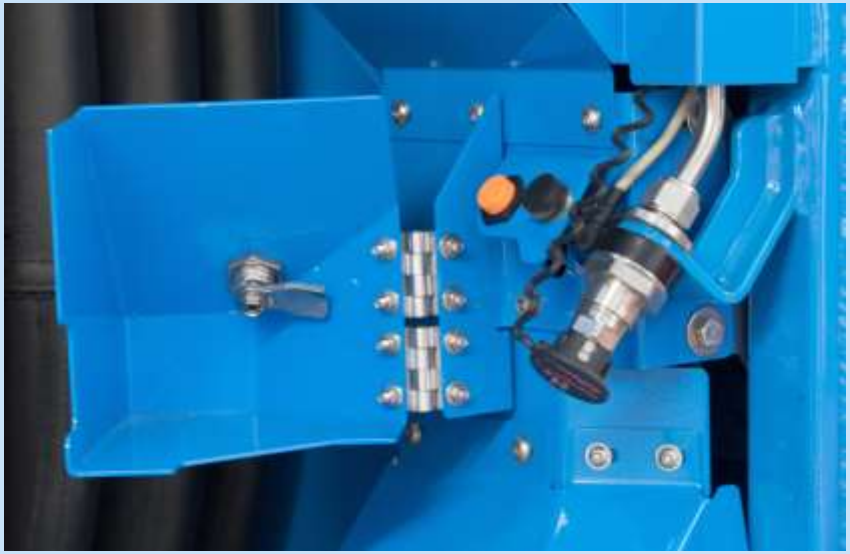
Hydrogen – Alstom's iLint



- Based on Alstom's 100-tonne two-car Coradia Lint 54 which has a 390 kW underframe-mounted diesel engine driving powered axles by a cardan shaft
- iLint has a traction motor instead of the Lint 54's diesel engine
- Maximum speed of 140 km/hr, weighs 107 tonnes (7 tonnes more than Lint 54)
- Hybrid unit, each coach has a 200 kW fuel cell that charges a 225 kW battery to give a peak power output of 425 kW per coach – peak 7.9 kW / tonne power to weigh ratio (25% more than a class 170)
- Battery capacity of 350 kWh provides sufficient peak power for long gradients
- On routes with frequent stops, energy savings from regenerative braking of around 30%
- Roof tanks on each coach hold 89 kg Hydrogen at 350 bar giving a range of between 600 and 800 km. Refuelled in 15 minutes.

Hydrogen – Alstom's iLint

Hydrogen Fuel Cells



Hydrogen fuelling point

HVAC and Hydrogen tanks

Hydrogen – Alstom's iLint

Energy management display

Hydrogen – A Canadian proposal

Metrolinx GO commuter network Toronto, Ontario

- 421 km network
- Operated by 12 x 49-tonne double-deck coach trains hauled by 5,400 hp (4,000 kW) diesel locomotives
- In 2010 decision taken to electrify 250 km of network
- Feasibility study to consider hydrogen powered trains as part of the electrification assessment agreed in 2017
- Study published in February concluded that "it should be technically feasible to build and operate a Hydrail system for the GO network"

Hydrogen – A Canadian proposal

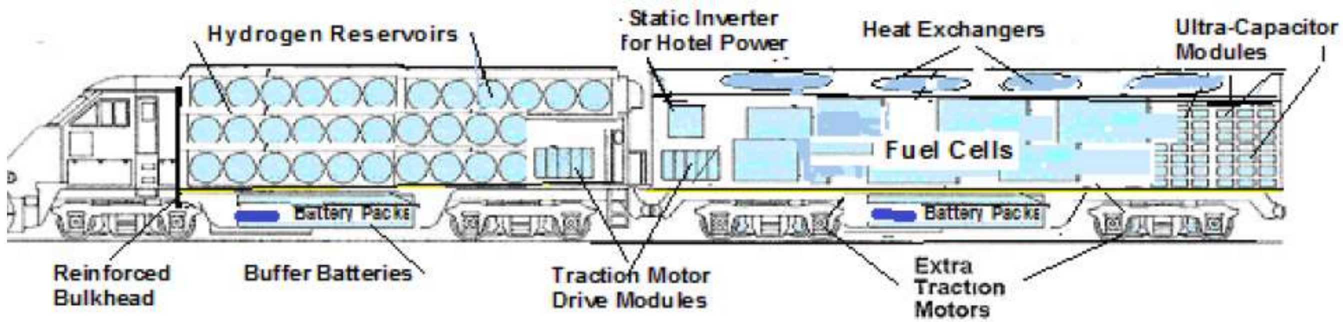
To do this would require

- 50 x 5,600 kW hydrogen locomotives, two for each 12-coach train as a single loco could not carry sufficient hydrogen
- Hydrogen stored at 700 bar
- 84 x 4-car hydrogen powered double deck units
- 40 tonnes of Hydrogen per day from 2.3 GWh of electricity
- 367 km hydrogen pipelines
- 250 MW of electrolysis plant
- Hydrogen infrastructure costing $833 to $1068 million compared with the $1762 capital cost for electrification

Hydrogen – A Canadian proposal

Proposed 5,600 kW hydrogen locomotive

"We also know that modern rail vehicles are complex machines where equipment needs to be installed in very confined spaces. Therefore, it would not be surprising if some system integration challenges are encountered during the design phase which require unplanned scope of work to resolve. We would be confident that these types of issues could be resolved through focussed engineering effort which would not have a significant impact on the development, test and build durations of the HFC rail vehicles."



Previous studies had considered a Metrolinx married-pair locomotive

Double-deck hydrogen units

"As for most other gas-fuelled passenger-transport vehicles, single-deck EMUs can use the space above the carriage roofs for fuel storage, but the limitation of overhead clearance constrains this option with double-deck EMUs. So, the precise effect of fitting Hydrail into double-deck EMUs has still to be determined and could reduce passenger-carrying capacity."

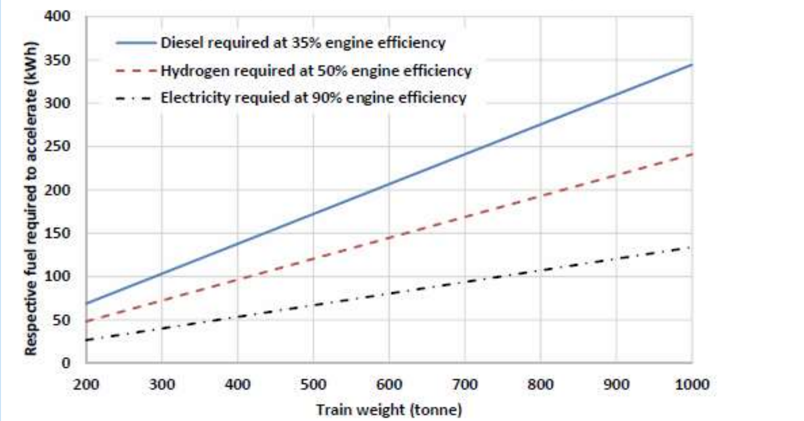
Hydrogen – An alternative fact

Regional Express Rail Program
Hydrail Feasibility Study Report

CPG-PGM-RPT-245

Revision B
February 2, 2018

FIGURE 4-11 RELATIONSHIP BETWEEN TRAIN WEIGHT AND FUEL REQUIREMENT [85]



hour (kWh). The respective engine efficiencies listed in Figure 4-11 are the typical fuel conversion efficiencies for each of the propulsion technologies currently available – diesel (35 percent)[86], hydrogen (50 percent) and electricity (90 percent)[87].

- 353 page report considers hydrogen trains have a 50% efficiency
- In doing so it ignores losses from the production and compression of hydrogen for storage
- Compression to 700 bar (350 bar on iLint) requires 20% of energy in gas
- Hence correct overall efficiency ≈ 25%
- Report notes that cost of electricity may affect viability of hydrogen trains, much more likely if the correct efficiency figure is used

Hydrogen – Is it the answer?

	Passenger multiple unit trains		
	Hydrogen / Battery	Electric	Diesel
Power/range constraints	Low energy density of hydrogen	Power supply through OLE	Diesel engine & tank
Typical kW/t	8 kW/t (iLint)	12.6 kW/t (class 385)	6.4 kW/t (class 170)
Efficiency (1)	29%	83%	27%
Regenerative braking	Yes	Yes	No
CO2	Depends how electricity is generated		2.6 kg per litre
Emissions	Only emission is water	None at point of use	NoX, particulates etc
Energy vector	Yes	No	No
Infrastructure required	Hydrogen distribution, storage and supply	OLE and power supply	Diesel storage and fuelling points

1. Does not consider efficiency of generating plant

Hydrogen – Answer: Yes in some cases

YES for non electrified medium-speed/ range services

- Almost mature technology - ready to carry passengers (in Germany)
- Offers DMU performance, efficiency and range
- Long term stability of fuel costs
- Synergies with renewable energy supply and hydrogen road vehicles
- Zero emissions

NO for high speed / long range services

- Limited range due to low energy density of hydrogen
- Not a bi-mode diesel module replacement
- Poor efficiency - Almost three times the energy consumption of an electric train
- Electric trains are more powerful

Not a replacement for electrification but it may be for short and middle distance diesel trains that comprise 2,438 vehicles (17% of UK fleet)

Hydrogen – Is it the answer?

iLints for the UK?

- UK loading gauge is an issue but unlikely to be a significant problem
- Roof space required may preclude modification of existing surplus units
- Best to start with a small fleet rather than just one prototype due to cost of a Hydrogen infrastructure

Hydrogen – Is it the answer?

Locomotives

2010 USA trial showed that hydrogen is a good way of powering shunters that have intermittent use

Russian LNG powered two-unit gas turbine locomotive

It is not clear whether hydrogen could power a high-powered freight locomotive. With its low volumetric energy density a separate tank vehicle is likely to be required as in the above example

Where hydrogen isn't the answer what is?

Batteries

- Potential for branch lines off the electrified network as demonstrated by IPEMU test
- This was an EMU with an eight tonne traction battery and a range of 80 km
- Cost effectiveness may be an issue
- Lithium ion batteries have half energy density of hydrogen
- Recharging time roughly same as discharge time

Alternative fuels

- Potential future development that keeps internal combustion engines
- Significant research into zero-carbon liquid fuels from Biomass and waste CO2
- Compressed or Liquid Natural Gas (LNG) emits 10% less CO2 than diesel with greatly reduced tailpipe emissions
- LNG offers greater range but requires to be cryogenically stored in liquid form

The Guardian

UK edition

The entrepreneurs turning carbon dioxide into fuels

The race is on to prove that CO2 can be taken from the air and recycled into profitable, carbon neutral fuels. But cost and investment obstacles remain

Russian LNG Shunter

Where hydrogen isn't the answer what is?

Electrification – existing

- 42% of UK mainline network is electrified
- 72% of UK passenger fleet are electric trains
- Electric fleet has greatest CO_2 impact – Can this be reduced?


The Guardian
UK edition
Dutch electric trains become 100% powered by wind energy
The national railway company, NS, said that its renewables target had been met a year earlier than planned

Electrification – future

- Most efficient traction with lowest CO_2 footprint
- Zero CO_2 if generated from renewable energy
- No emissions at point of use
- Government has to be convinced it is cost-effective

Electrification Scheme	£million per track km
Great Western	2.8
EGIP	1.5
Denmark	1
BR East Coast	0.3

Cost effective electrification is currently the only alternative to diesel traction for high-power / long range traction

Hydrogen – Conclusion

Hydrogen trains are part of the future but they are not -

1st Law of Thermodynamics
“Energy cannot be created it can only be converted from one state to another”

Newton’s 2nd Law of motion
“The rate of change of momentum of a body is directly proportional to the force applied”

Whatever decision makers might say these laws of physics can’t be changed

Thanks for your attention